2015

Evaporation of Spray from a Rotary Bell Atomizer

Rajan Ray
University of Windsor

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Evaporation of Spray from a Rotary Bell Atomizer

by

Rajan Ray

A Dissertation
Submitted to the Faculty of Graduate Studies through Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy at the University of Windsor

Windsor, Ontario, Canada

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Evaporation of Spray from a Rotary Bell Atomizer

By

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15 July, 2015
Declaration of Co-Authorship / Previous Publication

I. Co-Authorship Declaration

I hereby declare that this thesis incorporates the outcome of a joint research undertaken in collaboration with Chris Sak, Materials Engineering Department, Automotive Research & Development Centre, FIAT Chrysler Canada under the supervision Dr. Paul Henshaw, University of Windsor. The collaboration is covered in Chapters 2, 3 and Appendix A, B, C of the thesis. In all cases, the key ideas, primary contributions, experimental designs, data analysis and interpretation, were performed by the author, and the contribution of co-authors was primarily through the provision of data.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from the co-authors to include the above material in my thesis.

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ABSTRACT

Evaporation of paint solvents is a significant part of an automobile's environmental footprint. Relationships between evaporation of droplets and application parameters were developed to optimize the spray process and reduce the environmental footprint by reducing paint waste in the booth. A Phase Doppler Anemometer (PDA) was used to calculate the evaporation of spray from a rotary bell atomizer (RBA). The change in volume flux between consecutive planes was found to be significant. The total evaporation when spraying water was 0.93 cm$^3$/s and 0.46 cm$^3$/s between 22.5-30.0 cm and 30.0-37.5 cm axial distances, respectively. Tests were performed to determine the effects on evaporation of water spray for three rotary bell atomizer operational parameters: shaping air flow rate, bell speed, and liquid flow rate. Evaporation rate increased with higher flow rate and bell speed, but no statistically significant effects were obtained for shaping air flow rate or interactions between parameters. For clearcoat sprays, evaporation increased with increasing bell speed and increase of flow rate from 100 to 200 cm$^3$/s. The combination of higher electrostatic potential and lower flow rate decreased the mean particle diameter. Particle mean velocity increased with increasing bell speed and flow rate. The trend of mean diameter decreasing with an increasing bell speed that was found in water and clearcoat, was also found for basecoat. However, the measurements with basecoat had a low statistical viability, and were deemed unsuitable for calculating the flux through parallel planes, which is required for calculating the evaporation. A model was proposed by combining two existing models from the literature; and the RBA nozzle parameter, $K_1$, and the evaporation rate, $K$, were calculated for water and clearcoat at 24°C. $K_1$ was found constant for clearcoat but was flow rate
and bell speed dependent for water. The value of K was found to be between 860-1270 μm²/s and 1300-2000 μm²/s for water and clearcoat, respectively. The initial particle diameter for different bell speeds and flow rates can be calculated using this RBA constant and the model. A model for the evaporation of droplets at any axial distance was also development.
DEDICATION

The author dedicates this piece of work to all of his teachers who encouraged and sacrificed in different level of studies.
ACKNOWLEDGEMENTS

The author would like to express his deepest gratitude to his advisor Dr. Paul F. Henshaw for his excellent advice, guidance and continuous encouragement throughout the period of study. Grateful acknowledgement to Dr. Nihar Biswas as his experience, knowledge and judgments helped the author to overcome so many difficulties. His continuous support was the essential part of this current research. The author is also grateful to the members of the examination committee Dr. Ronald Barron and Dr. Xiaohong (Iris) Xu and Dr. Edwin Tam for their useful suggestions, comments and help throughout the research.

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A debt of gratitude is also extended to Mr. Chris Tighe, Mr. Chris Sak and Mrs. Marie Mills of ARDC, FCA Canada for their assistance during the experiments.

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<td>Liquid and surface contact area (m²)</td>
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<td>B</td>
<td>Atmospheric pressure (Pa)</td>
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<tr>
<td>$d_p$</td>
<td>Droplet diameter (m)</td>
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<tr>
<td>$d_L$</td>
<td>Ligament diameter (m)</td>
</tr>
<tr>
<td>D</td>
<td>Maximum diameter of the cup (m)</td>
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<td>$d_{32}$</td>
<td>Sauter mean Diameter (m)</td>
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<td>$D_v$</td>
<td>Average diffusion co-efficient of vapor molecules in the saturated films around the drop (m²/s)</td>
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<td>Liquid volume flux (cm³/cm²/s)</td>
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<td>Nozzle parameter (m²)</td>
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<td>$M_L$</td>
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<td>T</td>
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<td>$U_V$</td>
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<td>$U_{\delta_{22.5-30.0}}$</td>
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<tr>
<td>$U_{\delta_{30.0-37.5}}$</td>
<td>Uncertainty of the slope between 30.0 cm and 37.5 cm (cm$^3$/s)</td>
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<td>$\nu$</td>
<td>Tangential velocity at the edge of the bell (m/s)</td>
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<td>$\dot{V}$</td>
<td>Volumetric flow rate of Liquid (cm$^3$/s)</td>
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<td>$x$</td>
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<td>$\eta_a$</td>
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<tr>
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<td>Liquid viscosity (kg/m.s)</td>
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<td>$\rho_l$</td>
<td>Liquid density (g/m$^3$)</td>
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<td>Air density (kg/m$^3$)</td>
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<td>$\rho_L$</td>
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<tr>
<td>$\sigma$</td>
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<td>$Y$</td>
<td>Function of atmospheric pressure and wet-bulb temperature</td>
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<td>$\omega$</td>
<td>Angular speed of the rotating cup (rad/s)</td>
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<td>BS</td>
<td>Bell Speed</td>
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<tr>
<td>CFR</td>
<td>Clearcoat Flow Rate</td>
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<tr>
<td>EP</td>
<td>Electrostatic Potential</td>
</tr>
<tr>
<td>FR</td>
<td>Flow Rate (liquid)</td>
</tr>
<tr>
<td>krpm</td>
<td>Thousand Rotations per Minute</td>
</tr>
<tr>
<td>kV</td>
<td>Kilovolt</td>
</tr>
<tr>
<td>PDA</td>
<td>Phase Doppler Anemometer (sometimes referred to in the literature as a particle dynamic analyzer)</td>
</tr>
<tr>
<td>RBA</td>
<td>Rotary Bell Atomizer</td>
</tr>
<tr>
<td>SA</td>
<td>Shaping Air Flow Rate</td>
</tr>
<tr>
<td>slpm</td>
<td>Standard Litre per Minute (standard conditions are 1 atm and 25°C)</td>
</tr>
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<td>BSA</td>
<td>Burst Spectrum Analyzer</td>
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CHAPTER ONE
INTRODUCTION

1.1 Background

Although substantial improvements have been achieved, surface coating is still the most important source of VOC emissions from the automotive industry. According to the Canadian National Pollutant Release Inventory (NPRI) 2014 report, the Canadian paint and solvent sector accounted for approximately 18% (323,000 tonnes) of total VOCs emitted in 2012 (Environment Canada, 2014). Almost all of this VOC came from the automotive surface coating (UN/ECE, 1999). The amount of evaporated solvent can be reduced in two ways. Firstly, the transfer efficiency of spray coatings can be improved, leading to the minimum use of paint. Secondly, substitution of current solvent-borne paints by water-borne paints or coatings with a higher solids content would lead to reduced VOC emissions. Both of these improvements are facilitated by a better understanding of the process of spray atomization.

All liquids evaporate. However, the rate of evaporation depends on the physical properties and surrounding environment of the fluid. Water, solvent-borne paints and fuel are regularly used liquids by industries. These liquids exhibit different rates of evaporation at room temperature and a substantial amount is lost during the application process. When a bulk liquid is disintegrated into smaller particles by atomization, it is termed as a spray. The particle diameter and velocity change during evaporation. Knowledge of the changing particle diameter and velocity is related to the evaporation and the operating conditions of the atomizer. It is important to relate all of these parameters and better understand the phenomena.
1.2 Coatings in the Automotive Industry

The early use of coatings started at the same time when humans started making clay pots. Different natural resins were used to coat the pots for both protective and aesthetic reasons (Bahadori, 2015). In modern times, almost every industrial product is coated. In the automotive industry, layers of air drying paints were used in the early 20th century (Lefebvre, 1989). Manual sanding and polishing took place after each layer was dried, which meant that several days were required to coat each vehicle. However, during the industrial boom of the Second World War, mass production of vehicles was required and enamel was invented for faster drying and curing. At the same time, the number of layers was reduced to save time. Primers were used for corrosion protection, primer surfacers for chip resistance and smoothness, and the top coat for color and weather resistance (Toda et al., 2012). In the late 1970’s, solvent emission was recognized as a major air pollutant and subsequently water-borne and electro-deposition paints were introduced. The modern automotive industry applies as many as five coating layers to the exteriors of vehicle bodies as illustrated in Figure 1.1.

