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APPLICATION OF PIV TECHNIQUE FOR THE INVESTIGATION OF FLOW FEATURES WITHIN METALLURGICAL VESSELS

by

WARREN JAMES ADOLPHE

A Thesis submitted in conformity with the requirements for the degree of Master of Applied Science in the University of Toronto

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A non-intrusive flow visualization technique, using particle image velocimetry (PIV) was developed to concurrently measure instantaneous velocity data for entire planes of flow within a water model. The apparatus constructed proved capable of measuring flow planes in variable orientations. This technique has proven suitable for measurements in shallow bath flows such as the bottom gas stirred Electric Arc Furnace (EAF). Three models were constructed for technique development and analysis, including one simplified bottom stirred EAF case. The data measured has been used to map both time average flow patterns and velocity distributions for different experimental conditions. Vorticity and mean square velocity fluctuations were calculated and plotted to determine the distribution of turbulent flow activity. The existing flow similarity theory was determined insufficient for the scaling of bottom stirred EAF parameters. The model and prototype systems operate within the same regimes allowing for qualitative comparisons of results.
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The evolution of electric arc furnace (EAF) melting technology has allowed modern day mini-mill steelmakers to expand capabilities and product ranges enabling them to compete with the integrated mills in the global market. The improvements in energy utilization has shifted the supply of many products traditionally produced by integrated mills to become the exclusive domain of the EAF based steelmakers. Over the past decade, development of the EAF has focussed upon increasing power input to achieve decreased tap to tap times. The net effect of this strategy is a decrease of the total energy input required to produce a heat of molten steel. The energy distribution for a typical modern AC EAF installation is provided in the Sankey diagram found in figure 1.1.

Figure 1.1: Sankey diagram of the energy distribution for a typical EAF installation
Electricity accounts for approximately 65% of the total energy input required to produce molten steel on a per tonne steel basis. Electrical power consumption in the EAF is a direct function of the power-on time required for scrap melting and bath superheating. Unfortunately, the electrical power input occurs within a localized area of the furnace central regions. Towards the end of a heat, the distribution of energy within the bath is primarily the result of convection due to thermal gradients with local areas being influenced by arc plasma jets, residual carbon boils and oxygen lances. Thus, conventional AC EAF scrap melting produces weak overall bath mixing especially in the regions furthest from the arc roots such as the tip regions adjacent to the tap hole. Consequently, significant temperature gradients from bath surface to interior have been reported [1-3].

Bottom gas stirring has been incorporated in several AC EAF installations to stir the otherwise stagnant steel bath. Stirring distributes the superheated steel from the furnace central regions to the bath outer regions resulting in minimized temperature and concentration gradients. The distribution of the energy also insures complete scrap melting for all regions of the furnace. The improved bath homogeneity results in increased reliability of the temperature and chemistry samples used to monitor heat progress. Thus, the operator can predict the end of a heat with greater accuracy. The net result is a decrease of the power-on time and consequently, decreased excess energy input to insure the target tap temperature is achieved. A summary of the typical benefits of bottom gas stirring reported in literature include [4-13]:

1) Yield increases of 0.5 – 1%
2) Typical tap to tap time decreases of 5 min.
3) Typical energy savings of 10 – 20 kWh/t
4) Reduction of electrode wear
5) Reduction of carbon boils and "cold" bottoms
6) Improved sulphur and phosphorous removal
7) Decreased dissolved nitrogen
8) Improved alloy recoveries
9) Cost saving of $0.95 – $2.30 per ton

Few attempts exist in the literature to model the flow phenomena occurring within the gas stirred EAF bath. The studies performed to date have analyzed only top pouring or simplified "thin slice" model geometries [14,15]. Furthermore, the flow patterns created within the bath remain unexamined to date. A literature survey shows that there is a corresponding lack of industrial data detailing measurements for the various flow regimes existing within the furnace. Consequently, a comparison between results obtained from numerical simulations with EAF operational data is difficult, at best. Measurement of the velocity profiles created within bottom gas stirred EAF bath can provide useful information regarding convective transport phenomena occurring during furnace operation. This information can also aid in the confirmation of the dominant mechanisms influencing scrap melting within the EAF.

Data for other metallurgical vessels, including the ladle and tundish, have been obtained using water models to simulate and study effects of different configurations. The flow patterns created by gas stirring in steel ladles have been thoroughly studied and are well documented and reviewed literature [16-27]. Much of the flow modeling work in literature is based upon the addition of dyes and particles to reveal short term flow patterns and residence time data. These approaches typically allow for only qualitative comparisons and produce little quantitative information regarding the flow structure. Quantitative data has been obtained for transfer operation flows using Laser Doppler Velocimetry (LDV)[28]. LDV measurements are performed point by point where each
measurement is taken sequentially in time. The underlying assumptions for this approach is that the flow for the system must be both regular and statistically stationary. These assumptions are most likely true in the ladle and BOF due to considerations of vessel symmetry and 1:1 aspect ratios. Unfortunately, the bottom gas stirred EAF bath exhibits a variable aspect ratio of 1:6 to 1:8 depending upon the furnace dimension considered. Furthermore, the incorporation of the EBT(Eccentric Bottom Tapping) results in a completely asymmetric system with respect to the bottom stirring configuration used. These issues are illustrated in figure 1.2.

Figure 1.2: Symmetry comparison of furnace hearths equipped with bottom gas stirring. a) top pouring geometry equipped with three (3) directional porosity Radex stirring elements exhibiting 120° symmetry; b) EBT furnace geometry equipped with TLS stirring system exhibiting no symmetry.

The furnace hearth on the left is the top-pouring geometry equipped with three (3) directional porosity stirring elements. This stirring element / geometry combination exhibits 120° symmetry within the vessel. The EBT furnace hearth on the right is equipped with a Thyssen Long Time Stirring (TLS) system incorporating four (4) stirring
elements. This stirring element / geometry combination exhibits no symmetry. Due to lack of data, absence of symmetry and variable vessel aspect ratio, no assumptions can be made regarding flows in bottom gas stirred EAF baths. This consideration necessitates the need to study a three dimensional model system. Observations of the flows produced in ad hoc models of the gas stirred EAF bath illustrate an irregular nature. Thus, to study the flows produced in bottom stirred EAF baths, it is necessary to concurrently measure and record data for large areas of the flow. Unfortunately, an extensive search of the modeling literature failed to produce an appropriate technique to achieve this goal.

The purpose of this thesis is to present a non-intrusive technique to visualize, record and measure the flow patterns produced by bottom gas injection stirring in the EAF shallow bath. This technique, in combination with the construction of an appropriate scale model can be used to create a database of the cause and effect relationships occurring in the steel bath due to bottom gas stirring. This data can then be used as the basis for the creation of a numerical model to simulate and analyze these flow processes. Following the simulations, the modeling technique can again be used to validate calculated results.

A systematic experimental technique has been developed for performing flow measurements in these complex shallow bath flow systems. As opposed to other techniques, such as LDV and hot wire anemometry (HWA) which measure velocities for single points, this technique permits the non-intrusive, simultaneous measurement of velocities for an entire plane within the bath. The basis of this technique is Particle Image Velocimetry (PIV) which has been traditionally used to measure flows in small systems. Typical systems analysed using PIV include pipe and duct flows operating in various flow regimes with typical dimensions of less than 150 mm [29,30]. This technique has been
adapted to quantify model systems with dimensions on the order of 1000mm. The necessary theory of PIV is reviewed in Section 1 of Chapter 2, concerning theoretical considerations.

To correlate lab data to a real furnace, a set of scaling criteria must be clearly defined. Discussed in Section 2 of Chapter 2 are the appropriate criteria that guide the construction of a laboratory scale, low temperature water model. It is shown that in a model system, not all physical processes can be scaled simultaneously and thus, some compromises were required.

Section 3 of Chapter 2 discusses the information that may be extracted regarding turbulence indicators from model flow measurements.

A detailed description of the equipment and settings used to perform the flow analyses is provided in Chapter 3. Also provided is the generic procedure used for all experiments performed.

The results of the experiments are presented and discussed in Chapter 4. The results are presented in two sections. Section 1 presents the two simplified model flow systems that were used to develop the experimental technique. The discussion of these results focuses upon technique considerations. Section 2 summarizes the results of measurements obtained in a simplified scale model of a bottom gas stirred EAF equipped with four (4) stirring elements. The results illustrate the ability of the technique to measure the flow differences exhibited in different furnace model regions and for different operational configurations. Factors contributing to the stirring in an EAF which were not simulated in this model include:

- Presence of unmelted scrap
- Carbon boils
• Arcs
• Slag door lance
• Slag Layer
• Temperature gradients

Trends from the simplified model analysis are noted.

Chapter 5 provides a list of conclusion for this work as well as recommendations for future work.
CHAPTER #2 – THEORETICAL CONSIDERATIONS

SECTION #1 - FLOW VISUALIZATION AND MEASUREMENT TECHNIQUE

2.1.0 – OVERVIEW

The environment within the EAF does not readily allow for the direct investigation of phenomena such as the flows created by bottom gas injection stirring. This problem has been previously resolved experimentally in other metallurgical vessels using low temperature scale models for flow visualization. In combination with the model, an appropriate flow visualization technique must be chosen which will allow for the extraction of the appropriate information with respect to the parameter of interest. Traditionally, streakline type flow visualization experiments have been performed yielding primarily qualitative data with respect to the flows produced with the particular system. This information is usually accompanied by residence or mixing time studies to provide the quantitative aspect of the flow. In the past, direct flow measurement required the insertion of a probe, such as a “hot wire” or pitot tube, into the flow to obtain point measurements. The development of non-intrusive techniques using particle tracer studies and LDV measurements increased the matrix of data extraction possibilities. Unfortunately, all of the above methods are deficient for the purposes of measuring the flows within the bottom gas stirred EAF bath for several reasons. These include:

1) Probes are intrusive to the flow
2) Streaklines only reveal short-term information
3) Dyes quickly obscure the flow.
4) Residence time diagrams yield little information regarding spatial flow structure.
5) LDV and particle tracers measure only discrete points within the flow.

The flows produced within the bottom gas stirred EAF bath are complex. To study flows of this nature, entire areas need to be simultaneously recorded and measured for a sufficient period of time. From this data, statistical values regarding the interactions occurring within the flow itself can be determined. Advances in LDV technology have allowed for the development of multi-point LDV which can probe as many as six points simultaneously. However, the maximum number of simultaneous points measured by this technique is limited due to bandwidth requirements. Furthermore, the measurement of entire flow fields is limited to steady systems. This is due to the time required to obtain a sufficient number of measurements for a given point. As the flow becomes increasingly random in nature, individual time-dependent LDV measurements become essentially meaningless for quantifying the flow structure. In the EAF, the production of turbulent flow, using bottom gas stirring, is a desirable goal as turbulence can be used to improve heat and mass transfer rates. These irregular flows have been one of the limiting factors in performing quantitative analyses within the EAF shallow bath.

In the past 10 – 15 years, the “new” technique of Particle Image Velocimetry has been developed to allow for the simultaneous measurement of entire areas within a flow. The theory for the PIV technique is currently well developed and understood. The relevant background for the PIV technique is presented in the following sections. The necessary considerations required for the adaptation of PIV to studying the bottom gas stirred EAF are also discussed.
2.1.1 – PARTICLE IMAGE VELOCIMETRY

The general steps for PIV experiments include:

1) Particulate matter is added to the flow system of interest.

2) The particles are illuminated in a plane using a sheet of coherent (laser) light.

3) The light scattered by the particles is recorded to a single or multiple set of frames using film or CCD camera.

4) The displacement for the flow is determined through the evaluation of the recorded images.

Figure 2.1.1.1 provides an illustration of a generic setup illustrating the general steps in the PIV procedure.

This approach to flow measurement requires the following considerations [33-37]:

Figure 2.1.1.1: Schematic diagram of a generic PIV arrangement.[32]
1) **Non-intrusive velocity measurement** – Velocities are obtained using an optical method without the use of probes that disturb the flow.

2) **Indirect velocity measurement** – The velocity of a fluid element is determined by measuring the velocity of fluid tracer particles that have been added to the flow.

3) **Whole field measurement** - Large areas of a flow field are recorded and measured simultaneously.

4) **Velocity Lag** – The assumption is that the particles move intimately with the flow. This assumption should be verified for each system. (Smaller particle are more reliable than larger particles)

5) **Illumination** – A high intensity light source is required to insure that the scattered light from the particles is sufficient to expose or excite the recording medium. (Larger particles scatter light more efficiently than smaller particles)

6) **Pulse width** – Duration of illumination must be short enough such that the images of the particle recorded appear “frozen” in time.

7) **Pulse time delay** – The time between light pulses or frames must be sufficiently long to allow for displacement determination. This time must also be short enough such that the out-of-plane component of velocity does not remove the particle image for the plane of interest.

8) **Tracer particle distribution** – The distribution of the trace particles must be essentially uniform for all areas of the flow to produce reliable results. As opposed to streakline techniques, flow structures are not visible in single PIV images.

9) **Particle density** – An appropriate quantity of particulate must be added to the flow to allow for the application of standard statistical PIV techniques. This is best illustrated in Figures 2.1.2a-c. PIV requires the level illustrated in b.
10) **Number of Illuminations per recording** – For pulsed techniques utilizing film, the number of images stored per frame must be determined. Direct digital usually record one image per frame.

11) **Number of components in the velocity vector** – Due to the planar illumination, only two components of the velocity may be determined. PIV methods do exist to resolve 3-D flows. This thesis is only interested in 2-D PIV.

12) **Extension of time** – Time period required for the recording of sufficient data for a given flow. Equipment limitations may come into effect.

13) **Size of interrogation window** – The sub-sample of the image to be interrogated (interrogation window size) must be sufficiently small such that velocity gradients do not have a significant effect upon the obtained result. This dimension also determines the maximum spatial resolution of velocity vector for a measurement.

### 2.1.2 – **Double Frame / Single Exposure PIV**

Different modes of PIV evaluation exist in literature with many attributing their roots to the examination of digitized photographic images. The recent improvement of CCD cameras and PC frame grabbers make the “direct” digital approach of DPIV (Digital Particle Image Velocimetry) both feasible and attractive. The scheme for the “double frame / single exposure” approach is given in figure 2.1.2.1. [38]
This approach is based upon obtaining two subsequent frames separated by a known period of time. Each frame contains a single image of each particle "frozen" in its respective position within the flow at the particular instant the image was "grabbed". Images 1 and 2 are "grabbed" at times \( t \) and \( t+\Delta t \) respectively, where \( \Delta t \) is precisely known. Calculation of the "straight-line" displacement of the two images, ignoring lag effects, is accomplished using the following procedure:

1) Image sub-sampling in to a regular grid of 32 x 32 pixel interrogation windows.

2) Both input data matrices, for a pair of corresponding interrogation windows are transformed from the spatial domain to the frequency domain using the Fast Fourier Transform (FFT). (This step converts integer 256 gray scale pixel values to the corresponding complex number values in the Fourier domain.)

3) The cross correlation value matrix is calculated in the frequency domain.

4) The resultant matrix values in step 3 are transformed back to the spatial domain using the inverse Fast Fourier Transform (FFT\(^{-1}\)).

