A TRANSIENT MODEL FOR LEAD PIPE CORROSION IN WATER SUPPLY SYSTEMS

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Civil Engineering
University of Toronto

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ABSTRACT

A Transient Model for Lead Pipe Corrosion in Water Supply Systems

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This thesis focuses on lead related drinking water quality issues in general and on hydraulic transient induced lead pipe corrosion events in water distribution systems in particular. Corrosion is a complex phenomenon, and particularly in water distribution systems, when its already challenging electro-chemical processes are influenced by numerous other physical and chemical factors. Lead pipe corrosion can itself be influenced by both the hydraulic transients and water chemistry events. To understand the relationship among hydraulic, chemical and material processes, an existing numerical 1-D transient-corrosion model for iron-pipe based systems is modified and extended to apply for systems having lead-pipes connected in series. The coupled hydraulic transient and advection-dispersion-reaction model with improved data handling facilities is applied for analyzing the transient induced lead pipe corrosion behaviors in the system for a range of options and establishes interrelationships among the parameters.
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I found Bryan W. Karney as not only an outstanding university professor, but as a great motivator with immense patience and feelings for the students as well. I would like to express my whole hearted admiration and thanks to him for providing me an interesting topic for the thesis and his continuous guidance, inspiration and supports in spite of his extremely busy schedule. All of this is greatly appreciated.

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<td>TDM</td>
<td>Time driven method</td>
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<td>THM</td>
<td>Trihalomethanes</td>
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<td>WCM</td>
<td>Wave characteristics method</td>
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<td>WDS</td>
<td>Water distribution system</td>
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<tr>
<td>RMIC</td>
<td>Recommended maximum impurity contents</td>
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CHAPTER 1

INTRODUCTION

“A man can surely do what he wills to do. But, he can’t determine what he wills.”

Arthur Schopenhauer: The World as Will and Idea

The behavior of water distribution systems and their associated elements are inherently complex in nature, and each system is different from the others. Water quality within the distribution system is largely influenced by the prevailing physical, hydraulic, chemical and microbiological processes of each system. The degradation of the supply water quality is usually a consequence of some combination of poor quality of water at the intake, improper treatment in the treatment plant, cross connections, possible negative-pressure intrusion at leakages in the pipes and joints, corrosion of the pipes and fittings/fixtures, dislodging of corrosion scales and bio films, inadequate disinfectant residuals, longer residence time in the system, reaction of the disinfectants with organic and inorganic compounds, and bacterial re-growth, re-suspension of sediments due to hydraulic transient events and formation of the disinfectant by-products (Grayman et al. 2000).

This research specifically focuses on the influence of the hydraulic transient events, and key water quality parameters such as hydroxyl ion concentration (pH) and the dissolved oxygen (DO) of the bulk water, on lead pipe corrosion and consequential lead release processes. A one dimensional numerical transient-corrosion model is developed, to
evaluate the inter-relationships between pH, DO, transient and corrosion processes in the system with multiple diameter lead pipes connected in series. In the proposed numerical model there is computational flexibility associated with changing pipe diameters, lengths, and different combinations of the pipes in series, as well as from changing head of the reservoirs located at upstream and downstream ends, pipe wall roughness, opening and closing speed of the valve to simulate their hydraulic responses on the corrosion process. The model is extensively run in order to anticipate the effects of change in pipe diameter, reservoir heads, pipe wall roughness, pH, DO, combination of the different sets of pipes (diameter and lengths), on hydraulic transient events and particularly corrosion in the lead pipe based service systems.

1.1 Significance of Thesis

The understanding of the response of the water supply system to both hydraulic transient and electro-chemical corrosion events has been increasing rapidly. The major development has been better techniques of hydraulic analysis including topologically complex networks including the system pipe junctions (nodes), pipes (links), loops and associated hydraulic devices such as reservoirs, tanks, pumps and valves (Fernandes 2002). Consideration of the dominant water quality events and hydraulic transient phenomena that is responsible for the pipe ruptures, contaminant intrusion through leakages, accelerated corrosion as a result of the generation of extra turbulence, high velocities and re-suspension of the sediments are important for comprehensive modeling of the distribution system behavior. Sudden shut down of the pumps or closing of the valves, instantaneously may generate transient pulses of high pressure waves that travel to and fro in the pipe system, and that have considerable
capacity of adversely affecting water quality. The transient flow significantly influences the overall mass transport processes and as a result can affect quality of the water in the distribution system as stated earlier. This potential change in the mass transport processes may be especially important from the internal corrosion standpoint, since rapid alteration of the flow velocity, due to transient phenomena, can facilitate transport of fresh oxidants from the bulk water to the pipe wall surface, resulting in accelerated corrosion (Naser 2006). Based on this concept, a corrosion induced water quality model for lead is developed herein. The solution of the large non linear systems of the equations, even for the simplest steady state condition, is not an easy task. In fact, the required computer algorithms, to study temporal physical responses of the distribution system, specifically an evolution under almost steady state long term simulation that is called extended period simulation, has only quite recently been attempted (Fernandes 2002) and the overall field is still in its infancy.

This thesis emphasizes lead-pipe corrosion problems related to water chemistry, as well as hydraulic transient events. The governing parabolic second order partial differential equation, representing mass transport process dominated by the advection (flow velocity induced), dispersion and reaction in the distribution system, is solved numerically by using an implicit finite difference method. The method of characteristics is employed to solve the governing non-linear hyperbolic partial differential equations for the conservation of mass and conservation of momentum, representing hydraulic transient conditions in the water distribution system. Finally, the finite difference solution for the mass transport process and the method of characteristics solution for the hydraulic transient events are superimposed. The hydraulic model thus created can represent a spectrum range of flow conditions ranging from quasi steady, to unsteady incompressible or rapidly unsteady
(water hammer) states. The method of characteristics has advantageous attributes of accuracy, simplicity and numerical efficiency. The superimposing strategy of the two sets of the solution algorithms (for mass transport and hydraulic transients), was found to be produced good results in iron corrosion and the resulting numerical solution was determined to be stable, consistent, convergent, requiring no substantial increase in memory and is intrinsically compatible (Fernandes 2002). In simulating the distribution system most available water quality models assume either steady state flow or the concept of nearly steady state flows, particularly extended period simulation in which flows are updated at fixed times or when a new demand pattern is established, as per demand curve or pump schedule or valve operation. But, in reality, the system is seldom steady but subjected to everything from sudden valve opening/closures, to pump switching and power outage, to mechanical faults such as caused by a pipe burst. The system response to such an event is often fast and strongly influenced by fluid inertia and compressibility effects, which are not accounted for in traditional modeling (Fernandes 2002). But, the proposed model is capable of providing better understanding of the impacts of hydraulics on water quality and simulating dynamic responses of the system for a range of the flow conditions.

Many phenomena, from the corrosion of the lead pipes, to scale formation and a consequential lead release to bulk water, may significantly deteriorate water quality, and these concerns have therefore become a growing concern for municipalities and water scientists. Although installation of the new lead service pipes has been banned since 1970 (AWWARF 1996), many urban areas of the North America still have lead based service pipe lines. They are corroding, and continuously releasing lead into the system; thus, lead levels in the supply water may exceed the established safe level (10 µg/L) or even the
action level (15 µg/L) (Federal Register 1991). High lead level in drinking water is a real health risk as lead accumulated in the blood and bones may impede neurological and physical growth of unborn child or children less than six years of age, and can damage important organs of the human body including the brain, kidney and liver (USEPA 2005). Overall, a detailed and comprehensive investigation on transient-chemical induced lead pipe corrosion through integrated numerical modeling is both justified and reasonable.

The transient-corrosion model originally developed by Fernandes (2002), and latter improved by Naser and Karney (2005), was originally applied to an iron pipe based distribution system and with a single diameter pipe. For the present research, that model has been customized, extended and improved to create a lead based distribution system having multiple diameter pipes connected in series. To customize the model for lead pipe, properties related to the chemical kinetics of the lead reactions such as equilibrium constants, oxidation-reduction reaction rate constants, solubility products, and the appropriate atomic weights are incorporated into the adapted model. To include multiple diameter pipes connected in series, an important extension of the existing model is required, such as introduction of the new boundary condition for the junction of two different diameter pipes, and extension of the numerical solution scheme. The data generation system has been improved to include options for producing a time-series for each water quality parameter and hydraulic event for the entire simulation period (or specified time period) and for the specified reaches/points have been incorporated. In addition, generation of the spatial data for each water quality and hydraulic component with their identification labels has been added. This is important as completing a single runs, particularly with a simulation period of a few hours and all data generation options turned on, the computer
memory requirement is about 120GB. Thus, to reduce the volume of unwanted or unnecessary data and to save computer hard disk space, options for turn on/off for both the time series and spatial data for water quality and hydraulic components have been introduced into the model. The developed models is applied to simulate and evaluate for a wide range of hydraulic and water chemistry conditions, produce large representative data sets, and comprehensively analyze and establish relationships among hydraulic, water chemistry and corrosion parameters.

1.2 Objectives

The first objective of this thesis is to better understand lead chemistry and general corrosion processes of the lead pipes functioning in the water distribution system, specifically when these pipes are subjected to the hydraulic transient conditions and consequential lead release mechanisms. The investigation focuses on physical factors, key water chemistry parameters and hydraulic aspects involved in the corrosion processes.

The second objective is the customization, extension and improvement of the existing one dimensional numerical hydraulic transient-corrosion induced water quality model for the single diameter, iron pipe based system so that it can be used in at least a preliminary fashion to simulate and analyze behavior of the systems having lead based multiple diameter pipes connected in series. The chemical reactions considered in the model are oxidation of the metal surface of lead pipe due to the presence of dissolved oxygen (DO) and reduction due to the presence of hydroxyl ion (pH) in supply water, for which, initially produce lead ion (Pb$^{2+}$) and hydroxyl ion (OH$^-$), and finally forms scale of lead hydroxide (Pb(OH)$_2$). That is, this work is an investigation of the impacts of the
chemical species such as DO, pH in the water and hydraulic transient events on corrosion of the lead pipes.

The third objective of the thesis is the application of the proposed transient-corrosion model to a lead based distribution subsystem, to simulate and analyze the system responses and behaviors, against a wide range conditions. To investigate interrelationships and interdependence of the water quality and hydraulic parameters with regard to corrosion process in the lead pipe, comprehensive analysis of the data obtained through model simulations and applications. While it would be ideal to fully validate and calibrate the model, appropriate data sets were not available to the author and the model is thus presented in a preliminary way, recognizing it needs more complete testing.

1.3 Methodology

The mass transport processes in the distribution system is an important factor for determining corrosion of the metallic pipe surface and thus of water quality, especially, if the pipe metal is lead. In addition, prevailing hydraulics of the system is also important for water quality in the distribution system. In this thesis, to achieve the first stipulated objective, an extensive literature review on the use and availability of lead in the distribution system water, its corrosion behaviors, scale formation and lead release mechanisms, sampling and quantifications, variability and potential controlling processes was undertaken. Reviews of the general corrosion processes of the metal surfaces and their potential mitigation strategies have been performed. From the outcome of literature surveys, a strong knowledge base and thorough understanding of the general corrosion and lead pipe corrosion processes is developed.
To achieve the second objective, the author has thoroughly reviewed the formulation, coding and parameterization of the existing 1-D transient-corrosion model developed for the single diameter iron pipe based system. After reviewing and understanding of the prevailing implementation, the model has been extended for a system with multiple diameter pipes connected in series, customized for the lead pipe material and improved for the time series and spatial output specifications. These output options include component-wise (hydraulics and corrosion species) for specified time periods (entire simulation period or part thereof) and specific locations, for ease and flexibility of analysis and with proper labels for easy identification. The temporal and spatial mass transport process is formulated through the advection-dispersion and reaction equation. The chemical species participating in the corrosion reactions are tracked individually, to form a multi-component model. Hydraulic transient events are formulated by employing laws of conservation of mass and momentum, considering unsteady and compressibility effects of the water. Following the lead of others, the governing non-linear partial differential advection-dispersion-reaction equation is solved with an implicit finite difference method and the governing hyperbolic partial differential equations for hydraulic transient event are solved by utilizing method of characteristics. Finally, solutions for the advection-dispersion-reaction and hydraulic transient equations are superimposed to obtain the integrated transient-corrosion model. For coding of the mathematical formulations and solutions, the programming language FORTRAN 90 is used. In the model, the dominant oxidation and reduction reactions are incorporated those are responsible for electro-chemical corrosion of the system’s metal pipe surfaces.
To achieve the third objective, the model is simulated and applied for a range of conditions such as different static heads, combination of the sets of different diameter pipes/pipe lengths, flow velocities, residence times, changes in key water quality parameters (e.g., the concentration of dissolved oxygen (DO) and hydroxyl ion (pH) in bulk water), as well as the responses to different wall roughness conditions. From simulations and applications of the model, huge time series and spatial data for corrosion and hydraulic components are generated. To study and establish interrelationships and interdependences among different corrosion induced water quality and hydraulic parameters in the system, significant analyses of the data are undertaken.

1.4 Organization
The work done in this thesis focuses on the lead related water quality issues in the water distribution system in general, and specifically, transient induced corrosion development in the lead pipe based system, as well as on the impacts of water chemistry parameters on basic corrosion processes. In order to achieve the predetermined objectives, the thesis is organized in three main sections. The first section, Chapters 2 to 3 review of the lead and corrosion related issues, theories, challenges, forms of corrosion, typical management approaches for the general corrosion as well as the distribution system specific corrosion. In the second section, Chapters 4 to 5 provide an overview of the mathematical formulation of the prevailing hydraulic transient and water quality processes in the water distribution system, governing equations and their numerical solution schemes/approaches. The third section includes Chapters 6 and 7 presents the simulation results, as well as the application
of the developed model for a range of conditions, and the generated output is analyzed to study relationships and dependencies, and conclusions and recommendations.

More specifically, in the first part of the thesis, Chapter 2 reviews lead related health issues, availability of lead, sampling and quantifications, problems and challenges, disinfection, disinfection byproducts, corrosion inhibitors, lead control strategies and management approaches. The Chapter 3 reviews the general corrosion development processes, forms of corrosion, lead pipe corrosion process, impacts of water quality parameters, disinfectants, corrosion inhibitors, flow velocity, pipe wall roughness and transients on lead corrosion, mysterious behavior of brass and copper in home plumbing system, available lead corrosion models in brief, and corrosion mitigation and management approaches.

Next Chapter 4 presents a brief literature review of the mathematical formulation, assumptions and typical solution approaches of the hydraulic transients and water quality processes predominant in the distribution system and available commercial transient-water quality models. The Chapter 5 then describes the detailed mathematical formulation of the governing equations for the hydraulic transient events, numerical solution scheme, initial and boundary conditions in general and for the extension of the model. This chapter also presents the governing equation for the distribution system’s mass transport events, discusses the approximations of the solution, initial and boundary conditions, and summarizes the numerical solution scheme. In addition, it presents stability criteria for the numerical solution, and computation and data acquisition with the proposed model.

In the final part, Chapter 6 is dedicated to the main work of simulation and application of the proposed transient-corrosion model for various lead pipe systems for a
wide range of hydraulic and water quality conditions. This chapter discusses the huge generated output data from the model applications and analyses this to investigate inter-relationships and inter-dependencies of the hydraulics and water chemistry parameters for corrosion processes in the distribution system. Finally, Chapter 7 presents the tentative conclusions while summarizing the limitations of the present study and recommendations for the further studies.
“You see, one thing is, I can live with doubt and uncertainty and not knowing. I think it’s much more interesting to live not knowing than to have answers which might be wrong. I have approximate answers and possible beliefs and different degrees of uncertainty about different things, but I am not absolutely sure of anything and there are many things I don’t know anything about, such as whether it means anything to ask why we’re here.”

Richard P. Feynman

2.1 Introduction

Human beings are not always completely rational. This non-rationality expresses itself in how people perceive issues of the risk and safety (Glicker 1992). Inevitably, the future presents many challenges for us in dealing with the public and maintaining public confidence. The increased public awareness about the environment has magnified people’s concern about water quality and health related risk. Utilities must respect (and sometimes challenge) these concerns, values and perceptions of risk. Moreover, treatment challenges will inevitably arise in order to meet the new regulations. Changing societal values will affect the existing supply system. It is the responsibility of the utilities to reassure people that the supply drinking water quality is safe and that engineer’s decisions to modify it are based on sound scientific information (Glicker 1992).

There are inadequacies in existing lead and copper rule (LCR) in controlling corrosion and lead leaching due to poorly designed sampling and testing programs, and insufficient monitoring activities (Renner 2004). Scientists have recognized that current
regulations are often too weak and have called for changes in the testing for lead, for control of pipe corrosion and for supplier to properly notify residents of contamination problems. The important issue is that, to comply with LCR and disinfection by product regulation (DBPR), opposing actions are often required. That is, existing LCR and DBP regulations are sometimes in conflict and there is an urgent need to review and harmonize them. Scientists and engineers are seeking to better understand important lead & copper treatment chemistry issues.

There is undoubtedly a relationship between lead release and hydraulic transient phenomena as transient induced extra turbulence, changes frequency of stagnation, and events can disrupt biofilms or impervious barrier on the pipe wall that may result increased lead release (Vasquez et al. 2006). Biofilms develop an impervious barrier between the corroding metal surface and water that passivates and short circuits corrosion. However, many solid films are pervious and allow corrosion to continue. Film disruption is also affected by water quality (WQ). Huggins (2007) during discussion of the case of the City of London mentioned that due to high flow velocity (disturbance due to extra turbulence), more lead is expected to be released into the supply water. But, no significant literature is yet found on this issue. In this context, the effect of hydraulic transients on lead release in a distribution system is an interesting issue that merits investigation.

2.2 Health Effects of Lead

The accumulation of higher lead levels in the human body may be catastrophic, especially for the growing children and pregnant women. High lead levels interfere with physical and neurological development of unborn infants (slowing down mental development and
lowering birth weight) and young children and increase the blood pressure of adults. Children younger than six are most at risk due to their rapid rate of growth (USEPA 2005). Moreover, the human body stores lead in the blood and bones (Toronto Resources Manual 1995). Though concerns about lead are not new, its effects depend on the level of the exposure and the dosage. Higher doses of lead may result serious health effects such as the neurological (impairment of memory, decreased attention and concentration and mood disturbances), blood (reduces hemoglobin levels leading to decreased oxygen transport and shortened red blood cell life), reproduction (decreased sperm count), development of children (affecting motor, interaction and linguistic skills) and the renal system (development of kidney disease and failure). Lead levels for this concentration usually have not been found in drinking water (Sackville-Duyvelshoff 1989). But, low lead level may also impair intelligence (leading to low IQ values), hearing impairment, reduced attention span and poor classroom performance (USEPA 2005).

### 2.3 Regulations of Lead Levels in the Distribution System

To meet the requirements of 1986 amendments of the Safe Drinking Water Act, the United States Environmental Protection Agency (USEPA) promulgated the National Primary Drinking Water Regulations for the lead and copper on June 7, 1991 entitled the Lead and Copper Rule (Federal Register 1991 & 1992; Ramaley 1993). This regulation is highly complex, and uses an action level of 15 µg/L at the 90th percentile (more than 10% customer taps sampled) to trigger a number of additional responses and actions for monitoring drinking water and control corrosion depending on utility size (AWWARF 1996). If the action level for lead is exceeded, the system must also inform the public about
the steps they should take in order to protect their health, and may have to replace lead service pipes under their control (USEPA 1991). As per USEPA LCR-1991, monitoring program of the tap water must begin from January 1992 to July 1993 depending on size of the community, with the aim of reducing lead levels in water at the tap. It establishes the requirements for the treatment, public education and lead service pipe replacement (Ramaley 1993).

In 1980, the permissible lead level in the running water for human consumption of the European Community was 50 µg/L; and there was a directive that, in general, for the samples taken directly or after flushing shall not exceed 100 µg/L (EC 1980). In 1990, United Kingdom set 50 µg/L as the standard for any water and Germany decided that a value of 40 µg/L would be the maximum contaminant level (AWWARF 1996); in 1993, the World Health Organization revised its guidance for drinking water and set an acceptable average limit of lead to 10 µg/L (WHO 1993). In determining lead levels in water of the distribution system, an important problem is the protocol for sampling, as stagnation time, flushing duration and specific conditions of the installation have important influence on the results (Kuch and Wagner 1983; Schock 1990).

### 2.4 Status of Lead Related Problem in Canada

Across Canada there are still many lead based distribution and service pipe lines, especially in low rise old buildings, plumbing system may contain lead piping and/or lead based solders and fitting-fixtures. Huggins (2007) reported that in the City of London, in many places still there are lead based distribution and service piping. Recently they are replacing lead based distribution and service pipes, step by step, in response to the higher lead level
observed in the tap water. Graham (1990) reported that in the City of Toronto, 80% of the service pipes were lead based and most of the interior plumbing in homes was copper piping with lead solder joints. Consequently, in Toronto, lead concentration in the distribution system was higher such as 5 µg/L (ppb) when standing for < 5 hr, 18 µg/L when standing for between 5 to 8 hrs and 28 µg/L when standing for more than 8 hrs. But, USEPA guideline is that maximum lead level should be 10 µg/L for 8 to 18 hrs of standing water and corrosion control is required if the average lead concentration exceeds 10 µg/L for overnight standing water.

In 1994, the Scarborough Health Department and Scarborough Public Utilities Commission found higher lead level in drinking water. AWWA in 1990 demonstrated that a complete elimination of lead levels from the drinking water will not provide a great enough benefit to the public. The complete replacement of lead based service line is too expensive. For complete replacement of the lead service line, the benefit to cost ratio is 0.02 on the basis of 15 yrs record, much lower than the expected value of 1.0 (Murphy 1995). Considering the benefit-cost ratio, this study recommends treatment of water to ensure leaching of lead from the service lines to a minimum i.e., less than acceptable level instead of costly completely replacement of the lead pipes. Sackville-Duyvelshoff (1989) reported that for Ontario, out of the total 13,360 free flowing samples, 4 (four) contained lead level greater than 50 µg/L and average lead levels for all locations were below 10 µg/L. It is worth mentioning that all these samples were collected from the free flowing tap water not from the standing or first flush water, which is expected to contain a much higher lead content.
Lead pipes were banned in 1967 in Montreal, but the City permitted the use of surplus lead pipes for construction until 1970. Lead pipes never used in high rise buildings or buildings with more than eight units as these pipes were not strong enough to tolerate the resulting pressures. There are about 75,000 buildings erected before 1970 with eight or fewer units in Montreal connected to the municipal water supply system with lead pipes that may have lead levels higher than provincial limits (CanWest Media Works Publications Inc.). More than 1500 tests conducted on buildings those are using lead pipes and found that 45% of the buildings have lead levels higher than the provincial limits. The average of those was 14 µg/L that is slightly higher than the 10 µg/L the cutoff standard (CanWest Media Works Publications Inc.). It is worth mentioning that, these test results are for the samples collected after five minutes of flushing. First flush waters contain much higher lead levels. Through an interview, during a presentation to Canadian Water Networks (CWN) workshop held in October 2008, on quality of the drinking water in the City at University of Montreal, the City of Montreal officials (Mr. Clement Cartier) reported that lead levels in first flush tap waters in many buildings is in the range of 50 to 250 µg/L.

2.5 Possible Sources of Lead in the Distribution System

Broadly, there are a few potential sources of lead in the distribution system, such as physical sources, chemical reactions with disinfectants and corrosion of the service pipe lines, brass fittings and fixtures. Through internal corrosion of the lead service pipes, corrosion of the pipe jointing compounds and soldering, dissolution of brass and bronze plumbing fixtures, lead goosenecks, gaskets and valve parts, most of the lead may enter
into the distribution system (AWWARF 1996). It is believed that brass faucet and its assemblies are the source of lead in the distribution system, and hence it is important to investigate the extent of lead release from brass water faucet assemblies (AWWARF 1996). Potential other sources of lead contamination may be cistern materials, water storage tanks (Olem and Berthouex 1989; Yaziz et al. 1989; Young and Sharpe 1984), impurities in the coating on galvanized pipe (McFarren et al. 1977 after AWWARF 1996) and water treatment chemicals though its contribution is less than 1 µg/L (Ainsworth et al. 1977 after AWWARF 1996). Lead levels in the source water, treatment efficiency, the amount of lead materials containing between treatment plant to tap, and ability of water to solubilize lead from the system are also the factors affecting lead level in the systems (AWWARF 1990).

2.5.1 Physical Sources

There are several physical sources of lead in the distribution system including source water, lead based service pipe lines/plumbing system, goosenecks, well packers, lead-tin solder at the joints, brass fixtures/faucets containing certain percentage of lead etc. The surface based source water is usually contaminated by lead particulates from anthropogenic emissions such as combustion of gasoline (now banned), fossil fuels, and ore smelting (AWWARF 1990). Anthropogenic emissions of lead, which may be the cause of high lead levels in the surface based source waters are insignificant compared to lead in municipal sewage and solid wastes. In 1982, estimated lead emissions from anthropogenic sources, municipal sewage and solid wastes were 562 tons, 11,466 tons and 61,000 tons respectively in Canada (Environment Canada 1985). The USEPA study showed that lead concentration in source water is, generally, not a significant source of lead in potable water as residence time of
lead is less than the residence time of water; most of the lead particulates from the reservoir water are removed by sedimentation (USEPA 1988). In the treatment plant, lead is also required to remove and maintain up to a maximum level of 5 µg/L, in compliance with USEPA regulation (AWWARF 1990).

Lead pipes in the distribution systems and service lines are the major sources of lead in tap water. Due to high flow velocity (> 4 ft/s or 1.2 m/s) (Singley 1994), lead particles from the pipe wall may dissolve and enter into the flowing water. The use of lead pipes in the distribution systems in USA is now greatly reduced, and gradually disappearing (AWWARF 1990). But, goosenecks, well packers, lead-tin solders and brass faucets/fixtures release lead to the distribution system due to either chemical or galvanic corrosion (AWWARF 1990).

2.5.2 Chemical reactions with disinfectants

Chemical reactions of water and its other ingredients with disinfectants used for the treatment of water can often cause lead level to rise in distribution systems. Gradually this issue is becoming a major concern. In this regard, the National Sanitation Foundation (NSF) standards 60 and 61 (National Sanitation Foundation 1988) were developed as a certification program for water treatment chemical additives. The standard 60 contains minimum requirements for the control of potential adverse health effects from the water treatment products. Though loosely, almost for the same purpose, prior to standards 60 and 61, there was the Water Chemical Codex developed by National Research Council’s Food and Nutrition Board (AWWARF 1990) that recommended maximum impurity contents (RMIC) for lead in treatment chemicals, so as to ensure that the maximum contaminant
level (MCL) for lead of 50 µg/L is not exceeded after treatment. If the ingredients of water treatment chemicals is known, then for certain dosage level, it is possible to determine recommended maximum impurity contents (RMIC). The chemicals such as aluminum sulfate, ammonium sulfate, calcium hydroxide, calcium oxide, granular activated carbon, powdered activated carbon, ferric oxide, ferric sulfate, ferrous sulfate, sodium aluminate and sodium carbonate (soda ash) used for the treatment of water are potential sources of lead, as identified by Codex (AWWARF 1990).

2.5.3 Sources of Lead from Corrosion

Lead is relatively corrosion resistant compared to other materials used for the water distribution pipes; its durability has led to its popularity as a plumbing material. Because of corrosion, the leaching of lead into water is common in supply systems, especially when the water is corrosive. But, lead leaching from transmission and distribution pipes has not been considered as a significant source because most of the steel and cast iron pipes used contain a low lead level and are lined with anticorrosive material (AWWARF 1990). Though use of lead pipes in the distribution and service lines is now rare (AWWARF 1990), yet it can still occur. Corrosion of check valve counter weight of water meters (installed before 1982), lead gaskets used for joining large valves and pipes, caulking compounds used for sealing joints and material used for bell and spigot joints are likely sources of lead in the distribution system, though the associated amounts are generally assumed to be insignificant as exposed lead surface area and contact time are small (AWWARF 1990).

Use of lead service pipes that were installed in almost 73% of US utilities in the past (Chin and Karalekas 1985), goosenecks for malleability (small piece of pipe used to
connect service line to the distribution main), lead lined iron service & plumbing system, zinc for galvanizing steel pipe that contains about 1.4% of lead, lead based solders used in the re-setters, and lead-tin solders used in copper plumbing pipe are significant potential sources of lead.

2.6. **Quantification of Lead Levels in the Distribution System**

Determination of lead level in the distribution system is a critical issue. Lead concentration levels vary spatially and temporarily within the same utilities. In determining the exact amount of lead in the distribution system, representative sampling and rigorous laboratory analysis are of great importance. There are EPA guidelines for determining lead level through laboratory studies. But, there are some limitations in the EPA guidelines too. By following EPA guidelines, determination of lead level exactly may not be possible due to certain flaws in sampling and testing procedures. But, determination of exact lead level in the distribution system is of prime importance in formulating any strategic lead management programs. For this reason, a search for consistent and acceptable sampling and testing procedures in determining lead level in the distribution system is still necessary.

2.6.1 **Sampling**

Sampling for lead is a problem, since it is difficult to get a sample representative of the actual water consumed. Proper sampling protocol is crucial in accurately determining the exposure to lead. Recently some flows in US-EPA’s LCR standard sampling and testing protocols have been identified by different water scientists, and that demands urgent and careful investigation. LCR sampling is done at the tap for first one liter and usually in
summer. Recently Kimbrough (2007) pointed out that, the LCR first draw one liter sampling procedure minimizes the ability to detect the influence of corrosion of lead solder and plumbing, the current main contributing sources of lead. In addition, a one liter sample has insufficient volume as it might represent only one meter length of pipe from the tap or sampling point.

Triantafyllidou et al. (2007) found an inconsistency in the USEPA sampling protocol. They stated that standard USEPA sample handling procedures can underestimate or miss most part of the new lead particulates in water samples, especially solder particles. As in typical system, samples collected in plastic bottles without acidification and keep for an unspecified period of time before analysis in the lab. During this period lead particulates, if present, may settle and become attached to the plastic sample bottle wall like trivalent chromium as reported by Parks et al. (2004 as discussed by Triantafyllidou et al. 2007) such particulates would not necessarily dissolve completely in 0.15% HNO₃ though lead particles from brass corrosion can be dissolved as it is chemically quite smaller. Even when full digestion performed, un-dissolved particles that attach to the sample bottle wall are not poured out into the glassware in which full digestion may occur. The amount of lead present in the water samples may be five times higher than that obtained using approved USEPA protocols. Presence of chlorides, warmer temperatures and low pH in the human stomach, may render this missed particulate lead as bio-available when ingested, and might be retained in the digestive tract for long time. Considering this issue, lead particles in the plastic bottles should not be allowed to sit before acidification, so that they can not be more resistant to dissolution in the USEPA method. More laboratory investigation is required in this regard to confirm their results and hypothesis.
In the case of lead analysis for Washington D.C., Lytle et al. (1993) used the traditional sampling method as after 12 hrs of stagnation; samples preserved immediately with 0.15% HNO₃ and were shipped weekly to USEPA drinking water research division lab in Cincinnati, Ohio. The authors mentioned on the basis of field and lab data that, standard 0.15% HNO₃ for dissolving lead particles and lead corrosion by products is effective. But, adequate time must be given to dissolve lead/solder particles in acid before analysis, and particle size should not be large enough to exceed the capacity of the acid to dissolve them. Standard sample preservation protocols for metal analysis remove most of the evidence of the presence of colloidal, particulate or particle bond lead. That is, standard USEPA method will not be able to recover particulate leads, which is an important scientific issue if an optimum water treatment control strategy for lead is to be developed.

Gardels and Sorg (1989) studied different types of faucets in the lab to develop additional information about lead leaching. From their study, it was found that new cast brass faucets could contribute lead to the drinking water in excess of the proposed no action level (10 µg/L). Various sampling procedures were used to evaluate the impact of sample size, and to determine flushing volume needed to remove most of the lead from a faucet. It was found that about 60-75% of the lead leached from a faucet appeared in the first 125 mL of water. After 200-250 mL of water flowing, about 95% of the lead was flushed. They suggested sample size to be 100-125 mL and both hot and cold water sides should be tested. With the USEPA proposed one liter samples, faucets that containing small amount of brass may not present a problem, even when water is very aggressive as a one liter sample will dilute the lead concentration in the water to less than 10 µg/L (assuming no lead contribution from other sources).
Wong and Berranger (1976) observed that lead concentration in the first liter is 240 µg/L and in the second liter is 17 µg/L; thus lead concentration declined sharply. Standing water should be cleared from the distribution system prior to drawing water for drinking. Levin (1986 as discussed by Moir et al. 1996) calculated that 42 million American might be exposed to ≥ 20 µg/L of lead from partially flushed systems.

2.6.2 Measurement and Analysis

Schock and George (1993) presented the lead level measurement and analysis techniques as well as comparative performances of the Graphite Furnace Atomic Absorption Spectrophotometry (GFAAS) and Field Test Kit for lead level measurement. Both of them can be used for measurement of lead level in the drinking water. They also presented the results of the evaluation and the conceptual design for the evaluation of the methods. In this way it is found that Field Test Kit is relatively free of an operator bias and the results are comparable to GFAAS, when the lead level is above the detection limit of the Kit (the detection limit for the Kit is 4 µg/L and for the GFAAS is 0.2 µg/L of lead). Relative precision of both the Kit and GFAAS varied with the concentration level. GFAAS, if used directly, is relatively more accurate than test Kit. Absolute precision of the Kit is ±3 µg/L for 10 to 100 µg/L of lead. Usually lead is analyzed using GFAAS following USEPA method 239.2 with calibration standards of 1.0-10 µg/L and a detection limit of 0.3 µg/L.