![Coating Layers]

Figure 1.1: Layers of coatings in the modern automotive industry (Toda et al., 2012; Poth, 2008)
The spray application of coating has also improved with the improvement of coating chemistry. In the early days, pneumatic guns and pressure pots of paints were the only instruments used for coating. Nowadays, computer guided robots with different types of atomizers are used in spraying. The steps of the process of coating in a modern automotive factory are shown in Figure 1.2.

Figure 1.2: Process steps of coating in modern automotive industry paint shop (Toda et al., 2012)

1.2.1 Atomization and Spray

When a bulk liquid is disintegrated into smaller particles, it is termed as a spray. Normally, a device called an atomizer is used to perform the disintegration. The formation and change of water droplets created by water spray are a natural phenomenon and is one of the core interests in meteorology. It is also important for several industrial processes like: large scale chemical spraying in agriculture, food processing, cooling of...
nuclear cores, fire extinguishing and application of inhaled medicine. In the automotive industry, spray is important for both paint application and engine combustion efficiency.

### 1.2.2 Rotary Bell Atomizer

A rotary bell atomizer (RBA) is a rotating device used to atomize different liquids into spray. In the automotive coating industry, it is a widely used applicator which produces very small droplets (diameter in tens of μm) and ensures smooth and consistent spray. The physical phenomenon of droplet formation by an atomizer is described in Chapter 6. The RBA allows close-in painting for high transfer efficiency and superior penetration into part recesses. It has an excellent pattern control, which limits over-spray considerably for reduced paint waste.

A common RBA consists of the following major assemblies: cartridge (optional), valve module, turbine, bell cup, shaping air ring and the electrostatic system. The cartridge is a detachable vessel which can be refilled. In assembly line spraying, a continuous liquid feeding system is attached to ensure a continuous supply of paint. The valve module controls the flow of liquid by different tubing passages and valves. The turbine is a high speed motor that rotates the bell cup in the range of 10 krpm to 120 krpm. The bell is a conical cup attached to the turbine. The liquid is injected into the centre of the rear side of the disk and the centrifugal force pulls the paint towards the edge of the cup (Nordson Corporation, 2011; Talbert, 2007). The shaping air ring has a series of small pinholes along its circumference from which air can be blown onto the outside of the bell circumference to control the spray pattern. The electrostatic system is used to provide a high voltage charge (usually between 60,000 to 90,000 volts DC) to the spray so that it
will be attracted to the grounded target (ABB, 2009). The RBA can be used without electrostatic charge, but this is rare. When the droplet is charged with electrostatic potential, droplets with a high surface charge spontaneously break into smaller droplets. The Rayleigh stability limit, which predicts the maximum size droplet for a given charge is a force balance between the electrostatic repulsion of charges on the surface of the liquid and the cohesive force of surface tension (Doyle et al., 1964; Abbas and Latham, 1967). A typical RBA is shown in Figure 1.3.

![Figure 1.3: ABB Rotary Bell Atomizer (RB1000 WSC series)](image)

1.2.3 Phase Doppler Anemometer (PDA)

A Phase Doppler Anemometer or Particle Dynamic Analyzer (PDA) measures the counts, diameter, flux and velocity of spray particles. It consists of transmission optics, receiving optics and a central processing unit. A simplified schematic diagram of the basic operation of a PDA is shown in Figure 1.4. The transmission optics shine two intersecting laser beams into the spray. The point of intersection of those beams is the sample volume
for the PDA and creates an interference pattern consisting of fringes (beats) of light intensity. As a particle passes through the sample volume, it reflects the fringe pattern into the detector, but the frequency of the pattern is proportional to the velocity of the particle. The distance, $d_v$, between peaks of the fringe is known, and the measured frequency is converted into time. Hence the distance over time is used to calculate the velocity of the particle by the processing unit (Figure 1.4).

Figure 1.4: Measurement principle of PDA, Courtesy of Dantec Dynamics (Reproduced with approval from Dantec Dynamics, 2015)

At the particle-laser interface, part of the light is reflected and part of the light is transmitted and refracted from the surface of the droplet, which is assumed to have a spherical shape. The relative light energy reflected from and transmitted through the sphere can be calculated using the Fresnel reflection coefficients. The light scattering components of either reflection or refraction can be measured to obtain information on the particle size. Two detectors in the receiving optics receive a portion of the scattered light at two different angles. This phase shift between the Doppler signals is a direct
measure of the particle diameter (Dantec Dynamics, 2015). It is also possible to measure the particle size using the measured intensity of the scattered light (deflected by the sphere) (Figure 1.5). However, the scattered light intensity depends upon the particle trajectory through the Gaussian beam and any optical attenuation of the light due to other particles and optical surfaces in the beam path (Dantec Dynamics, 2015; Albrecht et al., 2003). A typical PDA can detect a wide range of particles: from 1 µm to 100 cm (Dantec Dynamics, 2015).

![Figure 1.5: Light scattering in beam interference (adapted from Dantec Dynamics, 2015)](image)

1.3 Literature Review

The effects of different physical properties and rheological behavior of paint on atomization and particle size distribution were investigated by Basu et al. (2010). They used both solvent-borne and water-borne paints. A high capacity camera was used to calculate the particle flux and diameter. However, a high diameter uncertainty (more than 30%) was present and they could not mimic the actual spray booth scenario due to different experimental limitations. Wang (2009) used a PDA and an aerodynamic nozzle to calculate the particle size and evaporation of water spray. They found a better result
but their investigation was limited to water and nozzle type did not match to the current paint industry. Schwarzkoph et al. (2006) developed a method to minimize volumetric flux errors, measured using a PDA, from a pressure swirl atomizer. Measured and calculated flow rates differed by less than 30%. However, the researchers did not include droplet diameter measurement or flux in their experiments. Chen et al. (2006) used a turbulent evaporating spray jet of acetone and measured mass flux with a Phase Doppler Interferometer (PDI) at several axial stations. The combined liquid and vapor mass fluxes agreed satisfactorily with the total mass flow rate of acetone injected. The researchers did not focus on industrial applications. Di Domenico and Henshaw (2012) investigated the effects of different flow rate, shaping air flow rate, voltage, paint age and bell speed on the water-borne paint appearance of automotive panels. They found that conditions leading to smaller droplets (which were assumed to evaporate more in flight) resulted in lower wave scan values (flatter surfaces) compared to application conditions which created larger droplets, which were still wet when they collected on the target surface. Their observations went against conventional wisdom, which states that when more solvent is available, paint flow and levelling is enhanced. They postulated that conditions which created large, more slowly drying, droplets led to more wrinkling of the paint film due to evaporation of the solvent from the film (as opposed to in-flight). This theory was predicated on the assumption that a spray with smaller droplets will result in more evaporation than spray with large droplets. However, research was required to confirm the relationship between evaporation and droplet size.

Akafuah et al. (2012) reported measurements of the particle size distribution for a rotary bell atomizer using infrared thermography. Using a camera and high-speed strobe,
Salazar et al. (2012) investigated on relation between ligament length and liquid flow rate. For both cases a relation between droplet formation and evaporation was not studied.

1.4 Objective

Measurement of the evaporation of paints, and finding a relationship between the evaporation of droplets and applicator parameters for paint spray is the key interest of the current research. For new paint formulations, it is important to understand the effects of applicator parameters on coating and their relation to evaporation. This knowledge can also improve the transfer efficiency of the coating. The establishment of a method which can directly measure the evaporation of liquid will allow the identification of the effects of RBA process parameters on the evaporation of liquids. This will support the development of a model which can predict droplet diameter and evaporation of droplets along their flight path.

1.5 Scope

The scope of the current research includes:

1. Measurement of evaporation using a PDA
2. Quantifying the effect of RBA parameters on evaporation using water and clearcoat
3. Developing a combined model of formation and evaporation of droplets

1.6 Significance

For the paint industry, evaporation, particle diameter and operating parameters are very important. Researchers have investigated the relation between evaporation, particle
diameter and operating parameters. Several models have been developed for fluid droplet formation from atomizers as well as the evaporation of droplets during flight. However, a complete study of the formation and evaporation of droplets of water and clearcoat in sprays from a high speed rotary atomizer is still pending. The current study is an attempt to synthesize the complete understanding of the fate of the droplets of those fluids. The total understanding of droplet formation and its effect on various operating conditions can help the coating industry to optimize the process by reducing or enhancing solvent evaporation. Surface waviness is an important fact paint industry. For paint, higher surface waviness is linked to lower solvent evaporation during the application. Controlling the evaporation can control surface waviness and improve the aesthetics of the vehicle. This knowledge can potentially reduce the need to repaint vehicles in order to maintain quality, thereby reducing paint waste, improving the process time and application efficiency, improving the final finish, and reducing emissions.