5) Of the resultant values, one is a maximum. The distance in pixels for the origin (lower left corner of position \((1,1)\)) to the maximum is equal the net displacement of that 32 x 32 pixel element of the flow image.
The net displacement is determined statistically in step 3 by calculating the “degree of best match” between the two interrogation windows. This can be evaluated by the calculation of the discrete cross correlation function of two data sets.[38-40] This is expressed as:

\[ R_{II}(x, y) = \sum_{i=-K}^{K} \sum_{j=-L}^{L} I(i,j)I'(i + x, j + y) \]  \hspace{1cm} (2.1.1)

where:
- \( R_{II} \) Cross correlation value for a displacement of \((x,y)\)
- \( I \) Intensity for a pixel at point \((i,j)\)
- \( I' \) Intensity at pixel \((i+x,j+y)\)

The equivalent value may be determined in the frequency domain by taking advantage of the correlation theorem which states that the cross correlation of two functions is equivalent to the point by point complex conjugate multiplication of their Fourier transforms.[41,42] This is expressed by:

\[ R_{II} \leftrightarrow \hat{I} \cdot \hat{I}^{*} \]  \hspace{1cm} (2.1.2)

Where:
- \( R_{II} \) = Cross correlation function
- \( \hat{I} \) = Fourier transform value of the function \( I \)
- \( \hat{I}^{*} \) = Complex conjugate of the Fourier transform value of the function \( I' \)

Use of the correlation theorem allows for a reduction of computational time. The implementation of the FFT algorithm reduces the number of operations from \( O[N^4] \) to \( O[N^2 \log N] \).[41] This advantage in computational efficiency requires that the following issues are noted.

1) **Fixed sampling dimensions** – The FFT is a computationally efficient execution of the Discrete Fourier Transform (DFT). The efficiency of the FFT
accomplished by recursive implementation of a symmetrical property between even and odd coefficients of the DFT. The implementation of the FFT requires that the input data have a base-2 dimension due to the recursive nature (i.e. 16 x 16 pixels, 32 x 32 pixels etc.)

2) Periodicity of Data – The Fourier transform is an integral over the period of \(-\infty\) to \(+\infty\), (or sum for the DFT). In this implementation, the integral domain is finite. This evaluation over the finite domain is justified by the periodic assumption of the transformed integral (or sum). Thus, the interval summed is equivalent to one complete period.

3) Output Aliasing – The assumption of the input sets to the FFT-based correlation being periodic results in the correlation data also being periodic. If data of length \(N\) exhibits a displacement exceeding \(N/2\), then the correlation peak will be folded back into the correlation plane and appear on the opposite side. (i.e. a displacement of \(d_{x,true} > N/2\), the measured value will be \(d_{measured} = d_{x,true} - N\))

4) Bias Error – Increased displacements result in less data being correlated. This is due to the periodically continued data of the correlation template not contributing to the actual correlation value. Values on the edge of the correlation plane are computed only from the overlapping half and should be weighted accordingly. By not weighting the overlapping data accordingly results in the displacement value being biased to a lower value.

2.1.3 – Error Sources in PIV

The accuracy of the measured displacements is dependant upon many factors ranging from the recording process to the method of evaluation.[43] The total error in any measurement can be decomposed into systematic and residual components. The systematic errors arise from the inadequacies of the statistical method of cross correlation. Examples of this occur in the case of sub-pixel peak estimation or the presence of velocity gradients. These errors tend to follow a recognizable trends, making them predictable and consequently reducible. The residual error is the error that remains even when the systematic error has been removed from the system. This separation of systematic and residual errors is not always possible and thus, the errors have been
redefined as the sum of bias error (degree of over/under estimation) and rms measurement uncertainty error. This is expressed as:

\[ E_{tot} = E_{bias} + E_{rms} \]  \hspace{1cm} (2.1.3)

where:
- \( E_{tot} \) = Total error
- \( E_{bias} \) = Bias error
- \( E_{rms} \) = Measurement error

Determination of the relative contribution of the different error sources has been performed using a Monte Carlo simulation with synthetically produced images to test the PIV analysis routines. The simulation variables included many factors including particle shape, size, image density, dynamic range and image depth [44]. The errors determined are not a direct evaluation of the accuracy of any give PIV measurement. The results of these simulations allow for the general assessment of the error contained within the measured displacement values due to different PIV system parameters. Summarized, are the errors directly relating different aspects of the "single exposure / double frame" PIV technique using 32 x 32 pixel interrogation windows.

**Particle image diameter** – Using 32 x 32 pixel interrogation windows, a particle image diameter of approximately 2 pixels results in the minimum rms. and displacement bias errors.

**Particle image shift** – The rms. error associated with the 2 pixel particle diameter is approximately 0.01 pixels for measured displacements up to 10 pixels. For larger particle image diameters (i.e. 4 pixels) the error increases by 4 to 7 times of the 2 pixel particle
image diameter error. The associated bias error is constant between 0.01 and 0.02 pixels for 2 and 4 pixel image diameters.

**Particle image density** – This factor is influenced by the degree of in-plane (motion within the illuminated plane of interest) and out-of-plane motion (through the plane of interest). Simulations indicate that assuming zero in-plane loss of pairs and zero out-of-plane loss of pairs, a minimum of 8 particle image pairs are required for a particular interrogation window to assure 95% probability of correct detection.

**Quantization levels** – The rms. error is less than 0.025 pixels by using 8 bits/pixel for data storage.

**Background noise** - The addition of up to 50% background noise to the pixel images results in a maximum rms. error of 0.1 pixels for displacements up to 1.2 pixels.

### 2.1.4 – Equipment Selection Considerations

**Particle Velocity Error**

The indirect velocity measurement requires that the discrepancies between fluid velocity and particle velocity be determined. The ideal particle for fluid flow measurements is spherical in shape with neutral buoyancy with a surface capable of light scattering. The primary source of motion error is the force of gravity acting upon the particulate within the flow. The effects of buoyancy differences between particulate and fluid can be evaluated. Assuming spherical particles, the response relationship for a particle is given by [45]:

17
where:

\[ U_p(t) = U \left[ 1 - \exp \left( -\frac{t}{\tau_s} \right) \right] \]  \hspace{1cm} (2.1.4)

where:

\[ \tau_s = \frac{d_p^2 \rho_p}{18 \mu} \]  \hspace{1cm} (2.1.4a)

where:  
\( U_p \) = particle velocity  
\( U \) = fluid velocity  
\( T \) = time  
\( \tau_s \) = relaxation time  
\( d_p \) = particle diameter  
\( \mu \) = dynamic viscosity  
\( \rho_p \) = particle density

Equation (2.1.4) was derived using Stokes drag law for spherical particles under the influence of a uniform acceleration at low Reynolds numbers. This equation does not apply for motion with non-uniform acceleration or high Reynolds numbers since the equations of particle motion become much more complex. The relaxation time expression, \( \tau_s \), is maintained as the relative measure of the particles tendency to achieve velocity equilibrium with the flow.

**Laser selection**

The availability of Helium – Neon (He – Ne) lasers for wavelengths other than the red (632 nm) has made them a practical choice for the illumination flow. The availability of green wavelength (532 nm) with powers in the 30 mW range make He-Ne lasers suitable for the illumination of the flow. Other laser types traditionally used include, Nd:Yag lasers chosen for the high pulse intensity and argon ion lasers for the quality of the beam profile. The major consideration for the choice of laser colour relates to the CCD response curve for monochromatic wavelengths. The CCD used to record the flow in the experimental section of this thesis exhibits maximum response to the green wavelengths. The cost
effectiveness, simplicity and portability of He-Ne laser types, make them a reasonable choice for an illumination source.

\textit{Light sheet generation optics}

Traditionally, the laser beam is spread using a series of cylindrical lenses to produce a sheet of light. A schematic of a typical lens setup is found in figure 2.1.4.2.

The drawbacks of this type of setup are:

1) \textbf{Prohibitive Cost} – High quality cylindrical lenses are required for precision light sheet generation.

2) \textbf{Intensity loss} - \~4% per lens of the intensity is lost due to reflections if uncoated.

3) \textbf{Set up precision} – This equipment requires precise setup and alignment to produce the desired effect.

4) \textbf{Limitation in field of view} – Different lens combination are required for the generation different width light sheets within a desired range form the subject.

5) \textbf{Beam intensity profile} – Most lasers do not emit beams with a uniform intensity profile. Optics are required for the elimination of focal lines in the beam intensity for high power pulse lasers (Nd:Yag).
The one major benefit of this system is the control of beam divergence with respect to the thickness of the light sheet generated.

A second method to produce a sheet of light uses a multifaceted rotating polygon mirror and parabolic mirror [47]. This setup is found in figure 2.1.4.3.

![Figure 2.1.4.3: Light sheet generation apparatus utilizing a rotating polygon mirror. [47]](image)

The benefit of this system over the lens system is a larger field of view produced at short range from the subject and hence, the ability to interrogate larger flow systems. In addition, the quality of the light sheet is no longer dependant upon the laser beam intensity profile. A gaussian intensity distribution profile once spread using a set of lenses yields a reduced effective area for interrogation. In the scanning case, the entire concentrated beam is unidirectionally scanned across the field of view at a high rate. The result is a uniform intensity for all areas scanned. Drawbacks to this method include:

1) "Freezing" particles in space for single exposure PIV requires that the scan rate and the camera shutter be tuned to equal values to prevent the occurrence of a "beat " frequency resulting in unevenly or incompletely illuminated images.
Since cameras do not offer continuously variable shutter speeds, a variable speed motor is required to spin the mirror. (~$15K per set)

2) Different field widths require different polygon mirrors. These mirror/motor combinations are precision balanced which require special skill and equipment to manufacture and assemble. Thus, each setup could require the purchase of a new light sheet generation apparatus.

3) A columniation optic is required to control light sheet width.

4) Prohibitive cost due to considerations 1-3.

The ability to interrogate larger fields has been a limitation of PIV. The ability to overcome the field of view with uniform light sheet characteristics is an attractive asset to this study.

An alternative but analogous method to the rotating polygon was adopted. The apparatus used was a variable angle (up to ±38° optical deflection), variable cycle (0 – 300 Hz.) oscillating mirror/galvanometer system. This equipment produced the same light sheet characteristics as the rotating mirror with an added degree of control. The control was provided using a low cost function generator that supplied the drive electronics. The function generator allowed for the precise tuning of the light sheet sweep with the shutter speed of the CCD camera. The drawback to this system was that optics may be required to control the light sheet thickness depending upon the laser type used. As long as the subject model can be interrogated in the laser mid-field distance of 2 – 10 meters from the laser exit mirror, the beam divergence of the He - Ne does not exhibit a significant effect. Again, the cost effectiveness of the apparatus was the decisive factor.

*Consumer grade video equipment*

The use of consumer video equipment places a technical limitation on the dynamic range of flow analyses. The National Television Standards Committee (NTSC) RS-170
black and white camera format sets the frame rate for the CCD camera to 30 fps. (frames per second) of 525 x 484 pixels. The CCD array dimensions allow for a resolution of 16 x 15 vectors, using 32 x32 interrogation windows, (240 vectors) without interrogation window shifting (over sampling). This upper limit of the possible frame rate and resolution must be considered when choosing field of view and magnification for the flow analyses. Other CCD types are available which can provide increased resolution, however, these will not be covered here. Interested readers are referred to the book listed in reference 44.
CHAPTER 2 – THEORETICAL CONSIDERATIONS

SECTION 2- DESCRIPTION OF MODEL SCALING CRITERIA

2.2.0 - OVERVIEW

Studying the effects of bottom gas injection in the EAF requires the consideration of several characteristic parameters to describe the various regions of the system. To correlate experimental data to phenomena in the full scale furnace system, a set of scaling criteria must be clearly defined. Since it is impossible to simultaneously match all scaling parameters between model and prototype systems, the parameters of prime importance must be identified.

Previous publications have not been explicit regarding the proportioning of scaling criteria. Consequently, choices for scaling criteria for the furnace model are based upon the following considerations.

2.2.1 – SIMILITUDE

Similarity between model and prototype systems is dependent upon matching the criteria for the different system properties including [48]:

1) Geometric Similarity  -  Similarity of shape.
   - The ratio of any length in one system must correspond to the length in the other system.
   - This ratio is termed the scale factor

2) Kinematic Similarity  -  Similarity of motion.
   - The velocities at corresponding locations are in the same fixed ratio. (For geometrically similar models.)
   - Streamlines in one system are geometrically similar to the other.

3) Dynamic Similarity    -  Similarity of Forces
- The magnitude of the forces at corresponding locations is in a fixed ratio.

4) **Thermal Similarity** - Various mechanisms of heat transfer such as conduction, convection and radiation must be a fixed ratio for the model and prototype systems.

5) **Chemical Similarity** - Rates of chemical reactions at any location is proportional to the rate of the same reaction at the corresponding time and location for the two systems.

In this first study of EAF shallow baths the main goal is the measurement technique development and not precise modeling of the EAF bath conditions. Therefore, several simplifications have been. The factors not considered for modeling include:

- Presence of unmelted scrap
- Slag door lance
- Arches
- Slag Layer
- Carbon boils
- Temperature gradients

These simplifications allow for the thermal and chemical aspects of similarity to be neglected in this study. The model produced represents an isothermal condition of the bottom gas stirring elements operating in isolation of other factors that influence bath flow.

**2.2.2 - Geometric Similarity Criteria**

Three geometric factors were considered:

1) Bath Depth
2) Furnace diameter (and length)
3) Stirring element dimensions

Geometric similarity for all dimensions was maintained between the model and full scale systems where:
\[ \lambda = \frac{D_{f.s.}}{D_m} = \frac{H_{f.s.}}{H_m} = \frac{(di)_{f.s.}}{(di)_m} \]  

(2.2.1)

where:  
\( \lambda \) = Scale factor  
\( D_{f.s.} \) = Furnace diameter - full scale  
\( D_m \) = Furnace diameter - model  
\( H_{f.s.} \) = Bath depth - full scale  
\( H_m \) = Bath depth - model  
\( (di)_{f.s.} \) = Injector diameter - full scale  
\( (di)_m \) = Injector Diameter - model

A preexisting modeling form was modified to reproduce the scale dimensions of the new furnace. The resultant scale factor was calculated to be 1/8.78. This is referred in the discussions as the approximate 1/9 scale model.

2.2.3 - Dynamic Similarity Criteria

To ensure that both model and full scale furnace systems operate within the same regime, the parameters describing the local areas immediately adjacent to the stirring element positions and central plume regions of the bath must be evaluated. Parameters defining the conditions for the entire bath, or global system, must also be evaluated.

