Characterizing Smelt Shattering in Recovery Boilers

by

Ziqi Lin

A thesis submitted in conformity with the requirements for the degree of Masters of Applied Science
Department of Mechanical and Industrial Engineering
University of Toronto

© Copyright by Ziqi Lin 2014
Characterizing Smelt Shattering in a Recovery Boiler

Ziqi Lin

Masters of Applied Science

Department of Mechanical and Industrial Engineering
University of Toronto

2014

Abstract

In a kraft chemical recovery boiler, smelt is shattered into thousands of small droplets by one or more high pressure steam jets to increase smelt dissolution rate and reduce the likelihood of dissolving tank explosion. The safety implications of dissolving tank explosion due to inadequate smelt shattering dictate in-depth study of this phenomenon. An experimental apparatus was used to simulate the smelt shattering process using water as molten smelt and air as steam. The objective is to study gas-liquid interaction and to create guidelines for safer and more efficient smelt shattering operation. Experimental results showed that mean droplet size decreases when impingement distance is decreased and gas flow rate is increased. The atomization performance varies between different nozzle geometries and the atomization efficiency can be improved by changing the impingement angle.
Acknowledgments

I would like express my deepest gratitude for Professor Honghi Tran and Professor Bussmann for making me to be part of such a prestigious research group, and supervising me throughout this project. Their patience, support and encouragement were monumental in bringing this project into fruition.

I would also like express my deepest gratitude for Professor Andy Jones for taking his time and providing me the opportunity to tour the International Papers®, Texarkana Mill. This visit helped me tremendously in understanding my research objectives.

I would like to thank my colleagues and friends from the Chemical and Energy Lab: Atif, Liming, Eric, Hugo, Vitor, Jordan, Naz, Masoumeh, Sue, Carolyn, Anna, Wei, Shahed for their support and company during my research years; and especially Anton for his time and patience in his research carryover.

I also would like thank all the consortium members and NSERC for supporting this research opportunity and making this study possible.

Lastly, I could like to extend my appreciation to my parents for their constant support throughout my Masters program.

This thesis work was conducted as part of the research program on “Increasing Energy and Chemical Recovery Efficiency in the Kraft Process - III”, jointly supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and a consortium of the following companies: Andritz, AV Nackawic, Babcock & Wilcox, Boise, Carter Holt Harvey, Celulose Nipo-Brasileira, Clyde-Bergemann, DMI Peace River Pulp, Eldorado, ERCO Worldwide, Fibria, FP Innovations, International Paper, Irving Pulp & Paper, Kiln Flame Systems, Klabin, MeadWestvaco, StoraEnso Research, Suzano, Tembec, Tolko Industries and Valmet”.

iii
# Table of Contents

Acknowledgments .......................................................................................................................... iii

Table of Contents .......................................................................................................................... iv

List of Tables .................................................................................................................................. vi

List of Figures ................................................................................................................................. vii

1 Introduction ................................................................................................................................. 1
   1.1 Kraft Recovery Process ......................................................................................................... 1
   1.2 Smelt Shattering ...................................................................................................................... 4
   1.3 Research Objectives ............................................................................................................... 10

2 Literature Review .......................................................................................................................... 11
   2.1 Fundamental Atomization Concepts ...................................................................................... 13
   2.2 Empirical Relations for Gas Atomization ............................................................................. 15
   2.3 Gas-Liquid Atomization Application .................................................................................... 18
   2.4 Factors affecting droplet size distribution ......................................................................... 19
   2.5 Data Collection Techniques ................................................................................................. 21

3 Experimental Setup and Methodology ......................................................................................... 24
   3.1 Experimental Design ............................................................................................................ 25
   3.2 Experimental Setup ............................................................................................................... 31
   3.3 High-Speed Imaging ............................................................................................................. 33
   3.4 Data Processing Techniques ................................................................................................. 35

4 Results and Discussion .................................................................................................................. 37
   4.1 Effect of Nozzle Geometry .................................................................................................... 38
   4.2 Effect of Gas Flow Rate ........................................................................................................ 47
   4.3 Effect of Impingement Distance .......................................................................................... 55
   4.4 Effect of Impingement Angle .............................................................................................. 60
4.5 Comparing Experimental Data with Empirical Correlations ......................................... 66

5 Conclusions .................................................................................................................................................. 68

5.1 Implications and Recommendations for Future Work ................................................................. 70

6 References .................................................................................................................................................... 71
List of Tables

Table 3-1: Nozzle geometries used in the experiments. ................................................................. 28

Table 3-2: List of experimental parameters ..................................................................................... 30
List of Figures

Figure 1-1: The Kraft Recovery Cycle. [1] .......................................................... 2

Figure 1-2: A recovery boiler with the dissolving tank located at the base. [1] ....................... 2

Figure 1-3: Smelt spouts: (a) water cooled spout, (b) dry spout. [5] ................................. 5

Figure 1-4: Smelt atomization (a) front view, (b) top view. [5] ......................................... 6

Figure 1-5: Documented dissolving tank explosion incidents. [6] ..................................... 7

Figure 1-6: Examples of industry used shatter jet nozzles: (a) full cone, (b) flat with guard, (c) multi-hole, (d/e) slit. [5] ......................................................................................... 9

Figure 2-1: Liquid sheet disintegration stages: (a) stable sheet, (b) growth of waves in sheet, (c) ligament formation, (d) ligament breakdown. [15] ................................................................. 13

Figure 3-1: Experimental apparatus. [6] ........................................................................... 24

Figure 3-2: The smelt shattering process and the parameters studied. L represents impingement distance. θ represents impingement angle ............................................................... 25

Figure 3-3: Two consecutive video frames used to measure the smelt velocity. Picture taken from Texarkana Mill, International Paper®. ................................................................. 27

Figure 3-4: Schematic of lab scale experimental apparatus .................................................. 31

Figure 3-5: Imaging matrix (for illustration purpose) ......................................................... 32

Figure 3-6: ImageJ image processing steps ......................................................................... 34

Figure 3-7: Top view of TecplotTM 2D contour plots ......................................................... 35

Figure 3-8: Sample droplet size distribution graph. (Y-axis values have 1000x multiple factor) 36

Figure 4-1: Front view droplet atomization profiles for different gas nozzle geometries. Flowrate = 10 SCFM flow rate, impingement distance = 7" .......................................................... 39
Figure 4-2: Effect of nozzle geometry on the droplet SMD, droplet count and droplet volume distribution. ............................................................................................................................................................................. 40

Figure 4-3: Total imaged droplet volume vs droplet diameter for different nozzle geometries. 10 SCFM gas flow rate and 7 in impingement distance. (Y-axis values have 1000x multiple factor) ............................................................................................................................................................................................................................................. 43

Figure 4-4: Total imaged droplet volume vs droplet diameter for different nozzle geometries. 15 SCFM gas flow rate and 5 in impingement distance. (Y-axis values have 1000x multiple factor) ............................................................................................................................................................................................................................................. 43

Figure 4-5: Droplet count vs droplet diameter, for different nozzle geometries. 10 SCFM gas flow rate and 7 in impingement distance. (Y-axis values have 1000x multiple factor) ............ 44

Figure 4-6: Droplet count vs droplet diameter, for different nozzle geometries. 15 SCFM gas flow rate and 5 in impingement distance. (Y-axis values have 1000x multiple factor) ............ 44

Figure 4-7: Sample image for the full cone nozzle at 15 SCFM and 5 in impingement distance. Many small droplets are observed, but cannot be analyzed due to low image resolution. ........... 46

Figure 4-8: Shattering profiles for the hollow cone nozzle at different pressures and gas flow rates. ............................................................................................................................................................................................................................................................................................................. 49

Figure 4-9: Effect of gas flow rate on the droplet SMD, droplet count and droplet volume distributions at 7 in impingement distance, vertical nozzle orientation............................................................ 50

Figure 4-10: Droplet SMD as a function of gas flow rate at 7 in impingement distance. ............ 52

Figure 4-11: Total imaged droplet volume vs droplet diameter for different gas flow rates. Hollow cone nozzle at 7 in impingement distance. (Y-axis values have 1000x multiple factor). 53

Figure 4-12: Total imaged droplet volume vs droplet diameter for different gas flow rates. Wide-airflow nozzle at 7 in impingement distance. (Y-axis values have 1000x multiple factor)........... 53

Figure 4-13: Effect of impingement distance on the droplet SMD, droplet count and droplet volume distributions, at 10 SCFM gas flow rate. ............................................................................................................................................................................................................................................................................................................. 56
Figure 4-14: Droplet SMD as a function of impingement distance at 10 SCFM gas flow rate.... 58

Figure 4-15: Total imaged droplet volume vs droplet diameter for different impingement
distances. Hollow cone nozzle at 10 SCFM gas flow rate. (Y-axis values have 1000x multiple
factor)........................................................................................................................................... 58

Figure 4-16: Total imaged droplet volume vs droplet diameter for different impingement
distances. Wide-airflow nozzle at 10 SCFM gas flow rate. (Y-axis values have 1000x multiple
factor)........................................................................................................................................... 59

Figure 4-17: Effects of IA on the droplet SMD, droplet count and droplet volume distributions at
10 SCFM gas flow rate and 7 in impingement distance, for the hollow cone nozzle. The Black
circle represents the nozzle position. .......................................................... 61

Figure 4-18: Effects of IA on the droplet SMD, droplet count and droplet volume distributions at
10 SCFM gas flow rate and 7 in impingement distance, for the wide-airflow nozzle. .......... 62

Figure 4-19: Droplet SMD as a function of IA at 10 SCFM gas flow rate for the hollow cone
nozzle and 15 SCFM gas flow rate for the wide-airflow nozzle, both at 7 in impingement
distance. ........................................................................................................................................ 64

Figure 4-20: Total imaged droplet volume vs droplet diameter for different IAs. Hollow cone
nozzle at 10 SCFM gas flow rate and 7 in impingement distance. (Y-axis values have 1000x
multiple factor).................................................................................................................................. 65

Figure 4-21: Total imaged droplet volume vs droplet diameter for different IAs. Wide-airflow
nozzle at 15 SCFM gas flow rate and 7 in impingement distance. (Y-axis values have 1000x
multiple factor).................................................................................................................................. 65

Figure 4-22: Mean diameter vs gas flow rate for different correlations. .................................. 66
1 Introduction

Chemical recovery is a major operation in kraft pulping process, where waste chemicals used in the pulping process are converted back to pulping chemicals. The kraft recovery processes [1] have many different operations, some of which are considered very dangerous and require in-depth understanding. Smelt shattering, amongst these processes, is the focus of this thesis. This chapter discusses the kraft recovery process, the smelt shattering process, and the motivations and objectives of this research.