1.7 Organization of Dissertation

This dissertation is written in manuscript format and divided into chapters, with the major research findings reported in Chapter 2 to Chapter 6.

Chapter 2 describes the use of water as a surrogate of paints and the success of using PDA to measure the flux and other associated parameters. The change in flux between consecutive planes was found to be statistically significant, which demonstrated that evaporation can be quantified using PDA flux measurements. This chapter is published as a journal paper in “Atomization and Sprays” (Ray et al., 2015a)
Chapter 3 describes the effects on evaporation of water spray for three rotary bell atomizer operational variable parameters: shaping air flow rate, bell speed and liquid flow. Shaping air flow rate was set at either 200 standard litres per minute (L/min) or 300 L/min, bell speed was set to 30, 40 or 50 thousand rotations per minute (krpm) and water flow rate was varied between 100, 200 or 300 cubic centimetres per minute (cm³/min). The total evaporation (cm³/s) between 22.5 and 37.5 cm from the atomizer was calculated for all the combinations of those variables. Statistically significant effects were determined. This chapter has been published in a Special Issue of “Coatings: Innovative Coatings for Automotive Industry” (Ray et al., 2015b).

Chapter 4 reports experiments dealing with actual coatings, and clearcoat was used in this case. Parameters were varied, similar to the experiments for water described in Chapter 3. However, clearcoat has the added dimension of electrostatic potential. The relationships between evaporation of clearcoat and various operating parameters were determined. This chapter was submitted to the Journal of Coating Technology Research.

The use of metallic basecoat is described in Chapter 5. The same trends for parameter effects were found for basecoat. However, the measurements with metallic-pigmented basecoat had a low statistical viability, and were deemed unsuitable for calculating the flux through parallel planes, which is required for calculating the evaporation. Non-metallic (“straight shade”) basecoat was also used and ignored for flux calculations for the same reason. These results were not available at the time that the metallic results were compiled into a conference paper, thus the results for straight shade are shown in Appendix D (Ray and Henshaw, 2015a).
Chapter 6 describes a physics-based mathematical model for droplet formation and its evaporation during flight. The model was used for calculation of the RBA “nozzle” constant and evaporation rate for liquids. The model was verified for clearcoat and water for RBA.
1.8 References


Nordson Corporation (2011), *RA 20 Rotary Atomizer. Close-in painting capability with optimal coverage, greater operating flexibility and improved paint savings in a wide range of finishing applications*, Nordson Corporation, Amherst, Ohio, USA.


CHAPTER TWO

EVAPORATION OF WATER SPRAY FROM A ROTARY BELL ATOMIZER USING A PHASE DOPPLER ANEMOMETER

2.1 Introduction

Though a vehicle’s exterior finish represents less than 10% of its cost, it is responsible for approximately 80 to 100% of the total volatile organic compounds (VOCs) emitted in automotive production (70 to 80% are from the spray booth, while another 10 to 20% are emitted through the drying oven; Chang et al., 2002). A typical customer will not pay for any vehicle with a poor quality finish as it is perceived as an indication of overall poor quality of the vehicle. The challenge for the automotive industry is to maintain or improve finish quality while applying environmentally friendly coatings and application technologies.

Rotary “bell” atomizers are preferred in high volume paint applications because of their superior transfer efficiency. Paint is pumped into the inside of a rotating bell-shaped cup. It flows radially to the edge where it forms ligaments that break into droplets, creating a spray. The bell speed is an influential factor in paint spray. Shaping air flow rate is also used to control the spread of the spray. Other influential factors are the flow rate of the paint and the electrostatic potential. Three factors: flow rate, bell speed and shaping air flow rate and four interactions of these factors influence the surface waviness of the final finish (Di Domenico et al., 2012). Particle size and fluid atomization depend upon the characteristics of the paint and the operating parameters of the equipment. However, theories about droplet size affecting paint finish are at times contradictory. The intent of
this research is to correlate measured evaporation values to bell process parameters. As a first step, a Phase Doppler Anemometer or Particle Dynamic Anemometer (PDA) was used to calculate the total evaporation of water spray from a bell applicator. Subsequent research will examine the effect of varying bell parameters, followed by a similar investigation with clearcoat.

2.2 Literature Review

Various researchers have tried to elucidate the relation between process parameters and finished quality of the paint. Di Domenico et al. (2012) correlated bell speed, flow rate and shaping air flow rate with the finish quality (wave-scan elements, flop and lightness) and determined that decreasing flow rate, decreasing shaping air flow rate and increasing bell speed were found to decrease surface waviness. Basu et al. (2010) have observed that decreasing flow rate and increasing bell speed decreased the spray droplet size, which is assumed to result in more in-flight evaporation of solvent and a drier deposited film. Evaporation of solvent is a common phenomenon which depends upon spray droplet size, saturation of the surrounding air, and heat. A proper relationship between application parameters and evaporation is an ongoing effort of the current research. Corbeels et al. (1992) found that an increase in bell speed decreased the mean drop size by increasing the centrifugal and Coriolis forces. An increase in flow rate decreased the mean drop size at lower bell speed while no significant effect was found using higher bell speed.

Since measurement of volume flux (liquid volume per unit area per unit time) in a spray using a PDA system is based on particle diameter and rate of particle movement, the uncertainty in flux includes the uncertainties in both of these parameters. Such
measurement errors have been credited to several different sources, including improperly sized droplets (Aizu et al., 1993; Gre´han et al., 1991), lack of a uniform reference area for the measurements, and incorrect particle counts due to poor signal validation. More recently, researchers have put considerable effort to minimize the errors and increase the reliability of mass flux measurements made using PDA. Sommerfield and Qiu (1995) developed a technique to calculate accurate measurements of the local droplet concentration and the mass flux in evaporating sprays. Their method used a one-component PDA system and the integral value under the envelope of the Doppler signal estimates the instantaneous particle velocity.

Several researchers reported evidence of evaporation in sprays and significant progress was made to quantify the evaporation using both PDA systems and computational fluid dynamics (CFD). But the prediction capability is still limited by the theory which comes primarily from the different models for evaporation (Sirignano, 1993; Gouesbet and Berlemont, 1999). Actual validation of these models depends on the availability of comprehensive measurements of well-characterized evaporating sprays (Solomon et al., 1985; McDonell and Samuelsen, 1993, 1995; Sommerfeld, 1998). Chen et al. (2005) reported evaporation of spray using advanced phase Doppler anemometry in spray jets of octane. They found that turbulence effects are most effective in enhancing the evaporation of relatively small droplets that can follow closely the turbulent fluctuations of the gas flow. Schwarzkopf et al. (2006) found that the volumetric flow rate in the spray agreed with the feed volumetric flow rate within 30%. They state that this value is independent of the validation technique and works when special control is possible. It was postulated that if the phase Doppler operating variables are controlled in such a way
that the calculated total volumetric flow rate is matched to the measured volumetric flow rate, the droplet size and distribution becomes more reliable.

Kline and McClintock (1953) developed a method to estimate the experimental uncertainty, where uncertainty can be estimated from the uncertainties in the various primary experimental measurements. The method prescribes that if $A$ is a dependent variable (function) of independent variables $A_1, A_2... A_n$, and the uncertainties for $A, A_1, A_2... A_n$ are $X, X_1, X_2...X_n$ respectively, the uncertainty for $A$ can be calculated from the following equation:

$$X = \sqrt{\left(\frac{\partial A}{\partial A_1}X_1\right)^2 + \left(\frac{\partial A}{\partial A_2}X_2\right)^2 + \left(\frac{\partial A}{\partial A_3}X_3\right)^2 + \cdots \left(\frac{\partial A}{\partial A_n}X_n\right)^2}$$  \[\text{Eqn. 1.1}\]

2.3 Experimental Setup and Measuring Techniques

A high speed bell atomizer (ABB RB1000) was attached to a computer guided robotic arm system (ABB IRB-5500X) in a spray booth. In a rotary bell atomizer the fluid coating is pumped into the centre of the bell cup which rotates at a high speed. The fluid film becomes thin at the edge of the cup and forms ligaments which break into droplets. The fluid is atomized into extremely small particles and this improves the finishing quality (Figure 2.1).

![Figure 2.1: Rotary bell atomizer](image-url)
De-ionized water was fed into the atomizer for spraying. A PDA system (Dantec Dynamics A/S, Denmark) was used to calculate the particle flux of spray water. The PDA system consists of transmitting and receiving optics, a processor and the Burst Spectrum Analyzer (BSA) flow software package. It was assumed that the particles smaller than 1µm (particle detection size limit) are vapor. A nebulizer (Airlife-002002) created a cloud of water mist that was used to position the measurement volume correctly.