In considering the simplified system, the principal forces of interest are inertia, viscosity, buoyancy. Based upon measurements of density and viscosity, similarity exists between the kinematic viscosities of liquid steel and water (\( \nu_{\text{water}} = 1 \times 10^{-9} \text{ m}^2/\text{s} \); \( \nu_{\text{water}} = 0.913 \times 10^{-9} \text{ m}^2/\text{s} \).[49,50] This allows for the study of flow patterns within the EAF using a low temperature laboratory scale model.
Table 2.2.3.1: Physical properties of water at 20 °C and molten steel at 1600 °C

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Water (@ 20 °C)</th>
<th>Molten Steel (@ 1600 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Viscosity</td>
<td>( \mu )</td>
<td>0.001 Ns/m²</td>
<td>0.0064 Ns/m²</td>
</tr>
<tr>
<td>Density</td>
<td>( \rho )</td>
<td>1000 kg/m³</td>
<td>7.014 kg/m³</td>
</tr>
<tr>
<td>Kinematic Viscosity</td>
<td>( \nu )</td>
<td>1x10⁻³ m²/s</td>
<td>0.913 x10⁻⁹ m²/s</td>
</tr>
</tbody>
</table>

2.2.3.1 - LOCAL SIMILARITY CRITERIA

Many researchers have considered the modified Froude number, \( F_{rm} \), as the most important criterion to maintain hydrodynamic similarity between model and prototype flow systems. \([16-18,25-27]\) This quantity is expressed by:

\[
F_{rm} = \frac{\rho_G U_G^2}{(\rho_L - \rho_G) g H} = \frac{\rho_G U_G^2}{\rho_L g H} = \frac{[\text{Kinetic energy of injected gas}]}{[\text{Potential energy of gas bubbles}]} \quad (2.2.2)
\]

where:
- \( F_{rm} \) = Modified Froude number
- \( \rho_G \) = Gas density (kg/m³)
- \( \rho_L \) = Liquid density (kg/m³)
- \( g \) = Gravity constant (m/s²)
- \( H \) = Bath depth (m)
- \( Q \) = Gas injection flow rate (Nm³/s)
- \( U_G \) = Velocity of injected gas (m/s)

Equation (2.2.2) expresses the ratio of the kinetic energy of the stirring gas at the point of entrance to the furnace bath to the potential energy of a gas bubble at the injector opening at the bottom of the furnace. This value defines the dominant mechanism of stirring energy transfer to the bath. Consequently, \( F_{rm} \) is regarded as the primary scaling criterion for this hydrodynamic system, where:

\[
(F_{rm})_{\text{Full Scale}} = (F_{rm})_{\text{model}} \quad (2.2.3)
\]
This similarity has been previously accepted for scaling other metallurgical process vessels such as the ladle, BOF and the older top pouring EAF geometry.[14,16,19,24] The previously mentioned vessels are all characterized by relatively simple geometries and consistent aspect ratios. Unfortunately, the EBT EAF geometry is more complex. More than one characteristic dimension is required to describe the egg shaped bath. The literature does not provide for any example of Fr_m similarity holding for variable aspect ratio flow systems. The modified Froude number similarity may be considered only to characterize the areas adjacent to the plumes in the bath central region. Unfortunately, a better criterion has not emerged for the EAF as a whole, and thus it shall be maintained as primary similarity criterion for this study.

The modified Froude number can be expressed alternatively [16] as:

\[
Fr_m = c \frac{Q^2}{H d_i^5}
\]

where:

\[
c = \frac{16}{\pi^2 g \rho_l \rho_{Gi}} \left( \frac{M}{V_{STP}^M} \right)^2 \approx 3.3 \times 10^{-4} \frac{M^2}{\rho_l \rho_{Gi}}
\]

where:

- \( Fr_m \) = Modified Froude number
- \( \rho_g \) = Gas density (kg/m³)
- \( \rho_l \) = Liquid density (kg/m³)
- \( g \) = Gravity constant (m/s²)
- \( Q \) = Gas injection flow rate (Nm³/s)
- \( d_i \) = Injector diameter (m)
- \( H \) = Bath depth (m)
- \( V_{STP}^M \) = 22.4 (L/mol)
- \( M \) = Molecular weight (kg/mol)

Magnitudes of the constant, \( c \), for the model \( (c_m) \) and furnace \( (c_{f,s}) \) can be calculated using the respective system properties defined in Table A1 of Appendix A. If equation
(2.2.4) is combined with equation (2.2.3), the relationship for scaling the gas injection flow rates between model and full scale system results [16]:

\[ Q_m = \frac{Q_{f.s.}}{k \lambda^{3/2}} \]  

(2.2.6)

where:
\[ k = \left( \frac{c_m}{c_{f.s.}} \right)^{1/2} \]  

(2.2.6a)

where:  
- \( \lambda \) = Scale factor
- \( Q_{f.s.} \) = Stirring gas flow rate - full scale
- \( Q_M \) = Stirring gas flow rate - model
- \( c_{f.s.} \) = Modified Froude number constant - full scale
- \( c_m \) = Modified Froude number constant - model
- \( k \) = Proportionality factor

For the present system, \( k = 1.084 \). This value compares to previously published values with less than 5% difference [16]. The experimental gas flow rate calculated, using equation (2.3.5), was determined to be \( 4.39 \times 10^{-3} \) L/s.

The density ratio between gas and liquid is also an important consideration, because of the effects of the bubbles upon surface flow [26]. A dimensionless parameter, \( \Pi_p \), is used to describe this effect:

\[ \Pi_p = \frac{\rho_{gi}}{\rho_L} = \frac{Injection \ gas \ density}{Liquid \ density} \]  

(2.2.7)

where:  
- \( \Pi_p \) = Density ratio
- \( \rho_{gi} \) = Gas density (kg/m\(^3\))
- \( \rho_L \) = Liquid density (kg/m\(^3\))

The stirring gas used for the flow visualization experiments was compressed air. The density ratio values found in table 2.3.2 for the steel/argon and water/air systems show a
difference by two orders of magnitude between the calculated values. Both values are, however, significantly smaller than one. A consideration for future work is the replacement of air with helium as the stirring gas. This substitution would decrease density ratio differences to one order of magnitude.

Matching both $\lambda$ and $Fr_m$ does not necessarily insure hydrodynamic similarity between the model and prototype systems. Dynamic similarity in scaling must be evaluated by determining the local Reynolds number values for the stirring gas at the point of entrance to the bath in both the model and furnace systems.[51] The required Reynolds similarity is stated as:

$$\left(Re_{di}^G\right)_m = \left(Re_{di}^G\right)_{fs}$$  \hspace{2cm} (2.2.8)

where:

$$Re = \frac{\rho LU}{\mu} = \frac{LU}{\nu} = \frac{[\text{Kinetic energy of the plume}]}{[\text{Viscous dissipation within the bath}]}$$  \hspace{2cm} (2.2.9)

where:

- $(Re_{di}^G)_{fs} = \text{Local Reynolds number for gas injector - full scale}$
- $(Re_{di}^G)_m = \text{Local Reynolds number for gas injector - model}$
- $\rho = \text{Gas density (kg/m}^3\)$
- $L = \text{Bath depth (m)}$
- $U_G = \text{Velocity in injected gas (m/s)}$
- $\mu = \text{Dynamic viscosity of gas (kg/ms)}$
- $U_P = \text{Plume velocity (m/s)}$

The literature for gas stirring was again deficient with regard to the scaling of the stirring elements. The systems handled to date were tuyere type systems with a single orifice. Literature for porous plug systems used scale models that approximated the porous plug with a single orifice. The geometry of the stirring elements for this model was sufficiently large as not to allow this type of approach. Since it was not clear how the gas entered the
bath through the porous refractory examination of this case was performed for three scenarios with respect to stirring element operation. These are illustrated in figure 2.2.3.1.

1) Option 1 - the entire area of the stirring element as scaled directly for the set of furnace dimensions supplied.

2) Option 2 - the effective area of the stirring element was reduced to a ring corresponding to the dimension of the gas diffuser apparatus.

3) Option 3 - the effective area was reduced further to the sum of the orifice areas in the diffuser plate.

![Figure 2.2.3.1: Schematic representations of the three stirring element scaling options.](image)

The above Reynolds numbers were evaluated for the system parameters listed in table 2.2.3.2. The local Reynolds number evaluated for the value for all cases was less than the critical value, \( \text{Re} \geq 2100 \), defined in reference [52] characterizing the operation of the model injector region in the laminar bubbling regime. Thus the flow regimes of the full scale and model systems represent the same operating regime. However, the Reynolds values determined for each model/prototype pair are not equal. In all cases, the Reynolds values differ by one order of magnitude. Therefore, the model and prototype stirring elements are not dynamically similar using the strict definition. Since hydrodynamic
similarity is not maintained for the stirring element regions, the flows exhibited in the scale model do not reproduce the flows that occur within the furnace and no direct correlation or scaling of the results can be performed. This problem can possibly be eliminated by the varying the stirring element dimensions in the experimental equipment. A sacrifice of the geometric similarity criterion for the stirring element dimensions may be required to preserve Reynolds similarity for flow system. Thus, for this case the geometric criterion, equation (2.2.1) would be amended to account only for the furnace dimensions and ignore the stirring element dimension dependence:

Table 2.2.3.2: List of dimensionless groupings for the injector and plume region for the full scale and model for all three stirring element operational options.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value (Full Scale)</th>
<th>Value (Model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified Froude Number</td>
<td>[ F_{m}^{r} = \frac{\rho_{g} U_{g}^{2}}{(\rho_{g} - \rho_{L}) g L} = \frac{\rho_{g} U_{g}^{2}}{\rho_{L} g L} = \frac{c Q^2}{H d_l^2} ]</td>
<td>2.4 \times 10^{-7}</td>
<td>2.4 \times 10^{-7}</td>
</tr>
<tr>
<td>Local Reynolds Number (Gas Injector)</td>
<td>[ Re_a^{Q} = \frac{\rho L U}{\mu} = \frac{LU}{\nu} = \frac{4 M Q}{\pi 22.4 \mu_{g} d_i} ]</td>
<td>23.2</td>
<td>3.7</td>
</tr>
<tr>
<td>Density ratio (Gas/Liquid)</td>
<td>[ \Pi_{\rho} = \frac{\rho_{Gi}}{\rho_{L}} ]</td>
<td>6.12 \times 10^{-5}</td>
<td>1.15 \times 10^{-3}</td>
</tr>
</tbody>
</table>

As stated previously, the modeling of flow is not the primary objective of this thesis. Consequently, the differences of the flows exhibited are neglected. In future studies, the problems in scaling will need to be corrected prior to obtaining accurate modeling results for the flows within bottom gas stirred EAF.
2.2.3.2 - Global Similarity Criteria

The global dimensionless parameters for the two systems are summarized in Table 2.2.3.3. These parameters include the global Reynolds numbers for the bath and stirring energy ratio, \( \Pi_c \). These values complete the list of parameters considered for model scaling.

Table 2.2.3.3: List of dimensionless groupings for the full scale and model systems for all the stirring element operational options.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value (Full Scale)</th>
<th>Value (Model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Reynolds Number (Bath)</td>
<td>( \text{Re}_B^L = \frac{\rho_L L U_p}{\mu_L} )</td>
<td>8.23 x 10^5</td>
<td>1.1 x 10^4</td>
</tr>
<tr>
<td>Stirring Energy Ratio</td>
<td>( \Pi_c = \frac{\dot{e}<em>{km}}{\dot{e}</em>{pm}} = \frac{1}{4} Fr_m \Phi(\Pi'_p), \Pi'_p = \frac{\rho_p g H}{P_H} )</td>
<td>4.6 x 10^-3</td>
<td>6.0 x 10^-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.0 x 10^-3</td>
<td>5.23 x 10^-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.53</td>
<td>0.68</td>
</tr>
</tbody>
</table>

The global Reynolds numbers, \( \text{Re}_B^L \), classify both model and full scale systems within the turbulent flow regimes for the global bath, however, the values differ significantly in value.

This again illustrates that dynamic similarity is not preserved.

The stirring energy parameter, \( \Pi_c \), expresses the ratio of kinetic and potential stirring power terms for the particular conditions.[53] The equation for \( \Pi_c \) is:

\[
\Pi_c = \frac{\dot{e}_{km}}{\dot{e}_{pm}} = \frac{1}{4} Fr_m \Phi(\Pi'_p)
\]

(2.2.10a)

where:

\[
\Phi(\Pi'_p) = \frac{\Pi'_p}{(1 + \Pi'_p) \ln(1 + \Pi'_p)}
\]

(2.2.10b)

where:

- \( Fr_m \) = Modified Froude number
- \( \Pi_c \) = Stirring energy ratio
- \( \Pi'_p \) = Hydrostatic pressure ratio
- \( \dot{e}_{pm} \) = "Kinetic" portion of stirring power (W/kg)
- \( \dot{e}_{km} \) = "Potential" portion of stirring power (W/kg)
For typical EAF operation, this equation simplifies to a dependence upon $F_{rm}$ alone [54]:

$$\Pi_\varepsilon = \frac{1}{4} F_{rm} \quad (2.2.11)$$

The values for $\Pi_\varepsilon$, in Table 2.3.3, show that the kinetic energy introduced by the gas injection velocity is negligible in comparison to the buoyancy energy of the gas bubbles in both systems and for all operational cases considered. The controlling mechanism for both the model and prototype case is similar.

### 2.2.4 – Summary

The literature is both deficient and unclear with respect to the proper criteria used to guide the scaling of the bottom gas stirred EBT EAF bath system. Unfortunately, a better set of criteria to govern more complex flow systems such as the bottom gas stirred EAF bath does not exist in the literature. Therefore, the existing theory has been applied and evaluated for this simplified system. The result is that no direct correlation of experimental measurements to the industrial furnace system is possible due to dynamic similarity not being preserved in both local and global system values. If precise modeling is the goal for future studies, a complete reexamination of the of the similitude theory as applied to the bottom stirred EBT EAF shallow bath is required. Although, exact scale similarity was not achieved, the values calculated for all global and local similarity parameters do illustrate that the model and prototype systems are operating within the same regimes. Thus, qualitative data regarding patterns and distributions can be determined from a model as such, however, the results should be reviewed with the appropriate skepticism.
CHAPTER #2 – THEORETICAL CONSIDERATIONS

SECTION #3 - ASPECTS OF TURBULENCE

2.3.0 - OVERVIEW

The creation and control of turbulent flow conditions within a process vessel can result in beneficial enhancements such as improved heat and mass transfer rates. In the case of EAF steelmaking, the benefits would be improved thermal and chemical bath homogeneity with the extra benefit of decreased energy and materials consumption. These effects are the result of the convection patterns produced by the bubbling of stirring gas through the bottom of the furnace and their interactions with furnace geometry. Information detailing the structure of these flow effects would be informative for the design and configuration of these systems.

This section examines some of the relevant equations of turbulence theory. These equations will illustrate the values that can be extracted from velocity measurements that can provide information regarding the distribution and type of flow within various regions of a model bath system.

To determine the time average flow pattern requires the measurement and storage of velocity data for a sufficient density of points over an appropriate length of time. The task of performing these measurements in turbulent or unsteady flow systems requires the resolution of several issues. The first issue is the determination of a sufficient spatial resolution of measurement points. Observations of flows in a model EAF demonstrates that all points within the flow system are interdependent. The appearance of an observed flow feature is the
result of the interactions of surrounding flow structures that are in existence at that time. Furthermore, the problem of obtaining sufficient resolution is compounded by the requirement that the measurements are to be performed concurrently. In this thesis, the simultaneous measurements for the entire flow field have been accomplished using Particle Image Velocimetry (PIV). The second issue was the time scale for which a sufficient number of measurements are recorded to provide representative output of the flow conditions. The empirical solution of this problem was handled on a case by case basis. The final issue requiring attention was that of extracting useful information from the recorded data and its possible interpretation in terms of system effects. This is the focus of this section.

2.3.1 – STATISTICS OF TURBULENCE

Instantaneous measurements for velocity can be represented as in equation (2.3.1), by a time average term plus a time varying term, where average of the time varying component trends to a value of zero.[55] This is illustrated in figure 2.3.1.

\[ U'_i = \overline{U}_i + u_i \]  \hspace{1cm} (2.3.1)

where: \( U'_i \) = Instantaneous velocity
\( \overline{U}_i \) = Time average velocity
\( u_i \) = Time varying velocity component
It is important to note that the term average is used and not the mean. The mean with respect to time is express as follows.

$$\bar{f} = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} f \, dt$$  \hspace{1cm} (2.3.2)

where: \(\bar{f}\) = Mean value  
\(f\) = Instantaneous value  
\(T\) = Total time

This value is useful only if the average value is independent of time. An example system exhibiting mean properties is flow through a pipe with a constant pressure drop maintained between the ends of the pipe. If doubt exists as to the independence of time upon the averaging, it is more correct to use ensemble averages of sample data. This is expressed as:
where:

\[ f(t) = \text{Time average value} \]

\[ f(t) = \text{Instantaneous value at time } t \]

\[ N = \text{Sample size} \]

The ensemble average is the basis used for the derivation of the equations in turbulence theory. [56] For this reason, this will be the concept adhered to for the following discussions.