2.7 Lead Control Strategies

In general, lead level control strategies for drinking water systems may target either short term or long-term goals. The short term strategy is usually to flush for a certain time prior
to drinking; a long-term strategy might involve corrosion control, or the prohibition on sales of lead based solder, fittings/fixtures and pipes. Removal of all lead service pipes and lead based solders may be an effective long term solution. Though complete replacement of the lead based distribution, service line and plumbing system is relatively expensive and would not provide much benefit (AWWA 1990). For example, for complete replacement of the lead service line, benefit to cost ratio is merely 0.02 (Murphy 1995). Instead, to find a more cost effective solution, it is suggested to treat the water with carefully selected corrosion inhibitors and/or suitable disinfectants to maintain a lead level less than acceptance level. For this, a goal is to identify the level of risk that customers may face, develop a policy on lead and implement this policy with clearly defined steps. Flushing of taps for 3-5 minutes, if water has been standing for more than 5 hrs is an effective short term solution.

Dudi et al. (2005) conducted an investigation to test the effectiveness of traditional protocol (NSF standard 61, section 8) in detecting the hazard creating potential of brass plumbing. The study showed that, though these types of small brass devices clearly pose a public hazard, they unfortunately pass easily through the leaching protocol. The standard is not based on concentration, but rather on the total mass that is leached to water during stagnation. This means that, for the devices holding small volume, a very high lead concentration is required to fail the standard, whereas, devices holding larger volume will fail at lower concentrations of lead. They found that small devices made of pure lead can pass the NSF leaching test. The NSF test, therefore, lacks the rigor necessary to prevent installation of the devices that pose a health hazard. Therefore, reforms are needed to prevent such unacceptable outcomes in the future.
The suggested steps to reduce lead, if 90% of first draw samples are not below the 15 µg/L, the LCR prescribes steps to minimize the corrosivity of the water. For example, manipulating pH & alkalinity or adding corrosion inhibitors such as orthophosphate. When pH is high (>10), inorganic carbon is effective in reducing the lead level. Low pH (i.e., NSF pH5) water is not aggressive if there is high concentration of phosphate inhibitor, but it increased copper leaching by 14 times relative to samples without phosphate; moreover, high pH and low carbonate waters are highly nonaggressive to lead leaching. Usually high pH and low alkalinity conditions are targeted to control lead leaching. They found that more than 25 times less lead was leached to the NSF pH5 water with phosphate, relative to the same water without phosphate.

Frey (1989) based on lead information survey (LIS) results proposed certain specific criteria such as

- pH >8.0 in 95% of all samples
- average lead level <10 µg/L, and
- lead level <20 µg/L in 95% of all samples.

If either of the first two criteria is not met, a corrosion control plan needs to begin and if either 2nd or 3rd criterion is exceeded, a public education program must be implemented. They found that with age, lead levels noticeably decreased, especially when plumbing age is 5 yr or more, this trend is clearer. With higher pH lead levels decreased significantly and effects of alkalinity (CaCO₃) are not prominent to reduce lead level.

Schock (1989) discussed chemical characteristics of water that is necessary for corrosion control programs and that influence the effectiveness of different corrosion
control strategies. In Britain, orthophosphate, pH adjustment through lime addition, and poly phosphate feeding are all used to reduce lead levels. Lead corrosion control is complicated because of many interdependent reactions. Formation of effective carbonate films depends on both the pH and the dissolved inorganic carbonate (DIC). It is found that pH level changes with temperature, and a 5-10°C temperature difference can cause a significant pH change. He mentioned that even low rates of corrosion 0.05 mil/yr could result 2.8 mg/L of lead release after 8 hr of stagnation in a 3.05 m long, 19 mm internal diameter lead pipe. Lead solubility is relatively more sensitive to pH than to dissolved inorganic carbonate (DIC) or alkalinity and the system with high DIC is capable of dissolving more lead. Finally, he concluded that orthophosphate (0.5 mg/L as PO₄) is more effective than carbonate over a wide pH range. Orthophosphate plus pH control can provide substantial reductions in lead leaching. Silicate (SiO₂) might be an important inhibitor but little research has been done on it as corrosion inhibitor. Polyphosphate may not be effective in controlling lead solubility. Calcium carbonate (CaCO₃) has wide acceptance to protect from lead leaching but research is also required to determine its effectiveness. There are contradictory results such as model results showing that high pH is required to control lead leaching, but field results indicate that lead leaching is controlled even at far lower pH levels.

Lytle et al. (1998) examined the theoretical effects of aeration on lead and copper corrosion control, and found that under a proper set of initial conditions, aeration is a useful drinking water treatment and lead corrosion control process. It can remove CO₂, which directly affects pH and dissolved inorganic carbon (DIC), the parameters that influence lead and copper solubility. If the initial pH and DIC are appropriate, aeration can be an effective
corrosion control strategy. Aeration produces consistent water quality, and may be advantageous because of relatively low costs and simple operational and maintenance needs. DIC may include some dissolved CO₂ (in the form of carbonic acid H₂CO₃), hence removal of CO₂ by aeration (DIC reduction as well) serves as a corrosion control alternatives. Some authors also mentioned that an iron dome can prevent escaping of CO₂, which subsequently can increase lead concentration by increasing corrosion of lead service pipes through higher DIC & lower pH or increasing H₂CO₃. Water that is suitable for aeration has a relatively low pH and high DIC (CO₂) content. But, there is some concern with aeration, as in low DIC water, there is enough potential for deposition of CaCO₃ and increased microbiological activity. They presented guidelines to assess feasibility of aeration for corrosion control, and suggested that bench scale/pilot scale testing is still advisable under certain circumstances.

2.8 Summary

In this chapter, the origin of lead in the source water, treatment plants, supply water and its potential health related issues are discussed through a literature review. In addition, presented reviews of the lead control strategies such as short term and long term, using combinations of the chemicals for lead control, the benefit-cost ratio of total replacement of the pipes from the system and chemistry of the water treatment for lead level control, pros and cons of the lead and copper rule (LCR) of the USEPA, safe level and action level for lead in the supply water, consistencies/weakness of the LCR, quantification of the lead level in the supply water, the sampling protocol as suggested by the LCR, inconsistencies of the traditional sampling protocol, passing rule for the lead containing brass
fitting/fixtures (by volume not by concentration) and a few suggestions to improve the sampling technique for consistent quantification of the lead levels in the system. From the discussions presented in this chapter, explicitly it can be stated that- a) lead remains difficult to measure; b) the severity and its release is complex; and c) the epidemiology shows lead to be a problem, but being more specific is not easy.
CHAPTER 3
CORROSION OF WATER DISTRIBUTION SYSTEMS

“One of the fundamental tasks of engineering and science, and indeed of mankind in general, is the
extraction of information from data.”

J. V. Beck and K. J. Arnold

3.1 Theoretical considerations

In general, corrosion is an electrochemical process. Broadly it can be classified as two
distinct types: external and internal corrosion. Dealing with flow and quality of the water in
distribution system, internal corrosion is of main concern as it may cause loss of hydraulic
conveyance, failure of pipes, and leakage due to buildup of corrosion products on the pipe
wall as well as causing an unwanted change in water quality due to entering corrosion
products into the water flowing through the distribution system (AWWARF 1996).

The effect of external corrosion on distribution system is not that significant from
hydraulic and water quality standpoints; it affects mainly the longevity and structural
integrity of pipes. Internal corrosion in a distribution system may be of different types (e.g.,
chemical corrosion and galvanic corrosion), though often the term electrochemical
corrosion is used. In electrochemical corrosion, electrons are transferred from the anode to
the cathode (internal circuit) through an electrolyte solution (external circuit) and
discharges to a suitable electron acceptor. The anode is sacrificed and buildup occurs at the
cathode, as shown in Figure 1.
The distribution of the anodic-cathodic areas, and the potential differences between these areas, are the primary determinants of the form of corrosion (e.g., uniform, pits or tubercles). Uniform corrosion is perhaps possible for small areas (where potential difference is small) and pit or tubercles is typical of scattered or larger areas (where potential difference is large) (Larson 1975). In equilibrium conditions, net corrosion is zero and for corrosion to occur disequilibrium in the following basic corrosion reaction is required:

\[
Me \leftrightarrow Me^{z+} + ze^{-} \tag{3.1}
\]

Where:

- Me = base metal
- Me\(^{z+}\) = metallic ion
- e\(^{-}\) = electron
- z = the number of electrons transferred in the reaction

The metal corrodes in the forward (oxidation) reaction and ions are reduced in the reverse reaction; and at equilibrium, the rate of the forward and reverse reactions are the same, which is rare in natural systems. The potential difference exists usually at the phase
boundary of the metal and electrolyte, which is the driving force for ion movement from the metal. The equilibrium potential of a single electrode can be calculated by using Nernst equation, from which it can be seen that net dissolution of metal can only occur if the potential is above the equilibrium potential (AWWARF 1996).

In a pipe system, the corrosion reaction rate depends on pH, dissolved oxygen (DO), chemical composition of the water, and the type of metal used for the pipes; the reaction mechanism must be known, if all the factors that affect the corrosion rate are to be understood (Bockris et al. 1961). At low pH and high potential, corrosion occurs at a higher rate as it is found from the so-called Pourbaix diagram: such conditions cause the metal species to be highly anodic; by contrast, with high pH and potential, solid products may form due to corrosion but builds up as a layer/scale on the metal surface and gradually decreasing and blocking the corrosion rate with time (Sontheimer et al. 1981). Higher pH level usually reduces the solubility of lead and copper in water. By using CaCO₃ in the water, the desired pH level can be maintained and for this, Langelier Index (LI) is important, which is a measure of water’s pH relative to its pH for saturation with CaCO₃.

The scale formed on the pipe wall may have some benefit from corrosion reduction perspective, but might have some deleterious effects from hydraulic and water quality standpoints. As scale formation results reduction of hydraulic conveyance, degradation of water quality especially, when scales dissolve due to transient pressure waves and differential thermal expansion. Thickness of the scales should therefore, be maintained as thin as possible by maintaining water quality in the distribution system. Water quality may deteriorate due to the corrosion reactions itself, because of release of metal ions to the water and solubility of scale, especially in case of heavy metals like lead (AWWARF 1996).
3.2 Corrosion Kinetics

It is known that if the system is not in electrochemical equilibrium, corrosion can occur. During corrosion, the electrons produced by the oxidation of the metal (anode) are accepted by both half reactions of \( \text{H}^+ \) and \( \text{O}_2 \) at the cathode; that is, the anodic metal dissolves through releasing electrons, which are accepted in the reaction of protons and oxygen as follows (AWWRF 1996):

\[
2\text{H}^+ + 2e^- \Leftrightarrow \text{H}_2 \quad (3.2)
\]
\[
\text{O}_2 + 2\text{H}_2\text{O} + 4e^- \Leftrightarrow 4\text{OH}^- \quad (3.3)
\]

For equilibrium, the total current produced by metal oxidation at the anode must be equal to the total current generated in the cathodic reactions. In the anodic and cathodic reactions, the reactants (electrons and ions) transported from the bulk liquid to the cathode, and the products (electron and ions) transported to the bulk liquid from the anode. Corrosion processes can be controlled by the either anodic or cathodic reactions.

As the rate of corrosion is controlled by the slowest step in the series of processes and to control corrosion, it is helpful to be able to determine this slowest step. The rate controlling step is related to the conditions within the distribution system, such as a corrosion process under high flow velocity is controlled by the electron transfer process, on the other hand, at low flow velocity or stagnation conditions, it is controlled by a mass transport process. To understand the corrosion rate, this reaction mechanism must be known as the reaction for oxidation of iron or lead does not show that \( \text{H}^+ \) or \( \text{OH}^- \) is a reactant or product, but the reaction rate depends on \( \text{pH} \) (Bockris et al. 1961). That the \( \text{OH}^- \) ion is part of the three steps of the reaction explains this dependency (AWWRF 1996).
3.3 Types of Corrosion

Depending on the material being corroded, the system structure, the formation of the scale and the hydraulic conditions, the nature of the corrosion can be uniform, galvanic, localized or pitting, inter-granular, stress, de-alloying, erosion and concentrated cell corrosion. The major types of corrosion are briefly discussed below.

3.3.1 Uniform Corrosion

Usually uniform corrosion may occur for a single metal. In the case of uniform corrosion, poly-electrodes form on the metal surface (Petrocelli 1960). In this event, alternately same site of the metal surface acts as microscopic anode and cathode that is, shifting of the anode site occurs and for such shifting, the rate of corrosion becomes uniform over the entire surface (AWWARF 1996). The possible causes of the corrosion cell formation on single metal surface may be the imperfections or heterogeneous nature of the metal, that causes different crystal structure or variations of the concentrations of oxidants and reductants, and results momentarily difference in the potential. Uniform corrosion can also be explained through electron transport due to metal surface oxidation model. In this form of corrosion, oxygen reduction occurs at the film surface, and transport of ions to and away from the oxide film takes place, but these ions are probably not transported through the external portion of the metal (AWWARF 1996).

3.3.2 Galvanic Corrosion

Galvanic corrosion may occur if the system consists of dissimilar metals. In galvanic corrosion, one metal become the anode and the other the cathode, usually depending on
their tendency to corrode, a tendency evaluated by their relative position on the galvanic scale/series developed by Larson (1975). Corrosion occurs on the less noble metal (anode) and buildup tends to occur on the more noble metal (cathode). But, sometimes it is possible to influence the relative position of the metals on this scale by external environmental factors, such as composition of electrolyte (water or soil) or temperature (US Army Corps of Engrs. 1995). That is, under certain conditions, two metals may reverse their respective order of potentials.

The potential for corrosion, in general, depends on distance between the metals on the galvanic scale/series, but corrosion behavior of some metals can also be influenced by other factors including the relative area of the cathode to anode, closeness of metals and the increased mineralization/conductivity of the water (AWWARF 1996). To prevent or minimize galvanic corrosion, the same metal should ideally be used for all components in the distribution system. The concept of changing relative position of the metals on the galvanic scale by modifying the external environment can also be investigated to prevent corrosion of the potentially more harmful/hazardous material such as lead pipe, lead containing brass and lead-tin solder in the distribution system.

### 3.3.3 Localized Corrosion

Localized corrosion is also called pitting; it may occur with dissimilar or even with single metal surface. It is a highly localized form of attack and characterized by the fact the vertical penetration is much greater than the horizontal extent, and is therefore, most destructive in nature (US Army Corps of Engrs. 1995). It may be due to galvanic or uniform corrosion that occurs when there are imperfections in the metals or scales and
regions of high stress in the metal. The mechanism of pitting is not yet understood completely. Imperfections in the metal or areas of high stress act as the anode, which is relatively small, and remains at the same location due to characteristic potential difference between these regions, and the metal corrodes rapidly. The special type of localized corrosion, which is called stress corrosion, may occur if the region of high potential is due to constant stressing that often ultimately ends up with system failure (AWWARF 1996).

3.3.4 Concentration Cell Corrosion

As corrosion potential is a function of both the metal characteristics and the environment surrounding the metal, particularly the concentration of the aqueous solution species; a difference in such concentration may cause development of the corrosion cell. This type of corrosion is also called crevice, gasket or deposit corrosion, since it occurs in localized areas where a small volume of stagnant solution usually exists (US Army Corps of Engrs. 1995). Due to this corrosion process, potential difference between two places tends to equalize. A varying level of concentrations of dissolved oxygen or hydrogen ion at different places on the metal surface may cause this type of corrosion. Common places of concentration corrosion are sharp corners, spot welds, lap joints, fasteners, flanged fittings, couplings and threaded joints (US Army Corps of Engrs. 1995). There are different types of concentration cells exist including oxygen cells or metal ion cells. If the formation of concentration cells is due to variations of the dissolved oxygen then it is called as differential oxygenation cell corrosion and the potential difference between two sites can be calculated by Nernst equation (AWWARF 1996).
The surface areas in contact with an electrolyte containing high concentration of oxygen acts as cathode by contrast areas with less concentration of oxygen act as anode i.e., potentially corroding surface. Similarly, the electrolyte contains more metal ions at the cathode, relative to the anodic areas where metal ion concentration is comparatively less (US Army Corps of Engrs. 1995). The common areas for differential oxygenation cell corrosion are between two metal surfaces and for equalization, assuming pH level is constant throughout, oxygen from the higher concentration areas is reduced since oxygen is not produced by either anodic or cathodic reactions (Uhlig 1938). The part of the metal in contact with higher level of oxygen acts as the cathode and the part of the metal in contact with lower level of oxygen acts as the anode and corrodes. The pitting or deepening of crevices is the result of continuous attack at the low oxygen site, and a major cause of scale roughness is the formation of tubercles that can increase the pumping cost significantly (Larson 1975).

3.4 Management of Corrosion

In general, both the internal or external corrosion can be managed by design considerations, by employing corrosion resistant materials for construction, by employing cathodic protection, by using protective coating and by using chemicals or corrosion inhibitors and adjusting water quality parameters that is applicable especially for the water distribution system (US Army Corps of Engrs. 1995, AWWARF 1996).
3.4.1 Management by Adjusting Water Quality Parameters

Water quality and its modification are important for the management of corrosion in water distribution systems. By adjusting certain water quality parameters such as pH, alkalinity, dissolved oxygen content, the presence of calcium carbonate, the concentration of natural organic matter or the hardness of the water, management of internal corrosion of the water distribution system (including pipes, fittings and fixtures) can be achieved (AWWARF 1996). The general trends are not always accurate, but far easy to summarize:, low pH tends to increase corrosion and high pH level tends to protect the system from corrosion; the presence of a high concentration of dissolved oxygen (DO) tends to increase the rate of corrosion, whereas higher alkalinity & concentrations of dissolved inorganic carbon (DIC) tends to protect the system by providing protective coatings; maintaining a chlorine residual tends to increases metallic corrosion but reduces microbial induced corrosion; polyphosphates reduces tuberculat ion and tends to increase the corrosion at low dosages; orthophosphate reduces corrosion by forming a protective film, whereas silicate by forming protective films and increasing pH & alkalinity reduces the rate of corrosion; ammonia increases solubility of the metals thus corrosion, calcium hardness provide protection and reduce corrosion, total dissolved solids (TDS) tends to increase conductivity and thus the corrosion rate; high levels of chloride & sulfate increase corrosion; hydrogen sulfide increases corrosion rate and organic matter or natural color decrease corrosion by coating pipe surfaces (AWWRF 1996).

Usually the pH has an enormous effect on corrosion of the pipe metal surface in the pipeline systems. But, depending upon ambient temperature environment, the effect of pH on corrosion can be completely different. For example, for waters in Cambridge, USA,
it is found that at temperatures of 22\(^0\)C and 40\(^0\)C, there is no effect of hydrogen ion concentrations on corrosion for pH in the range from 4.1 to 10 and 4.3 to 9.0 respectively; in this case, the rate of diffusion of dissolved oxygen primarily controls the corrosion rate of metal surface (Whitman et al. 1924). Larson and King (1954) demonstrated that for corrosion to occur the influence of dissolved oxygen and pH is secondary and water quality is a primary factor, especially at low flow velocities.

3.4.2 Management by Using Inhibitors

Certain chemicals such as phosphates, polyphosphates, orthophosphates, silicates, carbonates, chromates, and hydroxides are used to minimize the corrosive environment and thus to control corrosion of metal pipes. Collectively these compounds are known as corrosion inhibitors. The required concentration of the corrosion inhibitors in electrolyte is the function of composition of the environment, ambient temperature, fluid flow velocity, existence of the internal or external stresses in the metal, composition of the metals and existence of the other metallic contact, as well as other factors. To control corrosion effectively by using the inhibitors, the specific types and concentration of the inhibitors are required. This type and concentration for the different metals can be determined through comprehensive experiments with due consideration for the location and degree of the corrosive attack. Yet, even with carefully controlled use of the inhibitors, determined through painstaking experiments, corrosion of the metal surface may occur, particularly under deposits of the foreign matter, and in crevices that are relatively inaccessible to the inhibitors (US Army Corps of Engrs.1995).
3.4.3 Management by Cathodic Protection

The corrosion of the metal pipes that are exposed to electrolytes can be mitigated through an electrical method, which is called cathodic protection. In this method, the corrosion is controlled through forcing a designed current (equal to the corrosion current) to flow from an auxiliary anode to the metal pipes to be protected that ultimately served as the cathode. Cathodic protection can be achieved in two basic methods including the sacrificial or galvanic and impressed current systems. The sacrificial method involves the use of the current generated due to metallic connection of the two electrochemically dissimilar metals; alternatively, the impressed current systems uses an external direct current source and auxiliary anodes connected so as to cause the energized materials to corrode.

In the sacrificial system, the current discharges from the anode through electrolyte to the cathode (the pipes to be protected); the current generated depends on the inherent potential between the anode and the cathode. The sacrificial system has some relative advantages such as requiring no external power, needing little regulation, ease-of-installation, minimum cathodic interference, uniform distribution of current, minimum right of way/easement cost. Yet efficient use of the protective current also has some disadvantages such as limited driving potential, lower current output, possibly ineffective in high resistivity environments, and that a poorly coated structure may require many anodes.

In the impressed current system, the external power source is usually a rectifier but other sources also can be used such as batteries, solar cells, wind powered generators, fuel cells, thermoelectric generators etc. This system has some relative advantages such as the ability to design it for a wide range of voltage and current, large areas can be protected, variable voltage and current output is available, that it is applicable in high resistivity
environments, and that it is effective in protecting uncoated or poorly coated structures. Its disadvantages include the possibilities of cathodic interference problems that it is subject to power failure, that it has right of way restrictions, it requires periodic inspections, and it obviously requires a costly external power; moreover, over protection can cause coating damage (US Army Corps of Engrs.1995).

3.4.4 Management by Design Considerations
Corrosion can also be managed through proper engineering design. This is achieved mainly by avoiding the crevices where moisture or water soluble compounds can be accumulated. The engineering design includes avoiding loosely joined surfaces, bolting, back-to-back angles, rough welds, weld spatter, sharp edges, corners, discontinuities and intermittent welding. Smoothing of the sharp edges, corners, welds, and weld spatter by grinding may help prevent the crevice corrosion (US Army Corps of Engrs.1995). Proper selection of the metals for combining/joining purposes also an important issue for reducing corrosion reactions such as position of the selected metals in the galvanic series; if closely spaced (the anodic to cathodic), there is a possibility of less intense corrosion reactions. By contrast, if the selected metals are widely spaced in the galvanic series, then there is a possibility of strong corrosion reactions as there is a large potential between the anode to cathode to drive the reaction. By avoiding large surface area differences for the two dissimilar metals when connected, it is also possible to manage corrosion, since the rate of galvanic corrosion depends on the relative exposed areas. For example, if a small piece of zinc is connected with a large piece of iron, then zinc will be corroded rapidly though the iron surface will receive some small protection. Using coatings to prevent the corrosion is
often, effective, but improper coating can decrease life of the metal surface instead of increasing it, particularly as a result of the local defects that cause accelerated corrosion due to the galvanic action. Isolating dissimilar metals from direct contact, providing insulation so that electric circuit remains incomplete, allows the galvanic attack to be mitigated. Avoiding connection of the old and new metal pipes/plates also allows corrosion to be minimized. Connection of the old and new same metal pipes or plates in presence of the electrolytes may result the galvanic corrosion to occur as formation of the galvanic cell is not limited to only dissimilar metals when in contact. Generally the new metal surface is anodic relative to a corroded surface, which is why new pipes, installed to repair a section within an old pipe line, often corroded more rapidly than the old corroded pipes. If metal pipe is connected with reinforcing steel bars of the concrete in the presence of an electrolyte, the metal pipe usually corrodes at an accelerated rate as the reinforcing steel is passive, and hence this type of connection is to be avoided. The ambient temperature of the electrolyte environment can also control the galvanic corrosion when two dissimilar metals are in contact. With high temperature, the anode-cathode sequence can be reversed relative to normal temperatures; for example, zinc is normally anodic to steel but at relatively high temperature (60°C to 77°C), potential of zinc decreases and becomes cathodic. That’s why use of the galvanized steel pipe should be avoided when water temperatures are expected to be that high, otherwise base metal steel will be corroded (US Army Corps of Engrs.1995). This is clearly a rare problem in water supply systems.
3.4.5 Management by Protective Coating

Corrosion can be managed by coating the metal surface. There are different types of coatings including organic, inorganic or metallic coatings. Organic coatings consist of an organic binder containing an inhibitive to serve as the corrosion protection. Metallic coatings (e.g., aluminum, zinc, chromium, stainless steel) are also used for as corrosion protection. To protect the galvanic corrosion of steel, zinc rich coatings are used extensively (US Army Corps of Engrs.1995).

3.5 Lead Leaching due to Galvanic Corrosion

In a distribution system, even if there is no lead based mains, services or plumbing systems, there may still be a high lead level in the tap water. Kimbrough (2007) found through real field data analysis that in a system with totally lead free iron mains, copper service, plastic plumbing, with no use of lead solders and certified lead free corrosion resistant meters, that recently installed brass fixtures/faucets contributed to considerably higher lead (mean value 16.6 µg/L), copper, nickel and zinc levels in the drinking water compared to traditional plumbing systems (mean lead level 2.4 µg/L). From this finding, he inferred that, contribution to lead and copper levels in the tap water from dissolution, due to corrosion of merely interior brass fixtures and faucets can be considerable. In support of his inference he found that three water samples from plastic plumbing contained high lead as well as copper, zinc and nickel but in the samples, the lead levels were relatively low compared to the copper and zinc levels that indicate brass corrosion. Despite this, the LCR, USEPA considers brass corrosion as a minor cause of higher lead level in the drinking water. But, the observed lead level in a plastic pipe system declined within two years to a lower level.
than the older traditional system; this implies that the source of lead was exhausting rapidly indicating the relatively smaller source, which is quite consistent with Kimbrough’s inference. This finding challenges the assumptions of the LCR about the main sources of lead and copper in the drinking water not being the interior brass fixtures and faucets. That is, to control the lead level in the tap water, focus must be given to the interior fixtures and faucets used almost equally like lead service lines/solders etc. A similar result was found by Moir et al. (1996).

Moir et al. (1996) presented the results of their examination for lead and copper concentration in 36 homes, 3 apartments and a school. They found that, for the overnight stagnation, the lead concentration in water was not significantly different though out of the 36 homes, 30 homes were serviced by the lead pipes and 6 homes were serviced by other piping. This result indicates that the source of much of the lead in drinking water is the water distribution system within the homes, instead of the lead based service pipe line.

Singley (1994) studied the effects of water quality on lead corrosion under three different conditions (e.g., the lead pipes, the lead based solders, and the brass & bronze fixtures). He presented the reactions or lead chemistry in detail, in addition to the galvanic calculations. He mentioned that for the lead pipes, the corrosion is due to establishing a cell on the lead surface and transferring the electrons from one point to another. The kinetics of corrosion is poorly understood and the effects of many naturally occurring substances are unknown. The optimum technology for reducing lead by water quality modification is not easily predicted. For the solders and alloys, the galvanic corrosion is due to the direct contact of the dissimilar metals. The pipe corrosion can be reduced by increasing the pH level or reducing the dissolved oxygen or chlorine. The solder and alloy corrosion are
almost insensitive to water quality changes. It can be expected that lead levels in drinking water will gradually decrease as the ban on lead solders takes effect and exposed lead surfaces are removed by corrosion.

Lytle et al. (1993) mentioned that during a corrosion control study using an electron microscope for the Washington D.C. area that particulate materials were found even in the acid-preserved samples. These particles were tin instead of lead, which indicates the probable source of lead to be lead-tin solder. Reiber (1991) conducted an investigation with a specialized flow cell to evaluate the impact of the galvanic action on the solder-sweated joints. The cell closely approximates the geometry of solder-sweated joint and hydraulics of the pipe flow. From the investigation, his observation is that, addition of the orthophosphate inhibitors (1 mg/L) with the near neutral pH solution, substantially reduces the galvanically stimulated solder corrosion. At lower pH (≤ 6.0), orthophosphate addition has no effect on corrosion. Addition of chlorine (0 to 3.0 mg/L) may not alter the long-term galvanic corrosion rates. The degree of passivation is substantially less with lower pH (5.0 or 6.0) and the galvanic effects are a powerful corrosion accelerator on the coupled solder-copper surfaces. That is, the extent of the surface passivation is directly linked to the pH level, and also related to the solubility of the protective lead-tin oxide scales.

3.6 Mysterious Behavior of Brass and Copper in Home Plumbing System

Galvanic corrosion occurs when two dissimilar metals are connected, causing one metal (anode) to be sacrificed and the other (cathode) to be protected. Renner (2004) mentioned that even with conventional water chemistry in some environments, when brass is connected to copper, lead can become cathodic relative to copper in spite of its position
above copper on the galvanic series. Contrary to this, Edward (1999) mentioned that in the presence of chloramines, brass is highly anodic and copper is cathodic, and in the case of home water distribution system, the whole copper network can act as the cathode that forces release of lead from the relatively small anodic brass faucets/fixtures, and as a result, the lead leaching rate can increase 4 to 100 fold compared to normal values. Larson’s (1975) modified galvanic series (AWWARF 1996) dictates that if brass and copper are connected galvanically, then they should normally be anodic and cathodic respectively as their positions on the series are successive. That means, with respect to the relative positions of brass and copper on the Larson’s (1975) galvanic series, it is not usual that brass will be highly anodic instead; weakly anodic behavior is to be expected.

3.7 Impacts of the Chemicals and Flow Hydraulics on Corrosion

3.7.1 Impacts of the Chemical/Coagulant used for Water Treatment

The lead based solder, if galvanically connected to copper, then its corrosion rate can be considerably affected by the coagulant type used during water treatment. Edwards and Triantafyllidou (2007) showed that the presence of the higher chloride or higher chloride to sulfate mass ratio (CSMR) in the drinking water distribution system can increase lead leaching dramatically, especially from the lead based solder galvanically connected to copper (by factors 1.2 – 2.7 for brass and 2.3 – 40.0 for lead solder and copper pipe joints), but can still protect leaded material when lead is not connected to the copper. They also mentioned that the galvanic connection of brass to copper can reduce the lead leaching over long term, and the presence of alkalinity as CaCO₃ below 50 µg/L level (results low pH), may have more hazardous effects on lead leaching. The effects of CSMR and galvanic
connection on lead release into drinking water are currently under study and this further investigation is well justified.

Renner (2004) mentioned that the cause of high lead levels (>300 ppb (300 µg/L) in 157 houses and >15 ppb (15 µg/L) in more than 1000 houses) in Washington D.C.’s drinking water may be the modification of the disinfection program in 2000 from chlorine to chloramines (mix of chlorine and ammonia). It was expected that the changes in water chemistry with the old lead pipes was responsible for this. Edwards’ (1999) work on chloramines and galvanic corrosion explains the causes of high lead levels when the service line is not made of lead. His preliminary experiments confirmed that chloramines are prone to mobilizing lead from brass and also the galvanic corrosion is enhanced by chloramines. Schock (1989) found that with chlorine and lead service pipe, highly oxidizing PbO₂ scales formed on the pipe wall, and with chloramines this oxidizing potential lowered and dissolved the PbO₂ scale, consequently raising lead contaminant levels. His work is groundbreaking research that has important implications for water quality.

Studies and theories put forward by Schock (1989) and Edward (1999) need to be confirmed with further investigations. If their work is confirmed, then there are serious weaknesses in the federal testing program, and conflicts between the DBPR and the LCR. In addition, it raises the prospect that other cities also have or may soon have similar problems. Corrosion control in drinking water systems is still not entirely clear and more research is needed.

Imran et al. (2006) found that different source waters, including groundwater (GW), surface water (SW) and desalinated water, have different corrosion effects with various pipe materials. With some water, the pipe materials are less corrosion sensitive and
with certain other types of water, the pipe materials are highly corrosion prone. In addition, changing one parameter to mitigate the corrosion of certain types of pipe materials might increase the corrosion of other types of pipe materials. For example, due to an increase in the alkalinity level, corrosion of copper and lead pipes is typically increased but iron corrosion is reduced; on the other hand, increasing sulfate level will reduce the lead pipe corrosion but increase the iron pipe corrosion. These conflicting behaviors demand the tradeoffs between the water quality and the corrosion response be expertly navigated.

Vasquez et al. (2006) investigated the total lead release in the presence of free chlorine and chloramines with different types of water such as GW, SW and desalinated water. Many utilities are using chloramines instead of chlorine to comply with the DBP regulations. With chloramines more total lead release was found than that of chlorine for the desalinated water, but with the finished GW & SW, no differences in total lead releases were found. They presented an explanation of why higher lead levels were observed in Washington DC’s drinking water. The electrical potential in the drinking water is higher in the presence of chlorine relative to chloramines. This higher potential changes hydrocerussite to lead dioxide and, lead dioxide (PbO₂) is less soluble than hydrocerussite, resulting in a lower lead release. That’s why, with chlorine as a disinfectant, less lead release is likely relative to chloramines. The free chlorine (HOCl or OCl⁻) is a stronger oxidant and disinfectant than monochloramine (NH₂Cl). They opined that the oxidation (chemical, biological) and turbulence are responsible for lead release in waters.