1.1 Kraft Recovery Process

There are two predominant methods of making wood pulp: mechanical pulping and chemical pulping. Amongst chemical pulping, the kraft pulping is the most widely used since it can extract very fine wood fibers, which are essential for making high strength paper products.

In the kraft pulping process, trees are first debarked and shredded into wood chips, and then converted into wood pulp in a digester, using pulping chemicals called white liquor. White liquor is an aqueous solution of sodium hydroxide (NaOH) and sodium sulfide (Na$_2$S). Wood is dissolved in the white liquor into cellulose fibrous material that will be further processed into pulp for papermaking. The remaining mixture of organic material (lignin) and inorganic material (spent pulping chemical), called black liquor, enters a kraft recovery cycle shown in Figure 1-1. The black liquor first enters evaporators and concentrators to obtain 72% solid content, before entering the recovery boiler to burn the non-fibrous organic material, like lignin, to produce energy. A recovery boiler schematic is shown in Figure 1-2. The inorganic component of the heavy black liquor collects on the char bed at the bottom of the recovery boiler and reacts with carbon dioxide and sulfur to form sodium carbonate (Na$_2$CO$_3$) and sodium sulfide (Na$_2$S), also known as smelt. [2]
Figure 1-1: The Kraft Recovery Cycle. [1]

Figure 1-2: A recovery boiler with the dissolving tank located at the base. [1]
The molten smelt then flows out of the bottom of the recovery boiler through a number of smelt spouts to ensure sufficient drainage. The outflowing smelt stream is shattered into small droplets using one or more high pressure steam jets before falling into a dissolving tank. The smelt dissolves in water to form a solution called green liquor which is then directed to the causticizing plant to convert Na$_2$CO$_3$ to sodium hydroxide (NaOH). [1] The resulting mixture of NaOH and Na$_2$S is white liquor, which is used to process more wood chips.
1.2 Smelt Shattering

The focus of this thesis is the smelt shattering process. The remainder of this chapter presents different facets of smelt shattering, and the motivation for this research.

Molten smelt has a density of about 2000 kg/m\(^3\) and a surface tension of 0.21 N/m. [3] It is composed of about 2/3 Na\(_2\)CO\(_3\) and 1/3 Na\(_2\)S, with small amounts of sodium sulfate, sodium chloride, potassium carbonate, potassium sulfide, potassium sulfate, and potassium chloride. [4] Smelt has a freezing point of about 750\(^\circ\)C and is fluid when molten. The temperature of molten smelt inside the recovery boiler is about 800\(^\circ\)C. [5] The temperature of smelt can be gaged by appearance, as higher temperature smelt has a brighter red glow.

Approximately 40\% of the black liquor dry mass is converted into smelt. [4] Per smelt spout, smelt flows out of the boiler at a rate of approximately 1 liter per second, and falls into the dissolving tank. [5] However, the smelt flow rate can increase in a smelt run-off condition (an unusual surge in smelt flow), or when a plugged smelt spout is cleared.

**Figure 1-3** illustrates two types of smelt spouts. A U-shaped smelt spout is most commonly used, with heat exchangers inside the lips to cool the spout in order to prevent corrosion and extend operating life. However, not all spouts are cooled and the ones that are not are called “dry” spouts. The spouts are often made of carbon steel, but some mills are using newer materials due to corrosion issues at the smelt-no smelt interface located at the tip of the spout lip.
Figure 1-3: Smelt spouts: (a) water cooled spout, (b) dry spout. [5]

Just outside the smelt spouts, one or two high pressure steam jets are used to shatter/atomize each smelt stream, before it falls into the dissolving tank. **Figure 1-4** illustrates smelt atomization. Steam is used instead of compressed air to prevent the oxidization of smelt, which changes it from sulfide to sulfate, which cannot be converted back to white liquor. Smelt is atomized before falling into the dissolving tank for two reasons: to increase the dissolution rate by increasing the surface area, and to minimize the intensity of vapour explosions due to smelt-water interaction.
When the 800°C smelt spray falls into water in the dissolving tank, water vapour forms instantly at the contact point between smelt and water. This sudden expansion in volume is a vapour explosion, which poses a significant safety concern. Even normal dissolving tank operation is very loud and violent. When smelt shattering is ineffective: when the steam flow rate is reduced, or the smelt flow rate increases, or the viscosity of the smelt increases, dissolving tank operation becomes more violent. In severe cases, a so-called “dissolving tank explosion” can occur, causing substantial equipment damage, production loss associated with an unscheduled boiler shutdown, and even personnel injury.

Over the past 30 years, about one explosion incident has been reported in North America each year [6], although other less catastrophic incidents likely go unreported. Figure 1-5 shows the occurrence of documented dissolving tank explosions since 1973. Despite the importance of safety, the pulp industry has not focused much attention on smelt shattering, which is not well understood. This study of smelt shattering will help define best practices for this industry.
Figure 1-5: Documented dissolving tank explosion incidents. [6]

The exact cause of dissolving tank explosions is not very well understood. It is likely due to insufficient atomization of smelt, which results in a large amount of smelt rapidly interacting with water within a small volume, leading to a severe vapour explosion. Recently, another member of the Energy and Chemical Recovery research group at the University of Toronto conducted an experiment to monitor the sound intensity of the dissolving tank with the shatter jets turned on and off. The results show that turning off all the shatter jets leads to an immediate increase of 3 dB in sound intensity, representing a doubling of sound energy. Thus, without sufficient smelt atomization, the dissolving tank operation quickly becomes more violent.

During the operation of a boiler, there are a number of reasons why smelt atomization can perform poorly; some of them include [5]:

- At the start-up of a recovery boiler, after a shut-down, the char bed may include a large quantity of char floating in molten smelt. These lumps of char can plug a spout opening, causing an accumulated smelt surge after the char is cleared. The shatter jet may not be able to sufficiently atomize the high volume smelt flow. The char may also change the
chemical properties of smelt, causing it to become more viscous and more difficult to atomize.

- Visibly slower jelly roll smelt flow, caused by low temperature or high viscosity is more difficult to atomize using the steam jet. The change in viscosity is due to contamination from char and soot.
- Low smelt flow rate results in the smelt stream wiggling sideways, often falling into the dissolving tank without sufficient atomization. Slow smelt flow, caused by either low volume flow or spout plugging, may flow after the end of the spout in such a way that the steam jet completely misses it.
- The steam jet may get plugged over a long period of operation due to residual smelt and green liquor splashing. As the jet plugs, the atomization efficiency decreases, leading to poor shattering performance.

It is imperative to ensure that smelt is sufficiently atomized before falling into the dissolving tank, to reduce the likelihood of a severe dissolving tank explosion.

Unfortunately smelt atomization practices vary significantly between pulp mills, as there is no standard configuration, or guidelines for smelt shattering.

Shatter jet nozzle geometries and placement location also vary between pulp mills. Figure 1-6 shows different shatter jet nozzles used at different pulp mills. There are round profile nozzles shown in Figure 1-6 (a) and (b), the multihole nozzle in Figure 1-6 (c), and slit profile nozzles in Figure 1-6 (d) and (e). Different nozzles are designed for different nozzle locations relative to the spout, and each has their own advantages and disadvantages. For example, the nozzle in Figure 1-6 (b) is constructed to protect it from smelt build-up, but this design makes it more difficult to access the nozzle orifice should it become plugged. Round profile nozzles are considered more efficient since the total orifice area is much smaller, leading to a reduction in steam flow rate. The slit profile nozzle can cover a wider area, allowing smelt to be atomized even if there is a misalignment between the nozzle and the smelt stream.
Figure 1-6: Examples of industry used shatter jet nozzles: (a) full cone, (b) flat with guard, (c) multi-hole, (d/e) slit. [5]

The number of shatter jet nozzles per spout, and how the nozzles are positioned, also varies between different pulp mills. Some mills install the nozzles above the smelt stream and direct the steam downwards either vertically or at a slight angle. Other mills position the shatter jet below the spout, so that the steam is directed towards the smelt stream and the boiler wall. The shatter jet steam pressure can range between 3.5 bar (50 psi) to 15.5 bar (225 psi), while steam temperature ranges between 150°C to 250°C. [7] Quoted steam consumption rates range between 180 kg/hour (400 lbs/hour) to 2250 kg/hour (5000 lbs/hour), depending on the scale of smelt production and the size of the boiler. [5]
1.3 Research Objectives

The research conducted for this thesis follows on that of Taranenko [5], who constructed a lab-scale apparatus to study cross-flow smelt atomization using air/water-glycerin mixtures and a simple round nozzle. Taranenko showed that increasing air velocity and nozzle proximity decreases average droplet size, and increasing water flow rate increases average droplet size. Viscosity does not have a significant effect on the droplet size, unless a weak jet is used to shatter a highly viscous fluid.