The simplest useful statistical properties relating to turbulence which can be extracted from a set of instantaneous velocity measurements are the mean squares and second order mean products of the time varying velocity terms \( u_i \).

The sum of the mean square values \( \overline{u_i^2} \) determined for any interrogation plane yields a value proportional to “turbulent kinetic energy per unit mass of fluid”. [57]

The complete expression for turbulent kinetic energy is represented in equation 2.3.4.

\[ q^2 = \frac{1}{2} \rho \left( \overline{u^2} + \overline{v^2} + \overline{w^2} \right) \]  (2.3.4)

where:

\[ q^2 = \text{Turbulent kinetic energy} \]

\[ \rho = \text{Density of the fluid} \]

\[ \overline{u^2} = \text{Mean square velocity fluctuating component in x-direction} \]

\[ \overline{v^2} = \text{Mean square velocity fluctuating component in y-direction} \]

\[ \overline{w^2} = \text{Mean square velocity fluctuating component in z-direction} \]
2.3.2 - EQUATIONS OF MOTION

The incompressible form of the Navier-Stokes equations is the mathematical expression of the conservation of momentum for a continuum fluid with viscous stresses proportional to rate of strain. These equations are generally accepted to describe flows in liquids and gases and provide the basis for calculation of the velocity field distribution within a given flow system. The equations can be written as [58]:

\[ \frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla) \vec{V} = \nabla \cdot p - \frac{1}{\rho} \nabla p + \nu \nabla^2 \vec{V} \]  \hspace{1cm} (2.3.5)

where:

\[ \vec{V} = \text{velocity vector} \]
\[ \rho = \text{Density of the fluid} \]
\[ g = \text{gravity} \]
\[ p = \text{pressure} \]
\[ \nu = \text{kinematic viscosity of the fluid} \]

The terms in equation (2.3.5) are described as follows:

i.) Local acceleration of a fluid particle.
   (Term is zero for steady flow.)

ii.) Convective acceleration of a fluid particle.
    (Term is zero for uniform flow.)

iii.) Gravitational acceleration.

iv.) Pressure acceleration due to pumping action of the flow.

v.) Viscous dissipation due to fluid frictional resistance.
The Navier-Stokes equations are usually used in conjunction with the continuity equation to allow for closure of the number of variables equaling the number of equations. The continuity equation is an expression of mass balance per unit volume. Assuming constant density, the continuity equation is expressed as:

$$\nabla \cdot \mathbf{V} = 0 \quad (2.3.6)$$

Substitution of the expression of instantaneous velocity (2.3.1) into the incompressible form of the Navier-Stokes equations (2.3.5), performing ensemble averaging and using the continuity equation yields the result of the Reynolds equations. The $x$-component of these equations is [59]:

Differential notation for the $X$-component

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} = - \frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \nabla^2 U - \left( \frac{\partial U}{\partial x} \frac{\partial \bar{U}}{\partial y} + \frac{\partial U}{\partial y} \frac{\partial \bar{U}}{\partial z} \right) + g_x \quad (2.3.7)$$

The left-hand sides of these equations, as in the Navier-Stokes equations, represent the inertial forces per unit volume of the average flow. The first two terms on the right-hand side represent the forces due to the average pressure and viscosity. The extra terms appearing in the right-hand side are the Reynolds stress quantities. These stresses can be summarized in a $3 \times 3$ matrix called the turbulent stress dyadic representing the stresses resulting from three dimensional velocity fluctuations.

$$\text{Stress Dyadic} = \begin{bmatrix} u^2 & uv & uw \\ vu & v^2 & vw \\ wu & vw & w^2 \end{bmatrix} \quad (2.3.8)$$
These stresses are represented by the mean squares and mean products of the time varying terms of the fluid velocity components.

2.3.3 – VORTICITY

A second indicator of turbulence that can be extracted using measured data is the determination of vorticity. This is generally expressed as [60]:

\[ \zeta = \nabla \times \bar{V} \]  

(2.3.9)

where:  
\[ \zeta \] = Vorticity  
\[ \bar{V} \] = Velocity vector

In a two-dimensional (x,y) plane, the vorticity value about the third dimension (z) is calculated by:

\[ \zeta_z = \left| \frac{\partial V'}{\partial x} - \frac{\partial U'}{\partial y} \right| \]  

(2.3.10)

Where:  
\[ \zeta_z \] = Vorticity about the z-axis  
\[ V' \] = Instantaneous velocity in the y-direction  
\[ U' \] = Instantaneous velocity in the x-direction

The value produced is a measure of the local spin of a fluid element due to the shear stresses resulting from the time varying velocity fluctuation terms. The distributions of these values indicate the rotational nature within the flow system and map out the locations of unstable flows which result in the production and maintenance of turbulence for the particular plane.
2.3.4 - SUMMARY

The spatial resolution of flow indicators may be estimated through the simultaneous measurement of velocity vector quantities given a sufficient density of interrogation points. Simple statistical quantities with respect to the fluctuating nature of the flow may be used to evaluate the mean flow characteristics as well as provide indication of the presence and distribution of turbulent energies that result from bath stirring.
CHAPTER #3 - MODELS, APPARATUS AND EXPERIMENTAL

3.0 – OVERVIEW

The apparatus required to perform the experimental flow analyses was divided in four major sections:

1) Flow systems (3 cases)
2) Light sheet generation
3) Fluid seeding particles
4) Image acquisition and recording

3.1.0 – FLOW SYSTEMS

Three water models were constructed for the purposes of flow visualization experiments:

1) Thin slice thermal driven flow
2) Thin slice bubble driven flow
3) 1/9" scale model of a bottom gas stirred EAF

The thin slice cases were constructed to produce simplified flows for the purposes of eliminating the procedural errors in experimental image data acquisition. The scale furnace model was constructed as the simplified industrial shallow bath case for analysis.

3.1.1 - THIN SLICE THERMALLY DrIVEN FLOW

A photograph of the thermally driven thin slice apparatus is found in figure 3.1.1.1. The shell I was a rectangular box constructed from 3.00 mm Acrylite FF clear extruded acrylic sheet. The dimensions of the shell were 340.00 mm x 31.75 mm x 170.00 mm. The shell was filled with water to a bath depth of 90.00 mm.
The flow was created by a temperature drop set up across the tank (hot surface to cold surface). A temperature drop of approximately 25°C was supplied to drive the thermal flow.

The "cold walls" were constructed from rectangular copper tube (cross section 19.05 mm x 6.35 mm). A schematic of the cold wall assembly is found in figure 3.1.1.2. Type K thermocouples were attached to monitor the wall temperature along its length for the duration of some experiments.
The "hot walls" were constructed from copper plates brazed together to form a box of dimensions 40 mm x 25 mm x 75 mm. The heat was supplied by a 220 VAC, 3 kW hot water tank element. This element was connected to a 110 VAC circuit which included a switch and variac. The power was controlled by varying the voltage supplied to the element. The operating range of the element was variable between 0 — 750 W. This setting corresponded to an input voltage of 65V to the heater element. Type K thermocouples were used to monitor the temperature along the hot surface during some experiments. The length of the heater element used was much longer than required. Therefore, to prevent any damage or injury a water-cooled sheath was assembled. The sheath consisted of a copper coil fitted over a piece of thin walled aluminum tubing. The sheath was assembled to fit snug over the exposed section of the heater element. The water supply to the cooling coil was connected in series following the "cold wall" assembles and emptied into a lab drain.
3.1.2 - Thin Slice Bubble Driven Flow

Top and side views of the thin slice bubble driven flow case and supporting apparatus is found in figure 3.1.2.1 a and b. The shell for this flow system was identical to the thermal driven case and was constructed in the same fashion with the same materials. The driving force for the flow was provided by a single injector, located in the center of the bottom plate. The injector was constructed from single a piece of 6.35 mm I.D. Vinylon inner braided tubing into which a cut off inflation needle was inserted. The orifice created was 1.00 mm in diameter. The components were resistance fit together flush with the bottom of the tank inner surface and sealed using acrylic cement. Once complete, the shell was filled with water to depth of 90.00 mm.

![Figure 3.1.2.1 a and b: Photographs of the thin slice bubble driven case shell. a) Top view showing the injector location; b) Side view.](image)

The stirring gas used was supplied from the lab compressed air system. The flow of air was controlled using a step down regulator to control the system pressure and rotameter (Matheson model: E1-3C601) to control the flow rate.
3.1.3 - 1/9TH SCALE BOTTOM STIRRED EAF MODEL

Photographs of the 1/9th scale 3-D furnace model and apparatus is found in figure 3.1.3.1 a and b.

Figure 3.1.3.1 a and b: Photographs of the 1/9th scale bottom gas stirred EAF model and supporting apparatus. a) Model setup showing the model, outer tank and gas supply apparatus; b) Top view of the furnace model showing the stirring element positions.

Drawings, detailing the dimensions of the bottom gas stirred Mannessman Demag furnace hearth, were supplied by Inland Steel Bar Company. From these drawings, an approximate 1/9th scale 3-D molding form was constructed with the outer dimensions of the form corresponding to the scaled inner dimensions of the furnace hearth. The materials used in the construction were plywood and plaster of paris. Photographs of the molding form are found in figures 3.1.3.2 a and b.
To fabricate the model shell blank, the molding form was mounted to a linear tracking motor assembly. The linear tracking assembly was mounted in the vertical position and fastened to the lab wall. This setup allowed for incremental control of the mold position during the forming process. The material chosen to form the shell of the model was 1.58 mm thick Acrylite GP clear cast acrylic sheet.

The bodies of the stirring elements were constructed from clear cast acrylic resin tubing, 104.78 mm I.D. The plates to seal the bottom of the units were cut from 6.35 mm acrylic sheet. The diffuser plates that support the porous media were cut from 1.58 mm acrylic sheet. The stirring elements were shaped
to fit flush with the bottom of the furnace shell in their appropriate positions. A schematic of the stirring element assemblies is found in figure 3.1.3.3.

Holes were cut into the furnace shell blank to accommodate the stirring elements, which were attached to the shell using clear silicone adhesive. The stirring element assemblies also served as the legs of the model and thus, were leveled appropriately. To allow for air injection, a hole was drilled into the side of the lower chamber of each stirring assembly to accommodate a 7.95 mm I.D. Vinylon tube. Each tube, in turn, was attached to its own dedicated rotameter allowing for individual control of the stirring gas flow rates supplied to each of the stirring elements mounted in the furnace model.

A second outer tank was constructed to serve two purposes:

1) Structural support of the furnace model.
2) Optical correction for video recording.
Filling the furnace model to its scaled full bath depth required 31.5 L of water. A tank within a tank mode of setup was constructed to support the water contained within the model shell. Constructing the outer tank as a rectangular box also served to correct for any optical distortion effects caused by the curved shape of the furnace shell. The result of having water on both sides of the furnace shell allowed for the inner model to effectively disappear yielding an undistorted image during the recording of the illuminated region. The material used to construct the outer tank was 19.05 mm thick Acrylite GP clear cast acrylic sheet. The inner dimensions of the tank were 1220 mm x 820 mm x 290 mm. The working depth of the tank was 230 mm, requiring 290 L of water.

3.2.0- Light Sheet Generation

The light source used to illuminate the interrogation planes for all flow systems was supplied by a green wavelength laser (532 nm). The smaller cases "A" and "B" were illuminated using a 10 mW He-Ne laser. For case "C", the largest physical model, a 20 mW He-Ne laser was used. To produce the actual sheet of light, a galvanometer optical scanning setup was used. Table 3.2.1.1 lists the components of the light sheet apparatus.
Table 3.2.0.1: Summary of components used for experimental light sheet generation.

<table>
<thead>
<tr>
<th>Component</th>
<th>Manufacturer</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mW He-Ne, laser 532 nm</td>
<td>Rental</td>
<td>Photonics Research Ontario. Toronto, ON, Canada</td>
</tr>
<tr>
<td>20 mW He-Ne, laser 532 nm</td>
<td>Rental</td>
<td>Photonics Research Ontario. Toronto, ON, Canada</td>
</tr>
<tr>
<td>G120DT Closed loop scanner</td>
<td>General Scanning Inc.</td>
<td>Optikon Corporation Ltd. Kitchener, ON, Canada</td>
</tr>
<tr>
<td>G100 series 5mm mirror</td>
<td>General Scanning Inc.</td>
<td>Optikon Corporation Ltd. Kitchener, ON, Canada</td>
</tr>
<tr>
<td>AE1000 Closed loop drive electronics</td>
<td>General Scanning Inc.</td>
<td>Optikon Corporation Ltd. Kitchener, ON, Canada</td>
</tr>
<tr>
<td>FG2A 2 Mhz Function generator</td>
<td>Wavetek</td>
<td>Newerk Electronics Mississauga, ON, Canada</td>
</tr>
<tr>
<td>GHOF 2D ± 12 V Dual Power Supply @ 3.0 A</td>
<td>Tectorl Inc.</td>
<td>Electrosonic Toronto, ON, Canada</td>
</tr>
</tbody>
</table>

The galvanometer was powered by a ± 12 V, 3 A dual DC power supply. The operational ranges of the galvanometer were as follows:

1) Variable sweep frequency 0-300 Hz.
2) Amplitude control up to ± 76° peak to peak optical beam deflection.

The control was achieved using a function generator to supply the galvanometer drive electronics. The input signal was a variable frequency sine wave with variable amplitude of 0 —10 V. The sweep was adjusted to a frequency of 125 Hz for all experiments. This frequency was chosen to allow the laser sweep to equal an even multiple of the camera shutter speed. Due to the sinusoidal nature of the input signal, each point in the field of view was illuminated exactly twice for every shutter frame (125 fps). A schematic of the light sheet apparatus may be see in figure 3.2.0.1.
The light sheet for both thin slice models was introduced into the tank through the clear tank bottoms. This was necessary in the thermal model due to the physical obstructions caused by the "cold walls" and heater element. In the case of the bubble driven model, the mixing created surface waves that distorted the light sheet. In the furnace model case, two arrangements were required:

1) Horizontal cut plane
2) Vertical cut plane

To allow horizontal planes to be measured, the laser sheet was introduced through the sidewall of the outer tank. Vertical planes such as furnace centerlines were illuminated with the laser in the same orientation but the light sheet was reflected off a mirror mounted above the tank at a 45° angle to create the vertical light sheet. Figure 3.2.0.2 is a schematic of the modes of light sheet
the vertical light sheet. Figure 3.2.0.2 is a schematic of the modes of light sheet introduction to the test cases. The light sheet apparatus was mounted on the linear tracking apparatus to allow for positional control. This allowed the light sheet to be adjusted to heights through the full range of the bath depth for horizontal plane interrogation and across the entire diameter for vertical plane interrogation.

![Schematic diagram illustrating light sheet generation.](image)

**3.3.0 - Fluid Seeding Materials**

In all experimental cases, the liquid used was tap water. In order to obtain images of the flows, the water was seeded with approximately 0.05 g/l of seed material. The seed material provided a tracer that moved through the flow intimately with its surrounding fluid. Thus in essence, the tracers are part of the flow. The surface of the tracer results in the laser light to be scattered allowing
the CCD to detect its position and track its translation within the illuminated region. The seed materials used in the experiments are listed in Table 3.1.3.1

Table 3.3.0.1: Summary of the seeding materials used for flow visualization experiments.