There is a conflict regarding relative lead release with chlorine and chloramines as Treweek et al. (1985) found that corrosion rate of lead is higher in a free chlorine environment than in a chloramines environment, especially in the case of lead-tin solder
joints. Lin and coworkers (1997) also found higher lead release rate in the presence of free chlorine than with the chloramines at constant pH. Brass containing 50% lead may release 200% greater lead with free chlorine environment, but when 3% lead is in brass, chloramines will release relatively more lead. On the contrary, Edwards & Dudi (2004) found that total lead release with chloramines is 4 to 6 times higher than with the free chlorine environment for the pH levels of 7.5 to 9.0. But, in a longer term examination in the presence of nitrates, they found the lead release with the chloramines environment is relatively lower than in a free chlorine environment.

Clearly there are conflicting results. Earlier studies found in general, higher lead release with chlorine, but the later studies found higher lead release with chloramines. Hence this issue needs to be investigated more carefully with different options and combinations. The lead release might also be affected by the hydraulic transient phenomena, and this relationship can be investigated through comprehensive numerical modeling.

3.7.2 Influence of the Corrosion Inhibitors Used

The complete replacement of the lead based service lines may not always be a feasible solution as it is highly cost intensive. To find the cost effective solutions, it is often suggested to treat water with the carefully selected corrosion inhibitors to minimize lead leaching from the service lines.

Holm & Schock (1991) presented a detailed calculation for the lead solubility. They found that, under certain conditions, polyphosphate based chemicals for the water treatment may increase the solubility of lead significantly. Their calculation shows that, for the solutions in equilibrium with hydrocerussite (\( \text{Pb}_3 \text{(OH)}_2 \text{(CO}_3\text{)}_2 \)) and same values of
alkalinity and pH, a solution containing polyphosphates will have a greater total dissolved lead concentration than a solution that does not contain polyphosphates. Addition of any complexing agents will also increase the total dissolved lead concentration. By contrast, addition of the orthophosphate can reduce the lead solubility appreciably and its optimum concentration is 0.4 mg/L. The orthophosphate concentration of more than 0.4 mg/L has little effect on reducing the lead solubility. That is, the use of orthophosphate is better than polyphosphate for reducing lead solubility in the distribution system.

Hozalski et al. (2005) investigated the effects of different corrosion control chemicals including orthophosphate, polyphosphate, blends of orthophosphate and polyphosphate and stannous chloride on lead release and bacterial re-growth. Chloraminated and filtered surface water were used in the experiments. They observed for the total lead, dissolved lead, heterotrophic plate count (HPC) bacteria and coliform bacteria, and found that orthophosphate (1 mg/L as P) yields the lowest lead concentration of all chemicals. None of the chemicals were able to maintain lead levels less than 15 µg/L (action level) for an 8-hr stagnation period with the new lead pipes, and HPC population increased due to the phosphate containing chemicals in the summer, but with the stannous chloride (SnCl₂) solution, led to lower HPC values. They also found that new lead pipes release more and are not well controlled by orthophosphates etc., as new surfaces may not have any protective layer of the scales between metal and water. Simply, pH level increase often effectively reduces the lead release; with a pH greater than 8.0, the lowest lead levels were observed, and alkalinity formed a protective (PbCO₃) scale layer and buffer pH. When alkalinity is less than 50 mg/L as CaCO₃, the lead concentration was highly sensitive to pH
(7.0 - 8.5), but when alkalinity is greater than 100 mg/L as CaCO₃, then the lead concentration was insensitive to the pH level.

McNeill and Edwards (2002) conducted surveys in 1994 & 2001 to investigate the trends in phosphate inhibitors use. They found that zinc orthophosphate and polyphosphate were the commonly used inhibitors, but a shift from poly/zinc orthophosphate to orthophosphate was observed from 1994 to 2001. The phosphate based inhibitors were found to be effective at preventing scale buildup and in controlling pipe corrosion. They pointed out that use of the inhibitors is not free from hazards as the inhibitors may result in increased biological activity, corrosion (especially polyphosphate), and add to treatment costs and residuals. They can increase the soluble lead and copper concentration in water as well as tuberculation of the pipes. The understanding of how and why inhibitors are used is the important step in developing effective strategies for corrosion control and maintaining water quality. Unfortunately many utilities do not know this. Though inhibitors usually decrease the corrosion, their effectiveness is highly dependent on the water quality. The dosing is important, as it can affect the corrosions, biological activity, disinfectant decay etc. Therefore, understanding of the drawbacks and benefits of inhibitor dosing are important.

As per the survey conducted by AWWA in 1999, 72% of 185 utilities were using the phosphate products, but in 1996, only about 39% of 900 utilities were using inhibitors. Use of the zinc orthophosphate and polyphosphate remained unchanged since 1994, but orthophosphate use has been increased dramatically and the use of blended combinations has decreased.

Ramaley (1993) mentioned that Newport-News water works replaced the lead service lines, used the zinc orthophosphate corrosion inhibitor and monitored the tap water
quality. Ramaley found that the lead & copper levels have reduced below action levels. He examined alternative treatment strategies for the lead corrosion control including pH adjustment to achieve the positive Langelier Index and feeding phosphate based corrosion inhibitors. But, he found for both the treatment strategies some important drawbacks such as i) Raising the pH level to achieve more +Ve Langelier Index can increase the Trihalomethane (THM) formation potential by 25% that would violate the USEPA’s THM maximum contaminant level (MCL), ii) Zinc orthophosphate was judged to be the best corrosion inhibitors available for lead control, but it has also some negative effects on the wastewater treatment plant, land application and breweries. However, the dose of the zinc orthophosphate (1:3) is relatively low compared with the other inhibitors.

3.7.3 Influence of the Flow Velocity

The fluid flow past the exposed surface of the metal may influence the corrosion process. The flow velocity may accelerate corrosion if the corrosion reaction is limited by the mass transport to or from the metal surface by one or more constituents in the fluid responsible for corrosion; by contrast, the flow velocity may decelerate the corrosion rate relative to that in stagnation condition, if there is increase in mass transport of a constituent that increases the surface passivity (Silverman 2004). Based on the collective study results, Fang and Liu (2003) concluded that the corrosion rate of the pipe wall increases with the increase in temperature and flow velocity as density, viscosity and diffusivity of the fluid and corrosion ion are direct function of the temperature and velocity. The flow velocity may cause the pipe wall surface erosion that is, erosion corrosion, which is a mechanical process instead of traditional electrochemical process responsible for most of the corrosion.
Efrid (2000) pointed out that, the increased turbulence and mass transfer, as a result of the high flow velocity, can accelerate corrosion and pipe wall erosion. Since, completely developed turbulent flow consists of the boundary layers with varying flow velocities down to the interface of fluid and solid, in which most of the changes the fluid stress, turbulence, mass transfer and interaction with the wall take place. The flow velocity is an important environmental factor for corrosion since the velocity influences factors responsible for the corrosion such as oxygen depolarization, film thickness, and resistance of the surface films. Transfer resistances are reduced by the high flow velocities, in such a way that the distance through which the corrosive ions must diffuse to reach the metal surface is also reduced. In this case, the corrosion rate may be controlled by removal of the protective layer of initial corrosion product from the metal surface that is more common or by transport of the corrosive species from the bulk solution towards the metal-fluid interface (Shawla and Gupta 1993).

Due to the high flow velocity, the formation and collapse of any vapor bubbles near the metal surface of the pipe may be the cause of cavitation corrosion. As the flow velocity at the interface of metal-fluid or boundary of the metal surface is very low, the low shear stresses developed can’t be responsible for removal of the corrosion product from the metal surface; it is possible only when the protective film is weak in tension, non-adherent and the surface is rough. The greater agitation of the fluid produced by the turbulent flow may result more intimate contact between the metal surface and corrosive fluid and thus increase the corrosion (Shawla and Gupta 1993). Corrosion rate may not increase linearly with the increase in the flow velocity. From experimental study results, it is found that the corrosion rate increases linearly with the increase in the flow velocity up to certain limit
(Pisigan and Singley 1987) and then gradually decreases (Fujii et al. 1985). Usually fluid flow in the pipe is turbulent in nature that results two regions in the boundary layer. One is the viscous) sub-layer close to the pipe wall surface and other is the turbulent region away from the pipe wall surface within the fluid, for which the changes in concentration levels at the wall and away from the wall occur (Silverman 2004).

3.7.4 Influence of the Pipe Wall Roughness

The roughness of the pipe wall surface plays an important role in corrosion, as it is associated with the convective mass transport in the laminar or turbulent flow regions. In the case of laminar flow, the wall roughness increases the effective area; in turbulent flow, the surface roughness increases the degree of the turbulence and decreases the rate of flow required for the corrosion to start (Shawla and Gupta 1993). The height of the roughness element, if greater than the thickness of the laminar sub-layer but less than the turbulent boundary layer, decreases the mass transfer (slower corrosion) as a result of the changed hydrodynamic situation (Levich 1962). As is the case with pipes, the roughness and frictional coefficients are not constant but changes continuously with the flow velocity and other factors (Ross and Badhwar 1965). Li and Li (2005) based on their experimental investigations with the copper pipe showed that, corrosion rate increases with the increase in the surface roughness as a result of the increased fluctuation of the local electron work function. This fluctuation in the electron work function can promote formation of the microelectrodes and accelerate corrosion of the rough surface. They presented the rationale for the accelerated corrosion with higher roughness conceptually: the electrons located at
the vicinity of roughness peaks can more easily leave than those are located at the flat valley areas.

Mathiesen et al. (2006) conducted an experimental study with the chloride containing solutions to investigate the influence of the different surface conditions on the pitting corrosion of stainless steel. Their study results indicate that, the metal surface with the electro-polished finish have the higher resistance to pitting corrosion compared with the mechanically grounded surfaces as a result of the reduction of the possible pit initiation sites. Based on this study result, they argued that to obtain a corrosion resistant surface, specification of the right surface condition is equally important along with the selection of the right stainless steel grade.

3.7.5 Influence of the Hydraulic Transient Pressure

In general, water distribution systems are complex, with many distinct elements such as the pipes having different lengths, diameters and materials, gradient differences and a variety of boundary elements including tanks, reservoirs, pumps, valves, booster chlorination devices etc. All these components are required to achieve the required quality and quantity objectives for the delivered water. As the water demands are changing, the pump and valve operations are also changing consistently to adjust to the new demands. These operational variations of the system can provoke a drastic physical response in the system, as there is a connection between the fluid properties (density and compressibility) and controlling constraint of mass conservation (Fernandes 2002). These operational changes can only be transmitted throughout the pressurized system by the minute changes in fluid density (Karney 1994). Water is slightly compressible. As a result of variations of the external
force environments, a small change in the density of water may produce huge change in the system pressure. This compressibility effect of the water is reflected through the mechanism of propagation of the pressure waves, and consequent changes to the system hydraulic conditions (pressure and velocity). In water distribution systems, the huge changes in momentum caused by the hydraulic transient event are accommodated through propagation/reflection of the pressure waves (Fernandes 2002).

The frequent hydraulic transient events in a drinking water distribution system may create totally different hydraulic characteristics in terms of the turbulent flow velocities and pressure distributions. As a result, there is a possibility of the water quality deterioration due to dislocation of the corrosion scales from the pipe wall surfaces or increased diffusion of the corrosion species contained in the bulk water with water at the metallic pipe wall. In addition, the water quality may also deteriorate as a result of the re-suspension of the sediments, and the effect on transport mechanism as well as increased risk of the pipe line bursts or leaks that could be disastrous to the community. During the transient low pressure events, the contaminated fluid from the external environment may enter into the system, and may cause disruption of the integrity of a water distribution system (Fernandes 2002).

Pipe or system bursts occur for many reasons but those due to transient high pressure events may cause system failure that might disrupt the water supply to the communities and create the need for huge cost intensive reinstallations. Both are problematic and undesirable, but the transient intrusion of the external contaminated fluid into the system through the leaks can be relatively more disastrous as it will create a serious threat to public health, one that may remain unnoticed for a long time and or that may be
difficult to fix. That is why, in designing the distribution system, comprehensive study of the hydraulic transient phenomena, their potential effects on the system, and the effective management strategies must be considered in order to maintain the system integrity for the design period. Proper assessment and consideration of the potential hydraulic transient events are important, as the over estimation or under estimation both are detrimental technically as well as economically. For this assessment, careful hydraulic transient modeling with all possible operational and management scenarios of a system would be required.

3.8 Modeling of Lead Mass Transfer Processes

The mass transfer or solubility of lead in the distribution system is governed by many physical and chemical parameters, such as the stagnation period of the water in the lead pipe. The extent of the lead based system determines the level of lead in a sample collected from a house, and is important to complete the reaction or reach solubility equilibrium (Schock 1990a). The time to reach the solubility equilibrium may be short for the new pipe and relatively longer for the older pipe (Schock 1980, Schock and Gardels 1983). Hence, to develop a comprehensive corrosion or solubility equilibrium model, fitting of a polynomial function to either experimental or monitoring data with terms relating to the factors such as pH, DIC, temperature, DO, length of the pipe, diameter, age etc. would be helpful (AWWARF 1996). A few typical lead mass transfer or solubility models are discussed below.
3.8.1 Statistical Model

An empirical model was proposed by Bailey and Russell in 1981. The model is a log-hyperbolic function in which the values of the different adjustable parameters are to be estimated for each pipe.

\[
[Pb] = \exp\left(\alpha - \frac{\beta}{T + \theta}\right)
\]

(3.4)

where,

\[
[Pb] = \text{lead concentration}
\]

\[
T = \text{the stagnation time}
\]

\[
\alpha, \beta \text{ and } \theta = \text{adjustable empirical parameters}
\]

This model is not suitable to predict the effects of stagnation and flushing on the concentration level for combinations of the different diameter pipes and lengths without calibration (Kuch and Wagner 1983). In addition, the model is not defined for the real case at the onset of stagnation period (AWWRF 1996).

3.8.2 Model for Turbulent Flow

Based on analogy to the heat transfer and well known hydraulic models, Kuch and Wagner developed the simplified model for the lead mass transfer into the water in 1983. This model is for the continuous steady state turbulent flow as follows:

\[
[Pb]^0 = [Pb]^e - \left([Pb]^e - [Pb]^v\right)\exp\left(-\frac{\kappa A}{\gamma}\right)
\]

(3.5)

where,

\[
[Pb]^0 = \text{concentration of lead leaving the pipe}
\]

\[
[Pb]^e = \text{solubility equilibrium of lead}
\]
$[Pb]^E$ = concentration of lead in water entering the pipe

$A$ = total area of the internal pipe wall

$\kappa$ = mass transfer coefficient

$\forall$ = rate of the flow volume

This model assumes that the flow rate is constant with time, that fully turbulent flow and the pipe cross sections are uniform. The diffusion process is assumed to be controlled by the transfer of lead from the pipe wall into the water, and complete radial mixing is assumed. To utilize this model for the computational purpose of the lead concentration, the pipe characteristics (length, diameter), ambient temperature, rate of the flow, maximum equilibrium concentration and diffusion coefficients of the dissolved species must be known with consistent units (AWWRF 1996).

To consider the effect of variable pipe characteristics (change in length, diameter) on lead mass transfer rate, the model is normalized for certain flow velocity (50 cm/s) as follows:


(3.6)

where,

$[Pb]^N$ = normalized lead concentration during flushing

The other parameters are as defined for the first model (Eqn. 3.5). Based on this model, typical plots for different lengths and diameters with normalized lead concentrations are presented, and from which it is clear that the long pipe with small diameter can produce relatively high lead concentration during flushing (AWWRF 1996).
3.8.3 Model for Stagnation

Kuch and Wagner (1983) developed their second model for describing the radial diffusion of lead under the stagnation conditions. The simplified form of this model is as follows:

\[
C_i = 1 - \exp \left[ -\frac{4F_o'}{(1/\beta_i') + (33.41 + (4/\pi F_o'))^{-0.5}} \right] \tag{3.7}
\]

where,

\[
C_i = \frac{[Pb] - [Pb]^0}{[Pb]^\infty - [Pb]^0} \tag{3.8}
\]

\([Pb]\) = lead concentration after stagnation time \(t\)

\(Fo'\) = \(D \cdot t / 4a^2\)

\(\beta_i\) = \(\beta_a \cdot 2a / D\)

\(t\) = time in minute

\(D\) = diffusion coefficient, \(-1.0 \times 10^{-9}\) m\(^2\)/s for Pb\(^{2+}\)

\(a\) = internal radius of pipe (m)

\(\beta_a\) = mass transfer coefficient

If there is a thick scale of the corrosion products or others on the pipe wall surface that obstructs the diffusion process, in that case \(\beta_a\) is important to know by trial and error.

Data required for the computation, utilizing the stagnation model are diameter of the pipe, diffusion coefficient for lead, maximum equilibrium concentration for lead, concentration of lead during flushing and mass transfer coefficient. The lead concentration after flushing can be computed by using the steady state turbulent flow model (Eqn. 3.5). Lead concentration along the length of the pipe is not constant and varies from \([Pb]^E\) at the entrance to \([Pb]^0\) at the end; though for computational purposes it is assumed to be constant at the beginning of the stagnation period. From plots for the normalized lead concentrations and for the different pipe diameters with respect to the stagnation time, it is observed that,
the relatively smaller diameter pipe produces increase in the lead concentration at a much faster rate (AWWRF 1996).

### 3.8 Summary

This chapter reviews the theoretical considerations of the basic electrochemical corrosion processes, corrosion kinetics prevailing in the water distribution system, types of corrosion including uniform, galvanic, localized or pitting, inter-granular, stress, de-alloying, erosion and concentrated cell corrosion, and the management processes of both the internal and external corrosion. This review shows that the corrosion can be managed effectively by the design considerations, by employing the corrosion resistant materials for construction, by employing the cathodic protection, by using the protective coating, by using the chemicals or corrosion inhibitors or by adjusting the water quality parameters, all of which are sometimes applicable for the control of corrosion in a water distribution system.

This chapter also critically reviews the lead leaching process due to the galvanic corrosion, including some mysterious behaviors associated with brass and copper fixtures in home plumbing systems. The impacts of the chemicals and flow hydraulics on corrosion including the impacts of the chemicals or coagulants used for the water treatment, the influence of the corrosion inhibitors, the impacts of the flow velocity, pipe wall roughness and hydraulic transient pressure events are also reviewed. In addition, review of the typical empirical modeling of the lead mass transfer processes in the water distribution systems are briefly mentioned including the fact that such models are usually based on assumptions of steady state turbulent flow model or simple stagnation assumptions. More realistic models are considered in the next chapter.
CHAPTER 4

HYDRAULIC TRANSIENTS AND CORROSION IN THE WATER DISTRIBUTION SYSTEMS

“One of the fundamental tasks of engineering and science, and indeed of mankind in general, is the extraction of information from data.”

J. V. Beck and K. J. Arnold

4.1 Introduction

There are many components in a water distribution system, and their characteristics and responses, as adjusted by their various operational modes, are a key part of system behavior. These adjustments might include flow rate changes, pump start up/shut down, opening/closing of the valves, operation of the tanks/reservoirs, drops/rises, use of the chemicals for water treatment/disinfection and internal corrosion management. Inherently changes are complex in nature and difficult to understand comprehensively. For most of the actions mentioned, important transient pressure events in the system may be generated. These transient events may cause system failure like pipe bursts, may re-suspend sediments, may allow intrusion of contaminated water into the system from the external environment, may influence the corrosion processes and thus water quality deterioration. Additions of the chemicals for the water treatment and corrosion inhibition, and the internal corrosion processes are directly the water quality related issues. Hydraulic transients may dislodge the bio-films/scales from the pipe wall and promote the contact of the oxidant species present in the bulk water with the metal surface of pipe, and as a result accelerate the pipe
corrosion. Due to corrosion of the pipe metal surface, the disinfectant byproducts and the use of the corrosion inhibitors, the water quality may also be affected considerably. Therefore, comprehensive studies of the hydraulic transients and related corrosion processes are important to the proper planning and robust designing of all water distribution systems.

4.2 Modeling Hydraulic Transient Phenomena

A hydraulic transient event in the distribution system indicates a fully unsteady flow with the large pressure fluctuations and rapid accelerations to the fluid mass. This may be caused from the sudden closing of a valve, a pump shutdown, tank and reservoir operations and many other specific causes. In each case, some of the kinetic energy of the fluid transforms into the strain energy in the water and the pipe wall, which ultimately generates the pressure waves with abnormal amplitudes. These pressure waves travel along the pipe to and fro, often oscillating for a time between high positive and low negative pressures at the same location. The transient events can create large disturbances in the distribution system that may affect the mass transport mechanism significantly. Many have investigated the hydraulic transient phenomena in the distribution system including Evans and Sage (1985), Chaudhry (1987), Karney and McInnis (1990, 1992), Funk et al. (1992), Wylie and Streeter (1993), Karney et al. (1994), Ghidaoui and Karney (1994), McInnis and Karney (1995), Karney and Ghidaoui (1997), Nash and Karney (1999), Fernandes (2002), Fernandes and Karney (2001), Izquierdo and Iglesias (2002), Samani and Khayatzadeh (2002), Fernandes and Karney (2004), Naser and Karney (2005) and Naser (2006).
In designing a distribution system, possible transient events are sometimes neglected due to a lack of understanding of their potential consequences, a lack that may cause the disastrous results. As the basic governing equations are non-linear hyperbolic partial differential forms, and moreover the behavior of hydraulic devices are complex, it is often difficult to acquire their performance data, and also difficult to compare the responses of the distribution systems against the observed transient events (Karney and McInnis 1992).

Laws of the conservation of mass and momentum are used to represent the transient events in the distribution system (Chaudhry 1987, Wylie and Streeter 1993) as follows:

\[
\frac{\partial V}{\partial t} + g \frac{\partial H}{\partial x} + \frac{fV|V|}{2D} = 0 \quad \text{(Momentum)} \tag{4.1}
\]

\[
\text{Or,} \quad \frac{\partial Q}{\partial t} + gA \frac{\partial H}{\partial x} + RQ|Q| = 0
\]

\[
\frac{\partial H}{\partial t} + \frac{a^2 \partial V}{g \partial x} = 0 \quad \text{(Continuity)} \tag{4.2}
\]

\[
\text{Or,} \quad a^2 \frac{\partial Q}{\partial x} + gA \frac{\partial H}{\partial t} = 0
\]

where, \( V = V(x, t) \) instantaneous average flow velocity
\( Q = Q(x, t) = AV(x, t) \) instantaneous flow in pipe
\( R = \frac{f}{2DA} \), \( D \) = pipe internal diameter
\( H = H(x, t) \) piezometric head
\( a \) = acoustic wave speed
\( g \) = acceleration due to gravity
\[ f = \text{Darcy-Weisbach friction factor.} \]

There are alternative approaches available in the literature for numerically solving these governing equations. The method of characteristics is one of the most popular approaches in solving the hyperbolic partial differential equations for the transient events, as it is both accurate and relatively convenient to use. Method of characteristics transforms the two partial differential equations (Eqns. 4.1 and 4.2) into the four ordinary differential equations (Chaudhry 1987, Wylie and Streeter 1993). This approach has the key advantages of utilizing this explicit solution approach are its established stability criteria, an easily recognizable approximation method, high numerical accuracy and straightforward physical interpretation (Wylie and Streeter 1993). Ghidaoui and Karney (1995) analyzed an approach to transform the hyperbolic partial differential equations (HPDE) into its characteristic forms by utilizing the total derivative concept. They used the fixed grid characteristics method in developing an equivalent HPDE that can be applied to analyze the theoretical aspects of the interpolation schemes.

A generalized algebraic formulation was presented by Karney and Ghidaoui (1997) that can be used to derive a flexible discretization for interpolating points between the grids. This flexible discretization method is able to combine interpolation approaches with the wave speed adjustment technique; it requires minimum interpolation points and is fast uses computer memory efficiently. For the transient induced water quality modeling purposes, the method of characteristics based solution for the hydraulic transient equations and the finite difference based solution for the advection-dispersion-reaction equation was coupled by Fernandes and Karney (2004). The governing equations for the hydraulic transients can
be solved by either Eulerian or Lagrangian methods. Eulerian approach involves the method of characteristics (MOC), finite difference (FD) and finite element (FE) methods, and Lagrangian approach utilizes an event oriented wave characteristic method (WCM). Boulos et al. (2005) and Wood et al. (2005) concluded through the results of comparison of MOC and WCM based computer models with other available models such as TransAM (McInnis et al. 1997) and H₂OSURGE (Boulos et al. 2003) and found that, both the models are accurate enough for solving transient pressure events, but in terms of the computational speed, WCM is more efficient as it requires few calculations.

4.3 Water Quality Modeling

When the water is transported through the distribution system, the water quality may be deteriorated as a result of the internal pipe wall corrosion, disinfectant byproducts, growth of bacteria in the low flow or dead zone, intrusion of pathogens or contaminated water from the outside environment, re-suspension of sediment and dislodging of corrosion scales/bio-films from the pipe wall surface. Though of course the initial quality of the water discharged from the treatment plant may often remain good enough and safe for the domestic use. Yet there are many factors responsible for deterioration of the water quality in the distribution system including corrosion of the pipe wall surface, leakage, transient low pressure, long standing time etc. To understand the impacts of each factor on water quality, it is helpful to quantify and simulate the potential water quality changes and then to devise various management options in the distribution system. Comprehensive water quality modeling would be helpful and might provide insight into the efficient and effective
operation of the system. It is expected that a comprehensive approach would maintaining specific water quality throughout the system.

Gradually the public expectations and awareness are increasing, and hence government is imposing more strict water quality regulations to minimize the drinking water related hazard and protect the public health more consistently. For this purpose, detailed and reliable water quality modeling is necessary, considering corrosion behaviors of the water-pipe/fixtures metal surface, contaminant intrusion potential due to the transient low pressures, decay of the disinfectants and growth of the bacteria due to longer stagnation period, adverse reactions with the disinfectants, impacts of the disinfectant by-products and corrosion inhibitors etc. Numerical modeling of water quality is based on coupling of the hydraulic (the relationships between conservation of mass and momentum to find spatial and temporal flow velocity, its direction, detention time and pressure) and water quality modules (the relationship among advection, dispersion and reaction processes to simulate corrosion/biological/reaction with disinfectants and find instantaneous water quality parameters). Proper numerical representations of the hydraulic, biological and corrosion processes to simulate the water distribution system responses realistically are the main challenges (Baral 2006). By applying the integrated hydraulic and water quality model, it is possible to evaluate the flow paths, mixing processes, traveling and detention times of the water and contaminants. For the realistic simulation of the prevailing processes, the calibration of both the hydraulic and water quality models based on field data is important (Elton et al. 1965). In addition, to check the reliability and applicability of the modeling with real time situations, validation of the modeling with different set of the practical data is also required. Validation and calibration of the hydraulic as well as water quality models
are the most critical stages for the reliable modeling (Coelho 1997). In 1995, Elton et al. pointed out a few applications of the water quality modeling such as calculating water age, tracking movement-mixing-dispersion of the contaminants, selecting chlorination dosage and its strategic location, analyzing source contribution and predicting water quality parameters, establishing relative contribution of the different sources etc. In addition, the water quality modeling can be used for simulating the electro-chemical corrosion processes that is most important for this thesis.

### 4.4 Modeling of the Transport Mechanism

Most of the water quality modeling is based on the governing partial differential equations representing transport of the water and contaminant constituent as well as prevailing advection, dispersion, reactions processes, and source and sink interactions. The governing equation for advection, dispersion and reaction is derived from the law of conservation of mass and Fick’s law that expresses transportation process of the single constituent. The result represents the advection process caused by the movement of the bulk water, dispersion process as a result of the pipe wall effects and contaminant decay due to the reaction process (Baral 2006). The advection-dispersion-reaction approach has widely been used in formulating water quality models (Axworthy and Karney 1996, Islam and Chaudhry 1998, Tzatchkov et al. 2002, Fernandes and Karney 2004 and Baral 2006). The general governing equation is a parabolic second order partial differential equation with reaction term as:

\[
\frac{\partial C_{i(x,t)}}{\partial t} + u_i \frac{\partial C_{i(x,t)}}{\partial x} - D_i \frac{\partial^2 C_{i(x,t)}}{\partial x^2} + r(C_{i(x,t)}) = 0
\]  

(4.3)

in which,
\( C_{i(x,t)} \) = concentration of the constituent within links \( i \), (M/L^3)  
\( x \) = longitudinal spatial dimension, (L)  
\( t \) = temporal variable, (T)  
\( u_i \) = mean flow velocity in the link \( i \), (L/T)  
\( D_i \) = longitudinal dispersion coefficient in the link \( i \), (L^2/T)  
\( r(C_{i(x,t)}) \) = the reaction (growth/decay) term

The reaction term \( r(C_{i(x,t)}) \) represents the growth or decay in the process that can be written as \( r(C_{i(x,t)}) = \pm k(C - C^*)C^{n-1} \), in which \( C^* \) is the limiting concentration, \( k \) is the reaction constant and \( n \) is order of the reaction. For the first order reaction, \( n = 1 \) and the reaction term appears as \( r(C_{i(x,t)}) = kC_{i(x,t)} \). The first term of the Equation 4.3 represents the temporal change in the constituent concentration, second term represents the advection process due to movement of the bulk water, and the third term indicates the dispersion process in the \( i^{th} \) link.

From Equation 4.3, if summation of the advection and reaction terms sets equal to zero, then steady state one dimensional continuity equation is obtained (Clarke et al. 1988, Boulos et al. 1994a and Boulos et al. 1994b) as follows:

\[
u_i \frac{\partial C_{i(x,t)}}{\partial x} + r(C_{i(x,t)}) = 0 \quad (4.4)
\]

In most of the cases, for contaminant transport modeling, the one-dimensional steady state approach is used to simulate their movement and distribution in the distribution system (Rossman 1993, Boulos et al. 1994a, 1994b, 1994c, 1995, Rossman and Boulos 1996) though a few models have been used for simulating extended periods events. A
model that has the facility of simulating a extended period is typically called a dynamic model; in that there is a provision for simulating temporal change in the constituent concentrations the name is meaningful, but it makes it harder to distinguish fully transient models. (Baral 2006).

An advective transport model based on the law of conservation of mass was developed by Rossman (1993) for contaminant tracking, computing concentration and water age, which is commercially known as EPANET. An event driven discrete simulation method was presented by Boulos et al. (1994a, 1994b and 1995) to simulate the temporal interactions of the water quality and hydraulics. Based on the results found from an analysis for sensitivity of the constituent transport to the dispersion in single pipe, it is concluded that the dispersion process dominates the transport mechanism when the flow velocity is low (Axworthy and Karney 1996). An implicit finite difference model was developed by Islam and Chaudhry (1998) based on the concept that decay and transport due to the dispersion and advection, and there is a complete mixing at the junction. This model was used to simulate the spatial and time dependent residual constituent under the slowly varying unsteady flow conditions. Their solution was limited to the small network and didn’t consider the high dispersion and low flow conditions.

The governing equation for the advection, dispersion and reaction processes in the distribution system was solved numerically by Tzatchkov et al. (2002) by following the Eulerian-Lagrangian method. They generated large system of the equations from numerical schemes by following the Green’s function technique and disintegrated them into three tri-diagonal systems for the each pipe and one for concentration at the junction.
And, since in the turbulent flow, advection is the dominating mass transport process, the term representing dispersion process in Equation 4.3 can be set equal to zero. This result the simplified but reasonably acceptable form of the mass transport equation valid for the quasi-steady, transient unsteady or turbulent flow conditions (Fernandes and Karney 2004) as:

\[
\frac{\partial C_{i(x,t)}}{\partial t} + u_i \frac{\partial C_{i(x,t)}}{\partial x} + r(C_{i(x,t)}) = 0
\] (4.5)

In their approach, the governing equations for the fully unsteady hydraulic conditions were solved by the method of characteristics and the governing equation representing the advection-reaction processes was solved by the finite difference method and finally coupled them for the integrated solution. In this model, the transport due to advection was considered dominant instead of dispersion. The numerical scheme used for solution of the governing transport equation is relatively stable, consistent and compatible with the hydraulic transient simulation (Baral 2006).

4.5 Available Software for Transient Flow and Water Quality Modeling

McInnis et al. (1997) developed a versatile computer based model TransAM in which wide variety of the boundary condition and advanced options exists and can be used for the simulation, analysis and design and test of the operational practices. University of Kentucky developed SURGE 5.2 computer model (AWWA 2001) for analysis and simulation of the surge events in the distribution system. This model can be used for analysis of the complex systems including pumps, valves and surge tanks. The model H₂OSURGE developed by MWH Soft Inc. is useful for simulation of the large pressure surge and analysis of cavitations and performance of the protection devices including open
or closed surge tanks, discharge tanks, pressure relief valves etc. (Boulos et al. 2003). Danish Hydraulic Institute (DHI) in association with BOSS International of USA developed EPANET 2.0 numerical engine based professional modeling software MIKE NET. This model is useful for simulation of the steady state flow, simulation for the extended period, water quality, application for supervisory control and data acquisition (SCADA) system and analysis of the nodal demands, fire demands, reservoir characteristics, system head curves, water age, constituents decay, flow path and concentrations. In addition, DYNASIM, H$_2$ONET, Water CAD, STONER, GINAS, SIMNET are available for the steady state and extended period modeling, FLOWMASTER and HYPRESS for the transient events modeling and EPANET, ODULA and PICOLLO for the water quality modeling (Baral 2006).