The objectives of the research presented here are to: (i) develop a standard methodology to capture droplet size distribution using automated image analysis, and (ii) provide recommendations and guidelines to industry on smelt shattering practice. Improvements were made to the existing apparatus in order to capture droplet size information over a matrix of positions. The improved apparatus was used to examine how the following parameters affect smelt shattering effectiveness:

- Shatter jet nozzle geometry
- Steam flow rate
- Steam impingement proximity
- Steam impingement angle

The nature of smelt atomization must be clearly understood in order to develop guidelines on proper smelt atomization techniques. Chapter 2 of this thesis reviews relevant literature associated with atomization, to identify the key parameters to be studied based on empirical correlations developed in other studies, and the expectations of the experimental results. Chapter 3 presents the experimental apparatus and the methodology of droplet analysis. Chapter 4 presents experimental results, and Chapter 5 concludes the thesis and presents recommendations for future work.
2 Literature Review

Atomization is the process by which liquid is disintegrated into numerous smaller droplets or particles. [8] There are many modes of atomization including twin fluid atomization (gas-liquid, liquid-liquid), centrifugal atomization, vacuum atomization, and ultrasonic atomization. [8] Atomization is an important process in many applications including spray combustion in engines, crop spraying, water treatment, spray painting and powdered metallurgy. [9]

Smelt shattering is an example of gas-liquid twin fluid atomization, also called cross-flow atomization [10], similar to processes in the powder metallurgy industry for generating small metallic particles. In gas-liquid atomization, the liquid stream is disintegrated by a high velocity gas jet in either ‘closed-coupled’ or ‘free-fall’ configuration. [8] In closed-coupled configuration, there is no distance between the outlet of the gas and liquid nozzle, whereas in free-fall configuration, the metal stream falls some distance from the nozzle into the confluence of a gas stream that emits from a gas nozzle which is not in contact with the liquid nozzle. In practical industrial atomization operations, a suitable process layout and atomizer design must be derived based on the lowest gas consumption for production of the finest droplets. [11]

In powder metallurgy applications, the mass median diameter, \(d_m\) (Equation 2.1), defined as the average droplet diameter by mass, is often used to characterize atomization. [12] \(d_m\) divides the sample equally by mass, where 50% of a sample mass below \(d_m\) and 50% is above \(d_m\). The Sauter mean diameter (SMD) \(d_{32}\) (Equation 2.2) is also often used, especially when evaporation is important because \(d_{32}\) reflects the same ratio of surface area to mass as that of the whole spray. The use of \(d_{32}\) for spray applications is justified because of its surface area dependency, and can also be used for heat transfer analysis. [13]

\[
d_m = \left( \frac{m_1}{M} d_1 + \frac{m_2}{M} d_2 + \cdots + \frac{m_I}{M} d_I \right)
\]  

(2.1)

\[
Sauter Mean Diameter (SMD) = d_{32} = \frac{\sum_{i=1}^{N} d_i^3}{\sum_{i=1}^{N} d_i^2}
\]  

(2.2)

Where \(m_I\) is the mass of a droplet of diameter \(d_i\), and \(M\) is the total mass.
In this literature review, several facets of cross-flow atomization are presented. First, fundamental atomization concepts and empirical correlation/modeling will be discussed, followed by air-liquid atomization and factors affecting droplet size. Lastly, data collection and droplet analysis techniques will be discussed.
2.1 Fundamental Atomization Concepts

Gas-liquid atomization can take many forms, yet Mehrotra [14] proposes that a fundamental mechanism of droplet formation involves 3 steps:

- The initiation of a sinuous wave which rapidly increases in amplitude;
- Detachment of the wave from the bulk of the liquid to produce a ligament with dimensions that depend on the wavelength at disintegration / (Primary Atomization);
- Break-up of the ligament into spherical droplets / (Secondary Atomization).

![Figure 2-1: Liquid sheet disintegration stages: (a) stable sheet, (b) growth of waves in sheet, (c) ligament formation, (d) ligament breakdown. [15]](image)

Bradley [16] develops a detailed mathematical model for the first two stages of atomization, to describe initiation of a disturbance of wavelength \( \lambda \), and the removal of the ligament. During the first stage of atomization, Bradley stresses that it is necessary to determine the wave number \( k_{\text{max}} \) with the fastest growing amplitude.

In the second stage of atomization, Bradley suggests that the ligament diameter \( D \) is related to the wavelength \( \lambda_{\text{max}} \) by a linear equation:

\[
D = \frac{\omega}{k_{\text{max}}} = \left(\frac{2 \pi}{k_{\text{max}}}\right)
\]  

(2.3)
where $\epsilon$ (on the order of 0.25) is determined from earlier studies on the air atomization of water. Finally, the cylindrical ligament of diameter $D$ breaks up by the Rayleigh instability [17] into a series of spherical droplets such that the predicted diameter, $d$, has a linear correlation:

$$d = \frac{D}{0.53} \quad (2.4)$$

Thus, the predicted droplet diameter is:

$$d = \frac{11.86\epsilon}{k_{\text{max}}} \quad (2.5)$$

Bradley [16,18] also presents a graphical method for evaluating the droplet diameter, for Mach numbers between 0.1 and 0.9, in terms of a dimensionless parameter $L$:

$$L = \frac{k_{\text{max}}\chi}{\rho_g U_g^2} \quad (2.6)$$

where $\chi$ is the surface tension, $\rho_g$ is the gas density, and $U_g$ is the gas velocity. From a dimensional analysis he suggests that the liquid metal viscosity should have negligible effect on the wave development. Combining (2.5) and (2.6) yields the resulting droplet diameter $d$:

$$d = \frac{2.95\chi}{L\rho_g U_g^2} \quad (2.7)$$
2.2 Empirical Relations for Gas Atomization

For a given nozzle design, the specific gas consumption, the ratio of gas consumed (volume or mass) divided by the corresponding liquid atomized (volume or mass), is an important parameter. [19] Data relating $d_m$ to specific gas consumption for several metals shows that $d_m$ decreases as the specific gas consumption $F$ increases: [19]

$$d_m = K F^{-1/2}$$

(2.8)

Where $K$ is a constant.

Dimensional analysis and measurement of atomized powder size lead to many empirical correlations for the prediction of $d_m$. Most have the following properties in common:

1. Mean particle diameter exhibits a log-normal relationship with respect to specific gas consumption and gas velocity;
2. Decreasing liquid flow diameter, increasing specific gas consumption, and increasing the Weber number (thus gas velocity) decreases mean particle diameter;
3. Constants are used to fit the correlations to different nozzle geometries and configurations;
4. Mass flow ratio and liquid stream diameter are factors in almost every correlation.

Some examples of correlations are presented below.

A widely cited example is the Lubanska correlation, established for free-fall gas atomization of metal powders: [20]

$$\frac{d_m}{D_l} = K \left[ \left( \frac{v_l}{v_g We} \right) \left( 1 + \frac{m_l}{m_g} \right) \right]^{1/2}$$

(2.9)

Where $D_l$ is the liquid metal stream diameter, $v_g$ is the kinematic viscosity of the gas, $v_l$ is the kinematic viscosity of the liquid metal, $We$ is the Weber number of the atomizing gas, $m_l$ is the mass flow rate of liquid metal, $m_g$ is the mass flow rate of gas, $K$ is a constant. The Weber number is defined as:
Where, $\Delta v$ is the difference between the gas and liquid velocities at the atomization point, $\sigma$ is the surface tension of the liquid, and $\rho_l$ is the liquid density.

The Lubanska correlation includes all relevant parameters influencing the droplet size distribution, correlates these parameters principally in the correct manner, and assembles these parameters in the correct order. The proportionality between the mass median diameter and the diameter of the melt stream means that finer particles can be achieved by reducing the melt stream. The dependency of $d_m$ on the mass flow ratio of liquid to gas means that a reduction of the melt mass flow or enhancement of gas mass flow leads to a shift of the size distribution to finer particles. Third, the dependence of $d_m$ on Weber number means that a higher gas velocity will produce smaller particles. [11]

The $K$ value in the Lubanska correlation accommodates different atomizer designs. Kramer [21] and Tillwick [22] found $K$ of 112 and 140 for different inclination angles of the nozzle. The Lubanska correlation offers valuable and uncomplicated direction as to how the process parameters work and what must be changed to modify the size distribution. [11]

Tornberg [23] proposes an alternative approach based on impact force and work in inert gas atomization, and derives the following relation for the average droplet diameter $d$:

$$d = \sqrt[3]{\frac{A \sigma}{\mu_l m g_l g (1-B \mu_l D_l)}}$$  \hspace{1cm} (2.11)

Where $\mu_l$ is the dynamic viscosity of the liquid, and $A$ and $B$ are atomizer-specific constants. The model accurately predicted experimental results for powder particle size in two atomization facilities. [23]

Ingebo [24] uses the Weber number to correlate drop size to the product of the Weber number and Reynolds number based on the orifice diameter using the following equation:

$$\left(\frac{D_L}{d_m}\right) = c_o (WeRe)^m$$  \hspace{1cm} (2.12)
Re is the Reynolds number, We is the weber number, $c_0$ and $m$ are constants. The Reynolds number is defined as:

$$Re = \frac{\rho N D}{\mu} \quad (2.13)$$
2.3 Gas-Liquid Atomization Application

Droplet formation is a result of momentum and energy exchange between a gas jet and a liquid stream; improved droplet formation is due to the efficiency of: [11]

- Increased gas kinetic energy (velocity) associated with an increased gas pressure
- Improved gas nozzle design
- Sensitive adjustment of the flow fields of the gas jets and the liquid stream

Twin fluid atomization covers all techniques which use the pressure energy of a fluid to atomize liquid. There are two types of twin fluid atomization: internal mixing and external mixing. Internal mixing gives optimum spray quality as high velocity gas commences mixing with liquid inside the nozzle and requires less gas supply. [27] In external mixing atomization, there are essentially two separate nozzle systems, for the melt and gas, and the atomization takes place where these meet, outside the nozzle assembly, resulting in larger droplets than internal mixing [27,28]

There are two types of external mixing atomization configurations: close-coupled and free-fall. In the closed-coupled configuration, there is no distance between the outlets of the gas and liquid nozzles, whereas in the free-fall configuration, the liquid stream falls some distance from the nozzle into the confluence of the gas stream emitted by a gas-nozzle which is not in contact with the liquid nozzle. [28] Because the gas velocity decays rapidly with increasing distance from the nozzle, the closed-coupled configuration realizes a closer coupling of the gas and the liquid streams, and raises the efficiency of momentum exchange, thus reducing the particle size. [11]
2.4 Factors affecting droplet size distribution

In many cases, gas velocity is the fundamental variable affecting $d_m$ in twin fluid atomization. [29] Other variables such as the liquid and gas flow rate, the liquid and gas pressure, fluid momentum, atomizer geometries and the relative position of the liquid and gas streams are not primary parameters. However, they do affect particle size by influencing the gas velocity. [12,29,30] For most atomizers, only a small portion of the input energy is used to provide the theoretical energy requirement for droplet formation. Fictional and other losses occur but most of the energy actually provides the spray with kinetic energy. [27] Therefore, it is important to optimize the efficiency of transfer of kinetic energy of the atomizing gas to the liquid stream.