<table>
<thead>
<tr>
<th>Seeding Material</th>
<th>Size</th>
<th>Density</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-HGS</td>
<td>$D = 10 \mu m$</td>
<td>$\rho = 1.4 \text{ g/cm}^3$</td>
<td>Dantec Measurement Technology Mahwah, NJ, USA</td>
</tr>
<tr>
<td>Silver coated hollow glass spheres</td>
<td>$2 &lt; D &lt; 20 \mu m$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HGS</td>
<td>$D = 10 \mu m$</td>
<td>$\rho = 1.1 \text{ g/cm}^3$</td>
<td>Dantec Measurement Technology Mahwah, NJ, USA</td>
</tr>
<tr>
<td>Hollow glass spheres</td>
<td>$2 &lt; D &lt; 20 \mu m$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSP-5</td>
<td>$D = 5 \mu m$</td>
<td>$\rho = 1.03 \text{ g/cm}^3$</td>
<td>Dantec Measurement Technology Mahwah, NJ, USA</td>
</tr>
<tr>
<td>Polyamide seeding particles</td>
<td>$1 &lt; D &lt; 10 \mu m$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade US1718 Aluminum Powder</td>
<td>$2 &lt; D &lt; 6 \mu m$</td>
<td>$\rho = 2.70 \text{ g/cm}^3$</td>
<td>Canbro Valleyfield, Que. Canada</td>
</tr>
</tbody>
</table>

3.4.0 - DATA ACQUISITION AND RECORDING

The sequences of images analyzed were acquired using the system illustrated in figure 3.4.0.1 and the components are listed in table 3.4.0.1.

![Figure 3.4.0.1: Schematic of the image acquisition system consisting of i) PC equipped with a frame grabber; ii) S-VHS VCR; iii) CCD camera.](image)

53
Table 3.4.0.1 Summary information for the image acquisition system.

<table>
<thead>
<tr>
<th>Component</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD Camera</td>
<td>Cohu 4915-2000, RS-170 format</td>
</tr>
<tr>
<td>CCD camera lens</td>
<td>Cosmicar, zoom lens 12.5 -75 mm, 1 : 1.8, part # - 51757</td>
</tr>
<tr>
<td>S-VHS VCR</td>
<td>Mitsubishi HS-U69</td>
</tr>
<tr>
<td>Computer</td>
<td>Intel 486/66 based PC</td>
</tr>
<tr>
<td>Frame Grabber</td>
<td>Coreco TCX / MX Version 1.03</td>
</tr>
<tr>
<td>Software</td>
<td>Optimas Version .5.2</td>
</tr>
</tbody>
</table>

Sequences of images were recorded using one of two methods that depended upon the nature of the flow system being interrogated.

1) Direct recording to the computer hard drive.
2) i - Videotape the live flow; ii - Playback and digitize at an appropriate frame rate.

For the thin slice thermally driven flow the image sequences were created using both methods 1 and 2. The buoyancy driven flow and scale furnace model cases were recorded only using method 2. One (1) fps was the maximum reliable frame rate to record directly to the hard drive therefore, to accurately measure the faster moving regions within the flow, a S-VHS VCR, with frame by frame playback capabilities, was required. Several minutes of video of the region of interest was first recorded and was later digitized at an appropriate frame rate.

The CCD camera required some setup to obtain low light images containing little electronic noise. Figure 3.4.0.2 shows a schematic of the adjustment controls on the side panel of the CCD camera. The default setting of the frame mode-interlaced scanning with an image interval of 30 Hz.
Electronic Iris

The electronic iris setting was set to the off position allowing for manual control over the iris f-stop.

Shutter Speed

The shutter speed was adjusted from the default 60 Hz. to 125 Hz. This was done to allow the galvanometer sweep input signal to be tuned to an even multiple of the shutter speed within its operational range of sine wave input 0—300 Hz. This allowed for each shutter frame to be completely illuminated two times yielding the appearance of an evenly illuminated plane within the tank. The 60 Hz. setting required a minimum sweep sine wave input signal of 240 Hz. or 8 complete sweeps per shutter frame. This setting would have operated the galvanometer and the top end of its range for long periods of time during the experimental stage of this work. Tests were performed at 250 Hz. input with a 125 Hz. shutter speed yielding an equivalent four complete scans per shutter frame. The illumination level produced identical images to the 125 Hz. input signal, therefore the 125 Hz. input signal was adopted for all experiments.
**Automatic Gain Control and Gain**

The Automatic Gain Control was set to off and the gain set to its lowest position. This was done to reduce electronic noise in the images.

**Gamma**

The gamma control was adjusted fully to the counter clockwise position corresponding to a value of one (1). This allows for the images to be recorded as they appear in the flow without intensity correction for the video monitor. This setting was recommended in the camera manual for connection to a frame grabber.

**Sharpness**

Once all of the other controls were set, the picture was brought into focus as best as possible using the camera lens. The sharpness control was then adjusted to obtain the clearest possible picture.

**3.4.1 — IMAGE ACQUISITION**

Each of the flow models was allowed to reach a "steady" flow state prior to the introduction of the seed material. Addition of the seed material caused a disturbance within the flow. Careful addition of the seed material into a high activity area of the flow reduced the time required for these effects to be minimized. This time varied between 15 – 60 minutes for the different models. Figure 3.4.1.1 shows a flow chart of the sequence of steps required to perform the PIV flow visualization experiments.
Prior to recording the flow, the interrogation field size was determined for the particular case. This value was dependent upon:

1) The camera lens
2) The camera CCD
3) The particular system of interest

The largest possible area was determined which allowed the velocity field to be resolved by a displacement of less than 8 pixels between the image pairs. This displacement was chosen due to the consideration of measurement errors as discussed in chapter 2.1. and a set of linear and rotational calibration cases used to debug the PIV software.

Once the dimensions of the interrogation window size were determined, a clear template with two grids was constructed to allow the following references

1) The dimensional limits for each image acquired by the CCD
2) The sub set of the acquired image measurements to be kept after cropping the excess field which was recorded.

A field larger than the region of interest was recorded for each image sequence. This allowed for the erroneous vectors due to edge effects in the PIV calculation.

Figure 3.4.1.1: Diagram illustration of the sequence of steps required for flow analysis.

3.4.2 - INTERROGATION AREA SIZE

Prior to recording the flow, the interrogation field size was determined for the particular case. This value was dependent upon:

1) The camera lens
2) The camera CCD
3) The particular system of interest

The largest possible area was determined which allowed the velocity field to be resolved by a displacement of less than 8 pixels between the image pairs. This displacement was chosen due to the consideration of measurement errors as discussed in chapter 2.1. and a set of linear and rotational calibration cases used to debug the PIV software.

Once the dimensions of the interrogation window size were determined, a clear template with two grids was constructed to allow the following references

1) The dimensional limits for each image acquired by the CCD
2) The sub set of the acquired image measurements to be kept after cropping the excess field which was recorded.

A field larger than the region of interest was recorded for each image sequence. This allowed for the erroneous vectors due to edge effects in the PIV calculation.
to be eliminated. The interrogation field sizes, pixel magnifications and spatial vector resolutions for each of the experimental model cases are listed in table 3.4.2.1

Table 3.4.2.1 Interrogation field sizes and the respective resolutions for each experimental case.

<table>
<thead>
<tr>
<th>Experimental Case</th>
<th>Cropped Interrogation Field Dimensions</th>
<th>Pixel Magnification</th>
<th>Vector spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - Thermally Driven Thin Slice</td>
<td>60mm x 45mm</td>
<td>1 pixel = 0.12mm</td>
<td>0.48mm</td>
</tr>
<tr>
<td>B - Bubble Driven Thin Slice</td>
<td>85mm x 90mm</td>
<td>1 pixel = 0.20mm</td>
<td>0.8mm</td>
</tr>
<tr>
<td>C - 1/10 scale Furnace Model</td>
<td>310mm x 290mm</td>
<td>1 pixel = 0.60mm</td>
<td>2.4mm</td>
</tr>
</tbody>
</table>

3.4.3 – FLOW INTERROGATION

The interrogation of each of the flow systems was performed by the following series of steps:

1) Flow system recording;
2) Digital image sequence acquisition;
3) ASCII data input file creation;
4) PIV flow analysis.

Prior to recording the flow for a particular area, a single image was grabbed with the clear template in place to indicate the limits of the region of interest to remain after data cropping. The template was then remove from view and the flow was recorded to videotape. Following the recording of the flow patterns, sequences of 60 – 150 images were digitized from the videotape using the frame by frame playback feature of the VCR. The images were individually created using the sequence recording macro contained within the Optimas 5.2 software package. The image properties of the saved images were:
The image sequences were transferred to a 200 MHz. Pentium based PC for analysis.

The PIV software used to calculate the flow velocity vectors was written in the Fortran language. The picture files were translated from the tiff format to the required ASCII input file format using a Microsoft Visual Basic 4 routine created for this purpose. Once the data files were created, the PIV program was initiated and the resultant vector field representing the flow was obtained. The PIV routine stored the x and y components of the instantaneous velocity vectors \( U' \) and \( V' \) as well as the time average values \( \bar{U} \) and \( \bar{V} \).

Once the output files were output from the PIV routine the data was cropped to the area of interest. The respective areas of interest were assembled to create the final composite files.

For the furnace model case some additional values were calculated in a post-processing step on the data file. The extra values were:

1) Average velocity magnitude \( \sqrt{U^2 + V^2} \)
2) Fluctuating components of Instantaneous velocity \( (u) \) and \( (v) \)
3) Sum of the planar mean square (MS) velocity fluctuation terms \( |u^2| + |v^2| \)
4) Instantaneous vorticity
5) Time average vorticity
Distribution maps were created for the following variables:

1) Average velocity vectors
2) Average velocity magnitude
3) Vorticity distribution
4) Velocity fluctuation component
CHAPTER #4 — EXPERIMENTAL RESULTS

4.0 — OVERVIEW

The results of the flow visualization experiments are presented in this chapter. In section 4.1, the results for the thermal driven flow and the bubble buoyancy driven flow are presented to illustrate the procedural issues for measuring model flow systems. The results of the scale furnace model are presented in section 4.2.

4.1.0 — THIN SLICE CASE RESULTS

Two thin slice flow systems were constructed for two purposes:

1) To develop and debug the necessary steps required to perform the experimental measurement of flows in water models.

2) To provide a comparative example of the different flows produced in thermal gradient driven systems versus bubble buoyancy driven systems.

The construction of the thin slice cases was not subject to any similarity criteria and therefore, the flows do not intentionally simulate any industrial processes. These systems produced flow patterns that were sufficiently simple in structure and regular in nature. Both experimental cases were constructed to gain experience in the use of lighting / image acquisition system for the measurement of different flow phenomena.

4.1.1 — THIN SLICE THERMALLY DRIVEN FLOW

The majority of the experimental procedure development was accomplished using the thermally driven flow system. This setup was chosen since the flow produced by this experimental case was the simplest in structure. More importantly, this flow contained short-range velocity gradients that proved difficult to resolve in the measurements. The
resolution of the flow in these velocity gradient areas required the appropriate combination of image sequence digitization frame rate and interrogation window size. The results of the flow analysis are presented in figures 4.1.1.1 a and b. Only ½ of the vectors measured are displayed for directional clarity. The conditions producing this flow were:

1) Cold wall temperature $\approx 15 \pm 2 \, ^\circ$C
2) Hot wall temperature $\approx 35 \pm 2 \, ^\circ$C

A schematic representation of the overall flow pattern as well as the grid of interrogation areas is provided in figure 4.1.1.2.

![Schematic of the overall flow pattern and grid of interrogation areas](image.png)

Figure 4.1.1.2: Schematic of the thin slice thermal flow system illustrating the interrogation areas (left side) and the resultant net flow pattern measured (right side). The hatched interrogation area is discussed in figures 4.1.1.3 a & b.

To resolve the velocity vectors, each half of the flow system was divided into six (6) equal interrogation areas. Within each of the areas, the recorded data was analysed using multiple frame rates and interrogation window sizes to resolve the spatial velocity gradients. The gray hatched area in figure 4.1.1.2 is used as an example and is presented with full vector density in figure 4.1.1.3. Three sub-regions were evaluated using the same input flow video but were digitized at different frame rates to produce the images sequences. This sub-region approach was typical for the flow interrogation with
the exception of the “middle” areas that did not require evaluation for vertical flows. The respective frame rates to determine the flow vectors were:

i) Region 1 – 1 fps (32 x 32 pixel interrogation windows)
ii) Region 2 – 15 fps (32 x 32 pixel interrogation windows)
iii) Region 3 – 15 fps (16 x 16 pixel interrogation windows)

![Diagram of vector plot](image)

Figure 4.1.1.3: Vector plot determined for the top left corner of the thermally driven flow. Different frame rate areas are denoted by colour. (white = 1 fps, 32 x 32 pixel window; light gray = 15 fps, 32 x 32 pixel window; dark gray = 15 fps, 16 x 16 pixel window)

Due to the vertical flow features only spanning 25 – 30 pixels in the digitized images, 16 x 16 pixel interrogation windows were required to resolve the flow along the cold and hot walls (type-2 regions). The remainder of the analysis was performed using 32 x 32 pixel interrogation windows with a padding factor of 2. The padding factor was used to shift the interrogation window by 16 pixels (or \(\frac{1}{2}\) of a single window) in both the x and y directions.
The effect of this was an increase of the measurement vector density by four times. This vector padding effect is illustrated in figure 4.1.1.4.

![Diagram showing vector padding effect](image)

**Figure 4.1.1.4:** Vector padding effect illustrated for the top left corner region of the thermal driven flow. Left - is the result for pixel shift = 0; Right - is result for pixel shift = 16 pixels (padding factor of 2).

For each interrogation area, it was determined empirically that 60 images were required to resolve the time average flow. Therefore, type-1 regions represent the average of 60 seconds of flow. Type-2 and type-3 regions represent 2 seconds of flow.

After the various sub-regions were analysed for each interrogation area, the data was assembled to produce the composite results. These are found in figures 4.1.1.1 a and b. The assembly of the data to produce a time average flow pattern is predicated upon the assumption of the flow having achieved steady state. One indicator of the steady flow assumption being valid is the degree of pattern match between adjacent interrogation areas. Both the flow pattern vector plot and velocity magnitude distribution maps illustrate excellent matching for all adjacent areas. The results also exhibit reasonable centerline symmetry for both halves of the flow. One peculiarity noted occurs where the two flows along the bottom of the tank meet. This did not occur at the tank
centerline. The up-flow occurred at a point past the right hot wall and maintained this position for more than 10 hours before the experiment was shut down.

4.1.2 – Thin Slice Bubble Driven Flow

The stirring energy was provided using gas injection from a centrally located orifice in the bottom of the tank. The gas flow rate was estimated from the recorded video to be approximately 0.45 mL/s. An estimate was required since the rotameter used to control the gas flow rate was set almost fully off and was reading a value of zero for this experiment. The flow pattern vector plot and velocity magnitude maps are found in figures 4.1.2.1 a and b. Again for clarity, only $\frac{1}{2}$ of the vectors have been displayed. The flow for the entire tank was originally resolved in four (4) equal sized interrogation areas as illustrated in figure 4.1.2.2. The two central regions were analysed using 120 frames, digitized at 30 fps and representing 4 seconds of real time. The two outer sections were digitized at 7.5 fps, using 120 frames representing 16 seconds of real time. For this experimental case, the interrogation areas were not subdivided. 32 x 32 pixel interrogation windows were used with a padding factor of 2 for the analysis.