Figure 2.2: Schematic diagram of the PDA system for spray measurement (adapted, Dantec Dynamics, 2013)

The spray booth was maintained with a constant temperature of 24±0.6 °C (75±1°F) and 65±2% humidity. The booth had a constant and uniform vertical downward air flow of 2.1 m/s. The air flow has a tendency to swirl at the outer wall of the booth but not at the centre of the booth where the PDA measurement volume was located. The operating computer, laser and photodetectors for the PDA were located outside of the spray booth and connected via fiber-optic cables to the probe and receiving/transmitting optics.

The average particle volume flux (cm$^3$/cm$^2$/s) was calculated in three planes along the z-direction. These x-y planes were perpendicular to the axis of rotation of the bell cup and
termed axial planes. The $x$ and $y$ directions extend radially from the centre of the spray. Points in the spray were sampled in 2.5 cm intervals by moving the robot arm holding the RBA relative to the fixed PDA probe and receiver. The 2.5 cm (one inch) distance was used for convenience. The direction and axes of the spray system are shown in Figure 2.2.

The volume flux through each of three axial planes was calculated using the PDA flux measurements made along an $x$-direction traverse that passed through the centre of the spray in each axial plane, and which extended beyond the visible range of the spray ($x=+45.72$ to $-45.72$ cm). But the PDA system must detect a minimum of 1500 particles to ensure statistical validity. A set of preliminary tests showed that this threshold was not reached beyond a radial distance of 10-12.5 cm. As a result, the spray at 2.5 cm intervals up to 10 cm on each side of the axes origin was considered, though the tests were done for the full visible range of the spray ($+45.72$ to $-45.72$ cm). Symmetry in the $x$ and $y$ directions was assumed. Therefore, each point measurement represents the flux in a half ring-shaped area termed the influence area. The influence areas at radial distances ($r$) of 0 cm, 2.5 cm, 5.0 cm, 7.5 cm and 10.0 cm were calculated to be 15.33 $cm^2$, 19.63 $cm^2$, 39.25 $cm^2$, 58.88 $cm^2$ and 78.50 $cm^2$, respectively (Figure 2.3). The measurements and calculations were repeated at axial ($z$) distances of 22.5 cm, 30.0 cm and 37.5 cm from the atomizer. All of the tests were performed with a constant 40,000 rotation/min bell speed, a shaping air flow rate of 200 standard litres/min, and a water flow rate of 200 $cm^3$/min.
Figure 2.3: Influence area associated with each radial distance of the test (x-y plane)

The PDA system includes the BSA Flow Software v.4.10 (BSA Flow Software Manual v.4.10, 2006), which calculates the average particle volume flux (cm$^3$/cm$^2$/s). The parameters used for the PDA system are given in Appendix A. The system was set to acquire data for a maximum of 10,000 particle counts at each position or to acquire for 5 seconds, whichever came first. This ensured a reasonable maximum number of counts at the most distal point in the spray where particle counts are lower, while not overloading the system at the centre of the spray where a higher particle density exists.

To estimate the uncertainty of the measurement, each test was repeated 20 times in order to calculate the variance. The variance was multiplied by 1.96 to calculate the 95% confidence limit of the measurement (BSA Flow Software Manual v.4.10, 2006; Albrecht et. al., 2003) and this value was used to calculate the uncertainty of the PDA.
measurements. The static repeatability of the positioning robot was 0.15 mm (ABB, 2009). The uncertainty of the positioning robot was incorporated into the calculation of the overall uncertainty of the test since it affects the influence area.

2.4 Results and Discussions

The PDA system was able to determine the average volume flux for points equal or less than 10 cm from the axis of spray (z-axis) (Figure 2.4). The average volume flux per unit area increased from the centre to a radius of 2.5 cm. Then it started decreasing on both sides of the spray. Since the source of particles is the edge of the bell cup, and the particles have a radial component of velocity when they leave the edge, their initial spatial configuration is a hollow cone. After a short distance, their radial velocity is dissipated by friction with air and only vertical (z) velocity remains. The shaping air flow rate blows from an annulus above the bell cup and provides downward-directed air that initially confines the spray.

Figure 2.4: Volume flux along a traverse of the spray
Although the PDA system will not quantify any flux for which the particle count is below 1500 because it might not be statistically viable, the number of particles and their maximum diameter at all points were measured and recorded by the PDA. It is noted that very low numbers of particles were detected during the maximum 5-second measurement time at any point beyond 10 cm radial distance (Figure 2.5). The spray beyond 10 cm was neglected. An estimate of the neglected volume flux was calculated using the maximum particle diameter and the available rate of particles passing through that area of influence. As a percentage of the total flux, these neglected volume fluxes were calculated to be only 6.6%, 5.2% and 4.9% of the whole flux, for 22.5 cm, 30.0 cm and 37.5 cm axial distances, respectively. It should be noted that the actual neglected volume flux should be lower than this number because our calculations used the maximum diameter, as opposed to the average diameter. This justified neglecting the flux at radial distances greater than 10.0 cm. Alternatively, this value may be considered an additional uncertainty of the planar flux measurements.

Figure 2.5: Particle count number along a traverse in the spray
Calculating the uncertainty in the evaporation begins with establishing an uncertainty in the measured flux. As mentioned in the previous section, the uncertainty in the flux measurement was determined experimentally by repeated measurements of the flux at each location. The variance of these repeated measurements was multiplied by a factor to determine the 95% uncertainty of each flux measurement. These values appear in Figure 2.6. Note that uncertainties for positive and negative radial distances are shown separately, but in later calculations are combined.

Table 1: Actual flow rate with uncertainty for all the radial and axial displacements.

<table>
<thead>
<tr>
<th>Radial Distance, r (cm)</th>
<th>Uncertainty of the flux measurement (cm³/cm²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.5 cm axial distance</td>
<td>6.0E-04</td>
</tr>
<tr>
<td>30.0 cm axial distance</td>
<td>8.0E-04</td>
</tr>
<tr>
<td>37.5 cm axial distance</td>
<td>1.0E-03</td>
</tr>
<tr>
<td>22.5 cm radial direction from the centre</td>
<td>1.0E-03</td>
</tr>
<tr>
<td>30.0 cm radial direction from the centre</td>
<td>1.4E-03</td>
</tr>
<tr>
<td>37.5 cm radial direction from the centre</td>
<td>1.6E-03</td>
</tr>
</tbody>
</table>

Figure 2.6: Uncertainty of the flux at different radial and axial distances

The next step was to calculate the volumetric flow rate ($\dot{V}$) of water at each radial distance, by multiplying the flux ($f$) times its influence area. The step was repeated for all the three axial distances. Table 1 shows the actual flow rate with uncertainty for all the radial and axial displacements. The uncertainty of flux ($U_f$) and the static repeatability of
the positioning of the robot \((U_r)\) were used as the uncertainty of the radius, and used to calculate the uncertainty of the volumetric flow rate \((U_\dot{V})\). The distance uncertainty and flux uncertainty were combined by applying the Kline-McClintock equation:

\[
U_\dot{V} = \sqrt{\left(\frac{\partial \dot{V}}{\partial f} U_f\right)^2 + \left(\frac{\partial \dot{V}}{\partial A_{inf}} U_{A_{inf}}\right)^2} \tag{Eqn. 1.2}
\]

where the volumetric flow rate is defined by, \(\dot{V} = f A_{inf}\)

The initial water flow rate was 200 cm\(^3\)/min or 3.33 cm\(^3\)/s, which was reduced to 3.29 cm\(^3\)/s at 22.5 cm (Table 1.1) axial distance. The flow rate was further reduced to 2.36 cm\(^3\)/s at 30.0 cm axial distance (Table 1.1). The difference of 0.93 cm\(^3\)/s is greater than the combined uncertainty of 0.06 cm\(^3\)/s of these two measurements. Likewise, the difference of 0.46 cm\(^3\)/s is greater than the sum of uncertainties at 30.0 cm and 37.5 cm axial distances, 0.07 cm\(^3\)/s. Therefore evaporation of the spray has been measured. The uncertainty in the total flow rate varies between 0.9 and 2.1\% of the flow. So, the difference in total flow between adjacent \(z\) distances is significant.
Table 1.1: Water flow rate of spray at different radial distances