The following subsections discuss the effects these parameters have on the droplet size distribution, from past studies in powder metallurgy.

**Effect of Temperature**

In some cases, the melt temperature can affect the particle size distribution. [31,32] As surface tension and viscosity decrease with increasing temperature, this can shift the particle size distribution to smaller diameters.

**Effect of Impingement Distance**

The aerodynamic force driving the droplet breakup process is the product of the gas density and the velocity difference squared, a quantity referred to as the dynamic pressure. The Weber number expresses the relative influence of the dynamic pressure of the gas stream that tends to destabilize the droplet to the liquid surface tension which resists deformation and breakup. The Weber number has an important influence on droplet breakup based on the magnitude of the dynamic pressure. [33] Fritsching [34] performed numerical simulations of the centerline gas flow field of converging-diverging gas nozzles, showing a significant decay in gas kinetic energy with distance from the nozzle.

Impingement distance and dynamic pressure play important roles in the secondary atomization stage, where molten droplets are disintegrated into fine powders along the length of the gas jet.
Short impingement distance and large dynamic pressure improve the chances for thorough secondary breakup and smaller average particle size. [33] Due to the low density of air/steam, the kinetic energy of the gas stream will quickly dissipate upon exiting the nozzle.

Rai, Lavernia and Grant [35] investigated the effect of gas pressure on the particle size distribution and confirm that $d_m$ decreases with increasing gas pressure and reduces the standard deviation of powder diameter. The value of the standard deviation generally decreases as $d_m$ decreases.

**Effect of Flow Rate and Geometry**

The gas/liquid mass-flow ratio is in many cases the most important factor that determines the droplet size. [36] It is also important to maximize the relative gas-liquid velocity in the break-up zone, and maximize the gas density if possible. [27] Increasing the feed rate of liquid or decreasing the atomizing fluid pressure will increase the mean particle size. Other factors include the momentum of the jet and the accuracy with which the gas stream is directed onto the center of the liquid stream. [37]

Laird proposed the following relationship between particle size and liquid/gas flow rate [38]:

$$d_m = \text{function} \left(\frac{v_{\text{liquid}}}{v_{\text{air}}}\right)$$  \hspace{1cm} (2.16)

Thus, $d_m$ decreases as $v_{\text{liquid}}$ decreases or $v_{\text{air}}$ increases.

Small and Bruce [39] confirmed that water pressure (air pressure equivalent) influences droplet size as:

$$d_m = \ln\left(\frac{P}{A}\right)^n$$  \hspace{1cm} (2.17)

$n$ and $A$ are constants and $P$ is the gas pressure. Therefore the droplet size decreases as $P$ increases.

A shallower gas jet impingement angle has been observed to produce smaller droplet diameters. [40]
2.5 Data Collection Techniques

Numerous techniques have been developed for particle/droplet collection and analysis, including: particle velocity lag, microscope and image analysis, light-scattering/absorption, light-scattering from diffraction, fast in-flight particle image/shadow techniques, laser Doppler anemometry, and electric signals due to particle blocking orifice. [41]

Fast in-flight particle imaging, also termed photomicrography, refers to microscopy techniques which measure magnified images of particles. Imaging techniques are relatively straightforward and the sizes and features of particles are measured in an essentially unambiguous way so that there are few approximations to contend with. However, there are some practical limitations: [41]

1. One is examining each particle at only one orientation;
2. It is not always clear whether some particles are agglomerates or individual particles touching each other.

Other imaging techniques include: direct observation, high magnification, high-speed camera, interferometry, light scattering and laser Doppler. [41]

When collecting samples within the spray itself, it is important to ensure that measurements are representative of the whole process and not providing misleading information on localized conditions. A matrix of positions must be used for non-axisymmetric sprays. Measurements must be combined in correct proportions according to the cross-sectional area of the spray and the mass flux. [41]

When determining the magnification, it is important to know that setting the magnification to see the smallest particles can mean that only parts of larger particles are in focus. Sufficient particles should be observed to make observations valid. Increasing the field of view will increase the number of particles per image, but sacrifice image resolution.

In digital image analysis, an image is divided into discrete pixels, with brightness calibrated by discretizing the intensity from black to white in many grey levels. Software can improve image
quality using enhancement techniques to remove background light intensity variations, and sharpen the images of particles which are not in focus. [41]

**Particle Size Analysis**

Most atomized droplets exhibit a Gaussian size distribution, in which case there is a linear relation between particle size and cumulative weight fraction when the data are plotted on a log-normal graph. [11,12] According to Unal and Yule [13,42], twin fluid atomization yields a fairly broad particle size distribution (\( \sigma_{LN} = 1.9\text{-}2.3 \)) for well-designed gas atomizers.

Mean diameters and size distributions are quantified using a probability density function, also known as the number distribution of particle diameter, as well as the mass or volume of particles as a function of diameter: [15]

\[
n(D) = \lim_{N \to \infty} \left( \frac{\text{No.of particles between } D - \frac{\Delta D}{2} \text{ and } D + \frac{\Delta D}{2}}{\Delta DN} \right)
\]

\[
V(D) = \lim_{N' \to \infty} \left( \frac{\text{No.of particles between } D - \frac{\Delta D}{2} \text{ and } D + \frac{\Delta D}{2}}{\Delta DV} \right)
\]

(2.18) (2.19)

n is the number distribution, and V is the volume distribution.

The classical statistical mean value \( D_{10} \) is seldom used because parameters related to the volume or mass of particles as a function of diameter are of more relevance.

Errors in particle size distribution measurements depend on:

1. The accuracy of the instrument;
2. The accuracy of a sample in representing the spray;
3. The statistical or ‘counting’ error.

A count of 4000 particles is sufficient to give \( \pm 2 \) percent accuracy throughout cumulative number distribution. [13]

Atomized particles may be non-spherical. A non-spherical particle may be compared to an equivalent sphere which has an equal value of the one of the following: projected area, surface area, or volume. The projected area is measured using an imaging technique.
According to Allen [43], the equivalent diameter on the basis of projected area best represents the true cross-sectional area of a droplet: [13]

\[ DeA = \left( \frac{4A}{\pi} \right)^{1/2} \]  

(2.20)
3 Experimental Setup and Methodology

This section presents an overview of the experimental setup and methodology used. A lab scale apparatus originally constructed by Taranenko [6] was used to study smelt-steam interaction using water and air as proxies. (Figure 3-1) The apparatus was designed to reflect a quarter scale version of an actual recovery boiler smelt shattering operation. A series of experiments were conducted to study the effects of nozzle geometry, impingement angle (IA), impingement distance and gas flow rate. A direct optical imaging technique using a high speed camera and image analysis software was used to capture, process and measure the droplet size information. Details of the methodology are described below.

Figure 3-1: Experimental apparatus. [6]
3.1 Experimental Design

Many factors affect smelt shattering effectiveness, including smelt viscosity, smelt flow rate, spout inclination angle, steam velocity, shatter jet placement and orientation, and nozzle geometry. Some of these parameters, such as spout inclination angle and smelt flow rate, cannot be adjusted in an actual recovery boiler and so were kept constant. The parameters that were studied can be adjusted in an actual recovery boiler: **nozzle geometry, steam flow rate, impingement distance and impingement angle**. The impingement distance (L) is the distance between the shatter jet nozzle exit and the point of contact between the gas and liquid streams. The impingement angle (θ) is the angle between the gas stream and the liquid stream at the point of contact. (Figure 3-2) This section examines these parameters in detail.

![Figure 3-2: The smelt shattering process and the parameters studied. L represents impingement distance. θ represents impingement angle.](image)

**Non-Variable Parameters**

Several parameters were not changed in the experiments. These non-variable parameters include **liquid viscosity, liquid flow rate and spout inclination angle**. The effect of liquid viscosity on atomization was studied by Taranenko [6] who concluded that atomization effectiveness is
independent of liquid viscosity unless a highly viscous liquid is shattered with a weak jet. The experiments described in this thesis were, therefore, conducted using pure water. The spout inclination angle was set to 15°, which is a common value used by the industry.

The liquid flow rate set in the experiment reflects a scaled down equivalent of a typical recovery boiler value. To correctly correlate the smelt-steam interaction to the laboratory experiment, the ratio of liquid to gas phase momentum is considered.

$$q = \frac{u_L^2 \rho_L}{P_{gas}}$$  \hspace{1cm} (3.1)

Where: \(u_L\) = liquid velocity, \(\rho\) = liquid density, \(P_{gas}\) = gas phase supply pressure.

To accurately represent the momentum/kinetic energy transfer between the liquid and gas phases, the experimental setup must have a similar momentum ratio:

$$q = \left(\frac{u_L^2 \rho_L}{P_{gas}}\right)_{Industry} = \left(\frac{u_L^2 \rho_L}{P_{gas}}\right)_{Experiment}$$  \hspace{1cm} (3.2)

Two methods were used to determine the smelt velocity: geometric analysis and video analysis.

**Geometric Analysis:** The geometric analysis determines the velocity by dividing the smelt flow rate by the cross-sectional area of the smelt flowing down the spout. Black liquor firing rate data was obtained from the Recovery Boiler #1 in Mill A. Recovery boiler #1 has 3 smelt spouts.

Using equation (3.3), the average smelt flow rate (SFR) down a single spout was determined to be approximately 0.9 L/s:

$$SFR = \frac{\alpha \Phi}{\chi \times \# \ of \ Spouts}$$  \hspace{1cm} (3.3)

SFR is smelt flow rate, \(\alpha\) is black liquor dry solids firing rate, \(\Phi\) is smelt to dry solids ratio (0.45), and \(\chi\) is specific volume of smelt (120 ft³/lb).

The smelt velocity \(V_s\) can be determined by dividing the smelt flow rate by the cross-sectional area \(A\):

$$V_s = \frac{SFR}{A}$$  \hspace{1cm} (3.4)
The cross-sectional area can be approximated by considering a trapezoidal-shaped spout geometry:

\[ A = \frac{1}{2} \times h \times (a + b) \]  

(3.5)

Using equation (3.3) and (3.4), the velocity was determined to be 1.86 m/s.

**Video Analysis:** The video analysis measures the smelt velocity by tracking a point of interest between two consecutive video frames.