![Figure 4.1.2.2: Interrogation areas used for the bubble driven thin slice flow measurements.](image-url)
The number of frames was chosen empirically by a comparison of the output flow patterns and velocity magnitudes produce using the PIV routine.

The results given in figures 4.1.2.1 a and b show a flow pattern which is more complex in comparison to the thermal case. The maximum velocity was approximately 10 mm/s in the central “plume” region as compared to 1 mm/s in the thermal flow. Furthermore, regions of zero velocity have been effectively eliminated in comparison to the thermal case.

Two distinct problems exist in the measurement data presented:

1) Discontinuities and matching problems between adjacent interrogation areas.

2) Distinct differences in the symmetry of the flow magnitudes and overall time average flow patterns.

The discontinuity problem was attributed to a technique error. The interrogation area chosen occupied the entire camera lens field of view for these measurements. In subsequent measurements, the interrogation area was purposely chosen to be smaller than the field of view at the particular magnification. Furthermore, the images recorded for adjacent areas were partially overlapping. These changes were made since “bad” vectors were most probable to occur along the edges of the vector plots due to the introduction and loss of data from the field of view. Therefore, this step allowed the edges to be cropped off.

The matching problems exhibited between adjacent interrogation areas illustrate that the flow does not maintain an absolute steady condition. The degree of pattern variation displayed in the plots is due the various areas being sequentially recorded in time. The time average flow patterns and magnitude maps also revealed periodic pattern fluctuations as well as geometric asymmetries within the flow system. Upon reexamination of the shell construction, it was discovered that the orifice was not located exactly in the center of the bottom plate. The orifice was located approximately 3.5 mm
off center, favoring the left half of the tank. Also discovered upon a review of the image sequences, the bubble flow was also found to favor the left side. An approximate measurement made from the images indicated that the tank was off level by as much as 5 mm over 1000 mm. These geometric and alignment problems seem insufficient to account for the magnitude difference recorded between the central interrogation areas. The flow patterns for these areas are similar in structure however, the flow magnitudes differ by 3 – 5 mm/s. This is approximately equal to a 100% deviation between the two areas. A second measurement of this system was performed using a lower image magnification. This magnifications allowed the tank to be interrogated using two areas, one for each half of the tank symmetry. As in the first attempt, 32 x 32 pixel interrogation windows were used with a padding factor of 2. Ninety (90) frames, digitized at a 15 fps, were analysed for each area. These conditions were chosen to match the particle displacement velocity ranges for the two sets of measurements for the central regions of the first measurement attempt. The results for this experiment are found in figures 4.1.2.3 a and b. The symmetry problems of figures 4.1.2.1 a and b do not appear in the second set of measurements. Re-examination of the image sequences provided no further information regarding the flow conditions for the asymmetrical result. The next factor considered was the time period for the measurement. Only four (4) consecutive seconds of flow were analysed therefore, it is possible that a short-term flow anomaly was in existence. The only remaining option to explain this case is operator error. The second measurement of the bubble driven flow in figures 4.1.2.3 a and b also illustrates how this technique can be used to provide a “quick” assessment of the overall flow conditions. The detail of the regions near the walls does not appear in the lower magnification measurement, however the overall flow conditions are reasonably represented for the system as a whole.
4.2.0 — 1/9TH SCALE FURNACE MODEL

The flow visualization experiments performed for the scale furnace model were:

1) **Regular** - All four (4) stirring elements are operating at the scaled industrial flow rate set point.

2) **Tip Stirring Element Off** - The tip stirring element is turned off. The three (3) central stirring elements located directly beneath the arc pitch circle are operational at the scaled industrial set point.

3) **Tip Stirring Element Alone** - The tip stirring element is operating at the scale industrial set point. The three (3) central stirring elements located beneath the arc pitch circle are turned off.

For each of the experimental cases, four (4) horizontal planes were interrogated at regular depth intervals. These levels are illustrated in figure 4.2.0.1

![Horizontal Plane Depth from Surface of the Bath](image)

<table>
<thead>
<tr>
<th>Horizontal Plane</th>
<th>Depth from Surface of the Bath</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>10 mm</td>
</tr>
<tr>
<td>Middle</td>
<td>30 mm</td>
</tr>
<tr>
<td>Bottom</td>
<td>50 mm</td>
</tr>
<tr>
<td>Hearth</td>
<td>70 mm</td>
</tr>
</tbody>
</table>

Figure 4.2.0.1: Schematic of furnace profile illustrating the horizontal interrogation plane levels for the scale furnace bath.

The results for each of the planes are presented in four (4) plots:

i) **Time Average Flow Pattern** — Composite vector plot of the six interrogation areas to produce a time average flow pattern. Provided is a reference vector of 35 mm/s for comparison.
ii) **Mean Velocity Magnitude Map** – Distribution of flow velocity magnitudes independent of direction.

iii) **Velocity Fluctuating Component Map** - Distribution of the summed mean square velocity fluctuation terms $\overline{u^2} + \overline{v^2}$.

iv) **Vorticity Map** - Distribution of the time average vorticity values calculated from the instantaneous velocity data.

For all horizontal cases, a segment in the central region of each plane of interest has not been quantified. This was due to the field of view limitation of the camera lens. The absence of data in this region was not of concern due to process issues in the full-scale furnace.

Figure 4.2.0.2 provides the picture segment designations used in the discussion. The central regions, in the hatched region, encompass the areas immediately adjacent to the stirring elements. The area labels, tip, mid and slag door, refer the regions between
the hatched central region and the furnace hearth walls. This scheme of interrogation areas was used for the flow recording and measurement of the horizontal interrogation planes. All depths for a particular interrogation area and operating condition were sequentially recorded to video. Each of the operating conditions was recorded prior to interrogating of the next area. For all cases, 32 x 32 pixel windows were used in the PIV routine with a padding factor of 4 (8 pixel shift between windows). The respective frame rates for the interrogation areas are provided in table 4.2.0.1

Table 4.2.0.1: Frame rates of the digitized image sequences for each experimental interrogation case.

<table>
<thead>
<tr>
<th></th>
<th>Interrogation Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tip Left</td>
</tr>
<tr>
<td>Regular</td>
<td>30 fps</td>
</tr>
<tr>
<td>Tip Off</td>
<td>15 fps</td>
</tr>
<tr>
<td>Tip Alone</td>
<td>30 fps</td>
</tr>
</tbody>
</table>

4.2.1.0 - CASE 1: REGULAR

All four (4) stirring elements were operated at $4.5 \times 10^{-3}$ L/s air. This flow rate corresponded to the scaled industrial stirring element set point. Results for the “regular” case are presented as the basis for comparison with the “tip stirring element off” and “tip stirring element alone” experimental cases. All corresponding plots for a particular parameter were produced using the same scale.

4.2.1.1 - TOP CUT (SEE FIGURES 4.2.1.1A & B)

The time average flow pattern is directed radially outward from the areas corresponding to the stirring element locations. This stirring configuration and furnace
shell geometry create interacting flows at this depth that exhibit two general types of features:

i) Additive flow

ii) Recirculatory flow

In the regions approximately one half of the distance between any two adjacent stirring elements, the strongest outward flows resulted with velocity magnitudes of up to 70 mm/s. These flows persisted to the hearth wall. Interaction with the hearth wall caused the flow to redirect and divide its momentum in two possible ways.

1) Downward, out of the plane of interest.

2) Horizontally along the wall and back into the plane of interest to interact with the flows of the other furnace areas creating the recirculation features in remainder of the near wall regions.

The flow magnitudes for the central regions were typically 10 – 30 mm/s. Outside of the central regions, velocities of less than 10 mm/s were common.

The flow produced in the furnace tip region was directed radially outward from the tip stirring element location exhibiting magnitudes of 10 - 30 mm/s. The intensity of the flow decreased to less than 10 mm/s at approximately one half of the distance to hearth wall.

The lower velocities in the near-wall regions for the top plane can be attributed to interactions of flows in opposing directions. These interactions resulted in recirculating features, with the net motion directed predominantly out of the plane of interest. These recirculations were found to persist through the bath depth.

Figures 4.2.1.1 c and d show that both the instantaneous velocity fluctuations and vorticity components are limited to the central regions of the furnace. The top cut planes
for all experimental cases displayed the largest spatial range and highest intensities for these effects. For all levels below the top interrogation plane, the effects of the velocity fluctuation components and vorticity do not reach beyond the central regions of the furnace. For this reason the remainder of the horizontal plane vorticity and velocity fluctuation plots will not be discussed and are found in Appendix B.

4.2.1.2 - MIDDLE CUT (SEE FIGURES 4.2.1.2A & B)

The time average flow features for the middle interrogation plane were similar to the top plane. The flow was directed radially outward from the stirring element locations. Also exhibited were similar additive and recirculatory flow features appearing in relatively the same positions. The maximum velocities were 50 mm/s for the additive flow features. The majority of this furnace plane exhibited velocities less than 10 mm/s. With the exception of the strong in-plane recirculation features seen in the mid-right and tip-right regions, the majority of the flow passes through this interrogation plane. The velocity magnitudes measured for the areas adjacent to the stirring elements in the central region were less than 10 mm/s. These magnitude values are incorrect for two reasons:

1) The presence of agglomerated bubbles on the surface of the bath.

2) The flow in the regions corresponding to the stirring element locations is directed normal to horizontal planes of interest.

The bubble agglomerates were caused by a set of guards which were supported approximately 5 mm above the bath surface. The bubbles were purposely trapped above the stirring element regions to prevent their appearance in the areas outside of the furnace central region. This prevented the true velocity measurement for the central regions, however the areas are of little interest for the furnace analysis. This method was employed for all horizontal planes below the top interrogation plane.
4.2.1.3 - Bottom Cut (see figures 4.2.1.3a & b)

The bottom horizontal interrogation plane corresponded to the level just above the curved hearth bottom (see figure 4.2.0.1). A wider dispersion of in-plane motion of magnitude $10 - 30 \text{ mm/s}$ was exhibited for this bath depth. Flow appeared to exist predominantly as recirculating features. The flow pattern for this depth shows the first indications of the return paths from the upper level flows produced by the plumes. These return flows are apparent in all areas and are generally directed back to the furnace central region. Also exhibited, are the return paths of the flows that have passed downward along the vertical hearth walls from the upper bath levels. The tip region closest to the EBT shows little activity produced with flow velocities of less than $0.5 \text{ mm/s}$.

4.2.1.4 - Hearth Cut (see figures 4.2.1.4a & b)

The hearth interrogation plane corresponded to approximately $40\text{ mm}$ above the deepest point in the model bath. This flow in this plane is primary directed from the hearth wall back toward the central regions of the furnace along the furnace bottom. Two major circulations for this depth are noted. One circulation creates a clockwise flow along the bottom of the tip region. The second is a large counter clockwise flow around the remainder of the hearth. The flow magnitudes again show a dispersion of values ranging from $10 - 30 \text{ mm/s}$. The areas adjacent to the EBT show low velocity magnitudes of less than $10 \text{ mm/s}$.

4.2.2.0 – Case 2: Tip Stirring Element Off

The tip stirring element has been turned off for this experiment. The three (3) central stirring elements located on the are pitch circle are operating at $4.5 \times 10^{-3} \text{ L/s air}$. 

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4.2.2.1 - Top Cut (Refer to Figures 4.2.2.1a & b)

The flows produced by this case were directed radially outward from the furnace central region. The additive flow features created by interactions of adjacent stirring elements are again present. In contrast to the regular case, these are not the only flows that maintain intensity to the furnace hearth wall. The absence of the tip stirring element has reduced the size of the recirculating feature occurring in the mid-right region. Furthermore, the recirculating zones along the wall of the furnace mid-left region have also been reduced in comparison to the regular case. The recirculating features produced in the slag door regions did not show any change and exhibited velocity magnitudes less than 10 mm/s. The flow magnitudes for the majority of the furnace central and mid regions were in the 20 – 70 mm/s range. The flow magnitudes at this depth are reduced significantly in the areas immediately adjacent to the hearth walls. The flow in these areas was directed downward and out of the plane of interest.

Flows produced in the tip region of the furnace differed significantly from the regular case. The additive flow features were produced by the combined effects of stirring elements 1 and 2 (see figure 4.2.4.1) resulting in a clockwise flow through the furnace model tip. The velocity magnitudes were less than 10 mm/s for the majority of this region.

4.2.2.2 - Middle Cut (Refer to Figures 4.2.2.2a & b)

The flows produced in the middle interrogation plane were similar to the regular case. The middle plane displayed low velocity values of less than 10 mm/s in the central, mid and slag door regions of the bath. Again, this was mainly due to the flow passing through this plane of interest. The dominant, in-plane, flow features were the additive effects produced by adjacent stirring elements. These local areas of flow exhibited magnitudes in the 20 – 40 mm/s range. This flow pattern produced in the tip region
resulted in a clockwise pattern, similar to the top cut. The magnitudes for the majority of the velocities in the tip region were slower than 5 mm/s.

**4.2.2.3 – BOTTOM CUT (REFER TO FIGURES 4.2.2.3 A & B)**

In comparison with the regular case at this depth, the features and flow velocity magnitudes differed very slightly for the central, mid and slag door regions of the bath. The tip region of the bath also displayed flow patterns and velocity magnitudes that were similar to the regular case. The areas immediately above and adjacent to the EBT exhibited velocity magnitudes of less than 5 mm/s. The extent of this low velocity region was similar for the two cases so far discussed, dominating approximately one half of the tip region.

**4.2.2.4 – HEARTH CUT (REFER TO FIGURES 4.2.2.4 A & B)**

The flow observed in the central, mid and slag door regions of the hearth interrogation plane were again similar to the flow for the same depth in the regular case. The major difference for this level was observed along the walls of the tip region. The flows in the 20 – 40 mm/s range observed in the regular case were not reproduced for this case. The majority of the tip region exhibited velocities slower than 5 mm/s. The flow velocities in the center of the tip region were 5 - 10 mm/s slower than similar areas for the regular case.

**4.2.2.5 – COMPARATIVE SYNOPSIS: CASES 1 AND 2**

The elimination of the tip stirring element from the furnace configuration produced flows that displayed little difference in the central, mid and slag door regions with respect to the horizontal interrogation planes. The tip region of the bath exhibited distinct
differences. The absence of the tip stirring element resulted in low activity flows for the majority of the tip region throughout the bath depth.

4.2.3.0 — Case 3: Tip Stirring Element Alone

The tip stirring element was operated at $4.5 \times 10^{-3}$ L/s air. The three (3) central stirring elements located beneath the arc pitch circle have been turned off for this experiment.

4.2.3.1 — Top Cut (Refer to Figures 4.2.3.1a & b)

The flow produced for this case was the least complex of all three cases examined. The isolated tip stirring element produced a flow directed radially outward in all directions. The interaction of the outward flow with the furnace wall produced a large-scale counter clockwise circulation around the slag door end of the furnace hearth. The magnitude range measured for this flow was 5 - 10 mm/s. The interaction of the outward flow with the large-scale circulation occurring in the mid-right region of the furnace produced a recirculating region that encompassed the majority of this area. The flow velocities ranged from 5 – 20 mm/s for this recirculating feature. The majority of the furnace central region exhibited low activity with velocities of 5 – 10 mm/s. The tip velocities at this depth ranged from 25 – 60 mm/s. Interactions between flows in the tip created a smaller recirculation feature that tended to travel along the right wall of the furnace and up into the tip. This area typically exhibited velocity magnitudes of 10 mm/s.
4.2.3.2 – MIDDLE CUT (REFER TO FIGURES 4.2.3.2A & B)

The majority of this plane exhibited low activity in the same general directions as in the top interrogation plane. The velocities in the slag door region were predominantly in the 5 mm/s range. The furnace mid and central regions exhibited velocities of 5 –10 mm/s. Flow velocities of 20 mm/s occurred along the furnace walls for the mid and tip regions of the bath. The effects of the recirculating feature along the right wall of the tip region were observed at this bath depth with a velocity range of 20 – 50 mm/s. This flow feature tended to move periodically along the furnace wall and up through the tip of the bath.