4.6 Summary

This chapter summarizes the importance of realistic considerations of the hydraulic transient events in designing the water distribution systems, the theories available for formulation of the hydraulic transient phenomena, their solution schemes and modeling approaches. It also summarizes the importance of water quality modeling in the distribution system, theories available and formulation of the governing processes for the water quality modeling, their solution approaches for the modeling, and integration of the water quality model with the hydraulic transient model. In addition, the chapter briefly summarizes commercially available models for the steady state and extended period simulations of hydraulic events, unsteady transient event simulations, SCADA and water quality simulations.
CHAPTER 5
MODEL DEVELOPMENT FOR LEAD CORROSION PROCESSES

“A model is used to help select the best among competing proposals. It is fundamentally irresponsible and unethical for modelers not to interpret the inherent uncertainty of their model output.”

William James, Rules for Responsible Modeling, CHI, 2005

“Things should be made as simple as possible, but not any simpler.” Albert Einstein

5.1 Introduction
Corrosion is essentially an electrochemical process, but in the WDS it can be affected by the flow velocity, turbulence and oscillation of the transient pressure waves as well. Due to electrochemical reactions between electrolytes (water) and metallic pipe material (lead), metallic ion (\(\text{Pb}^{2+}\)) is released to the bulk water and reacting with the hydroxide ion (\(2\text{OH}^-\)) finally produced lead hydroxide (\(\text{Pb(OH)}_2\)). This lead hydroxide is carried by the bulk water, and part of it often buildup on the pipe wall surface as solid scale. This scale can be detached from the pipe wall surface and mixed with the water due to high flow velocity/turbulence and oscillation of pressure waves created during transient events. As lead is poisonous and creates serious threat to human health; thus it is desirable to control its content in any form in the drinking water.

The electrochemical reactions responsible for the metallic pipe corrosion are dependent on chemical properties of the bulk water and pipe material, prevailing advection-dispersion processes and physical properties of the system. Considering the complex
interactions between electrical, chemical and hydraulic factors related to the corrosion processes in the WDS, highlights the importance of a realistic modeling effort. Through modeling, it is possible to investigate and predict the system responses to changing chemical and hydraulic parameters as well as associated water quality changes in the system. The above tasks can be done directly through field and laboratory tests, but this is laborious, time consuming, costly and overall hazardous. By contrast, once the model is developed, it is much easier to use, lower in cost and more time effective. Most significantly, numerical tests don’t create real hazards in the system during application and option testing. For lead corrosion control and inhibition, modification of the chemical properties of the bulk water (DO, pH), disinfectants (chlorine, chloramines) and addition of corrosion inhibitors (phosphate, orthophosphate, silicates, etc.) are necessary. By using appropriate model, responses of the system against such modifications can ideally be investigated conveniently and reliably to at least some extent. Certainly this is the long-term goal that the current work is a mere introduction to.

The development of an appropriate model for simulating the corrosion processes in the distribution system, considering all the hydraulic (flow velocity, turbulence, pressure, oscillation of the transient pressure wave), chemical (pipe materials, DO, pH, alkalinity, hardness, disinfectants and disinfectant bi-products, buffer capacity and corrosion inhibitors), and physical (temperature, diameter and length of the pipe, layout and mode of operation) conditions is an extremely difficult task. To get the real picture of the corrosion related interactions, a multi component 3-D model is likely required. As a preliminary step, a simplified 1-D model is considered with the aim of developing a base condition of the lead corrosion study through numerical modeling in the water distribution system. The
proposed model is expected to deal effectively with a range of hydraulic conditions, a few chemical parameters and physical conditions e.g., pipe material (lead), dissolved oxygen (DO), pH, pipe diameter and length, combination of the sets of different diameter pipes connected in series and mode of operations.

5.2 Corrosion Process in the Proposed Numerical Model

In the proposed 1-D lead corrosion model for the WDS – dissolved oxygen (DO) and hydrogen ion (pH) are considered the key oxidation and reduction process controlling parameters. In the primary reaction, the pipe wall material (lead) reacts with the dissolved oxygen (DO) and the hydrogen ion (pH) present in the bulk water, and produces lead ions ($Pb^{2+}$) and hydroxyl ions ($OH^-$). Then in the secondary reaction, lead ion combines with hydroxyl ion, and forms lead hydroxide ($Pb(OH)_2$). The advection-dispersion-reaction equation (ADRE) is used to represent the path of the each chemical species participating in the corrosion reaction.

In a WDS hydraulic transient events occur frequently and thus can influence the internal corrosion process. Hence, governing partial differential equations (conservation of mass and momentum) representing the hydraulics transient phenomena are used for modeling of the hydraulic transient events. The method of characteristics (MOC) is used to convert two governing partial differential equations (PDE) of the hydraulic transients into four ordinary differential equations, which then solved by the implicit finite difference method (Baral 2006). The partial differential equation representing ADR processes is solved by the implicit finite difference method and coupled with hydraulic transient component.
5.3 **Numerical Model Development**

Development of 1-D numerical models for both hydraulic transient events and the associated corrosion in lead based distribution system are the subjects of this study. In fact, the model originally developed by Fernandes and Karney (2004) to study the fate of chlorine in the distribution pipes and later modified by Naser and Karney (2005) to study the corrosion process during hydraulic transient conditions in a distribution system. Both the models were for iron based single diameter pipe distribution system. For this study, Naser and Karney (2005) model is modified, extended and developed for lead-based multiple diameter pipes connected in series; convenient time series (for each component of the hydraulics and corrosion parameters with a flexibility of specified time period) and component-wise spatial data acquisition with proper labels.

5.3.1 **Hydraulic Transient Model**

5.3.1.1 **The Governing Equations**

The governing equations representing hydraulic transient events in the distribution systems are quasi linear hyperbolic partial differential equations. For representing hydraulic transient response appropriately, inertia and compressibility effects of the water must be considered (Fernandes 2002). With the help of the laws of conservation of momentum and mass, modeling of 1-D flow in the water distribution system can be obtained (Chaudhry 1992 and Wylie and Streeter 1978). Solution of the following governing 1-D hyperbolic partial differential equations for the momentum and continuity are required, to determine the spatial and temporal hydraulic conditions in the system:

\[
\frac{\partial V}{\partial t} + g \frac{\partial H}{\partial x} + \frac{fV|V|}{2D} = 0 \quad \text{(Momentum)}
\]  

(5.1)
Or, \[ \frac{\partial Q}{\partial t} + gA \frac{\partial H}{\partial x} + RQ|Q| = 0 \]

\[ \frac{\partial H}{\partial t} + \frac{a^2 \partial V}{g \partial x} = 0 \] (Continuity) \hspace{1cm} (5.2)

Or, \[ a^2 \frac{\partial Q}{\partial x} + gA \frac{\partial H}{\partial t} = 0 \]

Where, \( V = V(x, t) \) the instantaneous average flow velocity, \( Q = Q(x, t) = AV(x, t) \) the instantaneous flow in pipe, \( R = \frac{f}{2DA} \), \( D \) = pipe diameter, \( H = H(x, t) \) the piezometric head, \( a = \) acoustic wave speed, \( g = \) acceleration due to gravity, and \( f = \) Darcy-Weisbach frictional coefficient.

5.3.1.2 The Method of Characteristics

To solve the governing partial differential equations, combination of numerical methods such as method of characteristics and finite difference method are used. The two basic governing partial differential equations are transformed first into a system of four ordinary differential equations by using the method of characteristics (MOC) as follows:

Let

\[ L_1 = \frac{\partial V}{\partial t} + gA \frac{\partial H}{\partial x} + RV|V| = 0 \]

Or \[ L_1 = gH_x + V_t + \frac{f}{2D} V|V| = 0 \] \hspace{1cm} (5.3)

And \[ L_2 = \frac{\partial H}{\partial t} + \frac{a^2 \partial V}{g \partial x} = 0 \]

Or \[ L_2 = H_t + \frac{a^2}{g} V_x = 0 \] \hspace{1cm} (5.4)
Combining Equations 5.3 and 5.4 linearly gives

$$L = L_1 + \lambda L_2$$  \hspace{1cm} (5.5)$$

Or

$$\lambda \left( H_x \frac{g}{\lambda} + H_t \right) + \left( V_x \frac{a^2}{g} + V_t \right) + \frac{fV|V|}{2D} = 0$$ \hspace{1cm} (5.6)$$

Total derivatives of $V$ and $H$ are

$$\frac{dV}{dt} = \frac{\partial V}{\partial t} + \frac{\partial V}{\partial x} \frac{dx}{dt} = V_t + V_x \frac{dx}{dt}$$ \hspace{1cm} (5.7)$$

And

$$\frac{dH}{dt} = \frac{\partial H}{\partial t} + \frac{\partial H}{\partial x} \frac{dx}{dt} = H_t + H_x \frac{dx}{dt}$$ \hspace{1cm} (5.8)$$

Defining the multiplying factor $\lambda$ as

$$\frac{g}{\lambda} \frac{dx}{dt} = \frac{\lambda a^2}{g}$$ \hspace{1cm} (5.9)$$

Then

$$\lambda = \pm \frac{g}{a}$$ \hspace{1cm} (5.10)$$

By using Equations 5.7, 5.8 and 5.9 in Equation 5.6 we get

$$\lambda \frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0$$

Or

$$\frac{g}{a} \frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0$$ \hspace{1cm} (5.11)$$

Only when

$$\frac{1}{\lambda} \frac{dx}{dt} = a$$ \hspace{1cm} (5.12)$$

And

$$\frac{g}{a} \frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0$$ \hspace{1cm} (5.13)$$
Only when \( \frac{dx}{dt} = -a \) \hspace{1cm} (5.14)

Equations 5.11 and 5.13 are the two ordinary differential equations with independent variable, \( t \). These two equations are valid only along the straight line characteristics but Equations 5.1 and 5.2 were valid everywhere in the \( x-t \) plane. This happens as a result of the simplifications. The Equations 5.12 and 5.14 represent two characteristic straight lines with slopes \( \pm \frac{1}{a} \) in the \( x-t \) plane as shown in Fig. 5.1 and also known as compatibility equations (Wylie and Streeter 1978).

![Figure 5.1: Characteristic lines in x-t plane (Wylie & Streeter 1978, Chaudhry 1992)](image)

**5.3.1.3 The Finite Difference Approximation**

Considering a pipeline divided into \( N \) equal reaches, length of each reach is \( \Delta x \) and time step is \( \Delta t \), where \( \Delta x = a \Delta t \). These characteristic lines (Figure 5.1) represent the path traversed by a disturbance i.e., a disturbance at point \( A \) at time \( t_0 \) would reach to the point \( P \) after time \( \Delta t \). Considering first a single pipeline system with a constant head reservoir at upstream end (at \( x = 0 \)) and a valve at the downstream end (at \( x = L \)). Assuming that the transient condition is produced by instantaneously closing the valve, and at the time of
closing the valve (i.e., t = 0), there is steady flow in the pipe. As a result of suddenly closing the valve at the downstream end, a pressure wave generates and travels to the upstream direction. Now assuming that the head \( H \), and flow velocity \( V \), and flow \( Q \) at the time \( t = 0 \) are known at both \( A \) and \( B \) points and want to compute \( H \), \( V \) and \( Q \) at time \( t = \Delta t \) i.e., at point \( P \) in Figure 5.1.

Multiplying by \( \frac{adt}{g} = \frac{dx}{g} \) and integrating Equation 5.11 within the domain \( A \) to \( P \) gives

\[
\int_{A}^{P} dH + \frac{a}{gA} \int_{A}^{P} dQ + \frac{f}{2gDA^{2}} \int_{A}^{P} Q|Q|dx = 0
\]  

(5.15)

Third term of the Equation 5.15 represents the frictional losses and to evaluate this, an approximation is required. One the simplest of these is

We get \( \int_{A}^{P} Q|Q|dx \simeq Q_{A}|Q_{A}|\Delta x \) through 1st order approximation.

Now Equation 5.15 can be written as

\[
H_{P} - H_{A} + \frac{a}{gA} (Q_{P} - Q_{A}) + \frac{f}{2gDA^{2}} Q_{A}|Q_{A}|\Delta x = 0
\]  

(5.16)

This Equation 5.16 can give reasonable results, except if the frictional term is large when instability can occur, an eventually avoided by using a small computational time interval \( \Delta t \) or higher-order approximation.

Possible 2nd order approximations of the frictional term are

\[
\int_{A}^{P} Q|Q|dx = \Delta x \frac{Q_{A} + Q_{P}}{2} \left| \frac{Q_{A} + Q_{P}}{2} \right|, \text{ for which iteration is required to approximate } Q_{P}
\]

Or, \( \int_{A}^{P} Q|Q|dx = Q_{P}|Q_{A}|\Delta x \) which is linear approximation and can be solved directly.
Using the linear approximation, Equation 5.15 can be written as:

\[ C^+ : H_p - H_A + \frac{a}{gA}(Q_p - Q_A) + \frac{f}{2gDA^2} Q_p |Q_A| \Delta x = 0 \]  \hspace{1cm} (5.17)

Similarly from Equation 5.13

\[ C^- : H_p - H_B - \frac{a}{gA}(Q_p - Q_B) - \frac{f}{2gDA^2} Q_p |Q_B| \Delta x = 0 \]  \hspace{1cm} (5.18)

Equations 5.17 and 5.18 are the basic compatibility relations that describe the transient propagation of pressure head and flow in a pipeline (Wylie & Streeter 1978).

For convenience Equations 5.17 and 5.18 can be rewritten as:

\[ C^+ : H_p = C_p - BQ_p \]  \hspace{1cm} (5.19)

And \[ C^- : H_p = C_M + BQ_p \]  \hspace{1cm} (5.20)

Where \[ C_p = H_{i-1} + BQ_{i-1} - RQ_{i-1} |Q_{i-1}| \]  \hspace{1cm} (5.21)

\[ C_M = H_{i+1} - BQ_{i+1} + RQ_{i+1} |Q_{i+1}| \]  \hspace{1cm} (5.22)

\[ B = \frac{a}{gA} \text{ (Pipeline impedance)} \]  \hspace{1cm} (5.23)

And \[ R = \frac{f\Delta x}{2gDA^2} \]  \hspace{1cm} (5.24)

The Equation 5.19 is valid along the +ve (positive) characteristic line AP and Equation 5.20 is valid along the –ve characteristic line BP; \( C_p , C_M , B \) and \( R \) are known constants. The Equations 5.19 and 5.20 can be solved easily for all interior points along the pipe, as they are two simultaneous equations with two unknowns. And with special boundary conditions, values at the boundaries at time \( t = \Delta t \) can be calculated. At time \( t = 0 \) conditions at all the grid points are computed which is steady state condition. Similarly for \( t = 2\Delta t \), \( t = 3\Delta t \) and
son on until full transient conditions for the system are determined or desired time duration is covered (Wylie & Streeter 1978, Chaudhry 1992).

5.3.1.4 The Implicit Finite Difference Method

Partial derivatives in the governing equations can be replaced by the finite difference approximations. These approximations can be either explicit or implicit. The implicit finite difference method is relatively stable though it requires more computational effort and resources. Yet micro-computers are now so powerful that computational speed and allocation of sufficient resources for implicit finite difference scheme is seldom a problem. The finite difference grid system is shown in Figure 5.2 where i-1, i and i+1 designate spatial grid points and j-1, j and j+1 indicate the temporal grid points. In the implicit finite difference method, the unknown head and discharge at a section at the end of time step \( j+1 \), are expressed in terms of the unknown values of the same kind at the neighboring sections, and equations for the whole system are solved simultaneously (Chaudhry 1992). Assuming that conditions at a time \( t_0 \) at \( j \) level have already been computed and their values at time \( t_0 + \Delta t \) i.e., at \( j+1 \) level are computed sequentially.

Replacing partial derivatives of the Equations 5.1 and 5.2 by the finite difference approximations:

\[
\frac{\partial H}{\partial x} = \frac{(H_{i+1}^{j+1} + H_{i+1}^{j}) - (H_i^{j+1} + H_i^{j})}{2\Delta x} \quad (5.25)
\]

\[
\frac{\partial H}{\partial t} = \frac{(H_{i+1}^{j+1} + H_{i+1}^{j}) - (H_i^{j+1} + H_i^{j})}{2\Delta t} \quad (5.26)
\]

\[
\frac{\partial Q}{\partial x} = \frac{(Q_{i+1}^{j+1} + Q_{i+1}^{j}) - (Q_i^{j+1} + Q_i^{j})}{2\Delta x} \quad (5.27)
\]
\[
\frac{\partial Q}{\partial t} = \frac{(Q_{i+1}^{j+1} + Q_{i-1}^{j+1}) - (Q_{i+1}^{j} + Q_{i-1}^{j})}{2\Delta t}
\]

(5.28)

\[
RQ|Q| = \frac{R}{4} [Q_{i+1}^{j+1} |Q_i^{j+1}| + Q_{i}^{j+1} |Q_i^{j+1}| + Q_{i-1}^{j+1} |Q_i^{j+1}| + Q_{i}^{j} |Q_i^{j}|]
\]

(5.29)

Now substituting Equations 5.25 to 5.29 into Equations 5.1 and 5.2 and on simplification following nonlinear algebraic equations for the each interior node can be found:

\[
C_1 [Q_i^{j+1} + Q_i^{j-1}] + C_3 [H_i^{j+1} - H_i^{j-1}] + \frac{R}{4} [Q_{i+1}^{j} |Q_{i-1}^{j+1}| + Q_{i}^{j+1} |Q_{i+1}^{j}|
\]

\[
= C_1 [Q_i^{j} + Q_i^{j+1}] + C_2 [H_i^{j} - H_i^{j+1}] + \frac{R}{4} [Q_{i+1}^{j} |Q_{i-1}^{j+1}| + Q_{i}^{j+1} |Q_{i+1}^{j}|
\]

(5.30)

\[
C_1 [H_i^{j+1} + H_i^{j-1}] + C_3 [Q_i^{j+1} - Q_i^{j-1}] = C_1 [H_i^{j} + H_i^{j+1}] + C_3 [Q_i^{j} - Q_i^{j+1}]
\]

(5.31)

Where

\[
C_1 = 0.5\Delta t, \quad C_2 = \frac{gA}{2\Delta x} \text{ and } C_3 = \frac{a^2}{2gA\Delta x}.
\]

Figure 5.2: Definition sketch of finite difference method
The terms on the left hand sides of the Equations 5.30 and 5.31 are functions of the variables at unknown $j+1$ time level, and terms on the right hand sides are functions of the variables at the known $j$ time level. In this method, Equations 5.30 and 5.31 for each interior node, along with the equations describing boundary conditions are solved simultaneously for the whole system by a banded matrix routine. For this method, no MOC equations are required for the solution, but iteration is required (Chaudhry 1992).

5.3.1.5 The Pipes Connected in Series with Different Diameters

The basic formulation of hydraulic transient phenomena for the single pipe system having same diameter and other pipe parameters all along provides the fundamental elements. For the treatment of complex piping system, i.e., multiple diameter pipes connected in series, an additional boundary condition is necessary. This can be obtained by changing a part of the basic formulation. As the system contains more than one pipeline, the interior sections of each pipeline are treated independently of other parts of the system at each instant of time (Wylie and Streeter 1978).

The end conditions of each pipeline must interface with the adjoining pipelines and each boundary condition is treated independently of other parts of the system. The explicit nature
of the solution of the governing equations provides these advantages (Wylie and Streeter 1978). The continuity equation is assumed to be satisfied and a common hydraulic grade line is assumed at the junction at each instant of time.

Referring to the Figure 5.3, assuming that the difference in the velocity heads at sections \((i, n+1)\) and \((i+1, l)\) and head losses at the junction are minor, then

\[ H_{P_{x,v}} = H_{P_{x,l}} \quad (5.32) \]

The characteristics equation for the reach \(i\) is

\[ C^+ : H_{P_{x+i}} = C_P - B_i Q_{P_{x+i}} \quad (5.33) \]

And for the reach \(i+1\) is

\[ C^- : H_{P_{x+i}} = C_{M_{x+i}} + B_{i+1} Q_{P_{x+i}} \quad (5.34) \]

The continuity equation at the junction is

\[ Q_{P_{x,v}} = Q_{P_{x,l}} \quad (5.35) \]

By solving Equations 5.32 and 5.35 simultaneously with Equations 5.33 and 5.34 we get

\[ Q_{P_{x,i}} = \frac{C_P - C_{M_{x,i}}}{B_i + B_{x+1}} \quad (5.36) \]

The other unknowns such as \(H_{P_{x,i}}\), \(H_{P_{x+l}}\) and \(Q_{P_{x,v}}\) are determined directly from the Equations 5.32, 5.33 and 5.34.

5.3.1.6 Boundary Conditions

Considered a large volume of water, reservoirs could be found at either the upstream or downstream ends; as a result, it is assumed that the water level in the reservoirs at the upstream and downstream remains constant during transient state conditions. As changes in the reservoir levels would be so small that can be neglected and hence boundaries may be
analyzed as constant level reservoirs (Chaudhry 1992). The condition of the upstream reservoir is governed by the negative characteristic Equation 5.20 and condition of the downstream reservoir is governed by the positive characteristic Equation 5.19. To develop the boundary condition for the reservoirs, it is required to write first equation defining the relationship between the piezometric head, discharge and reservoir level, then solve it simultaneously with the characteristic equation (Chaudhry 1992). For the valve at the downstream end, writing equations for the flow through the valve at steady and transient states, and then, solving these equations with the help of positive characteristic Equation 5.19, gives the flow through the valve at transient state (Chaudhry 1992).

5.3.1.7 The Stability Criteria
The selection of proper stability criterion is important for any computational approach. The computational schemes of the governing partial differential equations to be convergent, a stability criterion is to be satisfied. The term Courant Number or Condition \( C_r = \frac{a \Delta t}{\Delta x} \) is used for stability analysis. The computational model to be numerically stable Courant Number should be equal or close to the unity i.e., \( C_r = \frac{a \Delta t}{\Delta x} \approx 1 \), the optimum criterion is \( \Delta x = a \Delta t \). In selecting the spatial grid size \( \Delta x \), and computational time interval \( \Delta t \), care should be taken so that Courant Number can not be too large or less than the unity. By using small computational time increment \( \Delta t \), usually the Courant condition for the numerical stability is easily achieved. By adjusting celerity of the shock wave \( a \), equality of the Courant condition can also be achieved (McInnis et.al. 1997 after Baral 2006).
5.3.2 Water Quality Modeling

5.3.2.1 Implicit Formulation of the Advection Dispersion Reaction Equation (ADRE)

The basic partial differential equation governing advection-dispersion-reaction (ADR) processes in the lead based water distribution system is

\[ \frac{\partial C_{i(x,t)}}{\partial t} + U_{i(x,t)} \frac{\partial C_{i(x,t)}}{\partial x} = D \frac{\partial^2 C_{i(x,t)}}{\partial x^2} \pm S_i(C_{i(x,t)}) \]  

(5.37)

The Equation 5.37 is solved numerically by the application of the implicit finite difference method. The rectangular grid system in \(x-t\) plane is used for the solution of this advection-dispersion-reaction equation is presented below.

![Finite difference grid in \(x-t\) plane for the solution of ADRE](image)

Figure 5.4: Finite difference grid in \(x-t\) plane for the solution of ADRE

In this grid system, the point \((x,t)\) represents the distance \(x\), and time \(t\). The initial concentration \(C_{i(x,0)}\) of the constituents is assumed known (measured). The constituent concentration source is considered constant at the upstream boundary i.e., at \(x = 0\)
concentration, \( C_{(0,t)} \) is known (Dirichlet boundary condition). This indicates that a continuous and known source is contributing at this position. Considering the control volume (CV) marked by the dotted lines, \( J_{in} \) is the flux of constituent mass entering and \( J_{out} \) is the flux of constituent mass leaving the control volume, \( V = A \Delta x \) the volume influenced and considering mass balance in the control volume the Equation 5.37 can be written as

\[
V \frac{\partial C}{\partial t} = (J_{in} - J_{out})A \pm S_t(C_{i(x,t)})
\]  
(5.38)

in which \( S_t(C_{i(x,t)}) \) is combination of the source and sink terms.

The time derivative is for the positions \( x-1 \) and \( x \) are approximated as the average derivatives. Neglecting the error terms, the forward time finite difference approximation for the grid points \( t \) and \( t+1 \) can be written as

\[
\frac{\partial C}{\partial t} = \frac{1}{2} \left[ \frac{\partial C}{\partial t}_{x-1} + \frac{\partial C}{\partial t}_{x} \right] = \frac{1}{2} \left[ \frac{C^{t+1}_{x-1} - C^{t}_{x-1}}{\Delta t} + \frac{C^{t+1}_{x} - C^{t}_{x}}{\Delta t} \right]
\]  
(5.39)

or,

\[
\frac{\partial C}{\partial t} = \left[ \frac{C^{t+1}_{x-1} + C^{t+1}_{x} - C^{t}_{x-1} - C^{t}_{x}}{2\Delta t} \right]
\]  
(5.40)

The mass flux coming into the control volume including longitudinal dispersion \( D \) is expressed as

\[
J_{in} = \frac{1}{2} \left( J_{in}^{t}_{x-1} + J_{in}^{t+1}_{x-1} \right)
\]

\[
= \frac{1}{2} \left[ U^{t}_{x-1} C^{t}_{x-1} - \left( D \frac{\partial C}{\partial x} \right)_{x-1} \right] + \frac{1}{2} \left[ U^{t+1}_{x-1} C^{t+1}_{x-1} - \left( D \frac{\partial C}{\partial x} \right)_{x-1}^{t+1} \right]
\]  
(5.41)

Rearranging terms, the Equation 5.41 can be written as

\[
J_{in} = \frac{1}{2} \left( C^{t}_{x-1} U^{t}_{x-1} + C^{t+1}_{x-1} U^{t+1}_{x-1} \right) - \frac{1}{2} \left( D \frac{\partial C}{\partial x} \right)_{x-1}^{t} + D \frac{\partial C}{\partial x} \right)_{x-1}^{t+1}
\]  
(5.42)
Forward approximation for the derivatives gives

\[
\frac{\partial C'}{\partial x}_{x-1} = \frac{C'_x - C'_{x-1}}{\Delta x}
\] (5.43)

\[
\frac{\partial C''}{\partial x}_{x-1} = \frac{C''_{x-1} - C''_{x-1}}{\Delta x}
\] (5.44)

Substituting the Equations 5.43 and 5.44 in Equation 5.42

\[
J_{in} = \frac{1}{2} \left( C'_x U'_{x-1} + C''_{x-1} U''_{x-1} \right) - \frac{1}{2\Delta x} \left[ \left( DC \right)'_{x-1} + \left( DC \right)''_{x-1} - \left( DC \right)'_{x-1} - \left( DC \right)''_{x-1} \right]
\] (5.45)

that represent the influx coming into the control volume.

Utilizing the same averaging concept, expression for the efflux is

\[
J_{out} = \frac{1}{2} \left( J_{out}'|_{x} + J_{out}''|_{x} \right)
\] (5.46)

Where,

\[
J_{out}'|_{x} = U_x \left( C'_{x-1} + \frac{\partial C'}{\partial x}_{x-1} \Delta x \right) - D \left( \frac{\partial C'}{\partial x}_{x} \Delta x + \frac{\partial^2 C'}{\partial x^2} \Delta x \right)
\] (5.47)

\[
J_{out}''|_{x} = U_x \left( C''_{x-1} + \frac{\partial C''}{\partial x}_{x-1} \Delta x \right) - D \left( \frac{\partial C''}{\partial x}_{x} \Delta x + \frac{\partial^2 C''}{\partial x^2} \Delta x \right)
\] (5.48)

Expanding the first order partial derivatives as forward space approximation and the second order partial derivatives as central space approximation for the grid points \((x, t)\) & \((x, t+1)\)

\[
\frac{\partial C'}{\partial x}_{x-1} = \frac{C'_x - C'_{x-1}}{\Delta x} \quad \text{and} \quad \frac{\partial C''}{\partial x}_{x-1} = \frac{C''_{x-1} - C''_{x-1}}{\Delta x}
\] (5.49)

\[
\frac{\partial^2 C'}{\partial x^2} = \frac{C'_{x+1} - 2C'_x + C'_{x-1}}{\Delta x^2} \quad \text{and} \quad \frac{\partial^2 C''}{\partial x^2} = \frac{C''_{x+1} - 2C''_x + C''_{x-1}}{\Delta x^2}
\] (5.50)

\[
J_{out}'|_{x} = U_x \left( C'_{x-1} + \frac{C'_x - C'_{x-1}}{\Delta x} \Delta x \right) - D \left( \frac{C'_x - C'_{x-1}}{\Delta x} + \frac{C'_{x+1} - 2C'_x + C'_{x-1}}{\Delta x^2} \Delta x \right)
\] (5.51)
or, \( J_{out}^{+1} = U_x^t C_x^t - \frac{D}{\Delta x} \left( C_{x+1}^{t+1} - C_x^t \right) \) (5.52)

\[
J_{out}^{+1} = U_x^t \left( C_{x+1}^{t+1} + \frac{C_x^t - C_{x-1}^{t+1}}{\Delta x} \right) - \frac{D}{\Delta x} \left( \frac{C_x^{t+1} - C_{x+1}^{t+1}}{\Delta x} + \frac{C_{x-1}^{t+1} - 2C_x^{t+1} + C_x^{t+1}}{\Delta x^2} \right) \] (5.53)

or, \( J_{out}^{+1} = U_x^t C_x^t - \frac{D}{\Delta x} \left( C_{x+1}^{t+1} - C_x^t \right) \) (5.54)

Substituting the Equations 5.52 and 5.54 in Equation 5.46

\[
J_{out} = \frac{U_x^t C_x^t + U_x^t C_x^{t+1}}{2} - \frac{D}{2\Delta x} \left( C_{x+1}^{t+1} + C_x^{t+1} - C_x^t \right) \] (5.55)

And to obtain the net mass flux rate from the control volume, subtracting Equation 5.55 from Equation 5.45

\[
J_{in} - J_{out} = \frac{1}{2} \left[ U_x^t C_{x-1}^t + U_x^t C_{x-1}^{t+1} - U_x^t C_x^t - U_x^t C_x^{t+1} \right] + \frac{D}{2\Delta x} \left[ C_{x+1}^{t+1} + C_x^{t+1} - 2C_x^{t+1} + C_x^{t+1} + C_x^t \right] (5.56)
\]

In Equation 5.38, \( \pm S_i \left( C_i(x,t) \right) \) is the combination of source and sink terms and can be expressed as \((K.C.V + \beta.V)\) (Naser 2006). The term \((K.C.V)\) represents those terms that follow slower first order reaction rate and the term \((\beta.V)\) represents the terms that follow the relatively fast zero order reaction rate. In these relationships, \(K\) and \(\beta\) are the reaction coefficients associated with chemical kinetics (Naser 2006).

Expanding the first order reaction term we get

\[
K.V.C = K.A.\Delta x \left( \frac{C_{x+1}^{t+1} + C_x^t + C_{x-1}^{t+1} + C_{x-1}^t}{4} \right) \] (5.57)

This overall reaction term is assumed to occur both within the bulk flow and with the pipe wall material (Rossman 1993 after Fernandes 2002).
Then, \( S_i(C(x,t)) = \frac{K.A.\Delta t}{2} \left( \frac{C_{i+1}^{x,t} + C_{i}^{x,t} + C_{i-1}^{x,t} + C_{i}^{x,t}}{4} \right) + \beta.A.\Delta x \) \hspace{1cm} (5.58)

Now substituting Equations 5.40, 5.56 and 5.58 in Equation 5.38

\[
A.\Delta x \left[ \frac{C_{x+1}^{x,t} + C_{x}^{x,t} - C_{x-1}^{x,t} - C_{x}^{x,t}}{2\Delta t} \right] = \frac{1}{2} \left[ U_{x-1}^{x,t} C_{x-1}^{x,t} + U_{x}^{x,t} C_{x}^{x,t} - U_{x}^{x,t} C_{x}^{x,t} - U_{x+1}^{x,t} C_{x+1}^{x,t} \right] \Delta x \\
+ \frac{D}{2\Delta x} \left[ C_{x+1}^{x,t} + C_{x}^{x,t} - 2C_{x}^{x,t} + C_{x-1}^{x,t} + C_{x}^{x,t} \right] \Delta x \\
+ K.A.\Delta x \left[ \frac{C_{x}^{x,t} + C_{x+1}^{x,t} + C_{x}^{x,t} + C_{x-1}^{x,t}}{4} \right] + \beta.A.\Delta x \hspace{1cm} (5.59)
\]

Multiplying both sides by \( \left( \frac{2.\Delta t}{\Delta x} \right) \) and rearranging

\[
C_{x+1}^{x,t} \left[ 1 - \frac{\Delta t}{\Delta x} U_{x-1}^{x,t} - K \frac{\Delta t}{2} - D \frac{\Delta t}{\Delta x^2} \right] + C_{x}^{x,t} \left[ 1 + \frac{\Delta t}{\Delta x} U_{x}^{x,t} - K \frac{\Delta t}{2} + 2D \frac{\Delta t}{\Delta x^2} \right] + \left[ - \frac{\Delta t}{\Delta x^2} \right] C_{x+1}^{x,t} \\
= C_{x-1}^{x,t} \left[ 1 + \frac{\Delta t}{\Delta x} U_{x+1}^{x,t} + K \frac{\Delta t}{2} + D \frac{\Delta t}{\Delta x^2} \right] \\
+ C_{x}^{x,t} \left[ 1 - \frac{\Delta t}{\Delta x} U_{x}^{x,t} + K \frac{\Delta t}{2} - 2D \frac{\Delta t}{\Delta x^2} \right] + D \frac{\Delta t}{\Delta x^2} C_{x+1}^{x,t} + 2\Delta t.\beta \hspace{1cm} (5.60)
\]

The finite difference Equation 5.60 can be solved by using the Thomas algorithm for a series of pipe system (Hoffman 2001).