<table>
<thead>
<tr>
<th>Axial Distance (cm)</th>
<th>Flow Rate for Area of Influence, $V$ (cm$^3$/s)</th>
<th>Total Flow Rate, $\dot{V}$ (cm$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>2.5</td>
</tr>
<tr>
<td>22.5</td>
<td>0.177</td>
<td>0.558</td>
</tr>
<tr>
<td></td>
<td>±0.01</td>
<td>±0.04</td>
</tr>
<tr>
<td>30.0</td>
<td>0.158</td>
<td>0.484</td>
</tr>
<tr>
<td></td>
<td>±0.01</td>
<td>±0.04</td>
</tr>
<tr>
<td>37.5</td>
<td>0.137</td>
<td>0.367</td>
</tr>
<tr>
<td></td>
<td>±0.01</td>
<td>±0.04</td>
</tr>
</tbody>
</table>

From the water flow rate at each radial distance, the evaporation can be calculated by subtracting the flow rate at one axial distance from that at an adjacent axial distance. Table 1.2 shows the evaporation of water (cm$^3$/s) at different radial distances. This calculation is predicated on the assumption that from 22.5 to 37.5 cm, the spray follows a vertical trajectory such that the droplets do not enter adjacent areas of influence (i.e. jump from one annular area of influence to the adjacent one). Even without this assumption, the last column on the right of Table 1.2 is an accurate measure of the total evaporation between planes. The Kline-McClintock equation was used again to derive the following equation for calculating uncertainty during subtraction of flow rates for finding the amount of evaporation uncertainty ($U_e$):
For evaporation between 30.0 and 22.5 cm:

\[ U_e = \sqrt{\left( \frac{\partial e}{\partial \psi_{22.5}} U_{\psi_{22.5}} \right)^2 + \left( \frac{\partial e}{\partial \psi_{30.0}} U_{\psi_{30.0}} \right)^2} \]  

[Eqn. 1.3]

where evaporation \( e = \dot{V}_{30.0} - \dot{V}_{22.5} \)

For evaporation between 37.5 and 30.0 cm

\[ U_e = \sqrt{\left( \frac{\partial e}{\partial \psi_{30.0}} U_{\psi_{30.0}} \right)^2 + \left( \frac{\partial e}{\partial \psi_{37.5}} U_{\psi_{37.5}} \right)^2} \]  

[Eqn. 1.4]

where evaporation \( e = \dot{V}_{37.5} - \dot{V}_{30.0} \)

Table 1.2: Evaporation of spray at different radial distances

<table>
<thead>
<tr>
<th>Axial Distance (cm)</th>
<th>0</th>
<th>2.5</th>
<th>5</th>
<th>7.5</th>
<th>10</th>
<th>Total Evaporation, e (cm³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.5-30</td>
<td>0.019</td>
<td>0.074</td>
<td>0.425</td>
<td>0.167</td>
<td>0.240</td>
<td>0.925</td>
</tr>
<tr>
<td></td>
<td>±0.008</td>
<td>±0.018</td>
<td>±0.021</td>
<td>±0.022</td>
<td>±0.029</td>
<td>±0.036</td>
</tr>
<tr>
<td>30-37.5</td>
<td>0.020</td>
<td>0.117</td>
<td>0.151</td>
<td>0.125</td>
<td>0.048</td>
<td>0.461</td>
</tr>
<tr>
<td></td>
<td>±0.009</td>
<td>±0.020</td>
<td>±0.017</td>
<td>±0.031</td>
<td>±0.011</td>
<td>±0.022</td>
</tr>
</tbody>
</table>

The uncertainty in total evaporation, \( U_{te} \) (cm³/s) was calculated by applying the Kline-McClintock equation to the total water flow:
where total evaporation \(te = e_0 + e_{2.5} + e_5 + e_{7.5} + e_{10};\) \(e_0, e_{2.5}, e_5, e_{7.5}, e_{10}\) are the evaporation rates at 0 cm, 2.5 cm, 5.0 cm, 7.5 cm and 10 cm respectively; and \(U_{V_0}, U_{V_{2.5}}, U_{V_{5}}, U_{V_{7.5}}, U_{V_{10}}\) are uncertainties at 0 cm, 2.5 cm, 5.0 cm, 7.5 cm and 10 cm, respectively. The uncertainty was calculated for both axial distance intervals \((Ue_{22.5−30.0} \text{ and } Ue_{30.0−37.5})\)

The total evaporation \(te\) between 22.5 cm and 30.0 cm and between 30.0 cm and 37.5 cm axial distance were \(0.92\pm0.036\) cm\(^3\)/s and \(0.46\pm0.022\) cm\(^3\)/s respectively. Considering the uncertainty, there is no overlap in evaporation rates between the respective adjacent planes. The total maximum calculated evaporation uncertainties were 9.8\% and 9.9\%.

Figure 2.7 shows the distributions of particle sizes at a radial distance of 0 cm for various axial distances. The only significant difference between axial distances is in the small particles (5-10 \(\mu\)m), which decrease in number with an increase in axial distance. Evaporation is believed to be greater in large particles due to their greater individual surface area (Lefebvre, 1989). However, a 10\% change in the diameter of 20 \(\mu\)m particle represents more than the entire volume of a 10 \(\mu\)m particle, so the small particles are eliminated while the large particles decrease only slightly in size.
Using the total evaporation, it can be speculated that the evaporation rate decreases with the distance. In order to verify this, the slopes ($\delta$) from 22.5 to 30 cm and that from 30 to 37.5 cm need to be calculated and compared. For this the uncertainty of the slope ($U_\delta$) was calculated by adapting the Kline-McClintock equation as follows:

For slope between 22.5 and 30.0 cm

$$U_{\delta_{22.5-30.0}} = \sqrt{\left(\frac{\partial \delta_{22.5-30.0}}{\partial t e_{22.5-30.0}}\right)^2 \left(U_{t e_{22.5-30.0}}\right)^2 + \left(\frac{\partial \delta_{22.5-30.0}}{d r}\right)^2 \left(U_r\right)^2}$$  \[Eqn. 1.6\]

For slope between 30.0 and 37.5 cm

$$U_{\delta_{30.0-37.5}} = \sqrt{\left(\frac{\partial \delta_{30.0-37.5}}{\partial t e_{30.0-37.5}}\right)^2 \left(U_{t e_{30.0-37.5}}\right)^2 + \left(\frac{\partial \delta_{30.0-37.5}}{d r}\right)^2 \left(U_r\right)^2}$$  \[Eqn. 1.7\]
where $\delta_{22.5-30.0}$ is the slope between 22.5 cm and 30.0 cm and $\delta_{30.0-37.5}$ is the slope between 30 cm and 37.5 cm. $U_{\delta_{22.5-30.0}}$ and $U_{\delta_{30.0-37.5}}$ are slope uncertainties of respective adjacent planes.

The slopes for 22.5-30.0 cm and 30.0-37.5 cm were found to be $0.28\pm0.042\ \text{cm}^3/\text{cm}^2/\text{s}$ and $0.20\pm0.041\ \text{cm}^3/\text{cm}^2/\text{s}$. Because of the large uncertainty, it is not clear if the slope is different between intervals, and therefore, it can’t be stated with certainty if the rate of evaporation is decreasing as the spray propagates.

Droplet size normally varies with different factors such as fluid viscosity, surface tension, fluid flow, external air pressure and spray nozzle types. The viscosity of the clearcoat used in the automotive industry is higher than water. If other factors are constant, an increase in viscosity increases the amount of energy required to atomize the spray and hence the droplet size. The same is true for surface tension, but the clearcoat used in the industry usually has a lower surface tension than water. Because the two effects oppose one another, the effects on droplet size as a result of switching from water to paint are difficult to predict.

2.5 Conclusions

The flow rate of water spray from a rotary atomizer was measured, and its uncertainty quantified. The evaporation was calculated by subtracting the water flow rate between horizontal planes. The uncertainty of the evaporation is below 10% of the estimated evaporation and therefore the observed evaporation is significant. Future research is pending for the relation of evaporation with different factors like flow rate, bell speed,
shaping air flow rate and the temperature of the booth using both water and different types of paint spray.
2.6 References


CHAPTER THREE

EFFECTS OF BELL SPEED AND FLOW RATE ON EVAPORATION OF WATER SPRAY FROM A ROTARY BELL ATOMIZER

3.1 Introduction:

The exterior paint finish of a vehicle is a very important feature in the automotive industry. Rotary bell atomizers (RBA) are used because of their efficiency and production of fine droplets resulting in better finish quality. But this industry is also required to comply with emission standards, and a large portion of the volatile organic compound (VOC) footprint of an automotive assembly plant is due to the coating operations. Bell speed (BS), shaping air flow rate (SA), flow rate (FR) and voltage field of the spray medium are major RBA operational controlling factors which may affect the evaporation of paint. Understanding the effect of these parameters on evaporation is an important step in optimizing the paint finish, and lays the foundation for adoption of lower VOC coatings.