4.2.3.3 – BOTTOM CUT (SEE FIGURES 4.2.3.3A & B)

The flow for this level was again predominantly in a counter clockwise direction along the furnace wall. The flow velocities were in the 10 mm/s range with the slag door - right region exhibiting flows in the 20 mm/s range. The central region of the furnace showed little activity with typical velocities less the 5 mm/s. The tip alone case for this level exhibited the furthest extent of activity observed, with velocity magnitudes ranging from 10 – 35 mm/s. Smaller traveling recirculations occurring, again, along the right tip wall produced flows through the EBT area which were two to four times larger than either of the two previous cases.

4.2.3.4 – HEARTH CUT (SEE FIGURES 4.2.3.4A & B)

The activity in tip of the furnace for this depth was the result of the return flow from the upper levels of the bath. The higher velocities exhibited occurred along the tip walls and up into the tip itself. This point in the horizontal interrogation plane corresponds to the position of the EBT on the furnace bottom. Only this case has produced flow velocities greater than 5 mm/s for the EBT region. The flows in the EBT region, as in the bottom cut
plane, were up to 20 mm/s. The remainder of the bath displayed minimal activity except for the wall areas in the furnace mid region. Downward return flows exhibited velocities of up to 20 mm/s.

**4.2.3.5 – Comparative Synopsis Cases 1 and 3**

The operation of the tip stirring element alone produced a large slow moving counter clockwise circulation through the central, mid and slag door regions of the furnace. Overall, the bulk of the furnace displayed little activity in comparison to the regular case, with the exception of the areas immediately adjacent to the furnace mid region walls. These flow conditions persisted throughout the depth of the bath with few differences. The flows produced in the tip region exhibited the highest activity and furthest extent of stirring effects for all depths.

**4.2.4.0 – Tip Section Profiles**

The information yielded solely in horizontal plane cuts is not sufficient for the flow analysis. This is due to one dimension of the flow not being examined. The differentiation of inactive regions from highly active out-of-plane motion cannot be accomplished by the examination of the horizontal plane measurements alone. To improve upon the analysis of the stirring effects for the various cases, the interrogation of one vertical profile interrogation plane was performed. This area corresponded to the furnace centerline, extending from the tip stirring element through the EBT region. This is illustrated in figure 4.2.4.1.
4.2.4.1 – Regular (refer to figures 4.2.4.2a –d)

The activity exhibited through the depth of the furnace tip region produced characteristic velocity magnitudes of 20 – 70 mm/s. The effects extended over ¾ of the distance from the center of the stirring element to the furnace tip. The slow moving flow in the furnace tip was the result of tip circulation observed in the horizontal cuts. This slow moving region, unfortunately, persists in the areas adjacent to the EBT. Flow effects not illustrated in the measurements, displayed a periodically occurring brief flow which flushed out the entire tip region after which the flow system returned to the behavior illustrated in figure 4.2.4.1. The flow in this plane was typically produced in the following manner. The rising bubbles of the plume resulted in an upward flow. The surface caused the flow to
move radially outward from the vicinity of the stirring element toward the furnace walls. At the ½ way distance to the wall, the outward flow was redirected toward the hearth bottom. The bottom caused a bifurcation to produce two recirculating regions, one located between the outward flow and the surface. The second recirculation was located between then outward flow and the furnace bottom. The interaction of the high activity flow with the furnace model bottom produced the return flow back to the tip stirring element. The return path was not clear due to the curvature of the furnace shell bottom distorting the recorded images for these areas. Examination of the MS velocity fluctuation vorticity maps show indications of turbulent mixing exhibiting the most influential effect near the bath surface, diminishing with depth. The turbulent indicator maps for the vertical planes displayed the beneficial stirring effects that could not be detected in the horizontal planes. The effective range of the turbulent mixing appears to extend to approximately ½ of the distance to the hearth wall for depths above the bottom horizontal interrogation plane. The same observation cannot be made with confidence regarding the depths below the bottom plane due to the unreliability of the data in this region.

The distinct discontinuity of the values appearing in the turbulent indicator maps is the residual effect of the time periodicity of the flow. The plotted results are composites with the two halves being interrogated over different periods of time.

4.2.4.2 – Tip Stirring Element Off (Refer to Figures 4.2.4.3a –d)

The flow for this case is essentially unidirectional, back toward the furnace central regions. The maximum velocities for the entire tip region were 25 mm/s with the majority of the plane exhibiting velocities in the 5 – 15 mm/s range. The immediate area of the tip, in comparison with the regular case, exhibits an extended region of flow velocities slower than 5 mm/s. The turbulence indicators of MS velocity component fluctuations and vorticity show no contributing effects to the stirring for the entire tip region interrogated.
4.2.4.3 – Tip Stirring Element Alone (Refer to Figures 4.2.4.4a –d)

The tip stirring element alone produced flows which were similar in nature and in pattern to the flows for the regular case. In contrast to the regular case, the higher velocities of 50 – 70 mm/s for the outward flow are found to extend past ¾ of the distance from the stirring element to the tip. The flow then redirects toward the bottom as in the regular case causing a bifurcation resulting in two recirculating features. These recirculations are produced in the immediate areas of the EBT. The flow for this case displayed consistent movement of the fluid through the furnace model tip as opposed to periodically occurring flows of the regular case. The velocity fluctuations and vorticity maps also show improvement with respect to the range of the turbulence indicators measured. The ½ way distance to the tip is the effective limit for the higher turbulent activity as seen in the maps. However, only this case displayed turbulence indicators extending past the ½ way distance, into the areas surrounding the EBT.

4.2.5 – Furnace Results Summary

With respect to the data presented for the 1/9th scale furnace model, insufficient interrogation of the flow has been performed to derive any analytical conclusions regarding cause and effect relationships. Therefore, only the key points for each of the experimental cases are summarized as follows:

Case A – Regular

1) The regular case displayed the best overall mixing conditions for the bath as a whole.

2) Indicators of turbulence remain local to the areas adjacent to the stirring element regions and tend not to extend past the halfway point to the furnace walls.

3) Bath mixing outside of the furnace central regions and tip exhibit flow with little to no vorticity or velocity fluctuations.
Case B - Tip stirring element turned off

1) The tip injector is essential for inducing bath movement near the EBT regions of the furnace. Removing this stirring element greatly reduces the fluid motion and mixing in the furnace tip regions.

2) The time average flow and turbulent indicators exhibited in the tip region were significantly reduced, especially along the walls and EBT area.

3) The loss of the tip stirring element showed little effect on the central regions of the furnace.

Case C - Tip stirring element alone

1) This operating condition exhibited improved mixing in tip regions of the furnace in comparison to the regular condition.

2) The majority of the central, mid and slag door regions exhibit little to no activity.

3) With respect to the tip profile, turbulent indicators are exhibited over a larger range compared to the regular case.

4.3 - Technique Summary

The analyses of the thin slice cases allowed for the identification of important issues for the development of the experimental technique. This technique was capable of mapping the flow patterns produced in statistically stationary flows. The flexibility of the technique allows for both quick assessments and detailed, higher resolution flow measurements in shallow bath systems. In all cases, the flow patterns produced were significantly different than expected. Also resolved were unexpected flow features, anomalies and periodic behaviors which, using other measurement methods, would most probably been overlooked. Furthermore, these behaviors could not be recreated through the sole use of numerical modeling.

With respect to the image analysis, many of the data processing steps can be eliminated to streamline the procedure that is currently time consuming. More than % of
the time required for performing the flow measurements was consumed by data acquisition, digitization, preparation and management operations. These steps can be eliminated by using the raw images from the CCD camera as the input to the PIV routine. This mode of operation would calculate the velocities immediately from the acquired data. The use of videotape would become a secondary option rather than the basis for this technique. Furthermore, the recording and digitization step resulted in a degradation of image data. The images provided in figures 4.1.3.1 a and b provide an example. Both images were acquired for the top left corner of the thermal thin slice flow. The image on the left was acquired directly to the computer hard drive. The image on the right was acquired from the S_VHS videotape for the same flow. The degradation in terms of contrast and image clarity is obvious. The use of videotape also limits the analysis to consecutive image sequences. Eliminating this reliance upon the VCR would allow for an operational mode in which a series of sequential image pairs are averaged over time and only the final result stored to the hard drive. One important addition to be considered for future work would be to incorporate a data validation routine to systematically eliminate erroneous vectors that periodically result in the PIV process. The criteria for this checking routine would need to be developed.
The technique presented provides the ability to concurrently measure and resolve the velocities for entire planes of flow in a non-intrusive manner. This approach is attractive when considered against other non-intrusive techniques such as LDV and particle tracking since:

1) Point measurements do not provide any information regarding surrounding flow conditions in existence at the time of the measurement.

2) Large numbers of measurements are required to determine the time average trends of the underlying flow pattern.

It would be essentially impossible to reproduce the measurements presented in this thesis using either LDV, particle tracing or dye tracer techniques.
Figure 4.2.1, a & b: (a) Velocity plot of the time average flow pattern exhibited in the top oval plane of the regular operation case. (b) Corresponding velocity magnitude map for a.
Figure 4.2.1.1 c & d: a) Map of the summed MS velocity fluctuation components measured in the top cut plane for the regular operation case; b) Time-average vorticity map in the top cut plane for the regular operation case.
Figure 4.2.1.2a & b: a) Vector plot of the time average flow pattern exhibited in the middle cut plane of the regular operation case; b) Corresponding velocity magnitude map for a.
Figure 4.2.1.3a & b: a) Vector plot of the time average flow pattern exhibited in the bottom cut plane of the regular operation case; b) Corresponding velocity magnitude map for a.
Figure 4.2.1.4a & b: a) Vector plot of the time average flow pattern exhibited in the hearth cut plane of the regular operation case; b) Corresponding velocity magnitude map for a.
Figure 4.2.2.1a & b: a) Vector plot of the time average flow pattern exhibited in the top cut plane of tip stirring element off case; b) Corresponding velocity magnitude map for a.
Figure 4.2.2.2a & b: a) Vector plot of the time average flow pattern exhibited in the middle cut plane of tip stirring element off case; b) Corresponding velocity magnitude map for a.
Figure 4.2.3a & b: a) Vector plot of the time average flow pattern exhibited in the bottom cut plane of tip stirring element off case; b) Corresponding velocity magnitude map for a.
Figure 4.2.2.4a & b: a) Vector plot of the time average flow pattern exhibited in the hearth cut plane of tip stirring element off case; b) Corresponding velocity magnitude map for a.
Figure 4.2.3.1a & b: a) Vector plot of the time average flow pattern exhibited in the top cut plane of tip stirring element alone case; b) Corresponding velocity magnitude map for a.
Figure 4.2.3.2a & b: a) Vector plot of the time average flow pattern exhibited in the middle cut plane of tip stirring element alone case; b) Corresponding velocity magnitude map for a.
Figure 4.2.3.3a & b: a) Vector plot of the time average flow pattern exhibited in the bottom cut plane of tip stirring element alone case; b) Corresponding velocity magnitude map for a.
Figure 4.2.3.4a & b: a) Vector plot of the time average flow pattern exhibited in the hearth cut plane of tip stirring element alone case; b) Corresponding velocity magnitude map for a.
Figure 4.2.4.2a & b: a) Vector plot of the time average flow pattern exhibited in the tip profile for the regular operation case; b) Corresponding velocity magnitude map for a.
Figure 4.2.4.2c &d: c) Map of the summed MS velocity fluctuation components measured for the regular operation case; d) Time-average vorticity map for the regular operation case.
Figure 4.2.4.3a & b: a) Vector plot of the time average flow pattern exhibited in the tip profile for the tip stirring element off case; b) Corresponding velocity magnitude map for a.
Figure 4.2.4.3c &d: c) Map of the summed MS velocity fluctuation components measured for the tip stirring element off case; d) Time-average vorticity map for the tip stirring element off case.
Figure 4.2.4.4a & b: a) Vector plot of the time average flow pattern exhibited in the tip profile for the tip stirring element alone case; b) Corresponding velocity magnitude map for a.
Figure 4.2.4.4c &d: c) Map of the summed MS velocity fluctuation components measured for the tip stirring element alone case; d) Time-average vorticity map for the tip stirring element alone case.
A technique was developed to visualize, record and measure the flows in water model systems. Simultaneous measurements were accomplished for large areas of several flow systems using the double image / single exposure operational mode of PIV. With respect to the use of PIV for flow analyses:

1) The measurement technique is suitable for the study of statistically stationary flows in shallow bath closed systems such as the bottom gas stirred EAF. The strengths of this technique include:

   a) Non-intrusive flow measurement.
   b) Simultaneous measurement of complete or large sections of flow planes.
   c) The ability to measure the flow over sufficiently long periods to determine statistical quantities.
   d) Flexible, tunable and cost effective method of illuminating planes within the flow system.
   e) High measurement resolution which is difficult or impossible to produce using other flow visualization techniques.
   f) Post processing of the recorded data to allow of the examination of other flow quantities.

2) Data can be extracted from the instantaneous and time average measurements to reveal useful information regarding:

   a) Time average flow patterns of the model system
   b) Statistical measurement of the flow structure.
   c) Spatial distribution of velocity values in the flow.
   d) Degree of flow pattern periodicity.
e) Spatial distribution of turbulence indicators such as velocity fluctuations and vorticity.

f) Asymmetries in the flow which cannot be predicted by mathematical models.

3) The computational software is sufficient as is for the estimation of spatial trends of flow parameters. For accurate measurements, the software will require the following improvements:

a) A data validation scheme to check for the presence and replacement of bad vectors.

b) Sub-pixel peak estimation scheme. A bias error is contained within all measurements attributed to only the maximum cross-correlation value being chosen for the determination of the net displacement of the interrogation window. The new scheme should calculate the centroid of areas surrounding this peak to allow for sub-pixel accuracy in the measurements.

As the technique currently exists, many steps are required for the acquisition digitization, storage, translation and management of data images. These processes are both time and resource intensive. Streamlining the technique can be accomplished by inputting the raw CCD images directly into the PIV software. This has several benefits:

4) The input images would not be degraded by a recording step.

5) The need for large storage capacities would be reduced.

6) The use of the VCR to record the flow would become a secondary option as opposed to the primary vehicle for data acquisition.

7) Greater flexibility of operational modes and time periods for analysis. Larger amounts of data may be averaged for a set of measurements.

8) Possibilities of eliminating the dependence upon consumer grade NTSC RS-170 equipment standard, which currently limits the resolution and maximum frame rate of the grabbed image sequences.
Obtaining representative measurements for flow visualization experiments requires both an accurate measurement technique and a dynamically similar model. The scaling criteria in the literature is deficient for guiding the construction of a low temperature scale model of a bottom gas stirred EAF. The geometry and configuration of the system do not permit the application of the modified Froude number to characterize all flow regions within the simplified bottom gas stirred EAF bath. This issue will need to be addressed in future studies. Also required for a future study is the incorporation of other furnace parameters which influence the bath flow including slag layer, slag door lance, arc plasma jets, unmelted scrap and thermal gradients. Furthermore, the curvature of the furnace model bottom obscures the data images obtained in the profile cuts for the bath depths below the level of the vertical wall. This may only be remedied through the construction of a larger scale model to decrease the optical severity of the furnace curvature. Other modifications suggested for future trials include using helium as a stirring gas to improve buoyancy similarity effects as well as possibly sacrificing the geometric similarity for the stirring element dimensions in an attempt to achieve hydrodynamic similarity for the plume regions.