![Two consecutive video frames](image)

**Figure 3-3:** Two consecutive video frames used to measure the smelt velocity.


\[ V_s = \frac{\Delta d}{\Delta t} \]  

(3.6)

**Figures 3-3** were taken in Mill A, Recovery Boiler #1. The difference in distance is approximately 2.5 in and the time between frames is 0.034 seconds. Using **Equation 3.6**, the velocity was determined to be 1.87 m/s.

Returning to Equation 3.2, the laboratory air pressure between 15 psig to 50 psig for different nozzle geometries and gas flow rates was found to correspond to the liquid flow rates between 0.146 L/s to 0.266 L/s. Since the liquid flow rate will be maintained as constant, the liquid flow rate was chosen to be 0.2 L/s, approximately the average of these two values.
**Variable Parameter:**

**Nozzle Geometry**

One of the objectives of this research was to determine the implication of nozzle geometry on the liquid shattering effectiveness. Different nozzle profiles are expected to have a different effect on the shattering performance. There is no standard shatter jet nozzle for smelt shattering operation, as designs and sizes vary significantly. **Figure 1-6** shows different shatter jet nozzles used in the industry.

Broadly speaking, there are two types of gas jet profiles: round profile and slit profile. The nozzles used in this study reflect the geometries of real industry nozzles, but scaled down. Four different nozzle geometries were used: full cone, hollow cone, wide-airflow and flat. Specifications of these nozzles are presented in **Table 3-1**.

**Table 3-1:** Nozzle geometries used in the experiments.

<table>
<thead>
<tr>
<th>Nozzle Type</th>
<th>Image</th>
<th>Spray Profile</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hollow Conical</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td>Inlet: ¼” Male Material: Aluminum Length: 1 7/8” Consumption: 15 cfm (air) @ 100 psi</td>
</tr>
<tr>
<td>Full Cone</td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
<td>Inlet: ¼” Male Material: Brass Length: 1 1/16” Consumption: 1.5 gallon (water) per minute at 40 psi Angle: 60 degrees Orifice diameter: 0.10”</td>
</tr>
<tr>
<td>Flat</td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
<td>Inlet: ¼” Male Material: Brass Length: 1 7/8” Consumption: 4.0 gallon (water) per minute at 40 psi Notch Angle: 65 degrees Orifice diameter:</td>
</tr>
</tbody>
</table>
**Steam Flow Rate**

In a typical recovery boiler operation, the steam used for smelt shattering is at around 400 °F with nozzles using 500-750 lbm/hr at 150 psig. The density of steam at this condition is 0.31 lb/ft³.

Using **Equation 3.2**, the liquid flow rates (industrial and experimental) and the steam pressure, the average gas flow rate for the experiment is between 10 and 15 SCFM to reflect a similar momentum to that seen in the industry.

**Impingement Distance**

The impingement distance is the distance between the gas nozzle exit and the point of contact with the liquid stream. The distance between the nozzle exit and point of impingement on the smelt stream is about 2.5 feet (30 in). At a quarter scale, this distance converts to 7 in. To assess the effect of impingement distance, a range from 5 in to 9 in was selected.

**Impingement Angle**

The impingement angle (IA) is the angle between the liquid stream and the gas stream. To investigate the effect of different IAs, the gas nozzle was oriented downwards 85° to 92.5° from the horizontal, facing the spout. As result, the IA varies between 35° to 60°. Angles larger or smaller will potentially impact the spout or miss the target smelt stream.

**Table 3-2** summarizes all of the experimental parameter values evaluated in this study.
**Table 3-2: List of experimental parameters**

<table>
<thead>
<tr>
<th>Non-variable Parameters</th>
<th>Liquid Flow Rate</th>
<th>Liquid Viscosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spout Inclination</td>
<td>0.2 L/s</td>
<td>1 cP</td>
</tr>
<tr>
<td>15°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable Parameters</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle Geometry</td>
<td>Gas Flow Rate</td>
<td>Impingement Distance</td>
</tr>
<tr>
<td>Full Cone</td>
<td>10 SCFM (4.7 L/s)</td>
<td>5 in (12.7 cm)</td>
</tr>
<tr>
<td>Hollow Cone</td>
<td>12.5 SCFM (5.9 L/s)</td>
<td>7 in (17.8 cm)</td>
</tr>
<tr>
<td>Wide-Airflow</td>
<td>15 SCFM (7.1 L/s)</td>
<td>9 in (22.9 cm)</td>
</tr>
<tr>
<td>Flat</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.2 Experimental Setup

![Schematic of lab scale experimental apparatus.](image)

**Figure 3-4:** Schematic of lab scale experimental apparatus.

**Figure 3-4** shows the quarter scale apparatus constructed by Taranenko. [6]

Water is pumped from a base tank to an inclined tank using a 3600 RPM BurCam™ rotary pump, and flows down a 1.5 in diameter acrylic spout back into the base tank. A liquid flow meter is used to set the flow rate. An air nozzle is positioned above the end of the spout to shatter the exiting water stream. The air nozzle is connected to an 80 psig supply line controlled using two ball valves. A pressure gauge and a gas flow meter are used to control the air flow rate. To examine the effect of the impingent angle on liquid atomization, a lock ring adjustment joint is used to control the angle of the nozzle. A light source with a diffuser is placed behind the spray to provide even and sufficient lighting for low exposure setting.

Since the droplet distribution is non-axisymmetric, measurements taken have to be representative of the whole process so that they do not give misleading information on localized conditions. Therefore, a matrix of positions must be used. A Mega-Speed greyscale 512x512 pixel high speed camera was used to capture images of droplets over a 12 x 14 in matrix two feet below the spout. (**Figure 3-5**) The lens used was a Sigma DG 28-300 mm 3.5-6.3f. The lens was set to 200
mm, and aperture size to 3.5, to minimize the depth of field in order to capture only droplets in the focused plane. The depth of field is about 2”, so having the image planes 2” apart completely covers the spectrum of droplets across the 12x14” matrix. The matrix is composed of 42 (6x7) evenly spaced positions, 2” apart from each other in all directions. A grid is placed above the apparatus to identify the coordinates for the 42 imaging locations.

Figure 3-5: Imaging matrix (for illustration purpose).
3.3 High-Speed Imaging

To obtain a representative average droplet diameter at each location, a sufficient number of frames must be captured. A 95% confidence interval is commonly used to determine the required sample size using the following equation:

\[ \text{Required Sample Size} = \left( \frac{z_{\alpha/2} \sigma}{m} \right)^2 \]  (3.7)

\( z_{\alpha/2} \) is the critical value, \( \sigma \) is the estimated standard deviation, and \( m \) is the margin of error.

Margin of error is usually chosen at 0.05% for 95% confidence interval. However, it can also be determined using the formula:

\[ m = \frac{z_{\alpha/2}}{2\sqrt{n}} \]  (3.8)

Trials using prototype sample sizes of 100, 300 and 500 yielded required sample sizes of 576, 451 and 449, respectively. Therefore, a sample size of 500 was deemed sufficient.

Parameters Investigated

The droplet diameter distribution, droplet number distribution and droplet volume distribution are parameters of interest in this experiment. The droplet diameter is a measurement of the average size of individual droplets found at each of the 42 locations. The diameter is determined by the projected area diameter, which best represents the true cross-sectional area of a droplet.

[50] This diameter is then used to determine the Sauter Mean Diameter (SMD) using the equation below. The Sauter mean diameter is most commonly used to study spray and atomization behaviour.

The droplet count is a measure of droplet population density across the plane, and the droplet volume is a measure of mass distribution across the plane.

Droplet images were captured by a high-speed camera 2 feet below the spout. An image analysis macro was developed using ImageJ\textsuperscript{TM} software to convert greyscale images to binary images and filter out-of-focus droplets that cannot be accurately measured. Droplets cut off at the image
border are also removed. Images are dimensionally calibrated before measuring each droplet projected area. Due to the limited resolution of the high speed camera, it is difficult to determine if extremely small droplets are in focus since they only cover a few pixels in area. These droplets are discounted to prevent skewing of data, and only droplets larger than 0.6 mm in diameter are counted and analyzed. See Figure 3-6 for the image processing steps. The average droplet size and count is calculated from 500 images at each of the 42 locations. Additionally, droplets cut off by the frame edge, and some large droplet agglomerations, are also not captured.

Figure 3-6: ImageJ image processing steps.
3.4 Data Processing Techniques

The droplet size distribution data is presented using Tecplot™ to show the Sauter mean diameter distribution, droplet count distribution and droplet total volume distribution per frame across the 42 positions for each test configuration. Figure 3-7 shows a top view of the 6x7 matrix location relative to the spout.

![Figure 3-7: Top view of TecplotTM 2D contour plots.](image)

Droplet distribution graphs are constructed by counting the total number of droplets in different ranges of diameter. Then the total volume for each diameter range, calculated using the trapezoidal rule, is plotted vs diameter. The bin size is set to 0.1 mm diameter. A sample graph is shown in Figure 3-8.
Figure 3-8: Sample droplet size distribution graph. (Y-axis values have 1000x multiple factor)
4 Results and Discussion

This section presents a study of the influence of different parameters on smelt shattering effectiveness. In each case, one parameter was modified while other parameters were kept constant. The effectiveness of liquid atomization is quantified in two ways: droplet size distribution graphs and 2D contour plots.

A droplet size distribution graph displays the total number of droplets, or the fluid volume in different ranges of droplet diameter, for all of the imaged droplets in the 42 position matrix. The area under the curve for the latter graph represents the total fluid volume. The spatial variation of droplet Sauter mean diameter, droplet count and droplet volume are also presented, using 2D contour plots. These plots show where high concentrations of droplet size, count and volume are located spatially.

Each section of this chapter examines a particular parameter. All results in section 4.1, 4.2, and 4.3 were obtained for a 15° spout inclination, 0.2 L/s liquid flow rate, and vertical nozzle orientation. Results in section 4.4 were obtained for a 15° spout inclination, and 0.2 L/s liquid flow rate.
4.1 Effect of Nozzle Geometry

The nozzle geometry is one of the most important parameters to consider as shatter jet nozzles can be easily removed and replaced. The following presents the effect of nozzle geometry on the droplet size distribution. The nozzle profiles and their specifications are found in Table 3-1.