This research investigates the effects of BS, SA and FR on evaporation of water sprayed from a rotary bell atomizer, measured using a Phase Doppler Anemometer (PDA). Water was used to establish a method to investigate these effects, a method that will later be used for paints.

3.2 Literature Review

Basu et al. (2010) investigated the effects of physical properties and rheological behavior of paint on the atomization mechanism and particle size distribution. They used solvent-borne and water-borne paints with metallic flakes sprayed from a rotary bell atomizer. Using a CCD camera to measure the particle size by shadowgraphy, the mean particle
size ($D_{32}$) was found to decrease with increasing bell speed within the range of 30-50 krpm. Increasing shaping air flow rate was found to have a significant effect on particle size below 50 krpm bell speed with 210 g/min paint flow.

Wang (2009) provided experimental evidence of the well known theory that when the droplet sizes are smaller, the total surface area is larger, which leads to more evaporation. They used the PDA and an aerodynamic nozzle to calculate the particle size and evaporation of water spray, and found that increasing the droplet velocity improved the heat exchange process, which eventually increased evaporation.

Chen et al. (2006) used a turbulent evaporating spray jet of acetone and measured mass flux with a Phase Doppler Interferometer (PDI) at several axial stations. The combined liquid and vapor mass fluxes agreed satisfactorily with the total mass flow rate of acetone injected. Evaporation was higher with the higher axial mean slip velocity found for larger droplets while turbulence effects were effective to increase the evaporation of smaller droplets.

Di Domenico and Henshaw (2012) investigated the effects of different flow rate, shaping air flow rate, voltage, paint age and bell speed on the water-borne paint appearance on automotive panels. They found that flow rate, bell speed and shaping air flow rate are important variables that affect the smoothness of the paint finish. It was postulated that change of particle diameter due to change of these important factors are playing an important role in finishing properties.

Akafuah et al.(2012) reported on measurements of the particle size distribution for a rotary bell atomizer using infrared thermography. A steep decline of Sauter mean diameter (SMD) for an increase in bell speed from 20 to 30 krpm at 100 cm$^3$/min flow
rate was observed, followed by a lesser decrease in SMD with bell speed for bell speeds up to 50 krpm. Using a camera and high-speed strobe, Salazar et al. (2012) observed an increase of ligament length as a result of increasing liquid flow rate at the edge of a rotating bell atomizer at 25 krpm. A ligament becomes unstable and breaks into droplets when its length becomes large in relation to its diameter. Thus longer ligaments are thicker ligaments and end up creating larger diameter droplets.

Corbeels et al. (1992) found that an increase in bell speed always decreased the mean drop size by increasing centrifugal and Coriolis forces. Increasing the liquid flow rate generally increased the mean drop size at bell speeds lower than 20 krpm while little effect was found at higher bell speeds. Increasing the flow rate at a given bell speed always produced a broader distribution of drop sizes. Increasing the bell speed at a constant flow rate normally widened the drop size distribution.

Various researchers (Corbeels et al., 1992; Basu et al., 2010; Akafuah et al., 2012) found that increasing bell speed decreased the mean particle diameter at a constant flow rate. If particle concentration also increases with increasing bell speed, it is a clear indication that the total surface area is increasing and hence the evaporation is increasing.

### 3.3 Experimental Setup and Measuring Techniques

A high speed bell atomizer (ABB RB1000) was used, which was attached to a computer guided robotic arm system (ABB IRB-5500X). The spray mechanism could be controlled with this computer from outside of the spray booth. De-ionised Water was fed into the atomizer for spraying water. A PDA system (Dantec Dynamics A/S, Denmark) was used to calculate the volume flux of spray water. The total PDA system consisted of transmitting and receiving optics, a processor and the BSA flow software package. In
order to position the measurement volume correctly, a nebulizer (Airlife-002002) was used. A downward vertical airflow of 2.1 m/s was maintained in the booth. A steady temperature of 24±0.6°C (75±1°F) and 65±2% humidity was maintained inside the booth to avoid any physical change of droplets due to temperature and humidity change.

The average particle volume flux (cm³/cm²/s) was calculated in 3 parallel planes along the z-direction (axis of bell cup rotation). These x-y planes were perpendicular to the axis of rotation of the bell cup and termed axial planes. The distance from the bell centerline, in both the x and y directions, is termed the radial distance. Sample data were taken at a 2.5 cm intervals along the x-axis (similarity in the y direction was assumed) and same sample was taken 3 times with a random order. The volume flux through each of the axial planes was calculated using the PDA flux measurements and the calculated area of the annulus containing each measurement point. The volume flux was measured from \( x = +45.72 \) to \( -45.72 \) cm (Ray et al., 2015a).

The difference in volume flux between the top and bottom axial planes was used to calculate the total evaporation between axial distances. The total axial distance was 15 cm (\( z = 22.5 \) to 37.5 cm). The bell speed was set at 30, 40 or 50 thousand rotations per minute (krpm), where the shaping air flow rate was either 200 standard liters per minute (L/min) or 300 L/min. The water flow rate was varied between 100, 200 or 300 cubic centimeters per minute (cm³/min). A full factorial experimental design, using these parameters, was performed and the results used to calculate the total evaporation rate (cm³/s). Minitab software was used in designing the experiment and calculating the effects (Minitab, 2010).
The PDA system included the BSA Flow Software v.4.10 (BSA flow soft manual v.4.10, 2006), which calculated the average volume flux (cm$^3$/cm$^2$/s) through the measurement volume. The parameters used for the PDA system are given in Appendix A. The PDA software uses its own statistical validation, where a value more than 80% is considered a reliable result. To reduce sampling time, the system was set to collect data within 5 seconds. However, if the system obtained sufficient particle counts (10,000) it automatically truncated sampling.

The volume flux through each of two axial planes ($z=22.5$ and $z=37.5$ cm) was calculated using the PDA flux measurements made along an $x$-direction traverse that passed through the center of the spray, and which extended beyond the visible range of the spray. But the PDA system must detect a minimum of 1500 particles at each point to ensure statistical validity. A set of preliminary tests showed that this threshold was not reached beyond a radial distance of 7.5 cm. As a result, the spray at 2.5 cm intervals up to 7.5 cm on each side of the spray centerline was considered, although measurements were taken over the full visible range of the spray (+45.72 to −45.72 cm).

### 3.4 Results and Discussions

Figure 3.1 (a, b) shows the particle concentration in a transverse plane (37.5 cm distance) for different radial points ($x = -7.5$ cm to $+7.5$ cm) with flow rates of 100 and 200 cm$^3$/min. Each particle concentration shown is the average of 20 tests under the same conditions. Two trends were identified. The first one is that the particle concentration increased with increasing bell speed. And the second one is that the average mean diameter ($D_{32}$ in μm) decreased (Figure 3.1: c, d) at the same time. This can be explained by conservation of mass, as the liquid sheet at the edge of the bell cup became thinner at
higher bell speed, leading to smaller droplets, the number of droplets increased. Basu et al. (2012) had shown the same fact, using solvent-borne and water-borne paints; the average mean diameter ($D_{32}$ in $\mu$m) decreased with the increasing bell speed between 30-50 krpm. These two factors mean that the total surface area for evaporation of the water droplets increased with the increasing bell speed at a constant flow rate. A comparison chart of this analysis is shown in Appendix B. Akafuah et al. (2012) also reported a decrease in mean diameter with increasing bell speed and an increase with increasing flow rate. In cross-section, the spray may be thought of as emanating from the two edges of the bell cup, with velocities parallel to the cup edge (i.e. having radial and axial velocity components). But after a distance, spray from the two edges meets in the middle, creating a higher concentration of particles. Although the higher flow rate decreases the particle concentration at the center (from 13,400 to 11,400 part./cm$^3$), at radial distances of 2.5 cm or more, the value increases (from about 7,500 to 9,500 part./cm$^3$) averaging at radial distances of 2.5 and -2.5. The main phenomena here is that the particle distribution is flatter at higher flow rates. This may be due to the higher radial velocity of the paint at higher flow rates which spreads the paint cloud. The flattening is also observed when increasing bell speed.
Figure 3.1. Particle concentration (part./cm$^3$) with increasing bell speed for a) 100 cm$^3$/min flow rate; b) 200 cm$^3$/min flow rate; particle mean diameter D$_{32}$ (μm) with increasing bell speed for c) 100 cm$^3$/min flow rate, d) 200 cm$^3$/min flow rate
Higher bell speeds also increased the vertical droplet velocity (Figure 3.2: a, b). Each droplet carries out heat transfer within surrounding medium (air) and change its temperature during the flightpath. This heat transfer increases with the velocity of the droplet which should have increased the evaporation of the droplets here. It is noted that the droplet velocity decreased with higher flow rate at the center of the spray. Coincidently, the mean particle diameter increased with higher flow rate (Figure 3.1: c, d). Basu et al. (2010) also found that the mean particle diameter increased with the increasing coating flow rate. An increase in mean particle diameter with increasing flow rate decreases the average particle velocity. It is noted that the velocity decreased on the outer side of the spray. Akafuah et al. (2012) also reported that increasing bell speed decreases the mean diameter while Salazar et al. (2012) reported that increasing flow rate increases the mean diameter of the droplets.
Figure 3.2. Particle velocity (m/s) with increasing bell speed for a) 100 cm$^3$/min flow rate, b) 200 cm$^3$/min flow rate
Figure 3.3 shows the total evaporation (cm$^3$/s) calculated for different shaping air flow rate, bell speeds (krpm) and water flow rates (cm$^3$/min) between 22.5 cm and 37.5 cm (15 cm axial distance). It clearly shows that evaporation increased with increasing bell speed for a constant flow rate and shaping air flow rate. Figure 3.3b shows that at the higher shaping air flow rate (300 L/min) and 40 krpm bell speed, no significant change in total evaporation was found compared to 30 krpm to 50 krpm bell speeds. But the increase of total evaporation between 30 krpm and 50 krpm was significant. The uncertainty in total evaporation is shown in Appendix B.
Figure 3.3. Total evaporation rate (cm$^3$/s) for different bell speeds and flow rates at a) 300 L/min shaping air flow rate, b) 200 L/min shaping air flow rate.
Evaporation also increased with increasing flow rate, constant bell speed and shaping air flow rate. But the rate of change is less between 200 cm³/min and 300 cm³/min flow rate compared to between 100 cm³/min and 200 cm³/min flow rate. The change in shaping air flow rate does not have any significant effect on evaporation rate.