Expressing coefficients (known) of the Equation 5.60 in terms of known values of velocities with respect to each x-t grid points as

\[
I_1 = 1 + \frac{\Delta t}{\Delta x} U_{x-1}^{x,t} + K_x \frac{\Delta t}{2} + D I_{x-1}^{t} \frac{\Delta t}{\Delta x^2} \hspace{1cm} (5.61)
\]

\[
I_2 = 1 - \frac{\Delta t}{\Delta x} U_{x}^{x,t} + K_x \frac{\Delta t}{2} - 2D I_{x}^{t} \frac{\Delta t}{\Delta x^2} \hspace{1cm} (5.62)
\]
\[ I_3 = 1 - \frac{\Delta t}{\Delta x} U_{x-1}^{t+1} - K_{x-1} \frac{\Delta t}{2} - D_{x-1}^{t+1} \frac{\Delta t}{\Delta x^2} \]  
(5.63)

\[ I_4 = 1 + \frac{\Delta t}{\Delta x} U_x^{t+1} - K_x \frac{\Delta t}{2} + 2D_x^{t+1} \frac{\Delta t}{\Delta x^2} \]  
(5.64)

\[ I_5 = -D_{x+1}^{t+1} \frac{\Delta t}{\Delta x^2} \]  
(5.65)

\[ I_6 = D_{x+1}^{t} \frac{\Delta t}{\Delta x^2} \]  
(5.67)

and \( I_7 = 2.\Delta t.\beta \)  
(5.68)

Substituting Equations 5.61 to 5.68 in Equation 5.60 gives

\[ I_3 C_{x-1}^{t+1} + I_4 C_x^{t+1} + I_5 C_{x+1}^{t+1} = I_1 C_{x-1}^{t} + I_2 C_x^{t} + I_6 C_{x+1}^{t} + I_7 \]  
(5.69)

In Equation 5.69, all concentrations on the right hand side are known and unknown concentrations on the left hand side to be calculated by using trigonal matrix (Naser 2006).

### 5.4 Computations in the Model and Data Acquisition

For the convenient computations, data gathering and acquisition, the algorithm of the original numerical model developed by Fernandes (2002) and Naser and Karney (2005) is modified, extended and improved for the current work. Algorithm for the continuous (or for the specified time period) time series data generation for the reach to reach of the pipeline and for specific corrosion and transient related components/parameters is introduced. This gives convenience for the acquisition of only required corrosion and transient parametric time series data for the reach in interest by eliminating data acquisition for other reaches of no interest. With the use of this algorithm it is possible to save huge amounts of hard disk space and yet also provide for ease of handling and processing data, (only necessary data is gathered as output after model run). In reality, this numerical model normally generates
huge amount of output; if uncontrolled, one run for only a few hours can consume significant resources.. A good notebook computer (in 2007) with a hard disk capacity of 120 GB can accommodate only for a few hours run data when the program is not controlled for data gathering. In addition, algorithm for the spatial data generation for the selected reaches for the selected time period is introduced that also minimized volume of unnecessary data gathering and provides convenience in processing and analyzing model output data.

5.5 Summary

This chapter presents brief overview of the lead chemistry in WDS, the representation of the lead corrosion process in the proposed numerical model, the governing equations for the hydraulic transients, and the numerical model development and solution scheme. The governing equations are solved here using the method of characteristics, characteristic lines in x-t plane, and finite difference approximation are used for the water quality calculations. The formulation and solution scheme permit different diameter pipes connected in series, a variety of initial and boundary conditions and satisfy the convergence or stability criteria for the solutions.

This chapter briefly discusses implicit finite difference solution of the governing partial differential equations for the hydraulic transient events with definition sketch of the finite difference method. This chapter also presents the adopted water quality modeling approach, governing equation representing advection-dispersion-reaction processes in the water distribution system, finite difference grid in x-t plane for solution of the advection-dispersion-reaction equation (ADRE), Dirichlet boundary conditions, the control volume
concept, the detailed solution scheme for the ADRE, and considers the computation and
data acquisition methods in the model.
CHAPTER 6
MODEL SIMULATION, APPLICATION AND RESULTS ANALYSIS

“... implications of the characteristics of water are enormous, no mere list of its properties will describe a physical problem completely. Whether we are concerned with water quality ... with transient conditions in a pipe, natural phenomena also obey a set of physical laws that contributes to the character and nature of a system’s response. If engineers are to make quantitative predictions, they must first understand the physical problem and the mathematical laws that model its behavior.”


“A little inaccuracy sometimes saves tons of explanations.” – Moung Ka

6.1 Introduction

This chapter deals with the preliminary investigation into the corrosion processes of lead pipelines in water supply and distribution system with the help of the proposed integrated numerical transient-corrosion model. The model is simulated and applied to a typical case to investigate the implications of lead release associated with the hydraulic transient events, unsteady and turbulent flow conditions, and change in key water quality parameters that include pH and dissolved oxygen (DO). The initial case, for single pipe systems, was used by Fernandes and Karney (2004) to investigate the impact of hydraulic transient on water quality in iron pipelines with the 1-D model, Naser and Karney (2005) to investigate the corrosion events of iron pipe with 1-D and 2-D models, and Baral (2006) to investigate the impacts of multi-component WQ species on corrosion of the iron pipe with 1-D model.

In the present study, the schematic of the initial case is customized for the combination of pipes having different diameter connected in series, and for lead instead of
iron pipe. In this study, 1-D model is used to numerically identify the concentration of lead ions and WQ species in the system as a consequence of corrosion processes with various hydraulic conditions. In addition, thorough analysis of the modeling data is completed to investigate the quantitative relationships among hydraulic transient-water chemistry-corrosion events, and to understand patterns and trends of the impact of the hydraulics and key WQ species on lead ion release in a WD system.

6.2 Case Study

The system for case study as shown in Figure 6.1 comprises two reservoirs, two pipe segments with different diameter connected in series, and a check valve located at the extreme downstream end of the pipe line. In general, total length of the pipe is about 400 m, with the upstream segment 240 m long and the downstream segment 160 m. The diameter of the pipe located at the upstream reach is 0.02 m, and that located at the downstream reach is 0.013 m to 0.017 m, corresponding to the pipe diameter used in most of the lead based supply system in the City of London (Huggins 2007). There is a junction at 240 m, from the upstream reservoir, and the change in diameter is sudden from 0.02 m to 0.013 - 0.017 m. Elevations of the upstream and downstream reservoir water levels are considered as 50 m and -25 to -50 m respectively to produce large pressure waves. The pressure wave speed is assumed as 1000 m/s, steady state flow rate is approximately 0.80 liter/s when the pipe diameter is 0.02 m throughout and the valve is fully open; different friction factors (Darcy-Weisbach) for the new and old pipes are used. Roughly, 3 times higher friction factor value is assumed for the old pipe compared to the new pipe, to consider extra roughness due to sedimentation, scale formation and corrosion.
Figure 6.1: Qualitative representation of the reservoir-pipeline system (Courtesy: Ehsan M)

Water levels in the reservoirs are assumed constant, and there is no flow in the system initially as the valve is fully closed. The valve is momentarily opened fully, to introduce a transient oscillating pressure wave into the system. The pipe is discretized in the longitudinal direction, in general, into 120 equal parts for the upstream reach, and 80 equal parts for the downstream reach that gives a mesh size of $dx = 2$ m. For numerical stability, Courant number ($C_r$) is considered as unity, and the time step for hydraulic model is calculated as

$$ dt = \frac{C_r \Delta x}{a} = \frac{1 \times 2.0}{1000} = 0.002 \text{s} $$

The time step for the Advection-Dispersion-Reaction (water quality model) model is considered 60 times higher than the time step used in hydraulic model, that is, $dt_c = 0.002 \times 60 = 0.12 \text{ s}$. This time step ratio (water quality/hydraulic = 60) is considered as an “accumulation” term. The model is first run with certain initial values that include, in the case of the hydraulic model, total hydraulic head $H = 100$ m, spatial discretization $N_x = 200$, Darcy-Weisbach pipe friction factor $f = 0.02$, time step $dt = 0.002 \text{ s}$, and in case of the Advection-Dispersion-Reaction model, equilibrium constant ($K_{eq}$) = $1.0e57$, reaction rate
coefficient \( \beta = 1.0e01 \), initial lead concentration = 0.0mg/l, dissolved oxygen (DO) = 5.0 mg/l and pH = 7.0 (representing the opposite value of the concentration of hydroxide (OH) radical) that gives a base condition. These values are changed in the next runs, to investigate the impact of each parameter on transient hydraulics and corrosion vis-à-vis water quality of the system.

6.3 Results and Discussions

6.3.1 Modeling to Evaluate the Impacts of Discretization on Hydraulics

Transient hydraulic modeling in this study forms the base of Advection-Dispersion-Reaction; that is, water quality modeling, and hence, consistent result from the hydraulic modeling is important for getting consistent result from the water quality modeling. For transient hydraulic modeling, there are governing continuity and momentum equations (quasi linear hyperbolic partial differential equations) with two independent \((x, t)\) and two dependent \((V, H)\) variables. These governing partial differential equations were solved by using the method of characteristics (MOC), and coded by using FORTRAN 90 programming language originally by Naser and Karney (2005) for the single iron pipe system, that is modified and extended by the author, to apply for the lead pipe system, where combination of the different diameter pipes in series is used. In the original model, there was a system for spatial data collection, but in the modified and extended model, a provision for both the time series and spatial data collection with appropriate labels has been added. With this customized model, the hydraulic and corrosion effects of sudden change in the pipe diameter can be explored, and, in addition to spatial variation, temporal variation of the hydraulics, water quality and corrosion situations can be visualized.
6.3.1.1 The Effect of Time Step on Hydraulics and Corrosion Events

The transient responses of the system, against temporal discretization, in terms of the flow velocity and pressure head, at the upstream reach are presented in Figures 6.2 and 6.3. It is apparent from the Figure 6.2 that, there is almost no effect of the time step on flow velocity at the upstream reach, but the pressure head is a little affected (Figure 6.3). With smaller time step, positive peak levels of the pressure head are estimated a bit less though the overall amplitudes remain same.

The flow velocity and pressure head at the downstream end of the system are shown in Figures 6.4 and 6.5. From these figures, it seems clear that, responses of the system with different time step on the flow velocity and pressure head at the downstream end are also similar to the upstream reach of the system.

The flow velocity at the downstream end, rises from zero to about 1.0m/s, immediately after opening the valve, but at the upstream reach (L = 80 m), the flow velocity started to rise not at the same time, there is some time lag.
It is due to combined effect of the friction between pipe wall and fluid mass, viscosity of the fluid and material properties of the pipe or simply wave speed (Wylie and Streeter 1978). The time lag is about 0.33 s, and length of the pipe between downstream end (L = 400 m) to the upstream reach (L = 80 m) is 320 m, that is, velocity of the wave is 320 m/0.33 s = 970 m/s, which is close to 1000 m/s, the acoustic wave speed assumed in the hydraulic transient model simulation. Mass density of the fluid in pipe (ρ), temperature, dynamic viscosity coefficient (µ), pipe wall roughness or roughness height, bulk (K) and elasticity (E) modulus of pipe material etc. are positively correlated with this wave speed (Wylie and Streeter 1978). The initial pressure wave is generated at zero time in response to the hydraulic transient event at the downstream end, that is, immediately after opening the valve (Figure 6.5) and this wave travels to the upstream and reaches to L = 80 m (Figure 6.3) in approximately 0.33 s, that is, with a speed of about 970m/s or close to 1000 m/s quite consistently with the assumed wave speed.

Figure 6.3: Pressure head with different temporal discretization
In general, common characteristics of the waves (either longitudinal or transverse) change with distance from the origin of the wave, its wavelength and period increase, but amplitude and frequency decrease. Carefully examining the Figures 6.3 and 6.5, it is seen that within the first 2 s time period, there are three complete wave peaks at the downstream end (L = 400 m) of the system what is origin of the waves, and at the upstream reach (L = 80 m), there are two and half wave peaks, clearly the frequency decreases. The wave period
is significantly longer (0.17 s) at the upstream reach compare with the downstream end (about 0.055 s), and the amplitude at the upstream reach is realistically smaller (largest one is about 70 m at the upstream compare with 100 m at the downstream end).

Unlike hydraulic events, there is some significant effect of the computational time step on the advection-dispersion-reaction (ADR) modeling results. A typical result is presented in the Figure 6.6. From this figure, it is seen that, estimation of the lead corrosion is appreciably affected by the time step used in the hydraulic model simulation. With the smaller hydraulic time steps \( dt \), relatively higher values of the lead concentrations are observed in the water mass. This result is consistent because a definite relationship \( dt_c = 60dt \) between hydraulic time step and advection-dispersion-reaction time step \( dt_c \) is used in the model.

![Figure 6.6: Lead concentration with different temporal discretization](image)

Advection-dispersion-reaction model computes lead and other water quality related materials concentration as accumulation, and thus, from computational standpoint,
if the hydraulic time step is smaller, then correspondingly, the water quality time step \( dt_c \) would be small, and as a result, more accumulation of the substances are expected. As in the numerical model, average situation within the time steps are considered, that is, the time step small means better representation of the events and relatively accurate results are expected. Proper temporal or spatial discretization is important for accuracy of the numerical modeling results. For better accuracy of the results, mesh size should be as fine as possible. But there are some restrictions considering computational time, cost and hard disk space of the computer. Therefore, it should be selected based on volume of the data to be collected, importance and nature of the job.

6.3.1.2 The Effect of Hydraulic Head

The hydraulic head and the flow velocity are interrelated. If pipe diameter, pipe roughness and valve operation mode remain same, then the flow velocity is directly related to the hydraulic head. In Figures 6.7 and 6.8, the flow velocities at the downstream and upstream reaches of the system, with different initial hydraulic heads are presented. It is seen from both the figures that, the flow velocity with high hydraulic head (H = 100 m), rises rapidly, and then stabilizes relatively quickly, with a little lower value than the highest peak value. On the other hand, with low hydraulic head (H = 10 m), the flow velocity rises gradually step by step, and reaches to a steady state condition with almost highest value (Figure 6.8). But, with the hydraulic head H = 40 m, response of the system to flow velocity is found almost similar to the response with H=100 m (Figure 6.8).
In Figure 6.9, the response of the hydraulic transient model, in terms of the initial hydraulic head versus generated transient pressure head in the system is presented. Examining the results, it appears that, due to high initial hydraulic head, the transient pressure head and turbulence with high magnitude are developed, but dampens down relatively quickly. Maybe it is due to quickly reversal of the strong pressure waves and flow velocities within the system, and high wall/fluid mass friction. Darcy-Weisbach friction formula \( h_f = \frac{fLV^2}{2Dg} \) is used in formulating the hydraulic transient model. From this formula, it is revealed that, flow velocity has very significant effect on frictional loss (proportional to the square power of the flow velocity), that is, any change in the flow velocity would appreciably affect the frictional loss. The pipe diameter is another important hydraulic parameter for influencing transient responses of the system.

Figure 6.7: Flow velocity at d/s end with different initial heads
The effect of the pipe diameter can be visualized comparing the system responses of Baral (2006) and the present study. In Baral’s case, the pipe diameter was used as 1.1284 m, and in the present study diameter of the pipe used is 0.02 m. The gate operation mode in both the cases is same. After initiation of the hydraulic transient event, times taken to reach the system to a steady state condition are 18 s and 4 s in Baral’s and present study cases (Figure 6.9) respectively.

Inspecting the Darcy-Weisbach friction formula, it is clear that, the frictional loss is inversely proportional to the system’s pipe diameter. That is, if the pipe diameter is small,
then the system would reach to a steady state condition relatively quickly. Here the ratio of the pipe diameters used in two cases is 1.1284 m/0.02 m = 56, and the ratio of the times taken to reach the system to a steady state condition is 18 s/4 s = 4.5. Simple explanation of the difference in ratios may be that, in these studies, the systems are not as simple as the frictional cases only; there are transient events as well. In addition, hydraulic head vis-à-vis flow velocity is different in two cases, which is a dominating factor as explained earlier.

6.3.1.3 The Effect of Spatial Discretization

In the hydraulic transient model, there is some effect of the spatial discretization (longitudinal divisions of the pipe length) on hydraulic events. In Figure 6.10, the effect of spatial discretization on flow velocity at the extreme downstream end of the pipe system is presented for initial 4s time period. From this figure, it seems that there is clear impact of the spatial discretization on flow velocity in the system. With the smaller value of $dx$ (1 m) i.e., higher value of $Nx$ (= 400 and 200), the result appears relatively stable, spike free, and estimates a little low flow velocity at a steady state condition. The results are indicating

Figure 6.10: Flow velocities at the downstream end of the pipes with different spatial discretization
alternate acceleration and deceleration consistently with the pressure wave oscillation (Figure 6.11). Initially the flow velocity is zero, pressure head is high (= 50 m) as the valve is closed; when the valve is opened suddenly, the pressure head goes down (= -50 m) and flow velocity instantaneously rises to about 1.0 m/s, which is consistent with the Bernoulli’s energy theorem. And then flow velocity decelerates due to reversing of the pressure head, but after sometime, it again accelerates rapidly with the rising pressure head, and this process continues until reaching to a steady state condition. When \(dx\) is small, higher accuracy in the finite difference solution scheme is expected, and hence, this result would be comparatively more acceptable. In both the cases, it is observed that there is almost no difference in time required to reach in a steady state condition (about 4.0 s).

![Figure 6.11: Pressure head at the downstream end of the pipes](image)

In this case, the system reached to a steady state condition relatively quickly compared with the system used by Baral (2006) (Baral’s system took about 18 s) as diameter of the pipe
used in Baral’s system was much larger (=1.1284 m) and correspondingly, the steady state
discharge was also much higher.

The effect of spatial discretization on the flow rate is shown in Figure 6.12. These
results are consistently similar to the results shown in Figure 6.10 for the flow velocity. It is
seen from the Figure 6.12 that, initially the flow rate is zero when the velocity is zero, and
subsequently, the flow rates changes proportionately with the changes in flow velocities as
shown in the Figure 6.10. After certain time of the opening of the valve, the flow rate with
small $dx$ (=1 m) or high $Nx$ (=400) is observed a little less (Figure 6.12) than that with the
large $dx$, similarly as observed in case of the flow velocity (Figure 6.10). That is, there is
similar effect of the spatial discretization on the flow rate as well. The hydraulic
phenomenon of getting a little low flow velocity with the higher $Nx$ is related with the
pressure head of the system.

![Flow rate vs. time graph](image)

**Figure 6.12**: Flow rates at the downstream end of the pipes with
different spatial discretization
It is observed from Figure 6.13 that, with higher $N_x$ value, the model is estimating a little higher pressure head compare with the case when $N_x$ value is lower. That is, for balancing purpose, as per Bernoulli’s energy theorem, when the pressure head is higher, the velocity head must be consistently lower. The result presented in Figure 6.13, is not for the location close to the valve or downstream end, for which, velocity and flow rate are presented. As a result, it is not possible to get an exact relationship from this figure, but it can be considered an indicative result.

**6.3.1.4 The Effect of Pipe Wall Roughness**

The type of pipe used in the system is important and may impact appreciably to the hydraulic transient phenomena. New pipe has relatively smooth interior wall surface, and hence, low resistance compare with the old pipe, which has relatively rougher wall surface due to wear and tear, and deposition of scales on the wall surface. Naser and Karney (2005)
and Baral (2006) ran the models for new iron pipe having large diameter (= 1.1284 m) considering Darcy-Weisbach friction factor, $f = 0.05$. The present study is for lead pipe, which is usually used for the long time, as lead pipe is relatively durable and corrosion resistant compared with the iron pipe. Darcy-Weisbach friction factor is related to the ratio of roughness imperfection height ($\varepsilon$) and actual inside diameter of the pipe ($d$), that is, there is significant influence of actual inside diameter of the pipe on friction factor.

In the present study, lead pipe having small diameter (0.02 m to 0.013 m) is used instead of large iron pipe. And since, lead pipe is used for the long time. The height of roughness imperfection may be relatively greater for old pipe, as a result of the formation of scale, and wear and tear on the pipe wall surface. The range of the values of Darcy-Weisbach friction factor for different types of new pipe may vary from 0.007 to 0.10 (Giles 1962), but naturally, for the old pipes, this range of the values would be relatively greater depending on age, maintenance and other conditions. For the sake of study, a typical range of the friction factor for the old pipes can be assumed.

Considering these facts, model is run with $f = 0.015$ (when new pipe) and $f = 3 \times 0.015 = 0.045$ (when old pipe). That is, increasing the Darcy-Weisbach roughness factor three times for the old pipe compared with the new pipe. In Figures 6.14, 6.15 and 6.16, responses of the hydraulic transient model against the flow velocity, pressure head and flow rate for the new and old pipes are presented.

Transient responses of the model indicate that as friction factor, $f$ is higher in old pipe, the flow velocity is naturally lower (Figure 6.14), amplitude of the transient pressure head is low as well (Figure 6.15), and the system quickly reaches to a steady state condition compared with the system with new pipe (Figures 6.14 to 6.16). Magnitude of the flow
velocity, at the steady state condition with the new pipe is 1.45 m/s (approximately), and with old pipe, it is about 0.53 m/s, and their ratio is 2.74, that is, this ratio is almost directly proportional to the increase in friction factor. In the system with old pipe, transient pressure energy dampens very quickly (Figure 6.15). This is due to the fact that, propagation of the pressure waves encounter relatively greater resistance in the old pipes having higher pipe wall roughness, and as a result, dissipates internal energy quickly.
The ratio of the times required reaching the systems (with new pipe and old pipe) to the steady state conditions is about $3.6 \, \text{s}/1.30 \, \text{s} = 2.77$, interestingly which is very close to the ratio for the flow velocities.

The effect of friction factor on flow rate (Figure 6.16) seems consistently similar to the flow velocity (Figure 6.14). Response of the system against flow rate, with old pipe shows that flow rate and fluctuation are much lower compare with the system having new pipe, and the system reaches to a steady state condition relatively quickly. Ratio of the flow rates with the new and old pipes at steady state is about $0.00046/0.00023 = 2$, that is, due to high friction of the pipe wall surface, effective cross sectional area of the pipe is reducing. Ratio of the times (Figure 6.16) taken to reach the system at steady state condition with new and old pipes is about $1.5 \, \text{s}/0.5 \, \text{s} = 3$, which is consistently close to the ratio of the frictional factors for the old and new pipes.

![Figure 6.16: Effect of roughness on flow rate (new and old pipes)](image)

### 6.3.1.5 The Effect of Sudden Change in Pipe Diameter

At the junction of two pipes having different diameters, the continuity expression and the condition of a common hydraulic grade line elevation, provide two equations as the basis
for solution. When pipes used in series in the system and there is minor change in pipeline properties such as diameter or roughness, the transient flow response can be predicted by the use of an equivalent uniform reach length (Wylie and Streeter 1978). In this case, equivalent characteristic impedance i.e., total resistance \( B_{ei} = \frac{a_{ei}}{gA_{ei}} \) of the reach, and an equivalent resistance coefficient \( R_{ei} = \frac{f_{ei}\Delta x_i}{2gD_{ei}A_{ei}^2} \) for the \( i^{th} \) reach, are calculated by using the special formulas as defined in Wylie and Streeter (1978). Though there are some limitations to the system yet, if used with clear understanding, it can provide satisfactory results. In the present study, in most of the cases, diameter of the first pipe is 0.02 m and second pipe is 0.017 m, length of the first pipe is 240 m and second pipe is 160 m, initial wave speed is 1000 m/s and frictional coefficient is 0.015 for the new pipe. As the diameter of the pipes is very small, values of the equivalent characteristic impedance \( B_{ei} \) and resistance coefficient \( R_{ei} \) would be large, and is calculated as 324,475 and 29,202 respectively for the first pipe. For the second pipe, these values would naturally be higher (approximately calculated as \( B_{e2} = 4,492,363 \) and \( R_{e2} = 31,701 \)), as they are also related to the characteristic features of the second pipe such as reach length \( \Delta x_2 \), pipe diameter \( D_2 \), cross sectional area \( A_2 \) and acoustic wave speed \( a_2 \), which would influence the hydraulic transient responses of the system especially at the junction.

In Figures 6.17 and 6.18, responses of the transient model in terms of the flow velocity are presented. The Figure 6.17 is displaying flow velocities at the upstream reach (L = 80 m from the upstream reservoir) with single pipe condition throughout (diameter = 0.02 m) and a combination of the pipes in series (diameters 0.02 m and 0.017 m). From the results presented in Figure 6.17, it seems that, pattern of the flow velocity remains same in
both the systems, but magnitude of the velocity is lower when there is a combination of the pipes in series. The pipe with smaller diameter is connected at \( L = 260 \) m, that is, at this junction flow is considerably obstructed due to presence of the sharp edged circular barrier, and hence, the flow velocity is reduced at the upstream reach. The Figure 6.18 is displaying the model results for the downstream end, where flow velocity is relatively increased as a result of the combination of the pipes in series.

![Figure 6.17: Flow velocity at u/s reach with pipes in series](image1.png)

![Figure 6.18: Flow velocity at d/s end with pipes in series](image2.png)
At this location ($L = 400$ m), second pipe diameter is smaller, and thus, cross sectional area is small relative to the first pipe at the upstream reach. Considering this fact, increase in the flow velocity is natural, but as mentioned in earlier paragraph, if the equivalent model concept is applied then it can be seen that total resistance, that is, impedance and equivalent resistance coefficient for the second pipe are higher that would result reduction in flow velocity instead of increase relative to the first pipe. It is obvious that due to decrease in the pipe diameter, the resistance to flow will be increased, but on the contrary, due to reduction in the pipe cross sectional area, the flow velocity is supposed to be increased to maintain the law of conservation of mass or continuity equation valid.

Possible explanation for the flow velocity increasing is, the combined effect of these two contra events may be in favor of the increase in flow velocity as explained below. In this case, as a result of the reduction in pipe size, the flow velocity increased from 1.4 m/s to 1.58 m/s at a steady state condition and their ratio is approximately 1.13. But, pipe cross sectional area reduced from 0.00031416 m$^2$ to 0.000227 m$^2$ and their ratio is 1.384. From the standpoint of pure continuity equation, the flow velocity is expected to be increased to $1.4 \times 1.384 = 1.937$ m/s, which is much higher than what is increased in the model. The increase in equivalent resistance coefficient ($R_e$) is from 29,202 to approximately 33,814 (ratio is 1.157), which is expected to affect the flow at the downstream reach ($2^{nd}$ pipe). From the results of above analyses, it appears that, the impact of reduction in pipe cross section (ratio = 1.384) on the flow rate in $2^{nd}$ pipe would be relatively higher than the impact of increase in equivalent resistance coefficient (ratio = 1.157). That is, the increase in flow at the downstream reach/end is justified. But, if the length of the $2^{nd}$ pipe would higher or diameter of the $2^{nd}$ pipe would less enough, so that
equivalent resistance coefficient is greater enough than that for the 1st pipe, in that case, flow rate at the downstream end/reach would not be increased relative to the flow in the 1st pipe.

Responses of the hydraulic transient model, against combination of the pipes, in terms of the generated pressure head in the systems are presented in Figures 6.19 and 6.20. From these figures, it reveals that at both upstream (1st pipe) and downstream (2nd pipe) reaches, relatively more pressure waves are developed due to combination of pipes in series, but amplitude of these additional waves are relatively lower.

![Figure 6.19: Pressure head at u/s reach with pipes in series](image1)

![Figure 6.20: Pressure head at d/s end with pipes in series](image2)
The numbers of major pressure waves are same in both the system, amplitude of the major waves at the downstream reach (Figure 6.20) is same though there is some difference at the upstream reach (Figure 6.19). The cause of this difference in amplitude (reduction) at the upstream reach is extra friction (impedance), developed due to reduction in the pipe diameter and sudden change at the junction. At the downstream reach, number of pressure wave develops within first two seconds is about five that can be identified easily but, at the upstream reach, pressure wave breaks randomly and hence difficult to identify. It is mainly due to sharp change in cross section at the junction that creates an obstruction to free movement/oscillation of the waves within the pipe to and fro.

6.3.2 Water Quality Modeling for Lead Release

In general, the water quality of a distribution system is the function of multiple variables. The corrosion event and its associated chemicals have influence on water quality as well as longevity of the pipeline system. Basically, corrosion process can be considered as an electrochemical interaction between metal and its surrounding aqueous environment through forming a corrosion cell. In the distribution system, corrosion can be general, that is, uniform or localized and is responsible for damaging the metallic pipeline as well as deteriorating the water quality. From hydraulic standpoint, corrosion is one of the causes of increasing wall roughness and reduction in conveyance due to build up of scale on the pipe wall. From water quality perspective, release of metal (lead in the present study) in the form metallic compound to the bulk water in the system, and changes in properties of the important water quality related parameters including pH, DO and disinfectants, and degrading the drinking water quality.
Corrosion of the metallic surface of the pipe in WDS is related to many factors including pH level (acidity, alkalinity), DO, chemical composition of the water, age of pipe, buildup of the scales on the pipe wall and their permeability/solubility, fluctuations of the pressure/velocity due to transients, pipe diameter, uniformity of the pipe wall surfaces, flow velocity, turbulence, mixing/mass transfer processes, temperature and shear stresses (Naser 2006). Due to high turbulence in the system, the mixing and mass transfer mechanisms become stimulated through strong advection-diffusion processes and hence more dissolved oxygen/pH reaches to the pipe wall that facilitate increased corrosion (Naser 2006). From the above discussions, it seems clear that formulation and modeling of the corrosion processes are important with regard to both hydraulic and water quality perspectives.

The present study is considered as a preliminary or reconnaissance type numerical lead corrosion modeling. The basic chemical reactions used for the modeling purpose with the metallic lead, water, pH and DO are presented below.

**Primary Reactions:** In case of the system with lead pipe, oxidation and reduction reactions at anode and cathode would be as follows:

\[ Pb_{(s)} \leftrightarrow Pb^{2+} + 2e^- \]  \hspace{1cm} \text{(Anode)} \hspace{1cm} (6.1)

and \[ \frac{1}{2}O_2 + H_2O + 2e^- \leftrightarrow 2OH^- \] \hspace{1cm} \text{(Cathode)} \hspace{1cm} (6.2)

That is, Equation 6.2 indicates that, at the cathode, hydroxide ion is generating, which acts inversely as pH controlling parameter that is, if hydroxide ion (OH^-) concentration in a WDS increases, then pH level of the solution decreases. As it is known that, pH is the measure of hydrogen ion concentration, but in negative logarithmic scale.
Combining Equations 6.1 and 6.2 we get

\[
Pb(s) + \frac{1}{2}O_2 + H_2O \leftrightarrow Pb^{2+}_{(aq)} + 2OH^-
\]  \hspace{1cm} (6.3)

**Secondary Reaction:** From the above mentioned primary chemical reactions, metallic lead (Plumbum) ion is generated and released to the bulk water of the WDS, and then reacts with the hydroxide ion (which is produced simultaneously with the lead ion) and formed lead hydroxide through the chemical reaction as indicated in Equation 6.4.

\[
Pb^{2+}_{(aq)} + 2OH^- \leftrightarrow Pb(OH)_{2(s)}
\]  \hspace{1cm} (6.4)

### 6.3.2.1 Effect of Dissolved Oxygen on Lead Corrosion

The dissolved oxygen (DO) in a system is the primary cause of metal corrosion, and is one of the initial conditions in the advection-dispersion-reaction model. It is seen from the model results (Figures 6.21, 6.22 and 6.23) that, in presence of the higher initial concentration of the dissolved oxygen, the corrosion rate of lead is increasing almost proportionately. This result seems consistent, because the dissolved oxygen in the basic corrosion equation used in the model is the oxidizing agent, which influence the anodic reaction and create metallic ion (lead ion in this case, Pb\(^{2+}\)).

Through examining the Figure 6.21, it reveals that when initial DO level is higher than the base DO level (for neutral condition), in that case, its impact on metallic corrosion is relatively more. In the corrosion (ADR) model, base initial DO level is 5.0 mg/L and with this initial value, final lead concentration at the end of 400 m long pipe after 3600 s simulation is 0.05 mg/L. With initial DO level of 3.5 mg/L, maximum lead concentration at the end of 400 m long pipe for the same simulation period is 0.025 mg/L, and with initial
DO level of 6.5 mg/L, maximum lead concentration is 0.092 mg/L (Figure 6.21). Then the differences in lead concentration from that with the base initial level (when DO is 5.0 mg/L) are 0.025 mg/L and 0.042 mg/L and their ratio is 0.595. This result is indicating that with higher DO level in the system, the corrosion activity increases considerably.