The shattering profiles of the four different nozzle geometries are shown in Figure 4-1. The images were captured using a Canon T3i digital camera with an 18-55 mm IS lens. Images were processed using Paint.net and ImageJ to create binary images of the shattering profiles. All images correspond to the same operating condition of 10 SCFM at 7 in impingement distance and vertical gas nozzle orientation. The spout is located above the figure. At these operating conditions, the hollow cone nozzle and full cone nozzle demonstrate superior performance in liquid atomization over the wide-airflow nozzle and the flat nozzle. Overall, not only do the hollow cone and full cone nozzles produce smaller droplets, but the spread of the droplets is also much wider. For all nozzle geometries, the center region is observed to have the highest concentration of droplets as well as the largest droplets. The velocity is an important parameter in transferring gas kinetic energy to liquid. The velocity at the impingement point is critical in determining shattering effectiveness, and is different across different nozzle geometries.

Figure 4-2 shows and overview of the spatial distribution of Sauter mean diameter, droplet count and volume over the 12 in by 14 in matrix. The four nozzle geometries were tested at two different operating conditions: 10 standard cubic feet per minute (SCFM) at 5 in impingement distance, and 15 SCFM at 7 in impingement distance.
Figure 4-1: Front view droplet atomization profiles for different gas nozzle geometries. Flowrate = 10 SCFM flow rate, impingement distance = 7".
<table>
<thead>
<tr>
<th>Nozzle Geometry</th>
<th>Full Cone</th>
<th>Hollow Cone</th>
<th>Wide-Airflow</th>
<th>Flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Droplet SMD (mm)</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
</tr>
<tr>
<td>10 SCFM 7” Impingement Distance</td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
</tr>
<tr>
<td>15 SCFM 5” Impingement Distance</td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
</tr>
<tr>
<td>Droplet Count per Frame</td>
<td><img src="image13" alt="Image" /></td>
<td><img src="image14" alt="Image" /></td>
<td><img src="image15" alt="Image" /></td>
<td><img src="image16" alt="Image" /></td>
</tr>
<tr>
<td>10 SCFM 7” Impingement Distance</td>
<td><img src="image17" alt="Image" /></td>
<td><img src="image18" alt="Image" /></td>
<td><img src="image19" alt="Image" /></td>
<td><img src="image20" alt="Image" /></td>
</tr>
<tr>
<td>15 SCFM 5” Impingement Distance</td>
<td><img src="image21" alt="Image" /></td>
<td><img src="image22" alt="Image" /></td>
<td><img src="image23" alt="Image" /></td>
<td><img src="image24" alt="Image" /></td>
</tr>
<tr>
<td>Droplet Total Volume per Frame (mm³)</td>
<td><img src="image25" alt="Image" /></td>
<td><img src="image26" alt="Image" /></td>
<td><img src="image27" alt="Image" /></td>
<td><img src="image28" alt="Image" /></td>
</tr>
<tr>
<td>10 SCFM 7” Impingement Distance</td>
<td><img src="image29" alt="Image" /></td>
<td><img src="image30" alt="Image" /></td>
<td><img src="image31" alt="Image" /></td>
<td><img src="image32" alt="Image" /></td>
</tr>
<tr>
<td>15 SCFM 5” Impingement Distance</td>
<td><img src="image33" alt="Image" /></td>
<td><img src="image34" alt="Image" /></td>
<td><img src="image35" alt="Image" /></td>
<td><img src="image36" alt="Image" /></td>
</tr>
</tbody>
</table>

**Figure 4-2:** Effect of nozzle geometry on the droplet SMD, droplet count and droplet volume distribution.
The Sauter mean diameter distribution pattern varies from nozzle to nozzle. At 10 SCFM, the full cone and hollow cone produce better atomization than the wide-airflow and flat nozzles.

When the air jet impinges the liquid stream, the droplet trajectory is determined by the transfer of kinetic energy from gas to liquid. The gas jet atomizes the liquid by continually shearing layers off the liquid stream. The top layer of the liquid stream receives the most kinetic energy from the gas and is atomized more effectively, resulting in smaller droplets with high kinetic energy scattered across a wide area. The bottom layer receives the least amount of kinetic energy from the air jet resulting in larger droplet formation. As result, the larger droplets retain more of the original momentum of the liquid stream. According to Yule and Dunkley [32], only a percentage of the gas kinetic energy is transferred to the surface energy of the droplets. The remaining energy is transferred to the droplets in the form of kinetic energy. Thus, when the gas flow rate is inadequate the droplet trajectory may change, but the average droplet size remains relatively large.

Both the wide-airflow and flat nozzles yield less effective shattering, resulting in the largest droplet region to be further from the nozzle. This is likely due to the wider gas distribution these nozzles produce, which reduces the kinetic energy of gas that impacts the liquid stream. The hollow cone and full cone nozzles produce smaller droplets overall, and the center of the largest droplet region is closer to the nozzle. The shift in the net trajectory is discussed further in the next section that focuses on air flow rate. The area of highest droplet density corresponds to where the largest droplets are found. Thus, under the same operating condition, the hollow cone and the full cone nozzles have high droplet density below the nozzle, and the wide-airflow and the flat nozzles have high droplet density further from the nozzle. The droplet volume per frame distribution contours show information on the average volume of liquid at each array location. This data is derived from the droplet size and the droplet count distribution. Compared to the Sauter mean diameter distribution, the range of droplet total volume is significantly higher, because volume ~ diameter^3. Therefore, having a large concentration of large droplets yields a high volume. For all nozzle geometries, the high volume region is observed to be at the same location as the high droplet diameter region.
The importance of the 2D contour plots is to show the spread, or spatial distribution of the droplets over the 42 position array in terms of droplet diameter, count and total volume. In addition to minimizing the overall droplet diameter, it is also desirable to achieve a more uniform distribution across the array. The 2D contour plots, however, do not display the exact values of the droplet Sauter mean diameter, droplet count or liquid volume at each individual position in the array. Overall, the hollow cone nozzle appears to produce the smallest droplets as well as the most uniform distribution.

**Figures 4-3 to 4-6** illustrate droplet size distribution graphs on the basis of imaged volume and number, for different nozzle geometries over all 42 positions (21000 frames). The graphs show droplet size data for two different test configurations: 10 SCFM at 7 in impingement distance, and 15 SCFM at 5 in impingement distance.
Figure 4-3: Total imaged droplet volume vs droplet diameter for different nozzle geometries. 10 SCFM gas flow rate and 7 in impingement distance. (Y-axis values have 1000x multiple factor)

Figure 4-4: Total imaged droplet volume vs droplet diameter for different nozzle geometries. 15 SCFM gas flow rate and 5 in impingement distance. (Y-axis values have 1000x multiple factor)
**Figure 4-5:** Droplet count vs droplet diameter, for different nozzle geometries. 10 SCFM gas flow rate and 7 in impingement distance. (Y-axis values have 1000x multiple factor)

**Figure 4-6:** Droplet count vs droplet diameter, for different nozzle geometries. 15 SCFM gas flow rate and 5 in impingement distance. (Y-axis values have 1000x multiple factor)

**Figures 4-3 and 4-4** show the total imaged droplet volume as function of droplet diameter. (The area under the graph represents the total volume of imaged liquid.) The wide-airflow and flat
nozzles clearly generate more large droplets than the full cone and hollow cone nozzles. The hollow cone and full cone nozzles show similar volume distributions, as do the wide-angle and the flat nozzles. Although the droplet count decreases dramatically past about 4 mm (Figures 4-5 and 4-6). High imaged droplet volume is still observed for larger droplet diameters because droplet volume has a cubic relationship to the diameter. Smaller droplets, despite the low volume per droplet, still constitute a significant imaged droplet volume due to high quantity. Significant decrease in droplet count for full and hollow cone (Figure 4-6) is due to large fraction of small droplets not captured due to camera limitations.

Figures 4-3 and 4-4 indicate that total imaged volume (area under the curve) varies even though all nozzles were tested at the same liquid flow rate of 0.2 L/s. There are three main reasons for this: the spread of droplets, the size of droplets, and the velocity of the droplets observed at high gas flow rates or close nozzle proximity.

First, as shown in Figure 4-3, the round nozzles (hollow cone and full cone nozzles) produce a much wider spread of droplets than the slit profile nozzles (flat and wide-airflow nozzles). Therefore, a larger percentage of this volume is not captured within the 12x14 in matrix 2 feet below the spout. Second, as shown in Figure 4-7, the round profile nozzles are much more efficient at producing smaller droplets. This is more effective atomization as the number of very small droplets increases significantly, but not captured due to the limitation of the high speed camera. Finally, the velocity of the droplets affects the total volume imaged. The liquid flow rate is always 0.2 L/s, but the droplet velocity is in general higher at higher gas flow rates. When the droplet velocity is high, fewer of the droplets are captured since images are taken at the same frame rate. For example, if the imaging frame rate is 50 frames/sec, then one frame is always captured every 20 ms. Since the height of the frame is about 2 in, then droplets moving faster than 2 in/20ms = 100 in/s ≥ 2.78 m/s may not be captured, and droplets below that speed may be captured twice. Therefore, as droplet speed increases, the probability of droplets being imaged decreases, and since the liquid flow rate is constant, less droplet volume will be observed.
Figure 4-7: Sample image for the full cone nozzle at 15 SCFM and 5 in impingement distance. Many small droplets are observed, but cannot be analyzed due to low image resolution.

Overall, nozzle geometry affects droplet size/volume distribution. In general, the hollow cone and full cone nozzles have similar shattering characteristics in terms of both spatial distribution and number/volumetric distribution. A similar trend is observed for the wide-angle and flat nozzles. The round nozzles, based on their geometry, transfer more gas kinetic energy to the liquid stream, thus improving shattering performance. The slit profile nozzles distribute the gas over a larger area, thus transferring less kinetic energy to the liquid stream. The result is poorer shattering performance. However, the slit profile nozzles cover a larger area, and so if the stream of liquid shifted sideways due to a flow disturbance, the shattering effectiveness would be less affected compared to the round profile nozzles.