A full factorial analysis (Figure 3.4) was used to determine if there was any combined effect of these parameters on evaporation. Values of the three variables were normalized to the middle value. For flow rate, the actual values of 100, 200 and 300 cm³/min became -1, 0 and 1 respectively. The low and high values of shaping air flow rate were coded to -1 and 1. After eliminating non-significant variables (those for which $p>0.05$), the significant variables remaining were flow rate and bell speed. There were no interactions of input parameters (e.g. flow rate and bell speed combined) that had a significant effect on evaporation ($p$-value for all combinations of parameters were above 0.23). Since coded values were used, the relative effect of the parameters can be gleaned from the coefficients in the factorial fit. Hence flow rate has an effect three times that of bell speed in terms of its effect on the evaporation rate.
According to Di Domenico and Henshaw (2012), increasing the shaping air flow rate concentrates the pattern of spray at the same bell speed and flow rate, which results in more agglomeration of droplets and results in a wavier surface of the cured paint. In these experiments using water, it is noted that although shaping air flow rate might have caused agglomeration of the particles, it has an insufficient effect on the total evaporation.

3.5 Conclusions

In previous work, the PDA was demonstrated as an acceptable method to measure evaporation in water spray from a rotary bell atomizer. In this work, the PDA was used to show the effect on evaporation of water by varying bell parameters: shaping air flow rate,
bell speed and liquid flow rate. The effect of shaping air flow rate was found to be statistically insignificant. Evaporation increased with the increasing bell speed at a constant flow rate. Evaporation also increased with increasing flow rate at a constant bell speed.
3.6 References


CHAPTER FOUR

EVAPORATION OF CLEARCOAT FROM A ROTARY BELL ATOMIZER AND ITS RELATIONSHIP WITH BELL SPEED, FLOW RATE AND ELECTROSTATIC POTENTIAL

4.1 Introduction

In spite of their varieties of usage, all coatings contain a material which eventually forms a film on the target surface. The coating may be pigmented or unpigmented. One type of unpigmented coating is called clearcoat and it is widely used in the automotive industry on top of the basecoat to maintain the luster and impregnability of the original color. This is normally a clear, colorless urethane or polyurethane final finish. This shiny exterior finish is very important to the industry as it is one of the key factors for customer satisfaction.

The automotive industry has been striving for a uniform spray of atomized paint for a long time. Appearance is a major selling feature in this industry, and better appearance is directly related to the uniformity of spray. The industry is also fighting to limit the overall Volatile Organic Compound (VOC) emissions during coating. The painting process accounts for around 80% of the overall VOC emissions in the automotive industry. An optimized painting process not only limits the VOC emissions, but also reduces the painting cost for the industry.

Understanding the relationship between the process parameters and evaporation of paint is important to optimize finish. A thorough investigation is pending to understand a relation between the various paint application parameters with the evaporation from the coating. Bell speed (BS), shaping air flow rate (SA), coating flow rate (CFR) and
electrostatic potential (EP) of the spray medium are major operational controlling factors which may affect the evaporation of paint. A detailed investigation of these parameters on evaporation will not only optimize the use of coatings applied, but also increase the potential of better understanding of the link between these parameters with the appearance of the finished product.

A robot guided Rotary Bell Atomizer (RBA) was used to investigate the effects of BS, SA, CFR and EP on evaporation of clearcoat. Evaporation of the paint droplet was measured with a phase Doppler anemometer (PDA).

4.2 Literature Review

An early investigation by Fraser et al. (1962) determined that a liquid sheet is formed during atomization. A spinning cup was used with an impinging air stream flowing perpendicular to the spray (Fraser et al., 1962). They showed that the impinging air stream does not have an immediate impact on breaking the liquid sheet. The resulting drop size from the breaking of liquid sheet was a function of the sheet thickness. This was true for a wide range of operating conditions.

Corbeels et al. (1992) investigated the relation between bell speed, flow rate and mean drop size. A lower mean drop size was found at higher values of parameters like bell speed, centrifugal force and Coriolis force. A higher mean droplet size resulted from higher liquid flow rate and lower bell speed. They also reported a broad distribution of drop size with higher flow rate at a constant bell speed. The mean drop size distribution widened with higher bell speed and constant flow rate.
Wang (2009) used different types of nozzles to find a relationship between droplet size, surface area and evaporation of water at a constant pressure and temperature. He found that the evaporation decreases with increasing droplet size. He used a shooting water jet, opposite to the gravitational force and considered the direction as axial distance. With the increasing axial distance, the droplet diameter increased with decreasing particle velocity.

The particle size characteristics of metallic solvent-borne and water-borne paint sprayed from a RBA were measured by using shadowgraphy (Basu et al., 2010). A CCD camera was used to calculate the particle size. Within the 30-50 krpm bell speed range, the mean particle size (D$_{32}$) decreased with increasing bell speed, while the effect of shaping air flow rate was found significant only below 50 krpm bell speed, even though experiments were performed upto 70 krpm.

The relationship between different parameters: flow rate, bell speed, shaping air flow rate, electrostatic potential and the appearance of the paint was investigated by Di Domenico and Henshaw (2012). A full factorial two level DOE matrix was used. They theorized that a relationship is present between the particle diameter and the measured outputs: surface waviness and multi-angle color, which are characteristics of the appearance of the paint.

Higher flow rate and bell speed increased the evaporation rate when water was used as a fluid (Ray et al., 2015 b). In this case, shaping air was not a statistically significant factor. Electrostatic potential was not used when spraying water. The total evaporation between
22.5 and 37.5 cm from the atomizer (cm³/s) was calculated for all of the controlling parameters.

Infrared thermography was used to investigate droplet properties for different flow rate and bell speeds by Akafuah et al. (2010). A steady increase of Sauter mean diameter was observed for an increase in flow rate from 100 cc/min to 400 cc/min. They also reported that the Sauter mean diameter decreased with increasing bell speed.

4.3 Experimental Setup and Measuring Techniques

Solvent-borne liquid clearcoat was fed into a high speed bell atomizer (ABB RB1000) which was attached to a computer guided robotic arm system (ABB IRB-5500X). PPG NCTX clearcoat was used (62.7% solids concentration and 1.25 kg/L density, tested in FIAT Chrysler Canada Materials Laboratory). A PDA system (Dantec Dynamics A/S, Denmark) was used to compute the volume flux, particle diameter, velocity and particle size distribution at a fixed point in space. The robot arm moved the RBA so that various points in the spray could be measured. The whole system was controlled from the outside of the spray booth. The PDA system has a receiving optics, a processor and the BSA flow software package. A nebulizer (Airlife-002002) was used to align the PDA and robotic arm initially. The spray booth was maintained with a constant temperature of 24±0.6°C (75±1°F) and 65±2% humidity. The booth had a constant and uniform, mostly vertical, downward air velocity of 2.1 m/s. But the air had a tendency to flow towards the outer wall of the booth. In order to minimize this influence, the PDA was placed at the center of the booth. The major processing parts of the PDA, which included the operating computer, laser and photodetectors, were located outside of the spray booth. The
transmitting and receiving optics of PDA can easily attract the highly charged clearcoat, resulting coating on the lenses. To avoid this problem, several precautions were taken. All parts of the PDA were grounded and special chutes were attached to both the transmitting and receiving optics. The chutes were pressurized with compressed air, which constantly blew air away from the optics (Figure 4.1). This avoided any chance of clearcoat deposition on the lenses. Further, instead of spraying into space, a grounded, bare metal surface was placed 90 cm from the bell cup. The metal plate was replaced after every experiment. It helped the particles to be attracted downwards rather than the PDA itself. The plate also mimicked a target surface in the paint booth. Ray et al. (2015a) described how the experimental setup used for this current investigation was used to measure the evaporation in water spray.