It was the purpose of this thesis to present a technique to visualize and measure model shallow bath flows and not to specifically analyze any specific system. Consequently, conclusions may not be derived for the EAF model due to only a few select areas of the bath being interrogated to illustrate the capabilities of the technique. The results do provide guidance for the focus of further studies. The areas of the EBT should be the focus of detailed measurements for:
i.) Variable stirring configurations.

ii.) Variable gas flow rates. For each configuration.

Furthermore, the stirring elements located beneath the electrode pitch circle may not be in the most beneficial positions for scrap melting enhancement. Variable number and location configurations of stirring elements should be examined in future studies.

The use of water modeling to study the flow in bottom gas injection stirred EBT EAF is promising from the standpoint of studying both design and configuration on future generations of furnaces. If the similitude issue can be resolved, this system could also be used to study other rate controlled phenomena in the EAF such as decarburization during blow down.
APPENDIX – A – FURNACE MODEL SIMILARITY DATA

Table A1 details the dimensional values for the prototype and model scale furnaces used to calculate the similarity parameters reported in tables 2.2.3.2 and 2.2.3.3 in chapter 2. The three sets of data presented represent the three options in figure 2.3.3.1 for the scaling of the stirring element gas injection flow rate.

Table A1: Table of data for furnace and model furnace systems.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>Full Scale Value</th>
<th>Model Value</th>
<th>Full Scale Value</th>
<th>Model Value</th>
<th>Full Scale Value</th>
<th>Model Value</th>
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<tr>
<td>Furnace dimensions</td>
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<td>D</td>
<td>m</td>
<td>5.6</td>
<td>0.64</td>
<td>5.6</td>
<td>0.64</td>
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<td>R</td>
<td>m</td>
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<td>0.32</td>
<td>2.8</td>
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<td>Bath Depth</td>
<td>H</td>
<td>m</td>
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<td>0.12</td>
<td>1.05</td>
<td>0.12</td>
<td>1.05</td>
<td>0.12</td>
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<td>Injector Diameter</td>
<td>d_i</td>
<td>m</td>
<td>0.93</td>
<td>0.106</td>
<td>0.93</td>
<td>0.106</td>
<td>0.93</td>
<td>0.106</td>
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<td>Scaling Factor</td>
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<td>Molecular Weight Gas</td>
<td>M.W.</td>
<td>kg/mol</td>
<td>40</td>
<td>29</td>
<td>40</td>
<td>29</td>
<td>40</td>
<td>29</td>
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<tr>
<td>Gas Constant</td>
<td>R_g</td>
<td>J/kg mol K</td>
<td>8.314E+03</td>
<td>8.314E+03</td>
<td>8.314E+03</td>
<td>8.314E+03</td>
<td>8.314E+03</td>
<td>8.314E+03</td>
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<td>Reference Temperature</td>
<td>T_e</td>
<td>K</td>
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<td>273</td>
<td>273</td>
<td>273</td>
<td>273</td>
<td>273</td>
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<tr>
<td>Reference Pressure</td>
<td>P_H</td>
<td>kg/m³</td>
<td>1.01325E+05</td>
<td>1.01325E+05</td>
<td>1.01325E+05</td>
<td>1.01325E+05</td>
<td>1.01325E+05</td>
<td>1.01325E+05</td>
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<td>Gravity</td>
<td>g</td>
<td>m/s²</td>
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<td>9.80</td>
<td>9.80</td>
<td>9.80</td>
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<td>Bath Characteristics</td>
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<td></td>
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<tr>
<td>Liquid Temperature</td>
<td>T_L</td>
<td>K</td>
<td>1873</td>
<td>298</td>
<td>1873</td>
<td>298</td>
<td>1873</td>
<td>298</td>
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<tr>
<td>Liquid Density</td>
<td>P_L</td>
<td>kg/m³</td>
<td>7.20E+03</td>
<td>1.04E+03</td>
<td>7.20E+03</td>
<td>1.04E+03</td>
<td>1.04E+03</td>
<td>1.04E+03</td>
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<tr>
<td>Liquid Viscosity</td>
<td>u_L</td>
<td>kg/ms</td>
<td>6.00E-03</td>
<td>1.00E-03</td>
<td>6.00E-03</td>
<td>1.00E-03</td>
<td>6.00E-03</td>
<td>1.00E-03</td>
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<tr>
<td>Liquid Thermal Conductivity</td>
<td>k_L</td>
<td>W/m °K</td>
<td>41</td>
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<td>41</td>
<td>0.6</td>
<td>41</td>
<td>0.6</td>
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<td>Pressure Above the Bath</td>
<td>P_H</td>
<td>kg/m³</td>
<td>1.01325E+05</td>
<td>1.01325E+05</td>
<td>1.01325E+05</td>
<td>1.01325E+05</td>
<td>1.01325E+05</td>
<td>1.01325E+05</td>
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<tr>
<td>Liquid heat capacity</td>
<td>C_p</td>
<td>J/kg K</td>
<td>755</td>
<td>1.00E+03</td>
<td>755</td>
<td>1.00E+03</td>
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<td>1.00E+03</td>
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<tr>
<td>Gas Characteristics</td>
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</tr>
<tr>
<td>Gas Temperature</td>
<td>T_g</td>
<td>K</td>
<td>1873</td>
<td>298</td>
<td>1873</td>
<td>298</td>
<td>1873</td>
<td>298</td>
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<tr>
<td>Gas Density</td>
<td>ρ_g</td>
<td>kg/m³</td>
<td>1.783</td>
<td>1.293</td>
<td>1.783</td>
<td>1.293</td>
<td>1.783</td>
<td>1.293</td>
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<tr>
<td>Gas Viscosity</td>
<td>u_g</td>
<td>kg/ms</td>
<td>2.11E-05</td>
<td>1.71E-05</td>
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<td>1.71E-05</td>
<td>2.11E-05</td>
<td>1.71E-05</td>
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<tr>
<td>Gas Density at the injector</td>
<td>ρ_di</td>
<td>kg/m³</td>
<td>0.4499</td>
<td>1.1988</td>
<td>0.4499</td>
<td>1.1988</td>
<td>0.4499</td>
<td>1.1988</td>
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<tr>
<td>Gas Viscosity at the injector</td>
<td>u_di</td>
<td>kg/ms</td>
<td>8.94E-05</td>
<td>1.83E-05</td>
<td>8.94E-05</td>
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<td>8.94E-05</td>
<td>1.83E-05</td>
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<tr>
<td>Total Gas Flow Rate</td>
<td>Q_T</td>
<td>Nm³/s</td>
<td>3.398E-03</td>
<td>1.756E-05</td>
<td>3.398E-03</td>
<td>1.756E-05</td>
<td>3.398E-03</td>
<td>1.756E-05</td>
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<tr>
<td>Gas Flow Rate per Injector</td>
<td>Q</td>
<td>Nm³/s</td>
<td>8.496E-04</td>
<td>4.390E-06</td>
<td>8.496E-04</td>
<td>4.390E-06</td>
<td>8.496E-04</td>
<td>4.390E-06</td>
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<tr>
<td>Gas Flow Rate through the injector</td>
<td>Q_i</td>
<td>m³/s</td>
<td>3.367E-03</td>
<td>4.736E-06</td>
<td>3.367E-03</td>
<td>4.736E-06</td>
<td>3.367E-03</td>
<td>4.736E-06</td>
</tr>
<tr>
<td>Gas Superficial Velocity</td>
<td>U_g</td>
<td>m/s</td>
<td>4.957E-03</td>
<td>5.373E-04</td>
<td>4.957E-03</td>
<td>5.373E-04</td>
<td>4.957E-03</td>
<td>5.373E-04</td>
</tr>
<tr>
<td>Plume velocity</td>
<td>U_p</td>
<td>m/s</td>
<td>6.533E-01</td>
<td>8.764E-02</td>
<td>6.533E-01</td>
<td>8.764E-02</td>
<td>6.533E-01</td>
<td>8.764E-02</td>
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<tr>
<td>Plume velocity **</td>
<td>U_p</td>
<td>m/s</td>
<td>4.531E-01</td>
<td>6.093E-02</td>
<td>4.531E-01</td>
<td>6.093E-02</td>
<td>4.531E-01</td>
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<tr>
<td>Coefficient for Modified Froude Number</td>
<td>C</td>
<td></td>
<td>2.605E-01</td>
<td>1.870E-01</td>
<td>2.605E-01</td>
<td>1.870E-01</td>
<td>2.605E-01</td>
<td>1.870E-01</td>
</tr>
</tbody>
</table>

**Values are calculated with reference for formula provided.
**Unadjusted value for interactions.
where:

\[ \rho_{Gi} = \left( \frac{P_H + \rho_L g H}{P_o} \right) \frac{T_o}{T_{Gi}} \]  \hspace{1cm} (A.1)

\[ \mu_{Gi} = \mu G \left( \frac{T_i}{T_o} \right)^{0.75} \]  \hspace{1cm} (A.2)

\[ Q_i = \frac{\rho G Q}{\rho G_i} \]  \hspace{1cm} (A.3)

\[ U_{Gi} = \frac{Q_i}{A_i} \text{ where: } A_i = \Pi \left( \frac{d_{i(\text{effective})}}{2} \right)^2 \]  \hspace{1cm} (A.4)

\[ U_P \approx 4.2 \frac{Q^{1/3} H^{1/4}}{R^{1/3}} \text{ [from reference 20]} \]  \hspace{1cm} (A.5)

Table A2 summarizers and compares all of the calculated scaling parameter values calculated for the three possibilities.
Table A2: Summary of the values calculated for all scaling parameters considered for the furnace model construction.

<table>
<thead>
<tr>
<th>Dimensionless Parameter Values</th>
<th>Full Scale</th>
<th>Model</th>
<th>% Difference</th>
<th>Full Scale</th>
<th>Model</th>
<th>% Difference</th>
<th>Full Scale</th>
<th>Model</th>
<th>% Difference</th>
</tr>
</thead>
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<td>Aspect Ratio</td>
<td>0.1875</td>
<td>0.1875</td>
<td>0.1875</td>
<td>0.1875</td>
<td>0.1875</td>
<td>0.1875</td>
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<td>Modified Froude:</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Form 1 (eq. 2.2.2)</td>
<td>1.492E-10</td>
<td>2.840E-10</td>
<td>90.35</td>
<td>1.313E-05</td>
<td>2.498E-05</td>
<td>90.35</td>
<td>1.703E-03</td>
<td>3.241E-03</td>
<td>90.35</td>
</tr>
<tr>
<td>Form 2 (eq. 2.2.4)</td>
<td>2.394E-07</td>
<td>2.394E-07</td>
<td>0.00</td>
<td>2.106E-02</td>
<td>2.106E-02</td>
<td>0.00</td>
<td>2.733E+00</td>
<td>2.733E+00</td>
<td>0.00</td>
</tr>
<tr>
<td>Reynolds (Injector) (eq. 2.2.9)</td>
<td>25.186</td>
<td>5.736</td>
<td>63.69</td>
<td>399.318</td>
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<td>63.69</td>
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<td>217.17</td>
<td>63.69</td>
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<td>Density Ratio (eq. 2.2.7)</td>
<td>6.249E-05</td>
<td>1.153E-03</td>
<td>1744.66</td>
<td>6.249E-05</td>
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<td>1744.66</td>
<td>6.249E-05</td>
<td>1.153E-03</td>
<td>1744.66</td>
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<tr>
<td>Reynolds(Bath) (table 2.2.3.3)</td>
<td>8.231E+05</td>
<td>1.093E+04</td>
<td>98.67</td>
<td>8.231E+05</td>
<td>1.093E+04</td>
<td>98.67</td>
<td>8.231E+05</td>
<td>1.093E+04</td>
<td>98.67</td>
</tr>
<tr>
<td>Np</td>
<td>7.31E-01</td>
<td>1.20E-02</td>
<td>98.35</td>
<td>7.31E-01</td>
<td>1.20E-02</td>
<td>98.35</td>
<td>7.31E-01</td>
<td>1.20E-02</td>
<td>98.35</td>
</tr>
<tr>
<td>( \psi(N_p) )</td>
<td>0.76959823</td>
<td>0.99404504</td>
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<td>0.99404504</td>
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<td>Stirring Energy Ratio (eq. 2.2102)</td>
<td>4.607E-08</td>
<td>5.9503E-08</td>
<td>29.16</td>
<td>0.00405278</td>
<td>0.00523474</td>
<td>29.16</td>
<td>0.52583328</td>
<td>0.8791881</td>
<td>29.16</td>
</tr>
</tbody>
</table>

Assumptions
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No star - orifice area = whole packed bed area
* - orifice area = Ring of width of injector hole
**- orifice area = ring of discrete holes
Unadjusted - effect of injector not adjusted by cube root of 3 (for three injectors in the vessel central regions)
APPENDIX B

FURNACE VELOCITY FLUCTUATION AND VORTICITY PLOTS NOT PRESENTED
Figure B1 a & b: a) Map of the summed MS velocity fluctuation components measured in the top cut plane for the regular operation case; b) Time-average vorticity map in the top cut plane for the regular operation case.
Figure B2 a & b: a) Map of the summed MS velocity fluctuation components measured in the middle cut plane for the regular operation case; b) Time-average vorticity map in the middle cut plane for the regular operation case.
Figure B3 a & b: a) Map of the summed MS velocity fluctuation components measured in the bottom cut plane for the regular operation case; b) Time-average vorticity map in the bottom cut plane for the regular operation case.
Figure B4 a & d: c) Map of the summed MS velocity fluctuation components measured in the hearth cut plane for the regular operation case; d) Time-average vorticity map in the hearth cut plane for the regular operation case.
Figure B5 a & b: a) Map of the summed MS velocity fluctuation components measured in the top cut plane for the tip stirring element off case; b) Time-average vorticity map in the top cut plane for the tip stirring element off case.
of the summed MS velocity fluctuation components cut plane for the tip stirring element off case; b) Time-middle cut plane for the tip stirring element off case.
Figure B7 a & b: a) Map of the summed MS velocity fluctuation components measured in the bottom cut plane for the tip stirring element off case; b) Time-average vorticity map in the bottom cut plane for the tip stirring element off case.
Figure B8 a & b: a) Map of the summed MS velocity fluctuation components measured in the hearth cut plane for the tip stirring element off case; b) Time-average vorticity map in the hearth cut plane for the tip stirring element off
Figure B9 a & b: a) Map of the summed MS velocity fluctuation components measured in the top cut plane for the tip stirring element alone case; b) Time-average vorticity map in the top cut plane for the tip stirring element alone case.
Figure B10 a & b: a) Map of the summed MS velocity fluctuation components measured in the top cut plane for the middle stirring element alone case; b) Time-average vorticity map in the middle cut plane for the tip stirring element alone case.
Figure B11 a & b: a) Map of the summed MS velocity fluctuation components measured in the top cut plane for the bottom stirring element alone case; b) Time-average vorticity map in the bottom cut plane for the tip stirring element alone case.
Figure B12 a & b: a) Map of the summed MS velocity fluctuation components measured in the top cut plane for the hearth stirring element alone case; b) Time-average vorticity map in the top cut plane for the hearth stirring element alone case.
REFERENCES


References


37) Ibid. pp. 7


45) Ibid. pp. 13, 14

46) Ibid. pp. 35


60) Ibid. pp. 193,194