Finally, because the droplet contours for the full cone and hollow cone nozzles are very similar in terms of atomization performance and droplet size distribution, and because the same is true for the wide-airflow and flat nozzles, the subsequent analysis focuses on two categories of nozzles profile: the round nozzle profile and the slit nozzle profile, which will be represented by the hollow cone nozzle and the wide-airflow nozzle, respectively.
4.2 Effect of Gas Flow Rate

The gas flow is often characterized in terms of velocity. However, the different nozzles have different orifice geometries, and some have multiple orifices, and so it is difficult to quantify velocity for individual nozzles. Hence the gas flow rate is specified, as this is a good way to compare gas consumption efficiency. Since the orifice area is different for each nozzle, the pressure required to achieve a specific flow rate is also different. In general, a higher pressure is required for smaller orifices than larger orifices for the same gas flow rate. The velocity, however, is an important parameter in determining the shattering quality. Although the gas flow rate may be the same, it is important to realize the resultant gas velocity at the point of impingement is different across different nozzles geometries.

Figure 4-8 shows shattering profiles at different gas pressures, for the hollow cone nozzle at 7 in impingement distance. Note that the flow rate is not indicated at low pressures, as it cannot be accurately measured. It is clear that increasing gas pressure, and thus gas flow rate, decreases the overall droplet size and increases the spread of the droplets. The growth of liquid instability is also clearly observed as pressure increases.
Figure 4-8: Shattering profiles for the hollow cone nozzle at different pressures and gas flow rates.
<table>
<thead>
<tr>
<th></th>
<th>Droplet SMD (mm)</th>
<th>Droplet Count per Frame</th>
<th>Droplet Total Volume per Frame (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hollow Cone</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 SCFM</td>
<td><img src="image" alt="10 SCFM" /></td>
<td><img src="image" alt="10 SCFM" /></td>
<td><img src="image" alt="10 SCFM" /></td>
</tr>
<tr>
<td>12.5 SCFM</td>
<td><img src="image" alt="12.5 SCFM" /></td>
<td><img src="image" alt="12.5 SCFM" /></td>
<td><img src="image" alt="12.5 SCFM" /></td>
</tr>
<tr>
<td>15 SCFM</td>
<td><img src="image" alt="15 SCFM" /></td>
<td><img src="image" alt="15 SCFM" /></td>
<td><img src="image" alt="15 SCFM" /></td>
</tr>
<tr>
<td><strong>Wide-Airflow</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 SCFM</td>
<td><img src="image" alt="10 SCFM" /></td>
<td><img src="image" alt="10 SCFM" /></td>
<td><img src="image" alt="10 SCFM" /></td>
</tr>
<tr>
<td>12.5 SCFM</td>
<td><img src="image" alt="12.5 SCFM" /></td>
<td><img src="image" alt="12.5 SCFM" /></td>
<td><img src="image" alt="12.5 SCFM" /></td>
</tr>
<tr>
<td>15 SCFM</td>
<td><img src="image" alt="15 SCFM" /></td>
<td><img src="image" alt="15 SCFM" /></td>
<td><img src="image" alt="15 SCFM" /></td>
</tr>
</tbody>
</table>

**Figure 4-9:** Effect of gas flow rate on the droplet SMD, droplet count and droplet volume distributions at 7 in impingement distance, vertical nozzle orientation.
Figure 4-9 shows contour plots for the hollow cone and wide airflow nozzles at different gas flow rates, at 7 in impingement distance. As expected, increasing the gas flow rate reduces droplet size. In addition, varying the gas flow rate also shifts the position of largest droplet concentration. For example, at 10 SCFM, the hollow cone nozzle produces the region of largest droplets slightly away from the nozzle. (See Figure 3-6 for nozzle location) Increasing the air flow rate to 12.5 SCFM shifts the region to directly underneath the nozzle. Finally, at 15 SCFM the momentum transfer from the gas to the liquid is sufficient to eliminate droplets with a SMD above 1.7 mm. For the wide-airflow nozzle, at 10 SCFM there is a broad region of large droplets across the 12x14 in plane. Increasing the gas flow rate to 12.5 SCFM reduces the concentration significantly. Further increasing the gas flow rate to 15 SCFM further reduces the largest SMD region.

The shift in position of the largest droplets is due to the effectiveness of the momentum transfer between gas and liquid. If there were no gas supply, the trajectory of the liquid stream would reach somewhere outside the contour graph. (See Figure 3-6) A low gas flow rate creates a wide spread of large droplets across a large area away from the nozzle. Increasing the gas flow rate first reduces the size of the largest droplet region furthest from the nozzle (near the bottom of the contour plot). Increasing the gas flow rate shifts the largest droplet region closer and closer to the nozzle location. Finally, with sufficient gas flow rate, enough momentum transfer takes place and the average droplet size decreases.

Figure 4-10 shows the SMD as a function of the gas flow rate for the wide-airflow and hollow cone nozzles. Note that the hollow cone nozzle outperforms the wide-airflow nozzle at all gas flow rates, and the droplet SMD decreases for both nozzles as gas flow rate increases.
Figure 4-10: Droplet SMD as a function of gas flow rate at 7 in impingement distance.
Figure 4-11: Total imaged droplet volume vs droplet diameter for different gas flow rates. Hollow cone nozzle at 7 in impingement distance. (Y-axis values have 1000x multiple factor)

Figure 4-12: Total imaged droplet volume vs droplet diameter for different gas flow rates. Wide-airflow nozzle at 7 in impingement distance. (Y-axis values have 1000x multiple factor)
In general, increasing the gas flow rate decreases the droplet size. Although only a few gas flow rates were tested, the change in SMD over the 42 position matrix seems linear. In other words, there appears to be a linear negative correlation between the gas flow rate and SMD, regardless of the nozzle geometry. The geometry appears only to shift the graph position, but does not change the curve or the slope.

In Figures 4-11 and 4-12, total drop volume decreases as the gas flow rate increases, especially for large droplets. As mentioned in the previous section, as droplet spread increases, droplet size decreases, and droplet velocity increases, less of the liquid volume is imaged, resulting in a decrease in measured volume. The shift in droplet size is most apparent between 12.5 and 15 SCFM, for both nozzles, where a larger liquid volume is observed at lower diameter range at 15 SCFM (between 1 mm to 3 mm diameter) vs 12.5 SCFM, but vice versa for higher range diameters. This is due to the shift in droplet size as the flow rate increases.
4.3 Effect of Impingement Distance

The gas jet kinetic energy decreases with distance from the nozzle orifice, and so the distance between the air jet orifice and where it impinges the liquid stream (impingement distance) is an important factor to consider. The impingement distance is easy to adjust and significantly affects the shattering performance, as will be shown in this section. Figure 4-13 shows the effect of impingement distance on the shattering effectiveness, for the hollow cone and wide-airflow nozzles at 10 SCFM gas flow rate.
<table>
<thead>
<tr>
<th></th>
<th>Droplet SMD (mm)</th>
<th>Droplet Count per Frame</th>
<th>Droplet Total Volume per Frame (mm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hollow Cone</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 in Impingement Distance</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
</tr>
<tr>
<td>7 in Impingement Distance</td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>9 in Impingement Distance</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
<td><img src="image9" alt="Image" /></td>
</tr>
<tr>
<td><strong>Wide-Airflow</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 in Impingement Distance</td>
<td><img src="image10" alt="Image" /></td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
</tr>
<tr>
<td>7 in Impingement Distance</td>
<td><img src="image13" alt="Image" /></td>
<td><img src="image14" alt="Image" /></td>
<td><img src="image15" alt="Image" /></td>
</tr>
<tr>
<td>9 in Impingement Distance</td>
<td><img src="image16" alt="Image" /></td>
<td><img src="image17" alt="Image" /></td>
<td><img src="image18" alt="Image" /></td>
</tr>
</tbody>
</table>

**Figure 4-13:** Effect of impingement distance on the droplet SMD, droplet count and droplet volume distributions, at 10 SCFM gas flow rate.
Referring to Figure 4-13, decreasing the impingement distance affects the droplet size distribution in a similar way as increasing the gas flow rate. For the hollow cone nozzle, the contour pattern transition from 7 in impingement distance to 9 in impingement distance at constant flow rate is very similar to the contour pattern transition from 15 SCFM to 12.5 SCFM at constant impingement distance (7 in) for the wide-angle nozzle. This further suggests that the shattering characteristics and droplet size distribution may be independent of nozzle geometry, and that the same droplet size distribution can be achieved as long as there is sufficient gas velocity and kinetic energy transfer. Varying the impingement distance between 5 to 9 inches has a greater effect on atomization than changing the gas flow rate from 10 SCFM to 15 SCFM.

Figure 4-14 shows the SMD as a function of impingement distance. The hollow cone nozzle outperforms the wide-airflow nozzle over the range of impingement distances that were tested, and the droplet SMD increases as impingement distance increases. Again, the relationship between SMD and impingement distance appears to be linear. The slope of the two curves is also very similar. Figures 4-15 and 4-16 show droplet size distributions as a function of diameter for different impingement distances, for the hollow cone and wide-airflow nozzles, respectively. The shift in the volume distribution with decreasing impingement distance is similar to the shift with increasing gas flow rate. As expected, as the impingement distance increases, there are more large droplets.
**Figure 4-14:** Droplet SMD as a function of impingement distance at 10 SCFM gas flow rate.

**Figure 4-15:** Total imaged droplet volume vs droplet diameter for different impingement distances. Hollow cone nozzle at 10 SCFM gas flow rate. (Y-axis values have 1000x multiple factor)
Figure 4-16: Total imaged droplet volume vs droplet diameter for different impingement distances. Wide-airflow nozzle at 10 SCFM gas flow rate. (Y-axis values have 1000x multiple factor)
4.4 Effect of Impingement Angle

The IA (impingement angle) is the angle between the gas stream and the liquid stream at the point of contact, as illustrated in Figure 3-2. The angle is 40 degrees when the nozzle is oriented vertically and increases as the nozzle is rotated towards the spout. IA is an important factor to consider, not only because it can easily be adjusted, but because the angle at which the gas stream impinges the liquid stream has a significant effect on the net trajectory of the bulk of the liquid. For example, if the nozzle is oriented towards the spout (IA >40°), much of liquid will be directed back towards the spout and maybe even onto the boiler wall. Even if such a configuration increases the shattering effectiveness, it may not be desirable as it may lead to solid smelt accumulation on the boiler wall. In Sections 4.1 to 4.3, the default IA was 40°. Here we present results of varying the IA both towards the spout and away from the spout, to represent counter flow and concurrent flow, respectively. The angles tested include 35°, 50°, and 60°.