Figure 6.21: Change in lead concentration with dissolved oxygen

![Figure 6.21](image)

Figure 6.22: Impact of DO on lead corrosion when pipes are in series

The time series lead corrosion data extracted from the model as shown in Figure 6.22 indicates that, the time required reaching the corrosion process in stable state with
higher initial DO level is relatively longer, compare with the situations with lower initial DO levels. The times taken to reach the system in stable conditions are about 470 s, 456 s and 445 s with the initial DO levels of 6.5, 5.0 and 3.5 mg/L respectively. Differences of the higher/lower initial DO levels from the base DO level are same, but the differences in time of the corrosion activities are 14 s and 11 s. That is, the corrosion activity lasts for the long time with higher (6.5 mg/L) initial DO, and it is not exactly proportional to the difference in DO levels from the base DO level. From the time series data, it is also found that, with initial DO levels of 6.5 mg/L, 5.0 mg/L and 3.5 mg/L, the lead concentrations in the system at stable conditions are of 0.092 mg/L, 0.0425 mg/L and 0.019 mg/L respectively. That is, the differences in lead concentration levels with respect to the base condition are 0.0495 mg/L and 0.0235 mg/L though initial DO level differences are same (Figure 6.22).

From the above analyses, it seems that, higher initial DO level in a system can increase both the activity and duration of the corrosion process considerably. That is, initial DO level in the system has significant importance to the corrosion process, and can be an important regulating parameter for corrosion management in water distribution system. It is also seen from the Figure 6.22 that, there is some fluctuation in the lead concentration level at the beginning of simulation period, and it continues up to about 100s. This fluctuation may be due to combination of the pipes having different diameters in series. As a result of the joint in the pipe line, there is sharp change in roughness and obstruction to the flows that cause strong initial turbulence and thus instantaneously change in corrosion pattern.
A typical comparison of the effect of initial dissolve oxygen on lead and iron pipe corrosion is presented in Figure 6.23. From this figure, it reveals that, in general, the level of concentration of lead is higher compared to iron with the same initial dissolve oxygen (DO) level in WDS. This result indicates that, either corrosion rate of lead is higher relative to iron or may be the corrosion rates are same for both lead and iron, but, as the atomic weight of lead (207) is much higher than the atomic weight of iron (56). In spite of the same corrosion rate, concentration level of lead is higher in the system relative to iron. Since the basic corrosion equation for iron and lead with DO are same as shown in Equations 6.3 and 6.5, the higher atomic weight of lead would be the most likely cause of the relatively higher concentration level of lead in the system for the same DO level.

$$Fe_{(s)} + \frac{1}{2}O_2 + H_2O \rightarrow Fe^{2+} + 2OH^-$$  \hspace{1cm} (6.5)

There is another water chemistry related parameter “self diffusion co-efficient of ions” that has some effect on corrosion phenomena (Millero 2001, Singley 1994). The self diffusion co-efficient of lead ion (Pb$^{2+}$) is 9.45*10$^{-6}$ cm$^2$s$^{-1}$ and for iron ion (Fe$^{2+}$) is 7.19*10$^{-6}$ cm$^2$s$^{-1}$ (Millero 2001). That is, the diffusion rate of the lead ion is higher relative
to the iron ion, and hence, corrosion rate of the lead pipe might be higher compare to the iron pipe as well.

6.3.2.2 The Effect of pH on lead corrosion

The measure of concentration of hydrogen ion \((H^+)\) that is, pH in WDS is an important corrosion parameter, and hence, investigation on the impact of pH on lead pipe corrosion is an important issue. In ADR model, pH is given as the initial condition and its base value is set as 7.0, which indicates neutral water i.e., neither acidic nor alkaline or concentrations of the hydrogen ion \((H^+)\) and hydroxide ion \((OH^-)\) are equal. In a solution, if there is a high concentration of the hydrogen ion \((H^+)\) then pH value of the solution would be lower than 7.0 and it would be acidic. On the contrary, existence of the low concentration of the hydrogen ion \((H^+)\) in a solution indicates higher pH (>7.0) and the resulting solution would be alkaline. In the present study, concentration of the hydroxyl ion \((OH^-)\) is used to indicate pH level of water, but they are clearly opposite, that is, if concentration of \(OH^-\) is greater than 7.0, say 8.5 then it will indicate actually pH level of 5.5. That is, pH level shown in the results/graphics actually indicating concentration of \(OH^-\) and actual pH level of the solution would be calculated by subtracting that pH value from 14.0, that is, \((14.0 – \text{pH})\) in the graphs.

In Figure 6.24, the effects of pH on lead corrosion are presented, and in the Figure 6.25, a typical comparison of the effect of pH on lead and iron corrosion is presented. From Figure 6.24, it is seen that, in the simple lead based WDS, the effect of variation of the pH level on lead corrosion is prominent and interesting.
When initial pH level in the system is 7.0, lead concentration at the end of 400 m long pipe and after 3600 s of simulation is about 0.05 mg/L. With the actual initial pH level of 6.0 (14.0 - model pH 8.0) in the system, lead concentration is 0.50 mg/L that is, the difference from the base level is 0.45 mg/L (increase) and with the actual initial pH level of 8.0 (14.0 - model pH 6.0), the lead concentration is about 0.01 mg/L that is, the difference from the base level is about 0.04 mg/L (decrease). This result indicates that the lead corrosion is rapidly increasing with the decrease in pH level, but the decreasing trend of lead corrosion with the increase in pH with respect to the base level (neutral condition) is relatively slow.

With the decreasing level of pH from the normal value (pH = 7.0), the bulk water becomes acidic and produces a solution that helps in the electro-chemical activity relatively strongly.

It is known that the acidic water itself is more corrosive, actually acidic water is a good electrical conductor (electrolyte) and helps to form strong electro-chemical cell and thus promotes corrosion. The modeling result found from this study, is inline with Wagner (1993) concept that, at low pH, the hydrogen ion concentration is more in water that serves as oxidizing agent and results accelerated corrosion in the system. By comparing the ADR
modeling results with the dissolved oxygen and pH as initial conditions, it is observed that
effect of the dissolved oxygen and pH to the lead corrosion is vice versa i.e., due to the
presence of high DO in the system there is more corrosion (Figure 6.21), conversely due to
high pH level in the system corrosion rate is decreasing (Figure 6.24).

It appears from the corrosion modeling results that there is clear influence of the
initial pH level on corrosion of the lead and iron pipes similar to the initial dissolved
oxygen concentration level in the system (Figure 6.25). The lead and iron concentrations
along the 400 m long pipes having diameter of 0.02 m after simulation for 3600 s are
presented in Figure 6.25. From the results presented, it is seen that, relatively higher
concentration of lead (0.50 mg/L) is occurring in the system compare to iron concentration
(0.134 mg/L) with the same initial system pH level. Explanation of these phenomena is
similar as mentioned earlier (Article 6.3.2.1) in the case study for dissolved oxygen.
6.3.2.3 The Effect of Pipe Diameter

The effect of different pipe diameter on lead corrosion can’t be explained explicitly as it is interrelated with the flow velocity that is, when diameter of the pipe reduces, at that time the flow velocity increases, if all other hydraulic conditions remain the same. This flow velocity has significant effect on lead release rate to WDS. Two opposite corrosion events observed in the modeling study. It seen from Figures 6.26 (spatial data) and 6.27 (time series data) that, when the pipe diameter is large (1.0 to 1.2 m), then with the decrease in pipe diameter, corrosion rate decreases as flow velocity increases and residence time decreases. This result is contrary to the results found by Baral (2006) and Naser and Karney (2005). By contrast, when pipe diameter is relatively small (0.013 to 0.02 m), in that case, as diameter of the pipe decreases corrosion rate increases. This result is opposite compare to the corrosion phenomena with larger diameter pipes, but agrees with the results presented by Baral (2006) and Naser and Karney (2005).

Figure 6.26: Effect of pipe diameter on lead release in WDS (Spatial)
Baral (2006) worked with 1-D model for iron pipe and with low head (H = 20 m), and Naser and Karney (2005) worked with 2-D model for the similar system having iron pipe and low head (H = 20 m). But in the present study, the system is comprised of the lead pipe and high piezometric head (H = 100m). Generally, flow velocity in the pipe is a function of the piezometric head, pipe diameter, length and friction. That is, the piezometric head has influence on the flow velocity, and as the flow velocity is related with the lead/iron release, the above varying results are consistent as explained in the subsequent paragraph.

![Effect of pipe diameter on lead release](image)

Figure 6.27: Effect of pipe diameter on lead release (Time series data)

In case of the small diameter pipe (0.02 to 0.013 m) what is happening can be explained from the fluid dynamics standpoint. When the pipe diameter is small, the flow velocity is reducing (in this case, the pipe size is reducing from 0.02 to 0.013 m not to 0.017 m) with
the decrease in pipe diameter, unlike the system with relatively larger diameter pipe. Most probably, this reduction of the flow velocity in small diameter pipe, is due to significantly increase in overall pipe roughness against flow or equivalent resistance coefficient ($R_e$) (as explained earlier in Art. 6.3.1.5); as the pipe diameter is very small relative to the pipe wall roughness elements height (Giles 1962) as well as percentage of the reduction of pipe diameter is also high about 154%. The event of increasing metal (lead) release in the system with the decrease in pipe diameter can be explained from the advection-dispersion-reaction perspectives. When diameter of the pipe is small, due to high roughness, strong turbulence is expected to occur in the system, in spite of the low average flow velocity. In addition, residence time will be relatively longer. This strong turbulence and longer residence time stimulate advection-dispersion-reaction processes and result relatively more corrosion of the metal (lead). Instantaneous high velocity of the particles during turbulence may accelerate the mixing process of the corrosion species through advection and dispersion, promote close contact of the fresh corrosive material with the pipe wall, and hence, strong electrochemical reaction with the pipe wall material is possible.

6.3.2.4 The Effect of Pipe Wall Roughness

Pipe wall roughness is an important parameter that affects the corrosion process in WDS like hydraulic events as mentioned in Art. 6.3.1.4. Pipe wall roughness depends upon many hydraulic factors such as height of the boundary roughness element, thickness of laminar sub layer, pipe diameter, length, viscosity, flow velocity etc. Most of them have already been discussed in brief and are available in the standard text book of hydraulics. Here the
effect of roughness on the corrosion events would be discussed on the basis of advection-dispersion-reaction modeling results.

In Figures 6.28, 6.29 and 6.30, the effects of wall roughness on corrosion along the pipes axis (spatial data) and with time (time series data) for the small and relatively large diameter pipes are presented. From these figures, it reveals that, the effect of wall roughness on corrosion is significant, especially when the pipe diameter is relatively small. In case of the large diameter pipe, due to height of the roughness elements, age and scale formation on the wall, total resistance to the flow is relatively lower than that in small diameter pipe (as per Darcy-Weisbach, pipe diameter is inversely proportional to the frictional head). Hence, comparatively less turbulence is expected to develop theoretically in the large diameter pipe; consequently it will stimulate the advection-dispersion-reaction processes in the system relatively weakly that ultimately may results in less corrosion.

![Figure 6.28: Effect of the friction on lead corrosion (small dia, spatial)]
From the modeling results, it is observed that, with the old pipe (high friction) having diameter of 0.02 m, lead concentration is about 0.216 mg/L at the end of 400 m long pipe after 3600 s of simulation, and with the new pipe under same conditions, it is 0.05 mg/L. The difference in lead concentration between old and new pipe is 0.166 mg/L that is considerably high. On the other hand, when pipe diameter is 1.20 m, lead concentration at the end of 400 m long old pipe is about 0.107 mg/L and that with new pipe is 0.105 mg/L. The difference is only 0.002 mg/L, which is far less than 0.166 mg/L as found with small diameter pipe. And hence, the model results agree with the theoretical considerations presented in the preceding paragraph. That is, the effect of increase in wall roughness on lead corrosion is significant when the pipe diameter is small, but when the pipe diameter is relatively large, the effect of increase in roughness on lead corrosion is insignificant.
It is also seen from the modeling results presented in Figures 6.28 and 6.29 that, when two pipes having different diameter are used in series (there is a joint), sudden drop of the lead concentration occurred at the junction point. As diameter of the pipe at the upstream reach is larger than diameter of the pipe at the downstream reach, there is sudden contraction at the junction that accelerates the flow locally, and as a consequence, high flow velocity is expected to occur there. Due to this local high flow velocity, residence time of water at the junction point and downstream reach of the pipes decreases significantly relative to the upstream reach that naturally causes less contact time for the corrosion species with the pipe wall and low stimulation of the ADR processes and results in drop of the lead concentration.

It appears from the time series corrosion data presented in Figure 6.30 that, the impact of roughness or aging of the pipe on the corrosion process is considerably low in the case of large diameter pipe. In addition, when combination of the pipes is used, resulting
corrosion is expected to be far less than that of single pipe system. The modeling results indicating that, from the corrosion management perspectives, use of the relatively large diameter pipe and combination of the different diameter pipes in series are beneficial though initial cost would be higher.

6.3.2.5 The Effect of Flow Velocity

The effect of flow velocity on corrosion is still not clear. On this issue, there are debates and lots of contradictory observations and opinions. At high velocity, there is a possibility of strong stimulation of advection-dispersion-reaction processes that helps mixing and mass transfer phenomena, for which more oxidant species may reach close contact to the pipe wall surface and accelerate corrosion process. But, there is opposite concept as well. If the flow velocity is high, then residence time of the bulk water in the pipe decreases, and hence, interference to electrochemical reactions is possible that may cause low corrosion rate. The observations of recent scientists including Fang and Liu (2003), Crowe et al. (2001), and Efrid (2000) are that, if there is high flow velocity then corrosion rate would be higher i.e., corrosion rate is directly related to the flow velocity. On the other hand, observations of Baral (2006), Pisigan and Singley (1987) and Mahato et al. (1980) are different, they observed that, with high flow velocity corrosion rate is low i.e., corrosion process is inversely related with the flow velocity. That is, conflict still exists and therefore, further investigation on this issue is required.

For the present study, an integrated 1-D hydraulic transient and ADR model is utilized. The modeling results, related to the flow velocities in the pipe and corresponding corrosion events are presented in Figures 6.31, 6.32 and 6.33.
The results presented in Figures 6.31 and 6.32 indicate that, there is no definite interrelationship between the flow velocity and corrosion process in such a system. The corrosion rate is steadily increasing from the initial zero and continues, but flow velocity reaches to a steady state condition within 3 to 4 seconds from the start of simulation.
Results presented in Figure 6.31 is for the single pipe having diameter of 0.02 m and the results presented in Figure 6.32 is for the combined pipes in series having diameters of 0.02 m and 0.017 m connected at 240 m from the upstream end. The flow velocity at a steady state condition with the single pipe is about 1.4 m/s and that with multiple pipes in series is about 1.14 m/s. The lead concentration at six second from the simulation start in single pipe system is about 0.00037 mg/L and that in multiple pipes system is 0.00039 mg/L. These results are indicative that high flow velocity may cause low corrosion rate in the system. But, evaluating the modeling results presented in Figure 6.33, it seems that there is strong correlation between the corrosion process and the flow velocity. This figure clearly indicating that, if the flow velocity decreases then corrosion activity increases i.e., the relationship is inverse. This finding corresponds to the relationship established and explanation presented in the preceding article of this thesis (Art. 6.3.2.4).

![Figure 6.33: Effect of flow velocity on lead pipe corrosion](image)

Figure 6.33: Effect of flow velocity on lead pipe corrosion
In addition, the observation from the present study agrees with the observations of Baral (2006), Pisigan and Singley (1987) and Mahato et al. (1980).

The potential reason behind the high corrosion rate with the low flow velocity is relatively longer residence time of bulk water in the system that helps to electrochemical reactions, which is responsible for corrosion to occur in the system. Explanation of the relationships between the flow velocity and corrosion process has been outlined in the previous articles as well. It seems that, the result from this article is not exhaustive; there is still some contradiction. The flow velocity has influence on corrosion process, but this relationship can’t be linear i.e., the relationship may vary with the change in flow velocity. From the zero up to certain magnitude of the flow velocity, the relationship with corrosion process can be one type and beyond that magnitude of flow velocity, the relationship with corrosion process would be different. It is due to the fact that, velocity has some stimulating power to ADR processes that is in favor of the corrosion activity, but due to the high flow velocity, residence time is reduced appreciably, which is against the corrosion process. Singley (1994) observed that, when the flow velocity is less than 1.22 m/s (4 ft/s) at that instance, corrosion process is directly related, but when the flow velocity is higher than 1.22 m/s, in that case, the corrosion process is inversely related to the flow velocity. In the present study, similar results are observed as explained in preceding articles.

6.3.2.6 The Effect of Sudden Change in Pipe Diameter

In reality, often combinations of the pipes in series having different diameter are required, and hence, effect of the sudden change in pipe diameter on corrosion event is an important issue. Hydraulic effect of the sudden change in pipe diameter has been discussed in earlier
article of this thesis (Art. 6.3.1.5). At the junction, two pipes having different diameter are connected and sudden contraction is expected in most of the cases. This sudden contraction causes several changes in the local hydraulic parameters such as increase in the flow velocity to maintain law of conservation of mass or continuity theory, rise of total friction or equivalent resistance coefficient ($R_e$), development of the strong turbulence and pressure drop to maintain Bernoulli’s constant total energy theorem valid. All those hydraulic parameters can affect corrosion related events in WD system.

![Figure 6.34: Effect of diameter change on lead corrosion](image)

![Figure 6.35: Effect of diameter change on lead corrosion](image)
In Figures 6.34 and 6.35, results of the corrosion modeling related to the sudden change in pipe diameter are presented. Figure 6.34 is for small diameter pipes and Figure 6.35 is for relatively larger diameter pipes. At the junction, in case of the small diameter pipes, the ratio of the diameter change or contraction is $0.02/0.017 = 1.176$ and in the case of relatively larger diameter pipes, the ratio of the diameter change is $1.2/1.0 = 1.20$ that is, their degree of contractions are close. Inspecting the results presented in Figures 6.34 and 6.35, it is seen that corrosion rate drops at both the junctions. From hydraulic standpoint, at the junction of pipe, as mentioned earlier that, the flow velocity and local turbulence increases that affects corrosion activity negatively, and results drop in the corrosion rate. It is also seen that, corrosion rate at the upstream reach is higher in case of the small diameter pipes in series (Figure 6.34), but remain almost same in the case of larger diameter pipes (Figure 6.35). The possible explanation of this phenomenon is: the hydraulic effect of contraction (disturbance) at the junction is transmitted to the upstream reach, which is relatively dominant in case of the small diameter pipes compare with the large diameter pipes. For this hydraulic effect at the upstream reach, extra turbulence may occur that stimulates mass transfer and mixing processes through affecting advection, dispersion and reactions processes and results higher corrosion rate.

6.3.2.7 The Effect of Pipe Length

The length of pipe has direct influence on corrosion. When length of the pipe is more, in that case, it is expected that the concentration of corrosion material at the downstream reach would be relatively higher due to accumulation and acceleration of the corrosion rate. In the
present study, modeling results agree with this hypothesis (Figure 6.36). It is seen from this figure that, concentration of lead along the pipe length is higher for the longer pipes compare with the shorter pipes. That is, at the same locations, corrosion for the longer and shorter pipes would be different. The phenomenon of higher corrosion rate with the longer pipe is related with the pipe flow hydraulics. In general, for the longer pipe, total resistance to the flow is higher (Darcy-Weisbach friction formula) and then flow velocity would be lower.

![Figure 6.36: Effect of pipe length on corrosion (spatial)](image)

From hydraulic standpoint, the residence time is directly proportional to the length of the pipe and thus total roughness of the pipe, but inversely proportional to the flow velocity. If the total resistance of the pipe is high due to the longer pipe reach, then it affects the movement of the bulk water body in the pipe in a way that, relatively longer time is required to pass out the water mass i.e., longer residence time or contact with pipe wall material and as a result higher corrosion is expected. The model results shown in Figure 6.36 is indicating that, the movement of the bulk water is relatively slower (i.e., longer residence time) in 600 m, 800 m and 1200 m long pipes compare with the 400 m
long pipe and hence, at the same location, higher concentration of lead is occurred for the relatively longer pipes. The lead levels at 400 m point are about 0.05, 0.08, 0.12, and 0.22 mg/L in 400, 600, 800 and 1200 m long pipes respectively. The increase in lead levels relative to the base level with 400m long pipe are 60%, 140% and 340%, but corresponding decrease in the flow velocities are 18.5%, 29.26%, and 42.28%. That is, the increase in lead corrosion rate as a result of increase in the pipe length (consequently decrease in the flow velocity) is not consistently proportional. With little decrease in the flow velocity, there is major increase in the lead corrosion rate.

6.3.2.8 The Effect of Residence Time

The residence time of the bulk water in a WDS is the function of flow velocity and pipe length, and is one of the important parameter that affects corrosion processes. Residence time is also related to the requirement and loss of the disinfectants and formation of the disinfectant by products (DBP). The growth of biological products is also related to the residence time of the bulk water in a distribution system. In addition to electrochemical corrosion, biologically mediated corrosion is possible as a result of the longer residence time (Baral 2006).

As residence time is the function of the flow velocity/pipe length and flow velocity is the function of piezometric head, friction, and diameter of the pipe. In this study, residence time is controlled by changing the flow velocity and flow velocity is controlled by changing the piezometric head. Residence time may also be controlled by changing the pipe length or diameter. However, ADR modeling results are presented in Figures 6.37, 6.38, 6.39 and 6.40 to understand and correlate the effects of residence time on three water
quality parameters including metal concentration, pH and dissolved oxygen (DO).

In modeling study, with the hydraulic head $H = 100$ m, the flow velocity is found to be 1.40 m/s for which the residence time is 286 s with the pipe length of 400 m. On the other hand, with the hydraulic heads $H = 40$ m and 10 m, the flow velocities are 0.88 m/s and 0.443 m/s and the corresponding residence times are 455 s and 903 s for the same 400 m pipe. From comparison of the results (Figure 6.37), it appears that the corrosion rate of
lead is significantly higher (about 0.230 mg/L and 0.165 mg/L compare with the base 0.05 mg/L) with the increased residence time i.e., higher residence time is promoting electrochemical reactions and thus the corrosion activity. Inspecting the Figures 6.37 and 6.38, it is found that, the concentration of lead is much higher than the concentration of iron for the same hydraulic and chemical environments. This result seems consistent as the atomic weight of lead is much higher than that of iron. Approximate ratio of the concentration between lead and iron is $0.16/0.043 = 3.721$ and ratio of the atomic weight between lead and iron is $207/56 = 3.696$ that is, very close.

Figure 6.39: Effect of residence time on pH level in lead pipe

Figure 6.40: Effect of residence time on DO level in lead pipe
In Figures 6.39 and 6.40, the modeling results related to the effect of residence time on pH and DO concentration levels are presented. Reviewing the results, it is revealed that, pH level of the system is directly affected by the change in residence time of the bulk water, but DO level is affected inversely unlike pH level. When residence time changes from 286 s to 455 s, pH level in the system changes from 7.75 to 8.23 at the downstream end of a 400m long lead pipe i.e., as residence time is increasing, pH level is also increasing. But, exactly for the same situations, changes in the DO level is from 4.9962 to 4.988 mg/L i.e., DO level is decreasing with the increase in residence time.

### 6.4 Summary

In this chapter, mainly results of the proposed transient-corrosion model simulation, applications and data analyses with the typical case studies are presented and discussed. In the first part, detailed modeling to evaluate the impacts of discretizations and hydraulic parameters including the effect of time step on hydraulic and corrosion events, effects of the hydraulic head, spatial discretization, pipe wall roughness and sudden change in pipe diameter on hydraulic transient events are evaluated and discussed. In the second part, importance of the water quality modeling for lead release, primary reactions and secondary reaction for lead with key corrosion species of water that is used in the model are discussed in brief. In addition, modeling to evaluate the effects of the dominant water chemistry parameters responsible for corrosion including DO and pH on lead pipe corrosion, effects of the pipe diameter, wall roughness, flow velocity, sudden change in pipe diameter, pipe length and residence time on lead release are evaluated and analyzed in detail. The impact
of the residence time of the bulk water on level of concentrations of DO and pH are also evaluated.

From evaluation, analyses and discussions presented in this chapter, it is revealed that, there is strong influence of the spatial and temporal discretization on simulation of hydraulics especially corrosion events with the proposed model. The sudden change in pipe diameter (large to small) has interesting impact on flow condition at the upstream and downstream reaches. There is strong relationship with lead pipe corrosion and pH, with the increase in pH level, corrosion rate decreases significantly. But relationship with DO and corrosion is opposite, i.e., with the increase in DO level, corrosion rate increases. But the impact of pH on corrosion process is more dominant relative to DO. The effect of flow velocity on corrosion process is not yet fully clear, there are conflicting results and opinions. The present modeling results indicate that corrosion rate is directly related to the flow velocity up to certain extent and beyond that corrosion rate is inversely related with the flow velocity. From comparison of the corrosion results for the lead and iron pipes with exactly the same hydraulic and chemical environments, it is found that level of concentration of lead in water is considerably higher than that of iron. It may be due to the huge difference in atomic weights for lead and iron. It is found that, relative size of the pipe (diameter) has tremendous effect on lead corrosion. Two opposite corrosion results are observed with large and smaller diameter pipes.

The effect of wall roughness on corrosion event is found significant, especially when the pipe diameter is relatively small. The effect of residence time on lead corrosion as well as concentrations of dissolved oxygen and pH is also found interesting. It appears that the corrosion rate of lead is significantly higher with the increased residence time i.e.,
higher residence time is promoting electrochemical reactions and thus corrosion activity.
The residence time is directly affecting pH level of the system i.e., pH is increasing with
the increase in residence time, but inversely affecting the DO level.
CHAPTER 7
CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS

“Strange is our situation here upon earth. Each of us comes for a short
visit, not knowing why, yet sometimes seeming to divine a purpose. From the
standpoint of daily life, however, there is one thing we do know: that man is here
for the sake of other men.”

Albert Einstein: I Believe

7.1 Conclusions

There are two major objectives of this thesis. First is to customize the existing one
dimensional transient-corrosion model for the lead pipe system that was originally for the
single diameter iron pipe system, extend the model to cover the multiple diameter lead
pipes connected in series system, and time series data collection for the specified reaches
and time periods, and improve for both the time series and spatial data collection with
proper label for easy identification. Second is to investigate the impacts of hydraulic
environments and specified water chemistry parameters on the corrosion processes and
analyze the data to find the interdependencies and establish interrelationships among the
parameters. As the numerous physical and chemical factors are responsible for corrosion in
a distribution system, the proposed model naturally is not able to represent the lead
corrosion processes exhaustively. The model is to be considered as a typical and the results
and relationships found are good indicative as the base for future more detailed study.
From simulation and application of the developed transient-corrosion model for a range of hydraulic and chemical conditions and analyses of the transient hydraulics and corrosion data (spatial and time series), the following conclusions are drawn.

- It is apparent that, there is almost no effect of the time step on the flow velocity, but there is some effect on the pressure head. With the smaller time step, it is possible to simulate the generation and propagation of the transient pressure waves realistically. In this study, with the smaller time step, wave speed found to be 970 m/s, which is close to the assumed acoustic wave speed (1000 m/s). But, unlike the hydraulic events, there is significant impact of the computational time step on the advection-dispersion-reaction (ADR) modeling results. With the smaller hydraulic time steps, relatively higher values of the lead concentrations are observed in the water mass. The advection-dispersion-reaction model computes the lead and other corrosion related materials concentration as the accumulation. And therefore, from the computational standpoint, if the hydraulic time step is smaller, then correspondingly, the water quality time step would be small, and more accumulation of the substances are expected. That is, the appropriate temporal discretization is important for accuracy of the numerical modeling results. For better accuracy, the mesh size should be as fine as possible, but there are some restrictions considering the computational time, cost and hard disk memory of the computer. It is recommended to select the time step based on the importance and nature of the job.

- The hydraulic head and the flow velocity are interrelated. It is observed that, the flow velocity with the large hydraulic head rises rapidly, and then stabilizes relatively quickly, but with the low hydraulic head, the flow velocity rises gradually.
step by step, and reaches to a steady state condition with almost the highest peak values. It is also observed that due to the high initial hydraulic head, the transient pressure head and turbulence with high magnitude are developed, but dampens down relatively quickly. May be it is due to quickly reversal of the strong pressure waves and flow velocities within the system, and high wall/fluid mass friction.

- It is observed that, there is some effect of the spatial discretization on the hydraulic events. There is clear impact of the spatial discretization on the flow velocity and pressure head in the system. With the smaller spatial mesh size, the result appears relatively stable, spike free, accurate and estimates realistic flow velocity at a steady state condition.

- The type of pipe (old or new) used in the system is important and may have appreciable impact on the hydraulic transient phenomena. The new pipe has relatively smooth interior wall surface, and low resistance to the flow compare with the old pipe. Transient responses in the model indicate that with the old pipe, the amplitude of the transient pressure head is low; the system quickly reaches to a steady state condition and transient pressure energy dampens quickly. This may be due to the fact that, propagation of the pressure waves encounters relatively greater resistance in the old pipes having higher wall roughness heights.

- At the junction of the two pipes having different diameter, the continuity expression and the condition of a common hydraulic grade line elevation provide two equations as the basis for solution. Though there are some limitations of the system, but if used with reasonably clear understanding, it can provide the satisfactory results. It is observed that when two different diameter pipes are connected, at the junction, flow
is considerably obstructed. As a result, the flow velocity is reduced at the upstream reach. In addition, the flow velocity in the downstream smaller diameter pipe may increase or decrease depending upon certain additional conditions (impedance and equivalent resistance coefficient). Responses of the hydraulic transient model indicate that when there is a combination of two pipes, relatively more pressure waves (number) are developed, but amplitude of these additional waves are comparatively lower. Cause of this difference in amplitude may be the extra friction (impedance) that developed due to sudden change (contraction) at the junction.

- The presence of dissolved oxygen in water, influences the lead corrosion considerably, and is one of the initial conditions in advection-dispersion-reaction model. It is seen from the modeling result that, in the presence of the higher initial DO, the corrosion rate of lead is increased almost proportionately. But, when the initial DO level is higher than the base DO level (neutral), its impact on the lead corrosion is relatively prominent. This is due to the fact that, with higher DO level, the time required to reach the corrosion process in stable state is longer. Higher initial DO level in the system can increase considerably both the activity and duration of the corrosion process. That is, control of the initial DO level is an important regulating parameter for corrosion management in the water distribution system. It is also found that under the same hydraulic and chemical environments, the level of concentration of lead is higher compare to iron. The possible explanation for this difference in concentration may be that, the atomic weight of lead (207) is much higher than the atomic weight of iron (56), and hence, in spite of the same corrosion rate, the concentration level of lead is higher in the system.
relative to iron. Alternatively, as the diffusion rate of the lead ion is higher relative to the iron ion, the corrosion rate of the lead pipe might be higher compared to the iron pipe.

- The level of pH in a WDS is an important corrosion related parameter. In this study, the concentration of the hydroxyl ion ($OH^-$) is used to indicate pH level of water, that is, the pH level shown in the results actually indicating concentration of $OH^-$ and real pH level of the solution would be calculated by subtracting that pH value from 14.0. It is seen from the modeling results that, in the simple lead based system; the effect of variation of pH level on corrosion is prominent and nonlinear. The lead corrosion rapidly increases with the decrease in pH level, but the decreasing trend of corrosion with the increase in pH with respect to the base level (neutral condition) is relatively slower. With the lower level of pH from the neutral value (pH = 7.0), the bulk water becomes acidic and produces a solution that helps in the electro-chemical activity relatively strongly. The modeling result found from this study, is inline with Wagner (1993) concept that, at low pH, the hydrogen ion concentration is more in the water that serves as oxidizing agent and results accelerated corrosion in the system.

- The effect of different pipe diameter on lead corrosion can not be explained explicitly as it is interrelated with the flow velocity. This flow velocity has significant effect on the lead release rate. Two opposite corrosion events are observed in the modeling study. It seen that, when the pipe diameter is large, then with the decrease in the pipe diameter, the corrosion rate decreases. And when the pipe diameter is relatively small, in that case, as diameter of the pipe decreases the
corrosion rate increases. This result agrees with the results presented by Baral (2006) and Naser and Karney (2005). In the case of small diameter pipe, what is happening in the system can be explained from the standpoint of fluid dynamics. Here the flow velocity is reducing with the decrease in pipe diameter, unlike the system with relatively larger diameter pipe. This reduction in the flow velocity is due to significantly increase in overall pipe roughness or equivalent resistance coefficient (Re); as the pipe diameter is small relative to the wall roughness heights. The event of increasing lead release with the decrease in pipe diameter can be explained from the advection-dispersion-reaction perspectives. When the diameter is small, due to high wall roughness, strong turbulence is expected to occur in a system, in spite of the low average flow velocity; in addition, the residence time will be increased. This strong turbulence and longer residence time stimulate the advection, dispersion and reaction processes and results the relatively higher corrosion. Instantaneous high velocity of the particles during turbulence may accelerate the mixing process of the corrosion species through the advection and dispersion processes, promote close contact of the fresh corrosive material with the pipe wall, and hence, strong electrochemical reaction with the pipe wall material is possible to occur.

- The pipe wall roughness is an important parameter that affects the corrosion process in a water distribution system. From the modeling result, it reveals that, the effect of wall roughness on corrosion is significant, especially when the pipe diameter is relatively small.

- It is seen from the modeling results that, sudden drop of the lead concentration occurs at the junction, when the two pipes having different diameter are connected
in series. Possible explanation for this is, as the diameter of the pipe at the upstream reach is larger than the diameter of the pipe at the downstream reach, there is sudden contraction at the junction that locally accelerates the flow to maintain continuity. Due to this local high flow velocity, residence time of the water at the junction point decreases significantly relative to the upstream reach. That naturally causes less contact time for the corrosion species with the pipe wall, and thus, results in drop of the lead concentration.