Figures 4-17 and 4-18 show the effects of IA on shattering effectiveness. To compare the effect of IA for the round profile and slit profile nozzles, different operating conditions were used. In Figure 4-9, the contour graphs for the hollow cone nozzle at 10 SCFM appear very similar to the contour graphs for the wide-airflow nozzle at 15 SCFM. Hence, the hollow cone was tested at 10 SCFM and the wide-airflow was tested at 15 SCFM, to not only study the effect of IA, but to show any difference in shattering behaviour between the two nozzle profiles.
Figure 4-17: Effects of IA on the droplet SMD, droplet count and droplet volume distributions at 10 SCFM gas flow rate and 7 in impingement distance, for the hollow cone nozzle. The Black circle represents the nozzle position.
<table>
<thead>
<tr>
<th>Wide-Airflow</th>
<th>Droplet SMD (mm(^2))</th>
<th>Droplet Count per Frame</th>
<th>Droplet Total Volume per Frame (mm(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>60°</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>50°</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>40°</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>35°</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
</tbody>
</table>

**Figure 4-18:** Effects of IA on the droplet SMD, droplet count and droplet volume distributions at 10 SCFM gas flow rate and 7 in impingement distance, for the wide-airflow nozzle.
As the IA (impingement angle) changes, the net trajectory of the liquid stream also changes. The original 12 in by 14 in matrix captured a fewer of the droplets due to the liquid trajectory shift, and so the matrix was expanded to 14 in by 14 to capture more droplets. Due to the limitation of the setup, the matrix could not be expanded further as it had reached the inclined tank. In Figure 4-17, the black circle shows the position of the nozzle viewed from above. At 60° IA, a large percentage of the droplet size information is not captured as many droplets end up hitting the side of the apparatus above the imaging location. Consequently, the droplet distribution graphs for droplet count and volume are not accurate for this configuration. Decreasing the IA from 60° to 40° shifts the largest droplets closer to beneath the nozzle position. Further decreasing the IA results in a gas flow that is more aligned with the liquid stream. This has a significant effect on the droplet size distribution, as shown at an angle of 35°, as a uniform droplet size distribution is observed for both nozzles, and in particular for the wide-airflow nozzle. This high atomization effectiveness is achieved because both the gas stream and liquid stream are flowing in the same general direction, allowing more shearing to occur, which enables a greater transfer of gas kinetic energy to droplet surface energy.

These results of the effect of IA are significant because the IA can be modified at little cost. Increasing the gas flow rate requires more steam, which costs more. Decreasing the IA increases the risk of nozzle clogging from smelt accumulation and requires more maintenance. Changing the IA, however, is very simple and appears to have a direct effect on the shattering quality. In this particular case, orienting the nozzle towards the direction of the liquid flow improves shattering quality at no cost, and smelt accumulation on the boiler wall is not a concern. Figure 4-19 shows droplet SMD as a function of IA for the hollow cone and wide-airflow nozzles. Recall that the SMD at 60° IA is likely not accurate, since the value is based on a small sample of droplets. (See Figures 4-17 and 4-18 at 60° IA.) The SMD diameter decreases as IA decreases. The slopes of the two curves, for the two nozzle geometries, appear to be very similar, despite the different SCFM, again suggesting that shattering performance is largely independent of nozzle geometry.
**Figure 4-19:** Droplet SMD as a function of IA at 10 SCFM gas flow rate for the hollow cone nozzle and 15 SCFM gas flow rate for the wide-airflow nozzle, both at 7 in impingement distance.

**Figures 4-20 and 4-21** show droplet size distributions as a function of diameter for the hollow cone and wide-airflow nozzles, respectively for different IA. Data for 40° is not included since these results only covered a 12 in by 14 in matrix, whereas the area coverage was 14 in by 14 in for the other angles. The droplet volume curve for 60° is not accurate since many droplets hit the edge of the apparatus and were not captured. However, the transition from 50° IA to 35° IA shows a clear shift to the left, towards more smaller droplets and fewer larger droplets. The overall area under the curve is relatively constant. This is a clear indication of liquid atomization improvement.
Figure 4-20: Total imaged droplet volume vs droplet diameter for different IAs. Hollow cone nozzle at 10 SCFM gas flow rate and 7 in impingement distance. (Y-axis values have 1000x multiple factor)

Figure 4-21: Total imaged droplet volume vs droplet diameter for different IAs. Wide-airflow nozzle at 15 SCFM gas flow rate and 7 in impingement distance. (Y-axis values have 1000x multiple factor)
4.5 Comparing Experimental Data with Empirical Correlations

Many of the empirical correlations presented in Chapter 2 correlate the mean droplet diameter to gas and liquid flow rate, along with other parameters such as viscosity, surface tension and gas velocity. Since most of the correlations do not take into account impingement distance and IA, and the nozzle geometry is likely governed by a constant, the empirical correlations will be evaluated with data varying the gas flow rate, as shown in Figure 4-22.

![Figure 4-22: Mean diameter vs gas flow rate for different correlations.](image)

The constants for each empirical correlation were chosen to fit the graph. The mean diameter indicated for the hollow cone and wide-airflow nozzles is SMD and the mean diameter indicated for correlations is $d_m$. All correlations have a negative slope, as expected. The inverse root correlation and Tornberg correlation appear to accurately reflect the trend observed in the experimental data. The other two correlations by Lubanska and Wigg have indicate little change...
in droplet diameter over the range of gas flow, indicating that the change in gas flow rate do not have a strong impact on $d_m$. 
5 Conclusions

Smelt shattering phenomenon has been studied using a ¼ scale experimental apparatus, with water and compressed air as proxies for smelt and steam. A standard experimental methodology was developed to acquire detailed droplet size information across a matrix of positions using a high-speed camera. An image analysis macro was developed to automatically remove out-of-focus droplets and balance background lighting before measuring droplet sizes. Due to the low resolution of the camera, droplets of less than 0.16 mm diameter were not measured. The image analysis program measures and stores droplet size information that is used to plot 2D contour plots to show the spatial variation of droplet size, count and volume, as well as to generate droplet volume distribution graphs. The ranges of experimental operating conditions were calculated to replicate a scaled down version of the industry operating process. Experiments examined the effect of nozzle geometry, gas flow rate, impingement distance, and IA on the atomization effectiveness, as quantified by droplet size, droplet count and droplet volume distributions. Analysis of each parameter is presented below.

Effect of Nozzle Geometry

Four nozzle geometries were tested at different operating conditions. Nozzles with a round jet profile (hollow cone nozzle and full cone nozzle) produce similar droplet size distribution. Nozzles with a slit jet profile (wide-airflow nozzle and flat nozzle) produce similar droplet size distribution. However, the round profile nozzles generate smaller droplets than the slit profile nozzle, due to higher kinetic energy transfer between gas and liquid. Subsequent experiments varying the gas flow rate, impingement distance and IA showed that the same droplet distribution can be achieved by both round and slit profile nozzles under different operating conditions.
Effect of Gas Flow Rate

Increasing the gas flow rate decreases average droplet size. The Sauter mean diameter decreases linearly with the gas flow rate. Increasing the gas flow rate also changes the net momentum of the gas/liquid interaction, shifting the net trajectory of large droplets closer to beneath the nozzle position at a vertical nozzle orientation.

Effect of Impingement Distance

Increasing the impingement distance increases average droplet size. The Sauter mean diameter appears to increase linearly with the impingement distance. Decreasing the impingement distance also changes the net momentum of the gas/liquid interaction, shifting the net trajectory of large droplets closer to beneath the nozzle position at a vertical nozzle orientation.

Effect of Impingement Angle

Changing the IA between the gas and liquid streams has a significant effect on the droplet size distribution and droplet net trajectory. Increasing the IA above 40° (towards the spout) changes the net trajectory the large droplets closer to the spout. Decreasing the IA below 40° (away from the spout) shifts the net trajectory of the large droplets away from the spout. The Sauter mean droplet size decreases significantly when the nozzle is oriented away from the nozzle, enabling a greater transfer of kinetic energy between gas and liquid. The droplet size distribution is also significantly more even.
5.1 Implications and Recommendations for Future Work

The implications of gas flow rate and nozzle proximity on droplet size distributions was as expected. However, in an industrial smelt shattering environment, neither is desirable as increasing the steam flow rate increases operating cost, and decreasing nozzle proximity increases the likelihood of nozzle fouling.

Round profile nozzles such as the hollow cone or full cone atomize more efficiently than slit profile nozzles due to higher kinetic energy transfer. However, the coverage of a round nozzle is smaller. Thus, if the smelt stream has the tendency to move sideways, the shatter jet from a round profile nozzle may miss its target. Slit profile nozzles, although less efficient, are able to cover a larger area.

Decreasing the IA increases the atomization efficiency and also increases the spread of the droplets, at no additional operating cost or maintenance. However, the shallower the IA, the less likely the shatter jet will impact the smelt stream at low smelt flow rate. Under these circumstances, it is recommended to install two nozzles, one for start-up or low smelt flow conditions, and one for regular operating conditions.

Finally, although smelt shattering has been studied in detail using a scaled experimental apparatus, the results may not reflect actual smelt shattering practice. Future work could develop correlations based on the experimental results, to be used to predict the actual smelt shattering. Additional work would examine atomizing an extremely high viscosity liquid to represent “jelly roll” smelt, or using more sophisticated technique like Phase Doppler Anemometry to measure the droplet size distributions of extremely small droplets.
6 References


Institut für Werkstofftechnik, Badgasteiner Str. 3, 28359 Bremen, Deutschland, 2000

Federation, Princeton, New Jersey, 1992

and Sprays” Atomization of Melts for Powder Production and Spray Deposition. Oxford:
Clarendon, 1994


Phys., 6 (1973) 1724-1736


[18] D. Bradley, ibid. reference No. 17, 2267-2272

compiled by T.G. Gasbarre and W.F. Jandeska, Jr. (Princeton, NJ: Metal Powder Industries
Federation, 1990) 2, 1-13

J. Metals, 22 (1970) 45-49

Deposits” Dissertation, Universität Bremen, 1997

Spruhkompaktierprozesses bei der Zerstaubung von Metallschmelzen” Dissertation, Universität
Bremen, 1999