- The effect of the flow velocity on corrosion is a bit conflicting. Theoretically, at high velocity, there is a possibility of strong stimulation of the advection-dispersion-reaction processes that helps the mixing and mass transfer phenomena, for which more oxidant species may reach close contact to the pipe wall surface and accelerate the corrosion process. On the other hand, opposite concept is that, if the flow velocity is high, then the residence time of the bulk water in the pipe decreases, and hence, interference to the electrochemical reactions is possible, that may cause the slower corrosion rate. The observations of recent scientists including Fang and Liu (2003), Crowe et al. (2001), and Efrid (2000) are that, if there is a high flow velocity, in that case, the corrosion rate would be faster, that is, corrosion rate is directly related to the flow velocity. On the other hand, observations of Baral (2006), Pisigan and Singley (1987) and Mahato et al. (1980) are different, they observed that, with the high flow velocity, the corrosion rate is slower, that is, corrosion process is inversely related with the flow velocity. That is, conflict still exists and therefore, further investigation on this issue is required. Evaluating the modeling results obtained from the present study, it seems that there is strong correlation
between corrosion process and the flow velocity. If the flow velocity decreases then the corrosion activity increases, that is, the relationship is inversely proportional. The potential reason behind the high corrosion rate with the low flow velocity is, the relatively longer residence time of the bulk water in the system that helps prevailing electrochemical reactions. The flow velocity has influence on the corrosion process, but their relationship may not linear, that is, the relationship may vary with the change in flow velocity. From the zero up to certain magnitude of the flow velocity, the relationship with corrosion process can be one type and beyond that magnitude of the flow velocity, the relationship could be different. It is due to the fact that, the flow velocity has some stimulating power to the ADR processes that is in favor of the corrosion activity, but due to the high flow velocity, residence time is reduced appreciably, which is against the corrosion process. Singley (1994) observed that, when the flow velocity is less than 1.22 m/s (4 ft/s), at that instance, corrosion process is directly related to the flow velocity, but when the flow velocity is higher than 1.22 m/s, in that case, the corrosion process is inversely related to the flow velocity. In the present study, results similar to Singley (1994) are observed.

- It is often required to use combinations of the pipes in a series having different diameter. And hence, the effect of the sudden change in pipe diameter on corrosion event is an important issue. This sudden change (contraction) causes several modifications to the hydraulic parameters including the increase in local flow velocity to maintain law of conservation of mass and pressure drop to maintain Bernoulli’s constant total energy theorem valid, in addition, rise of total friction or equivalent resistance coefficient ($R_c$) in the smaller diameter pipe at the downstream
reach and development of the strong turbulence in the larger diameter pipe at the upstream reach. All those hydraulic parameters can affect the corrosion related events in the WD system. It is seen from the modeling results that, corrosion rate at the upstream reach is higher in the case of relatively smaller diameter pipes in series, but remain almost same in the case of larger diameter pipes. The possible explanation of this phenomenon is, the hydraulic effect of contraction (disturbance) at the junction is transmitted to the upstream reach, which is relatively dominant in the case of smaller diameter pipes compare with the larger diameter pipes. For this hydraulic effect, at the upstream reach, extra turbulence may occur that stimulates the mass transfer and mixing processes through affecting the advection, dispersion and reactions processes and thus results higher corrosion rate. The modeling results indicating that, from the corrosion management perspectives, use of the relatively larger diameter pipe and combination of the different diameter pipes in series are beneficial.

- The length of pipe has direct influence on corrosion. When the length is more, it is expected that, the concentration of corrosion material at the downstream reaches would be relatively more due to higher total friction and longer residence time. In the present study, modeling results agree with this hypothesis. It is seen from the results that, the concentration of lead along the pipe length is higher for the longer pipes compare with the shorter pipes. That is, at the same locations, corrosion for the longer and shorter pipes is different. The phenomenon of higher corrosion rate with the longer pipe is related with the pipe flow hydraulics. In general, for the longer pipe, total resistance to the flow is higher. As a result, the flow velocity
would be lower. From the hydraulic standpoint, the residence time is directly proportional to the length and roughness of the pipe, but inversely proportional to the flow velocity. If the total resistance of the pipe is higher due to the longer pipe reach, then it affects the movement of the bulk water body in the pipe in a way that, relatively longer time is required to pass out the water mass. Thus the longer residence time or contact period with the pipe wall material, and as a result, the higher corrosion is expected.

- The residence time of the bulk water in a WDS is the function of flow velocity and pipe length, and is one of the important factors that affect corrosion processes. The residence time is also related to the requirement and rate of loss of the disinfectants and formation of the disinfectant by products. Growth of the biological products is also related to the residence time of the bulk water in a distribution system. As the residence time is a function of flow velocity/pipe length, and the flow velocity is a function of the piezometric head, friction and pipe diameter; in this study, the residence time is controlled by changing the flow velocity, and the flow velocity is controlled by changing the piezometric head. The residence time may also be controlled by changing the pipe length or diameter. Reviewing the results, it is revealed that, pH level of a system is directly affected by the change in residence time, on the other hand DO level is affected inversely. That is, when the residence time is increasing, the pH level is also increasing. But, exactly for the same situations, the DO level is decreasing.
7.2 Limitations of the Study

The thesis is based on one dimensional transient-corrosion modeling. One dimensional modeling simulate cross-sectional (depth-width) average situation. But in reality, the hydraulic parameters (flow velocity, pressure, turbulence) and corrosion-water quality parameters (concentration of the species, mixing, dispersion, advection, reaction etc.) vary along the pipe axis as well as within the cross-section from the pipe wall surface boundary to the centre of the pipe. Naturally to simulate the real pipe flow situation, that is, what is happening in the pipe flow (variation of the hydraulic and water quality parameters both across and along the pipe), one dimensional model has limitations; it is unable to represent across the pipe variation of the related parameters, only can represent the average conditions at each computational grid points along the pipe. This is not enough for comprehensive study and understanding of the hydraulics and corrosion induced water quality events in a system. To fulfill these purposes, preferably three dimensional modeling or at least two dimensional modeling is required. It is not possible for this thesis due to time and resources constraints.

In a water distribution system, there are number of physical and chemical factors/parameters responsible for the lead pipe corrosion. Though all of these factors/parameters are not affecting the corrosion processes with the same weight, yet for comprehensive simulation of the corrosion processes, consideration and inclusion of all of them are required. For the present thesis, that is beyond the scope of the study. Only two dominant chemical parameters and most of the hydraulic conditions are considered.
7.3 **Recommendations for Future Work**

From the hydraulic perspective, the developed model can simulate hydraulic transient events for the relatively simple system only with different diameter pipes connected in series having two reservoirs and one gate valve. But in reality, the water distribution system is not that simple; obviously it has many different types of hydraulic components and complex pipe networks. For the simulation of such complex system, much extension and improvement of the model is required. From the corrosion standpoint, the model considers only two dominant chemical species responsible for corrosion of the lead pipes.

In practical case, there are numerous physical and chemical factors such as ambient temperature, disinfectants, disinfectant bi-products, corrosion inhibitors, formation of scale and bio-films on the pipe wall, dislodge of the scales and films, permeability of the scale, chemical composition of water etc. that influence the corrosion processes. For comprehensive simulation of the total corrosion processes in a system, inclusion of all those factors and parameters in an integrated model is required. Obviously it is very difficult task to include all corrosion related factors and parameters in the model at a time. But step by step it can be done. It is recommended to move forward to include a few more corrosion related chemical species in the model. For more realistic simulation of the lead corrosion events, in addition to the lead based pipe, the provisions for inclusion of some fittings and fixtures used in the system such as brass faucets, lead-tin solders, goosenecks, water meter, valves etc. that may contain certain percentage of lead should be incorporated in the hydraulic component of the model. Next research is recommended to consider this option as well.
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APPENDIX

CODING OF THE EXTENDED AND MODIFIED TRANSIENT-CORROSION MODEL WITH TYPICAL INPUT DATA
FINAL TRANSIENT-CORROSION MODEL FOR LEAD

! Original model was developed by Naser and Karney (2005) for the single diameter iron pipe based system and spatial data acquisition
! Extended and modified for the combination of multiple diameter lead pipes in series, and acquisition of component wise time series and spatial data (Monirul)

************************** Main Program **************************

! program Transient
!
  implicit double precision (a-h)
  implicit double precision (o-z)
!
  common /constants / 
  Upstream_Reservoir_Head, Downstream_Reservoir_Head, Wave_Speed, Gravity, Vinitial, Vinitial_1, Total_Simulation_Time, pi, Schmidt_Number, i_Time_Step_ADRE
  common /flow / Piezometric_Head(1000), Velocity(1000), Discharge(1000)
!  common /pipe / Pipe_Length, Pipe_Diameter, Pipe_Area
  common /pipe /
  Pipe_Length, Pipe_Diameter, Pipe_Area, Pipe_Length_1, Pipe_Diameter_1, Pipe_Area_1
  common /fluid / Fluid_Density, Fluid_Viscosity
  common /numerical / dt, dx, Courant_Number, Nx, Nt
  common /nodes / x(1000)
  common /valvedata /
  Valve_State, Time_Start, Time_End, Steady_State_Discharge, Steady_State_Head
  common /printdata / Critical_Length, Number_of_Section, Number_of_Section_New
  common /constituent/
  Concentration(3,1000), dtc, Cinitial(3), Equilibrium_Constant_1, Equilibrium_Constant_2, Equilibrium_Constant_3, Equilibrium_Constant_4, Reaction_Coefficient
  common /flowold / Old_Velocity(1000), Old_Discharge(1000)
  common /timeseries / iix1, iix2, iix3, iix4, iix5
  common /spatialdata / iit1, iit2, iit3, iit4, iit5, iit6, iit7, iit8, iit9, iit10

! Node number to record time series data
  iix1=10
  iix2=20
  iix3=30
  iix4=40
  iix5=50

! Times in second to record data for the spatial profiles along the pipe
  iit1=300
  iit2=540
  iit3=1800
  iit4=3599
iit5=500
iit6=800
iit7=1000
iit8=1200
iit9=1500
iit10=1800

!****************** Open Input Files *************************

! open (5, file = 'C:\Thesis_Corr_Proj\Lead\1D-Lead_Corr-Model-Input-modif.F90')
!

!****************** Open Output Files *************************

! open (6, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_InputData.d')
!
! **** Unformatted files for Velocity components and pressure head *****
!
! Files to store time series hydraulic data at various nodal points
open (9000, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Hyd Time Series_10.d')
open (9010, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Hyd Time Series_20.d')
open (9020, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Hyd Time Series_30.d')
open (9030, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Hyd Time Series_40.d')
open (9040, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Hyd Time Series_50.d')
!
! Files to store time series concentration data at various nodal points
open (9060, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Conc Time Series_10.d')
open (9070, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Conc Time Series_20.d')
open (9080, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Conc Time Series_30.d')
open (9090, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Conc Time Series_40.d')
open (10000, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Conc Time Series_50.d')
!
! Files to store spatial profile for hydraulic data at various time steps
open (15000, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Hyd Spatial Profile_20.d')
open (15010, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Hyd Spatial Profile_500.d')
open (15020, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Hyd Spatial Profile_1000.d')
!
! Files to store spatial profile for concentration data at various time steps
open (16000, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Conc Spatial Profile_20.d')
open (16010, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Conc Spatial Profile_500.d')
open (16020, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Conc Spatial Profile_1000.d')

open (12, file = 'C:\Thesis_Corr_Proj\Lead\Output\1D_Velocity-2.d')
open (13, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Velocity-3.d')
open (14, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Velocity-4.d')
open (15, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Velocity-5.d')
open (16, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Velocity-6.d')
open (17, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Velocity-7.d')
open (18, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Velocity-8.d')
open (19, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Velocity-9.d')
open (20, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Velocity-10.d')
open (21, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Velocity-11.d')
open (22, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Velocity-12.d')
open (2, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Discharge.d')
open (3, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Head.d')
open (4, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Valve-Head.d')
open (7, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Head-Along-Pipe.d')
open (8, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-At-Middle.d')
open (9, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Node-2.d')
open (10, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Along-Pipe.d')
open (71, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-1-1.d')
open (72, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-2-1.d')
open (73, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-3-1.d')
open (74, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-4-1.d')
open (75, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-5-1.d')
open (76, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-6-1.d')
open (77, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-7-1.d')
open (78, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-8-1.d')
open (79, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-9-1.d')
open (80, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-10-1.d')
open (81, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-11-1.d')
open (82, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-12-1.d')
!
open (710, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-1-2.d')
open (720, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-2-2.d')
open (730, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-3-2.d')
open (740, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-4-2.d')
open (750, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-5-2.d')
open (760, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-6-2.d')
open (770, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-7-2.d')
open (780, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-8-2.d')
open (790, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-9-2.d')
open (800, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-10-2.d')
open (810, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-11-2.d')
open (820, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-12-2.d')
!
open (7100, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-1-3.d')
open (7200, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-2-3.d')
open (7300, file='C:\Thesis_Corr_Proj\Lead\Output\1D_Concentration-Pipe-3-3.d')
! call input
! call cylinders
! call timestep
!
! *********************** Steady State Analysis ********************
!
Ctime=0.0
!
call initial_condition
!
call output(Ctime)
!
call INITIAL_CONDITION_CONCENTRATION
!
call Output_Concentration(Ctime)
!
call times(tstart)
!
i_ADRE=0
!
! *********************** Beginning of Transient Simulation *****************
!
do 10 it=1,Nt
   Ctime=Ctime+2.0*dt
!
   call Hydraulic(Ctime)
!
   call output(Ctime)
!
   i_ADRE=i_ADRE+2
if (i_ADRE.eq.i_Time_Step_ADRE) then
   call ADVECTION_DIFFUSION_REACTION
   call Output_Concentration(Ctime)
do 1 is1=1,Nx+1
Old_Velocity(is1)=Velocity(is1)
Old_Discharge(is1)=Discharge(is1)
1 continue
   i_ADRE=0
else
end if
!
   write (*,*) ' Time=',Ctime
10 continue
!
! ******************* The End of Transient Simulation *******************
!
   call times(tend)
!
   Total_Running_Time=tend-tstart
!
   write (6,30) Total_Running_Time
!
30    format (/2x,'Total Running Time =',f10.5,' seconds',/)
!
   stop
   end
!
!**************** Subroutine to Read Input Data ******************
!
   subroutine input
!
   implicit double precision (a-h)
   implicit double precision (o-z)

!
   common /constants /
Upstream_Reservoir_Head,Downstream_Reservoir_Head,Wave_Speed,Gravity,Vi
initial_1,Total_Simulation_Time,pi,Schmidt_Number,i_Time_Step_ADRE
   common /flow /
   Piezometric_Head(1000),Velocity(1000),Discharge(1000)
!
   common /pipe /
   Pipe_Length,Pipe_Diameter,Pipe_Area
!
   Pipe_Length,Pipe_Diameter,Pipe_Area,Pipe_Length_1,Pipe_Diameter_1,Pipe_Area_1
   common /fluid /
   Fluid_Density,Fluid_Viscosity
   common /numerical /
   dt,dx,Courant_Number,Nx,Nt
   common /nodes /
   x(1000)
   common /valvedata /
Valve_State,Time_Start,Time_End,Steady_State_Discharge,Steady_State_Head
   common /printdata /
   Critical_Length,Number_of_Section,Number_of_Section_New
common /constituent/
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Equilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
common /flowold     / Old_Velocity(1000),Old_Discharge(1000)
common /timeseries / iix1, iix2, iix3,iix4,iix5
common /spatialdata /iit1,iit2,iit3,iit4,iit5,iit6,iit7,iit8,iit9,iit10
!
!****************** Read L and D of the pipe ***********************
!
read (5,*) Pipe_Length,Pipe_Diameter
read (5,*) Pipe_Length,Pipe_Diameter,Pipe_Length_1,Pipe_Diameter_1
!
********** Read Fluid_Density and kinematic viscosity of the pipe **********
read (5,*) Fluid_Density,Fluid_Viscosity
!
********** Read reservoir head and initial discharge ******************
read (5,*)
Upstream_Reservoir_Head,Downstream_Reservoir_Head,Steady_State_Discharge
Steady_State_Discharge=Steady_State_Discharge/1000.0
!
********** Read number of internal nodal points in ********************
********** longitudinal direction ***************************
!
read (5,* ) Nx
!
**************** Wave Velocity **************************************
read (5,* ) Wave_Speed
!
************* Read Courant number ***********************************
read (5,* ) Courant_Number
!
*************** Reading computational time ************************
read (5,* ) Total_Simulation_Time
Total_Simulation_Time=Total_Simulation_Time/2.0
!
************* Reading Gravitational Acceleration ******************
read (5,* ) Gravity
!
************* Reading Valve Characteristics **********************
read (5,*) Valve_State,Time_Start,Time_End

****************** Desired Section for Printing Output Data ******************

read (5,*) Critical_Length

*********** Constants for Advection Diffusion Reaction Equation ***********

read (5,*) Schmidt_Number,i_Time_Step_ADRE

************** Initial Conditions for each Constituents **********************

read (5,*) Cinitial(1),Cinitial(2),Cinitial(3)

****** Reaction Rate Coefficient and Solubility Product Constant **********

read (5,*)
Equilibrium_Constant_1,Equilibrium_Constant_2,Equilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient

Equilibrium_Constant=Equilibrium_Constant_1*Equilibrium_Constant_2*Equilibrium_Constant_3*Equilibrium_Constant_4

*********************** Calculating Pi Number *****************************

pi=4.0*atan(1.0)

write (6,*) 'Pipe Length                     =',Pipe_Length
write (6,*) 'Pipe Diameter                    =',Pipe_Diameter
write (6,*) 'Pipe Length_1                    =',Pipe_Length_1
write (6,*) 'Pipe Diameter_1                  =',Pipe_Diameter_1
write (6,*) 'Fluid Density                   =',Fluid_Density
write (6,*) 'Fluid Viscosity                 =',Fluid_Viscosity
write (6,*) 'Water Level at Upstream Reservoir =',Upstream_Reservoir_Head
write (6,*) 'Water Level at Downstream Reservoir =',Downstream_Reservoir_Head
write (6,*) 'Steady State Flow Discharge       =',Steady_State_Discharge
write (6,*) 'Wave Speed                     =',Wave_Speed
write (6,*) 'No. of Nodes in Longitudinal Direction =',Nx
write (6,*) 'Courant Number                  =',Courant_Number
write (6,*) 'Total Simulation Time           =',Total_Simulation_Time
write (6,*) 'Gravitational Acceleration      =',Gravity
write (6,*) 'Valve Operation                =',Valve_State
write (6,*) 'Time to Start Valve Operation =',Time_Start
write (6,*) 'Time to Complete Valve Operation =',Time_End
write (6,*) 'Desired Section for Output Data =',Critical_Length
write (6,*) 'Schmidt Number for Water Quality Model =',Schmidt_Number
write (6,*) 'Ratio of Time Steps =',i_Time_Step_ADRE
write (6,*) 'Initial Concentration of Oxygen =',Cinitial(1)
write (6,*) 'Initial pH of Water =',Cinitial(2)
write (6,*) 'Initial Concentration of Lead(II) Ion =',Cinitial(3)
write (6,*) 'Reaction Coefficient =',Equilibrium_Constant
write (6,*) 'Reaction Rate Coefficient =',Reaction_Coefficient

! File and column headers for hydraulic time series data
write(9000,*) 'Time Series Data at=',(Pipe_Length+Pipe_Length_1)/Nx*iix1,' ',m'
write(9000,*) 'Time(s)',['velocity(m/s)']','Disch(m3/s)','Head(m)'

write(9010,*) 'Time Series Data at=',(Pipe_Length+Pipe_Length_1)/Nx*iix2,' ',m'
write(9010,*) 'Time(s)',['velocity(m/s)']','Disch(m3/s)','Head(m)'

write(9020,*) 'Time Series Data at=',(Pipe_Length+Pipe_Length_1)/Nx*iix3,' ',m'
write(9020,*) 'Time(s)',['velocity(m/s)']','Disch(m3/s)','Head(m)'

write(9030,*) 'Time Series Data at=',(Pipe_Length+Pipe_Length_1)/Nx*iix4,' ',m'
write(9030,*) 'Time(s)',['velocity(m/s)']','Disch(m3/s)','Head(m)'

write(9040,*) 'Time Series Data at=',(Pipe_Length+Pipe_Length_1)/Nx*iix5,' ',m'
write(9040,*) 'Time(s)',['velocity(m/s)']','Disch(m3/s)','Head(m)'

! File and column headers for concentration time series data
write(9060,*) 'Time Series Data at=',(Pipe_Length+Pipe_Length_1)/Nx*iix1,' ',m'
write(9060,*) 'Time(s)', various concentrations and pH

write(9070,*) 'Time Series Data at=',(Pipe_Length+Pipe_Length_1)/Nx*iix2,' ',m'
write(9070,*) 'Time(s)', various concentrations and pH

write(9080,*) 'Time Series Data at=',(Pipe_Length+Pipe_Length_1)/Nx*iix3,' ',m'
write(9080,*) 'Time(s)', various concentrations and pH

write(9090,*) 'Time Series Data at=',(Pipe_Length+Pipe_Length_1)/Nx*iix4,' ',m'
write(9090,*) 'Time(s)', various concentrations and pH
! 
! Cinitial(2)=10.0**(1-Cinitial(2))
! 
return
end
!
!****************** Calculating numerical mesh size ******************
!
subroutine cylinders
!
implicit double precision (a-h)
implicit double precision (o-z)
!
common /constants /
Upstream_Reservoir_Head,Downstream_Reservoir_Head,Wave_Speed,Gravity,Vinitial,V
itial_1,Total_Simulation_Time,pi, Schmidt_Number,i_Time_Step_ADRE
common /flow /
Piezometric_Head(1000),Velocity(1000),Discharge(1000)
!
common /pipe /
Pipe_Length,Pipe_Diameter,Pipe_Area
!
common /fluid /
Fluid_Density,Fluid_Viscosity
!
common /numerical /
dt,dx,Courant_Number,Nx,Nt
!
common /nodes /
x(1000)
!
common /valvedata /
Valve_State,Time_Start,Time_End,Steady_State_Discharge,Steady_State_Head
!
common /printdata /
Critical_Length,Number_of_Section,Number_of_Section_New
!
common /constituent/
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Eq
uilbrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
!
common /flowold /
Old_Velocity(1000),Old_Discharge(1000)
!
common /timeseries /
iix1,iix2,iix3,iix4,iix5
!
common /spatialdata /
iit1,iit2,iit3,iit4,iit5,iit6,iit7,iit8,iit9,iit10
!
!
!****************** Nodes in Longitudinal Direction ********************
!
!########### Changes for the variable diameters ############
!
dx=Pipe_Length/Nx
dx=(Pipe_Length+Pipe_Length_1)/Nx
do 10 i=1,Nx+1
  x(i)=(i-1)*dx
10 continue

! **************** Desired section to print the output data ***************
!
Number_of_Section=Critical_Length/dx+1.0
  if (Number_of_Section.eq.(Nx+1)) then
    Number_of_Section_New=Number_of_Section-1
  else
    Number_of_Section_New=Number_of_Section
  end if
!
!************************* Calculating Pipe's Area *************************
!
Pipe_Area=pi*(Pipe_Diameter**2)/4.0
!
! #Changes for the variable pipe diameters #
!
Pipe_Area_1=pi*(Pipe_Diameter_1**2)/4.0
!
return
end
!
!*********************** Calculating time step ****************************
!
subroutine timestep
!
! implicit double precision (a-h)
! implicit double precision (o-z)
!
common /constants  /
Upstream_Reservoir_Head,Downstream_Reservoir_Head,Wave_Speed,Gravity,Vinitial,Vinitial_1,Total_Simulation_Time,pi,Schmidt_Number,i_Time_Step_ADRE
common /flow       / Piezometric_Head(1000),Velocity(1000),Discharge(1000)
common /pipe       / Pipe_Length,Pipe_Diameter,Pipe_Area
common /fluid      / Fluid_Density,Fluid_Viscosity
common /numerical  / dt,dx,Courant_Number,Nx,Nt
common /nodes      / x(1000)
common /valvedata  /
Valve_State,Time_Start,Time_End,Steady_State_Discharge,Steady_State_Head
common /printdata /
Critical_Length,Number_of_Section,Number_of_Section_New
! common /constituent/
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Equilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
common /flowold / Old_Velocity(1000),Old_Discharge(1000)
common /timeseries / iix1, iix2, iix3,iix4,iix5
common /spatialdata /iit1,iit2,iit3,iit4,iit5,iit6,iit7,iit8,iit9,iit10
!

! dt=Courant_Number*dx/Wave_Speed
dtc=dt*i_Time_Step_ADRE
!
!*********** Calculating number of nodes in time direction **************
!
Nt=(Total_Simulation_Time/dt)+1
!
write (6,*) 'Spatial Step in Longitudinal Direction=',dx
write (6,*) 'Time Step for Hydraulic Model         =',dt
write (6,*) 'Time Step for Water Quality Model     =',dtc
!
return
end
!
!***************** Subroutine for Initial Conditions *******************
!
subroutine initial_condition
!
implicit double precision (a-h)
implicit double precision (o-z)
!
common /constants /
Upstream_Reservoir_Head,Downstream_Reservoir_Head,Wave_Speed,Gravity,Vinitial,Vinitial_1,Total_Simulation_Time,pi,Schmidt_Number,i_Time_Step_ADRE
common /flow / Piezometric_Head(1000),Velocity(1000),Discharge(1000)
!
common /pipe /
Pipe_Length, Pipe_Diameter, Pipe_Area
!
common /pipe /
Pipe_Length, Pipe_Diameter, Pipe_Area, Pipe_Length_1, Pipe_Diameter_1, Pipe_Area_1
!
common /fluid /
Fluid_Density, Fluid_Viscosity
!
common /numerical /
dt,dx,Courant_Number,Nx,Nt
!
common /nodes /
x(1000)
!
common /valvedata /
Valve_State,Time_Start,Time_End,Steady_State_Discharge,Steady_State_Head
!
common /printdata /
Critical_Length, Number_of_Section, Number_of_Section_New
!
common /constituent/
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Equilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
!
common /flowold /
Old_Velocity(1000),Old_Discharge(1000)
common /timeseries / iix1, iix2, iix3,iix4,iix5
common /spatialdata /iit1,iit2,iit3,iit4,iit5,iit6,iit7,iit8,iit9,iit10

Steady_State_Head=Upstream_Reservoir_Head-Downstream_Reservoir_Head
if (Valve_State.eq.1.0) then
  Vinitial=0.0
  Vinitial_1=0.0 ! Changes for variable diameter
else
  Vinitial=Steady_State_Discharge/Pipe_Area
  Vinitial_1=Steady_State_Discharge/Pipe_Area_1 ! Changes for variable diameter
end if
!
friction=Friction_Factor(Vinitial)
friction_1=Friction_Factor(Vinitial_1) ! Changes for variable diameter
!
do 10 i=1,Nx+1
  if (i.le.30) then
    Velocity(i)=Vinitial
    Discharge(i)=Vinitial*Pipe_Area
    Old_Velocity(i)=Velocity(i)
    Old_Discharge(i)=Discharge(i)
    Piezometric_Head(i)=Upstream_Reservoir_Head-(1.0+(friction*x(i)/Pipe_Diameter))*(Vinitial**2/(2*Gravity))
  else ! Changes for variable diameter
    Velocity(i)=Vinitial_1
    Discharge(i)=Vinitial_1*Pipe_Area_1
    Old_Velocity(i)=Velocity(i)
    Old_Discharge(i)=Discharge(i)
    Piezometric_Head(i)=Upstream_Reservoir_Head-(1.0+(friction_1*x(i)/Pipe_Diameter_1))*(Vinitial_1**2/(2*Gravity))
  endif
10  continue
!
Piezometric_Head(1)=Upstream_Reservoir_Head
!
return
end
subroutine Hydraulic_Boundary_Condition(simulation_time)
!
!
implicit double precision (a-h)
implicit double precision (o-z)
!
common /constants /
Upstream_Reservoir_Head,Downstream_Reservoir_Head,Wave_Speed,Gravity,Vinitial,Vinitial_1,Total_Simulation_Time,pi, Schmidt_Number,i_Time_Step_ADRE
common /flow / Piezometric_Head(1000),Velocity(1000),Discharge(1000)
!
common /pipe / Pipe_Length,Pipe_Diameter,Pipe_Area
common /fluid / Fluid_Density,Fluid_Viscosity
common /numerical / dt,dx,Courant_Number,Nx,Nt
common /nodes / x(1000)
common /valvedata / Valve_State,Time_Start,Time_End,Steady_State_Discharge,Steady_State_Head
common /printdata / Critical_Length,Number_of_Section,Number_of_Section_New
common /constituent/ Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Equilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
common /flowold / Old_Velocity(1000),Old_Discharge(1000)
common /timeseries / iix1, iix2, iix3,iix4,iix5
common /spatialdata /iit1,iit2,iit3,iit4,iit5,iit6,iit7,iit8,iit9,iit10
!
!

!               Downstream Valve Boundary Condition
friction=Friction_Factor(Velocity(Nx))
! Calculations based on Wylie and Streeter book
Valve_Es=0.117
!
Coefficient_B=Wave_Speed/(Gravity*Pipe_Area)
Coefficient_B=Wave_Speed/(Gravity*Pipe_Area_1)
! Changes for variable diameter

Coefficient_R=friction*dx/(2.0*Gravity*Pipe_Diameter*(Pipe_Area**2))
Coefficient_R=friction*dx/(2.0*Gravity*Pipe_Diameter_1*(Pipe_Area_1**2))
! Changes for variable diameter

Cv=(Valve_Taw(simulation_time)*Valve_Es)**2/2.0
!
Cv=(Valve_Taw(simulation_time)*Steady_State_Discharge)**2/(2.0*Steady_State_Head)
CP1=Piezometric_Head(Nx)+Coefficient_B*Discharge(Nx)
BP1=Coefficient_B+Coefficient_R*abs(Discharge(Nx))
if ((CP1-Downstream_Reservoir_Head).ge.0.0) then
Slope = 1.0
else
    Slope = -1.0
end if
Under_Radical = \((Cv \times BP1)^2 + 2.0 \times Slope \times Cv \times (CP1 - Downstream_Reservoir_Head)\)
Discharge(Nx+1) = -Slope \times Cv \times BP1 + Slope \times \sqrt{Under_Radical}
Piezometric_Head(Nx+1) = CP1 - BP1 \times Discharge(Nx+1)

! Velocity(Nx+1) = Discharge(Nx+1) / Pipe_Area
Velocity(Nx+1) = Discharge(Nx+1) / Pipe_Area_1 ! Changes for variable diameter

! Upstream Boundary Condition; Fixed Head Reservoir
! Piezometric_Head(1) = Upstream_Reservoir_Head
! friction = Friction_Factor(Velocity(1))
!
Coefficient_B = \(\text{Wave Speed} / (\text{Gravity} \times \text{Pipe Area})\)
Coefficient_R = friction * dx / \(2.0 \times \text{Gravity} \times \text{Pipe Diameter} \times (\text{Pipe Area}^2)\)
Cm1 = Piezometric_Head(2) - Coefficient_B \times Discharge(2)
    Bm1 = Coefficient_B + Coefficient_R \times abs(Discharge(2))
Discharge(1) = (Piezometric_Head(1) - Cm1) / Bm1
Velocity(1) = Discharge(1) / Pipe_Area

! return
end

!*********** Method of Characteristic Scheme for Transient Flow Equations
***********
!
subroutine Method_of_Characteristic(ii)
!
implicit double precision (a-h)
implicit double precision (o-z)
!
common /constants /
Upstream_Reservoir_Head, Downstream_Reservoir_Head, Wave_Speed, Gravity, V_initial, V_initial_1, Total_Simulation_Time, pi, Schmidt_Number, i_Time_Step_ADRE
!
common /flow /
Piezometric_Head(1000), Velocity(1000), Discharge(1000)
!
common /pipe /
Pipe_Length, Pipe_Diameter, Pipe_Area
!
common /pipe /
Pipe_Length_1, Pipe_Diameter_1, Pipe_Area_1
!
common /fluid /
Fluid_Density, Fluid_Viscosity
!
common /numerical /
dt, dx, Courant_Number, Nx, Nt
common /nodes     / x(1000)
common /valvedata /
Valve_State,Time_Start,Time_End,Steady_State_Discharge,Steady_State_Head
common /printdata / Critical_Length,Number_of_Section,Number_of_Section_New
common /constituent/
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Eq
uilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
common /flowold   / Old_Velocity(1000),Old_Discharge(1000)
common /timeseries / iix1, iix2, iix3,iix4,iix5
common /spatialdata /iit1,iit2,iit3,iit4,iit5,iit6,iit7,iit8,iit9,iit10
!
!
if (ii.le.30) then
  Ca=Gravity*Pipe_Area/Wave_Speed
  friction=Friction_Factor(Velocity(ii-1))
  Cp=Discharge(ii-1)+Ca*Piezometric_Head(ii-1)-
    (friction*dt/(2.0*Pipe_Area*Pipe_Diameter))*(Discharge(ii-1)*abs(Discharge(ii-1)))
  friction=Friction_Factor(Velocity(ii+1))
  Cn=Discharge(ii+1)-Ca*Piezometric_Head(ii+1)-
    (friction*dt/(2.0*Pipe_Diameter*Pipe_Area))*(Discharge(ii+1)*abs(Discharge(ii+1)))
  Discharge(ii)=(Cp+Cn)/2.0
  Velocity(ii)=Discharge(ii)/Pipe_Area
  Piezometric_Head(ii)=(Discharge(ii)-Cn)/Ca
else                                                                  ! Changes for variable diameter
  Ca=Gravity*Pipe_Area_1/Wave_Speed
  ! friction=Friction_Factor(Velocity(ii-1))
  !
  Cp=Discharge(ii-1)+Ca*Piezometric_Head(ii-1)-
    (friction*dt/(2.0*Pipe_Area_1*Pipe_Diameter_1))*(Discharge(ii-1)*abs(Discharge(ii-1)))
  ! friction=Friction_Factor(Velocity(ii+1))
  !
  Cn=Discharge(ii+1)-Ca*Piezometric_Head(ii+1)-
    (friction*dt/(2.0*Pipe_Diameter_1*Pipe_Area_1))*(Discharge(ii+1)*abs(Discharge(ii+1)))
  ! Discharge(ii)=(Cp+Cn)/2.0
  Velocity(ii)=Discharge(ii)/Pipe_Area_1
  Piezometric_Head(ii)=(Discharge(ii)-Cn)/Ca
endif
!

!
** Subroutine for Solving tridiagonal system of linear equations ****
** based on Thomas algorithm **************************
* The form of the tridiagonal matrix is:
* AD(1) AU(1) = AC(1) *
* AL(2) AD(2) AU(2) = AC(2) *
* AL(3) AD(3) AU(3) = AC(3) *
* ... = *
* AL(ne-1) AD(ne-1) AU(ne-1) = AC(ne-1) *
* AL(ne) AD(ne) = AC(ne) *
*
*************************************************************************
*
subroutine thomas (ne,AD,AU,AL,AC,AX)
*
implicit double precision (a-h)
implicit double precision (o-z)
*
dimension Pm(1000),Qm(1000),AD(1000),AU(1000),AL(1000),AC(1000),AX(1000)
*
AL(1) = 0.0
AU(ne) = 0.0
*
do 5 ip=1,ne
   Pm(ip)=0.0
   Qm(ip)=0.0
5 continue
*
   Forward Elimination
*
   temp = AD(1)
   Pm(1) = -AU(1) / temp
   Qm(1) = AC(1) / temp
   do 10 ip = 2,ne
      temp = AD(ip) + AL(ip)*Pm(ip-1)
      Pm(ip) = -AU(ip) / temp
      Qm(ip) = (AC(ip) - AL(ip)*Qm(ip-1)) / temp
10 continue
Back Substitution

! do 20 ip = ne,1,-1
  AX(ip) = Pm(ip)*AX(ip+1) + Qm(ip)
20  continue
!
return
end

************ Calculating axial velocity, lateral flow, ***************
************ and piezometric head at each grid node by ***************
************ solving momentum and continuity equations ***************
!
subroutine Hydraulic(Ctime)
!
implicit double precision (a-h)
implicit double precision (o-z)
!
common /constants /
Upstream_Reservoir_Head,Downstream_Reservoir_Head,Wave_Speed,Gravity,Vinitial,Vi
itial_1,Total_Simulation_Time,pi,Schmidt_Number,i_Time_Step_ADRE
common /flow /
  Piezometric_Head(1000),Velocity(1000),Discharge(1000)
!
common /pipe /
  Pipe_Length,Pipe_Diameter,Pipe_Area
!
common /fluid /
  Fluid_Density,Fluid_Viscosity
!
common /numerical /
  dt,dx,Courant_Number,Nx,Nt
!
common /nodes /
x(1000)
!
common /valvedata /
Valve_State,Time_Start,Time_End,Steady_State_Discharge,Steady_State_Head
!
common /printdata /
  Critical_Length,Number_of_Section,Number_of_Section_New
!
common /constituent/
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Eq
quilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
!
common /flowold /
  Old_Velocity(1000),Old_Discharge(1000)
!
common /timeseries /
iix1,iix2,iix3,iix4,iix5
!
common /spatialdata /
iit1,iit2,iit3,iit4,iit5,iit6,iit7,iit8,iit9,iit10
!
!
Calculating Boundary Conditions for
Piezometric Head, Axial Velocity, and Lateral Flow
!
call Hydraulic_Boundary_Condition(Ctime)
!
Calculating Piezometric Head, Axial Velocity,
and Lateral Flow for Internal Nodes by MOC

! do 20 itemp=3,2,-1
   do 10 i=itemp,Nx,2
      call Method_of_Characteristic(i)
   continue
20    continue
!
return
end
!
 !************************** Print output data **************************
!
subroutine output(CCtime)
!
! implicit double precision (a-h)
! implicit double precision (o-z)
!
common /constants /
Upstream_Reservoir_Head,Downstream_Reservoir_Head,Wave_Speed,Gravity,Vi
nitial_1,Total_Simulation_Time,pi,Schmidt_Number,i_Time_Step_ADRE
!
common /flow /
Piezometric_Head(1000),Velocity(1000),Discharge(1000)
!
common /pipe /
Pipe_Length,Pipe_Diameter,Pipe_Area,Pipe_Length_1,Pipe_Diameter_1,Pipe_Area_1
!
common /fluid /
Fluid_Density,Fluid_Viscosity
!
common /numerical /
dt,dx,Courant_Number,Nx,Nt
!
common /nodes /
x(1000)
!
common /valvedata /
Valve_State,Time_Start,Time_End,Steady_State_Discharge,Steady_State_Head
!
common /printdata /
Critical_Length,Number_of_Section,Number_of_Section_New
!
common /constituent/
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Eq
uililibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
!
common /flowold /
Old_Velocity(1000),Old_Discharge(1000)
!
common /timeseries /
iix1, iix2, iix3, iix4, iix5
!
common /spatialdata /
iit1, iit2, iit3, iit4, iit5, iit6, iit7, iit8, iit9, iit10
!
write (4,*), CCtime,Piezometric_Head(Nx+1),Nx*dx
   ! Head at the end of pipe
!
write (1,*), CCtime,Velocity(Number_of_Section),(Number_of_Section-1)*dx
!
Write time series data at the selected nodal points along the pipe
write (9000,111) CCtime,Velocity(iix1), Discharge(iix1),Piezometric_Head(iix1)
write (9010,111) CCtime,Velocity(iix2), Discharge(iix2),Piezometric_Head(iix2)
write (9020,111) CCtime,Velocity(iix3), Discharge(iix3),Piezometric_Head(iix3)
write (9030,111) CCtime,Velocity(iix4), Discharge(iix4),Piezometric_Head(iix4)
write (9040,111) CCtime,Velocity(iix5), Discharge(iix5),Piezometric_Head(iix5)
111 format(f9.4,5x,f9.4,5x,f9.4,10x,f9.4)
write (2,*) CCtime,Discharge(Nx/2+1),(Nx/2)*dx ! time series at the middle of pipe, Now it is open
write (3,*) CCtime,Piezometric_Head(Number_of_Section),(Number_of_Section-1)*dx !
do 10 iindex=1,Nx+1
   write (7,*) CCtime,(iindex-1)*dx,Piezometric_Head(iindex) ! spatial profile
10 continue
!
write (7,*) '***********************'

Nxt=2

if(Nxt.eq.iit1) then
do isecc=1,Nx+1
   write(15000,*) (isecc-1)*dx, Velocity(isecc),
   Discharge(isecc),Piezometric_Head(isecc) ! Spatial Profile
end do

else if (Nxt.eq.iit2) then
do isecc=1,Nx+1
   write(15010,*) (isecc-1)*dx, Velocity(isecc),
   Discharge(isecc),Piezometric_Head(isecc) ! Spatial Profile
end do

else if (Nxt.eq.iit3) then
do isecc=1,Nx+1
   write(15020,*) (isecc-1)*dx, Velocity(isecc),
   Discharge(isecc),Piezometric_Head(isecc) ! Spatial Profile
end do

else
   end if
!
999 format(f8.2, 5x, f8.3,5x, f8.3,5x, f8.2)

do isecc=1,Nx+1
   if (CCtime.le.600.0) then
write (11,*) CCtime,(isecc-1)*dx,Velocity(isecc)
    ! writes spatial profile of velocity
else
    if (CCtime.le.1200.0) then
        write (12,*) CCtime,(isecc-1)*dx,Velocity(isecc)
    else
        if (CCtime.le.1800.0) then
            write (13,*) CCtime,(isecc-1)*dx,Velocity(isecc)
        else
            if (CCtime.le.2400.0) then
                write (14,*) CCtime,(isecc-1)*dx,Velocity(isecc)
            else
                if (CCtime.le.3000.0) then
                    write (15,*) CCtime,(isecc-1)*dx,Velocity(isecc)
                else
                    if (CCtime.le.3600.0) then
                        write (16,*) CCtime,(isecc-1)*dx,Velocity(isecc)
                    else
                        if (CCtime.le.4200.0) then
                            write (17,*) CCtime,(isecc-1)*dx,Velocity(isecc)
                        else
                            if (CCtime.le.4800.0) then
                                write (18,*) CCtime,(isecc-1)*dx,Velocity(isecc)
                            else
                                if (CCtime.le.5400.0) then
                                    write (19,*) CCtime,(isecc-1)*dx,Velocity(isecc)
                                else
                                    if (CCtime.le.6000.0) then
                                        write (20,*) CCtime,(isecc-1)*dx,Velocity(isecc)
                                    else
                                        if (CCtime.le.6600.0) then
                                            write (21,*) CCtime,(isecc-1)*dx,Velocity(isecc)
                                        else
                                            write (22,*) CCtime,(isecc-1)*dx,Velocity(isecc)
                                        end if
                                    end if
                                end if
                            end if
                        end if
                    end if
                end if
            end if
        end if
    end if
end do
 Subroutine to calculate running time

subroutine times(rtime)
  use portlib
  implicit double precision (a-h)
  implicit double precision (o-z)
  rtime = timef()
  return
end

Valve Function

function Valve_Taw(simulation_time)
  implicit double precision (a-h)
  implicit double precision (o-z)
  common /valvedata/
  Valve_State,Time_Start,Time_End,Steady_State_Discharge,Steady_State_Head
  if (Valve_State.eq.1.0) then
    if (simulation_time.ge.Time_End) then
      Valve_Taw=1.0
    else
      Valve_Taw=(simulation_time-Time_Start)/(Time_End-Time_Start)
    end if
  else
    if (simulation_time.ge.Time_End) then
      Valve_Taw=0.0
    else
      Valve_Taw=-(simulation_time-Time_End)/(Time_End-Time_Start)
    end if
  end if
  return
end

Printing Results for Concentration of constituent
subroutine Output_Concentration(CCtime)
!
    implicit double precision (a-h)
    implicit double precision (o-z)
!
    common /constants /
    Upstream_Reservoir_Head, Downstream_Reservoir_Head, Wave_Speed, Gravity, V_initial, V_initial_1, Total_Simulation_Time, pi, Schmidt_Number, i_Time_Step_ADRE
    common /flow /
    Piezometric_Head(1000), Velocity(1000), Discharge(1000)
    common /pipe /
    Pipe_Length, Pipe_Diameter, Pipe_Area, Pipe_Length_1, Pipe_Diameter_1, Pipe_Area_1
    common /fluid /
    Fluid_Density, Fluid_Viscosity
    common /numerical /
    dt, dx, Courant_Number, Nx, Nt
    common /nodes /
    x(1000)
    common /valvedata /
    Valve_State, Time_Start, Time_End, Steady_State_Discharge, Steady_State_Head
    common /printdata /
    Critical_Length, Number_of_Section, Number_of_Section_New
    common /constituent/
    Concentration(3,1000), dtc, C_initial(3), Equilibrium_Constant_1, Equilibrium_Constant_2, Equilibrium_Constant_3, Equilibrium_Constant_4, Reaction_Coefficient
    common /flowold /
    Old_Velocity(1000), Old_Discharge(1000)
    common /timeseries /
    iix1, iix2, iix3, iix4, iix5
    common /spatialdata /
    iit1, iit2, iit3, iit4, iit5, iit6, iit7, iit8, iit9, iit10
!
    dimension pH(1000) ! It is indicating OH ion conc, if OH is higher then pH would be lower (pH=14-pOH, the basic relationship)

! Writes time series data for concentrations at the selected nodal points along the pipe
write (9060,222) CCtime, Concentration(1,iix1)*32000.0, pH(iix1), Concentration(3,iix1)*207.0*1000.0 ! Time series Conc data at nodal points
write (9070,222) CCtime, Concentration(1,iix2)*32000.0, pH(iix2), Concentration(3,iix2)*207.0*1000.0
write (9080,222) CCtime, Concentration(1,iix3)*32000.0, pH(iix3), Concentration(3,iix3)*207.0*1000.0
write (9090,222) CCtime, Concentration(1,iix4)*32000.0, pH(iix4), Concentration(3,iix4)*207.0*1000.0
write (10000,222) CCtime, Concentration(1,iix5)*32000.0, pH(iix5), Concentration(3,iix5)*207.0*1000.0
222  format(f15.9,5x,f15.12,5x,f15.12,10x,f15.12)
!
! Writes spatial Conc data at selected times

Nxt=1
if(Nxt.eq.iit1) then
do isecc=1,Nx+1
write(16000,*), (isecc-1)*dx, Concentration(1,isecc)*32000.0,
pH(isecc),Concentration(3,isecc)*207.0*1000.0  ! Spatial Conc data at diff times
end do

else if (Nxt.eq.iit2) then
  do isecc=1,Nx+1
    write(16010,*), (isecc-1)*dx, Concentration(1,isecc)*32000.0,
pH(isecc),Concentration(3,isecc)*207.0*1000.0
  end do
else if (Nxt.eq.iit3) then
  do isecc=1,Nx+1
    write(16020,*), (isecc-1)*dx, Concentration(1,isecc)*32000.0,
pH(isecc),Concentration(3,isecc)*207.0*1000.0
  end do
else if (Nxt.eq.iit4) then
  do isecc=1,Nx+1
    write(16030,*), (isecc-1)*dx,
Concentration(1,isecc)*32000.0, pH(isecc),Concentration(3,isecc)*207.0*1000.0
  end do
else
  end if

! 999 format(f8.2, 5x, f8.3,5x, f8.3,5x, f8.2)

!       write (9,*), CCtime,Concentration(NCC,2),dx
!
!       write (8,*), CCtime,Concentration(NCC,Number_of_Section),(Number_of_Section-1)*dx
!
!       do iindex=1,Nx+1
!         write (10,*), CCtime,(iindex-1)*dx,Concentration(NCC,iindex)
!10    continue
!       write (10,*),'***************************************************'
!
!       do isec=1,Nx+1
!         pH(isec)=14.0+log10(ABS(Concentration(2,isec)))
!         if (CCtime.le.100.0) then !CCtime.le.(2.0*Total_Simulation_Time/12.0-dtc/2.0).and.CCtime.le.(2.0*Total_Simulation_Time/12.0+dtc/2.0) then
             write (71,100) CCtime,(isec-1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
         else
             pH(isec)=14.0+log10(ABS(Concentration(2,isec)))
             if (CCtime.le.100.0) then
               write (71,100) CCtime,(isec-1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
             end if
         end if
         if (CCtime.gt.100.0) then
           write (71,100) CCtime,(isec-1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
         end if
       end do
else
  if (CCtime.le.200.0) then !(2.0*Total_Simulation_Time/6.0-
dtc/2.0).and.CCtime.le.(2.0*Total_Simulation_Time/6.0+dtc/2.0)) then
    write (72,100) CCtime,(isec-
1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
else
  if (CCtime.le.300.0) then !(2.0*Total_Simulation_Time/4.0-
dtc/2.0).and.CCtime.le.(2.0*Total_Simulation_Time/4.0+dtc/2.0)) then
    write (73,100) CCtime,(isec-
1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
else
  if (CCtime.le.400.0) then !(2.0*Total_Simulation_Time/3.0-
dtc/2.0).and.CCtime.le.(2.0*Total_Simulation_Time/3.0+dtc/2.0)) then
    write (74,100) CCtime,(isec-
1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
else
  if (CCtime.le.500.0) then !(2.0*Total_Simulation_Time/2.4-
dtc/2.0).and.CCtime.le.(2.0*Total_Simulation_Time/2.4+dtc/2.0)) then
    write (75,100) CCtime,(isec-
1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
else
  if (CCtime.le.600.0) then !(2.0*Total_Simulation_Time/2.0-
dtc/2.0).and.CCtime.le.(2.0*Total_Simulation_Time/2.0+dtc/2.0)) then
    write (76,100) CCtime,(isec-
1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
else
  if (CCtime.ge.(2.0*Total_Simulation_Time/1.714-
dtc/2.0).and.CCtime.le.(2.0*Total_Simulation_Time/1.714+dtc/2.0)) then
    write (77,100) CCtime,(isec-
1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
else
  if (CCtime.ge.(2.0*Total_Simulation_Time/1.5-
dtc/2.0).and.CCtime.le.(2.0*Total_Simulation_Time/1.5+dtc/2.0)) then
    write (78,100) CCtime,(isec-
1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
else
  if (CCtime.ge.(2.0*Total_Simulation_Time/1.333-
dtc/2.0).and.CCtime.le.(2.0*Total_Simulation_Time/1.333+dtc/2.0)) then
    write (79,100) CCtime,(isec-
1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
else
  if (CCtime.ge.(2.0*Total_Simulation_Time/1.2-
dtc/2.0).and.CCtime.le.(2.0*Total_Simulation_Time/1.2+d tc/2.0)) then
    write (80,100) CCtime,(isec-
1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
else
if (CCtime.ge.(2.0*Total_Simulation_Time/1.091-dtc/2.0).and.CCtime.le.(2.0*Total_Simulation_Time/1.091+dtc/2.0)) then
    write (81,100) CCtime,(isec-1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
else
    if (CCtime.ge.(2.0*Total_Simulation_Time/1.0-dtc/2.0).and.CCtime.le.(2.0*Total_Simulation_Time/1.0+dtc/2.0)) then
        write (82,100) CCtime,(isec-1)*dx,Concentration(1,isec)*32000.0,pH(isec),Concentration(3,isec)*207.0*1000.0
    else
        end if
    end if
end if
end do

!         write (7,*) Ctime,x(isec),Average_Concentration(NCC,isec)
100   format (2(f8.3,1x),3(e15.8,1x))
!
return
end
!
!     Initial Condition for constituent Concentration
!
SUBROUTINE INITIAL_CONDITION_CONCENTRATION
!
implicit double precision (a-h)
implicit double precision (o-z)
!
common /constants /
Upstream_Reservoir_Head,Downstream_Reservoir_Head,Wave_Speed,Gravity,Vinitial,Vinitial_1,Total_Simulation_Time,pi,Schmidt_Number,i_Time_Step_ADRE
common /flow      / Piezometric_Head(1000),Velocity(1000),Discharge(1000)
! common /pipe      / Pipe_Length,Pipe_Diameter,Pipe_Area
common /pipe      / Pipe_Length,Pipe_Diameter,Pipe_Area,Pipe_Length_1,Pipe_Diameter_1,Pipe_Area_1
common /fluid     / Fluid_Density,Fluid_Viscosity
common /numerical / dt,dx,Courant_Number,Nx,Nt
common /nodes     / x(1000)

common /valvedata /
Valve_State,Time_Start,Time_End,Steady_State_Discharge,Steady_State_Head
common /printdata / Critical_Length,Number_of_Section,Number_of_Section_New
common /constituent/
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Equilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
common /flowold / Old_Velocity(1000),Old_Discharge(1000)
common /timeseries / iix1, iix2, iix3,iix4,iix5
common /spatialdata /iit1,iit2,iit3,iit4,iit5,iit6,iit7,iit8,iit9,iit10

! DO 10 J=1,Nx+1
Concentration(1,J)=Cinitial(1)/32000.0
Concentration(2,J)=10.0**(-14.0+Cinitial(2)) ! It is indicating OH ion conc, if OH is higher then pH would be lower (pH=14-pOH, the basic relationship)
Concentration(3,J)=Cinitial(3)/207000.0
10 CONTINUE
!
RETURN
END
!
! Solving Advection Diffusion Reaction Equation
!
SUBROUTINE ADVECTION_DIFFUSION_REACTION
!
implicit double precision (a-h)
implicit double precision (o-z)
!
common /constants / Upstream_Reservoir_Head,Downstream_Reservoir_Head,Wave_Speed,Gravity,Vinitial,Vinitial_1,Total_Simulation_Time,pi,Schmidt_Number,i_Time_Step_ADRE
common /flow / Piezometric_Head(1000),Velocity(1000),Discharge(1000)
!
common /pipe / Pipe_Length,Pipe_Diameter,Pipe_Area
!
common /fluid / Fluid_Density,Fluid_Viscosity
!
common /numerical / dt,dx,Courant_Number,Nx,Nt
!
common /nodes / x(1000)
!
common /valvedata /
Valve_State,Time_Start,Time_End,Steady_State_Discharge,Steady_State_Head
!
common /printdata / Critical_Length,Number_of_Section,Number_of_Section_New
!
common /constituent/
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Equilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
!
common /flowold / Old_Velocity(1000),Old_Discharge(1000)
!
common /timeseries / iix1, iix2, iix3,iix4,iix5
common /spatialdata /iit1,iit2,iit3,iit4,iit5,iit6,iit7,iit8,iit9,iit10
!
!
dimension AD(1000),AU(1000),AL(1000),AC(1000),AX(1000)
!
DO 30 NC=1,3
!
! Boundary Condition at Upstream Node (x=0); No Flux Boundary
!
JJ=1
    IF (NC.EQ.1) THEN
        Concentration(NC,JJ)=Cinitial(NC)/32000.0
    ELSE
        IF (NC.EQ.2) THEN
            Concentration(NC,JJ)=10.0**(-14.0+Cinitial(NC)) ! It is indicating OH ion conc,
if OH is higher then pH would be lower (pH=14-pOH, the basic relationship)
        ELSE
            Concentration(NC,JJ)=Cinitial(NC)/207000.0
        END IF
    END IF

! Interior Nodes
!
JJ=2
    Coefficient1=1.0+Old_Velocity(JJ-1)*(dtc/dx)+(Decay_Coefficient(NC,JJ-1)*dtc/2.0)+(Diffusion_Coefficient(JJ-1,'OLD')*dtc/dx**2)
    Coefficient2=1.0-
    Old_Velocity(JJ)*(dtc/dx)+(Decay_Coefficient(NC,JJ)*dtc/2.0)-
    (2.0*Diffusion_Coefficient(JJ,'OLD')*dtc/dx**2)
    Coefficient3=1.0-Velocity(JJ-1)*(dtc/dx)-(Decay_Coefficient(NC,JJ-1)*dtc/2.0)-(Diffusion_Coefficient(JJ-1,'NEW')*dtc/dx**2)
    Coefficient4=1.0+Velocity(JJ)*(dtc/dx)-
    (Decay_Coefficient(NC,JJ)*dtc/2.0)+(2.0*Diffusion_Coefficient(JJ,'NEW')*dtc/dx**2)
    Coefficient5=-Diffusion_Coefficient(JJ+1,'NEW')*dtc/dx**2
    Coefficient6=Diffusion_Coefficient(JJ+1,'OLD')*dtc/dx**2
if (NC.eq.1) then
    Coefficient7=0.0
else
    if (NC.eq.2) then
        Coefficient7=0.0
    else

    Coefficient7=2.0*Reaction_Coefficient*Concentration(1,JJ)*Concentration(2,JJ)
end if
end if
AL(JJ-1)=0.0
AD(JJ-1)=Coefficient4
AU(JJ-1)=Coefficient5
AC(JJ-1)=Coefficient1*Concentration(NC,JJ-1)+Coefficient2*Concentration(NC,JJ)+Coefficient6*Concentration(NC,JJ+1)+Coefficient7*(2.0*dtc)-Coefficient3*Concentration(NC,JJ-1)

DO 10 JJ=3,Nx
Coefficient1=1.0+Old_Velocity(JJ-1)*(dtc/dx)+(Decay_Coefficient(NC,JJ-1)*dtc/2.0)+(Diffusion_Coefficient(JJ-1,'OLD')*dtc/dx**2)
Coefficient2=1.0-
Old_Velocity(JJ)*(dtc/dx)+(Decay_Coefficient(NC,JJ)*dtc/2.0)-(2.0*Diffusion_Coefficient(JJ,'OLD')*dtc/dx**2)
Coefficient3=1.0-Velocity(JJ-1)*(dtc/dx)-(Decay_Coefficient(NC,JJ-1)*dtc/2.0)-(Diffusion_Coefficient(JJ-1,'NEW')*dtc/dx**2)
Coefficient4=1.0+Velocity(JJ)*(dtc/dx)-(Decay_Coefficient(NC,JJ)*dtc/2.0)+(2.0*Diffusion_Coefficient(JJ,'NEW')*dtc/dx**2)
Coefficient5=Diffusion_Coefficient(JJ+1,'NEW')*dtc/dx**2
Coefficient6=Diffusion_Coefficient(JJ+1,'OLD')*dtc/dx**2
if (NC.eq.1) then
  Coefficient7=0.0
else
  if (NC.eq.2) then
    Coefficient7=0.0
  else
    Coefficient7=2.0*Reaction_Coefficient*Concentration(1,JJ)*Concentration(2,JJ)
  end if
end if
AL(JJ-1)=Coefficient3
AD(JJ-1)=Coefficient4
AU(JJ-1)=Coefficient5
AC(JJ-1)=Coefficient1*Concentration(NC,JJ-1)+Coefficient2*Concentration(NC,JJ)+Coefficient6*Concentration(NC,JJ+1)+Coefficient7*(2.0*dtc)
10 CONTINUE
!
! Boundary Condition at Downstream Node (x=Pipe_Length); No Flux Boundary
!
JJ=Nx+1
AL(JJ-1)=1.0
AD(JJ-1)=-1.0
AU(JJ-1)=0.0
AC(JJ-1)=0.0
!
call thomas (Nx,AD,AU,AL,AC,AX)
! DO 20 JJ=2,Nx+1
  Concentration(NC,JJ)=AX(JJ-1)
  IF (Concentration(NC,JJ).LT.0.0) THEN
    Concentration(NC,JJ)=0.0
  ELSE
    END IF
  IF (NC.EQ.3) THEN
    IF (Concentration(NC,JJ).GT.Equilibrium_Concentration_For_Lead(JJ)) THEN
      Concentration(NC,JJ)=Equilibruim_Concentration_For_Lead(JJ)
    ELSE
      END IF
    ELSE
      END IF
  END IF
20   CONTINUE
30   CONTINUE
!
RETURN
END
!
! Function to Calculate Turbulent Diffusion Coefficient
! Using Taylor's Approach
!
FUNCTION Diffusion_Coefficient(JJJ,Word)
!
implicit double precision (a-h)
implicit double precision (o-z)
!
common /constants /
Upstream_Reservoir_Head,Downstream_Reservoir_Head,Wave_Speed,Gravity,Vinitial,Vinitial_1,Total_Simulation_Time,pi,Schmidt_Number,i_Time_Step_ADRE
common /flow / Piezometric_Head(1000),Velocity(1000),Discharge(1000)
! common /pipe / Pipe_Length,Pipe_Diameter,Pipe_Area
common /pipe /
Pipe_Length,Pipe_Diameter,Pipe_Area,Pipe_Length_1,Pipe_Diameter_1,Pipe_Area_1
common /fluid / Fluid_Density,Fluid_Viscosity
common /numerical / dt,dx,Courant_Number,Nx,Nt
common /nodes / x(1000)
common /valvedata /
Valve_State,Time_Start,Time_End,Steady_State_Discharge,Steady_State_Head
common /printdata / Critical_Length,Number_of_Section,Number_of_Section_New
common /constituent/
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Equilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
CHARACTER*3 Word

RADIUS=Pipe_Diameter/2.0

IF (Word.EQ. 'NEW') THEN
friction=Friction_Factor(Velocity(JJJ))
Diffusion_Coefficient=abs(10.1*RADIUS*Velocity(JJJ)*SQRT(friction/8.0))
ELSE
friction=Friction_Factor(Old_Velocity(JJJ))
Diffusion_Coefficient=abs(10.1*RADIUS*Old_Velocity(JJJ)*SQRT(friction/8.0))
END IF

RETURN
END

Darcy-Weisbach Friction Factor

function Friction_Factor(Velocity_Scale)
implicit double precision (a-h)
implicit double precision (o-z)
common / constants /
Upstream_Reservoir_Head,Downstream_Reservoir_Head,Wave_Speed,Gravity,Vi
nitial_1,Total_Simulation_Time,pi,Schmidt_Number,i_Time_Step_ADRE
common / flow / Piezometric_Head(1000),Velocity(1000),Discharge(1000)
common / pipe / Pipe_Length,Pipe_Diameter,Pipe_Area
common / fluid / Fluid_Density,Fluid_Viscosity
common / numerical / dt,dx,Courant_Number,Nx,Nt
common / nodes / x(1000)
common / valvedata /
Valve_State,Time_Start,Time_End,Steady_State_Discharge,Steady_State_Head
common / printdata / Critical_Length,Number_of_Section,Number_of_Section_New
common / constituent /
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Eq
uilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
common /flowold    / Old_Velocity(1000),Old_Discharge(1000)
common /timeseries / iix1, iix2, iix3,iix4,iix5
common /spatialdata /iit1,iit2,iit3,iit4,iit5,iit6,iit7,iit8,iit9,iit10

Reynolds_Number=abs(Velocity_Scale)*Pipe_Diameter/Fluid_Viscosity
Reynolds_Number_1=abs(Velocity_Scale)*Pipe_Diameter_1/Fluid_Viscosity

if (Reynolds_Number.eq.0.0) then
    Friction_Factor=0.0
else
    Friction_Factor=0.948/Reynolds_Number**0.25
end if

return

Function to Calculate the Decay Coefficient in the Source Terms
!
Function Decay_Coefficient(Nnc,Jx)
!
implicit double precision (a-h)
implicit double precision (o-z)
!
common /constituent/
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Eq
quilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
!
if (Nnc.eq.1) then
    Decay_Coefficient=-Reaction_Coefficient*Concentration(2,Jx)
else
    if (Nnc.eq.2) then
        Decay_Coefficient=4.0*Reaction_Coefficient*Concentration(1,Jx)
    else
        if (Nnc.eq.3) then
            Decay_Coefficient=0.0
        else
            end if
        end if
    end if
end if
!
return
Function to Calculate the Constant Coefficient in the Source Terms

Function Gama_Source_Term(Nnc,Jx)
!
implicit double precision (a-h)
implicit double precision (o-z)
!
common /constituent/
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Equilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
!
if (Nnc.eq.1.or.Nnc.eq.2) then
  Gama_Source_Term=0.0
else
  Gama_Source_Term=2.0*Reaction_Coefficient*Concentration(Nnc-1,Jx)*Concentration(Nnc-2,Jx)*Equilibrium_Concentration_For_Lead(Jx)
end if
!
return
end
!
Function to Calculate Lead Concentration at Equilibrium
!
Function Equilibrium_Concentration_For_Lead(JJx)
!
implicit double precision (a-h)
implicit double precision (o-z)
!
common /constituent/
Concentration(3,1000),dtc,Cinitial(3),Equilibrium_Constant_1,Equilibrium_Constant_2,Equilibrium_Constant_3,Equilibrium_Constant_4,Reaction_Coefficient
!
Equilibrium_Constant=Equilibrium_Constant_1*Equilibrium_Constant_2*Equilibrium_Constant_3*Equilibrium_Constant_4
!
if (Concentration(2,JJx).gt.0.0) then
  Equilibrium_Concentration_For_Lead=sqrt(abs(Equilibrium_Constant*Concentration(1,JJx)/(Concentration(2,JJx)**4)))
else
end if
!
return
end
**INPUT FILE**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe length (m), Pipe dia Upper Part (m), Pipe Length (m), Pipe dia Lower Part (m)</td>
<td>240.0 1.200 160.0 1.000</td>
</tr>
<tr>
<td>Fluid density, Kinematic viscosity</td>
<td>998.2 0.000001007</td>
</tr>
<tr>
<td>U/S Head (m), D/S Head (m), Steady State Disch (l/s)</td>
<td>50.0 -50.0 1600.0</td>
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<tr>
<td>No. of section (Nx)</td>
<td>50</td>
</tr>
<tr>
<td>Wave speed (m/s)</td>
<td>1000.0</td>
</tr>
<tr>
<td>Courant No. = a*dt/dx</td>
<td>1.0</td>
</tr>
<tr>
<td>Simulation time</td>
<td>3600.0</td>
</tr>
<tr>
<td>Valve state, Time start, Time end</td>
<td>1.0 0.0 0.0</td>
</tr>
<tr>
<td>Characteristic length</td>
<td>500.0</td>
</tr>
<tr>
<td>Schmidt No., i_time_step_ADRE</td>
<td>1.0 60</td>
</tr>
<tr>
<td>Initial conc DO, pH, Metal Conc</td>
<td>5.0 7.0 0.0</td>
</tr>
<tr>
<td>Equilibrium Constant (=1.0e57) for Lead/Iron reaction, RRC (=10)</td>
<td>1.0e15 1.0e15 1.0e15 1.0e12 1.0e01</td>
</tr>
</tbody>
</table>

**Schmidt_Number,i_Time_Step_ADRE**

1.0 12

**Cinitial(1), Cinitial(2), Cinitial(3)**

5.0 7.0 0.0

**Reaction_Coefficient_1,Reaction_Coefficient_2,Reaction_Coefficient_3,Reaction_Coefficient_4,Solubility_Product_Constant**

1.0e25 1.0e25 1.0e21 1.0e21 1.0e-17