![Figure 4.1: Chutes used in the spray booth](image)

The z-direction was set equal to the axis of bell cup rotation. Measurements were taken in two x-y planes, perpendicular to the axis of rotation of the bell cup (axial planes). Points in the spray were sampled in 2.5 cm intervals along the x-axis by moving the robot arm horizontally relative to the fixed PDA probe and receiver.
Two axial planes, at 22.5 cm and 37.5 cm from the bell cup were selected. The total flux of liquid droplets was calculated for each plane and the difference was calculated as the total evaporation (cm$^3$/s) between those planes. The clearcoat flow rate (CFR) varied between 100, 200 and 300 cubic centimeters per minute (cm$^3$/min) with a constant 200 liter per minute (L/min) shaping air flow rate (SA). Bell speed (BS) was 30, 40 or 50 krpm, and electrostatic potential (EP) was set to 60, 70 and 80 kilovolts (kV). A full factorial matrix for all of the variable parameters was completed.

The PDA system was used to calculate the average volume flux (cm$^3$/cm$^2$/s) in both planes. Software is included with the system (BSA Flow Software v.4.10) which can calculate the average flux as well as diameter (µm) and velocity (cm/s). The setup parameters for the current test for PDA are given in Appendix C. The maximum number of particles was found at the center of the spray and the number decreased with radial distance. To ensure that the reasonable maximum time was allowed to detect any particles in the extreme distal vicinity of the spray, a maximum 5 seconds acquire time was set for the machine, and 10,000 was set as the maximum particle count to avoid system overloading.

The volume flux along the x-direction traverse which passed through the centerline of the spray, was measured for the extended visible range of spray (x= +45.72 to –45.72 cm). But to ensure statistical validity, the PDA can calculate different measurements only if a minimum 1500 particle count is present. A set of preliminary tests indicated that this threshold was only achievable at a radial distance of 12.5 cm and hence measurements up to 12.5 cm on each side of the spray were considered, with a 2.5 cm interval. Symmetry in the x and y directions was assumed.
4.4 Results and Discussion

Because of low particle counts, any flux measured beyond 12.5 cm from the axis of the spray was neglected. The volume of the neglected droplet flux was estimated to be a maximum of 3.5% and 1.2% of the total flux at 22.5 cm and 37.5 cm axial distances, respectively. The maximum diameter of the particles instead of the average diameter was used in this estimate so that it would be conservative. Therefore, neglecting the flux at radial distances greater than 12.5 cm resulted in a small error.

The average droplet volume flux increased from the center (x=0) to a radius of 2.5 cm and decreased thereafter (Figure 4.2). The spatial configuration of the spray is a hollow cone because of the initial radial displacement and component of velocity. The initial confinement of the spray is due to the constant shaping air flow rate which blows downward from an annulus above the bell cup. The droplet volume flux increased with an increasing coating flow rate (CFR). A higher flux rate was found within a 5 cm radial distance of the centerline using water spray compared to the same region using clearcoat (Ray et al., 2015b).
Figure 4.2: Volume flux along a traverse of the spray a) 200 cm³/s flow rate; b) 300 cm³/s flow rate with 200 L/min air flow rate, 40 krpm bell speed and 70 kV electric potential
Figure 4.3 shows the total evaporation for different bell speeds and flow rates with a constant 200 L/min shaping air flow rate flow. Evaporation increased with increased bell speed. Basu et al. (2010) found that within the 30-50 krpm bell speed range, with 180 L/min; shaping air flow rate, and 65 kV electric potential, the Sauter mean diameter ($D_{32}$) decreased with increasing bell speed. At 30 krpm the mean particle size ($D_{32}$) was around 38 µm and it decreased to 32 µm at 50 krpm bell speed under the same conditions. The decrease in mean particle size means that the liquid coating was divided among a higher number of smaller particles, resulting in a higher surface area for evaporation. They also found that the rate of decrease of mean particle size with bell speed was higher for bell speeds above 50 krpm. However, within a specific air flow rate (128 - 240 L/min), mean particle size did not significantly change for different airflow rates within this range. Ray et al. (2015b) and Di Domenico and Henshaw (2012) also found that airflow rate had very little impact.

Figure 4.3: Total evaporation of spray ($\text{cm}^3/\text{s}$) for various bell speed at various flow rate with 70 kV electric potential and 200 L/min shaping air flow rate
Figure 4.4 indicates that the relationship between bell speed and particle size found by previous researchers is also applicable to clearcoat. A higher bell speed has a direct relation to decreasing mean particle diameter. For clearcoat, with a 100 cm$^3$/s flow rate, 200 L/min shaping air flow rate, 70 kV electric potential and at \( z=22.5 \) cm, the mean diameter at the center of the spray was around 30 \( \mu \)m for a 30 krpm bell speed, and decreased to 25 \( \mu \)m for a 50 krpm bell speed. The mean diameter also gradually decreased with the radial distance of the spray. A lower flux due to lower particle numbers, and a higher travel distance combined to decrease the mean diameter of the particles at higher radial distances. A higher flow rate also increased the mean diameter for the same conditions. At 200 cm$^3$/s coatings flow rate, the mean diameter at the center of the spray was around 32 \( \mu \)m for a 30 krpm bell speed, and it decreased to 26 at a 50 krpm bell speed.

Akafuah et al. (2010) reported that Sauter mean diameter decreased around 5 \( \mu \)m with an increase of bell speed from 30 to 40 krpm at a constant 100 cm$^3$/min flow rate. A further increase to 50 krpm decreased the Sauter mean diameter only 2 \( \mu \)m. At 40 krpm bell speed, Sauter mean diameter increases with an increasing flow rate. A 3 \( \mu \)m increase was reported for a flow rate increment of 100 cm$^3$/min to 200 cm$^3$/min flow rate. Any further increase had a moderate effect on the Sauter mean diameter (around 1 \( \mu \)m per 100 cm$^3$/min increase). They used water as a working fluid and electrostatic charge was not used.
Figure 4.4: Particle mean diameter, $D_{32} \, (\mu m)$, with increasing bell speed for a) 100 cm$^3$/s flow rate; b) 200 cm$^3$/s flow rate at 200 L/min air flow rate and 70 kV electric potential
Basu et al. (2010) found that mean diameter also decreased with increasing electric potential. They found that within the 30-50 krpm range, at 180 L/min shaping air flow rate, the mean diameter decreased by around 2 μm for a 10 kV electric potential increase. The current research has found a decrease of particle diameter of 2 to 3 μm as a result of rising the EP from 60 kV to 70 kV at a 200 cm³/s CFR, but an exact number cannot be confirmed due to the uncertainty of the measurement (Figure 4.5 a). A higher mean diameter was also found for 200 cm³/s coating flow rate at the same electric potential (Figure 4.5 b).
Figure 4.5: Particle mean diameter, $D_{32}$ (μm) with increasing electric potential for a) 100 cm$^3$/s flow rate; b) 200 cm$^3$/s flow rate at 200 slpm air flow rate and 40 krpm bell speed
Wang (2009) figured out that the radial droplet velocity decreased from the center of the spray to its edge along the radial distance. Higher bell speeds were observed to increase the vertical droplet velocity (Figure 4.6: a, b) in this research. As the velocity increased, the particles travelled through more air which resulted in an increase in the heat exchange, which increased the evaporation of the droplets. Coincidentally, the mean particle diameter increased with higher flow rate (Figure 4.5 a, b). Basu et al. (2010) also found that the mean particle diameter increased with increasing coating flow rate. An increase in mean particle diameter with an increase in flow rate may indicate a higher rate of agglomeration of smaller particles into larger particles, which eventually decreases the average particle velocity. According to the law of conservation of momentum, the velocity of a particle decreases after agglomeration with a lower velocity one. No significant change in the mean velocity was found at ± 5 cm radial distance, which indicates less agglomeration in that area.
Figure 4.6: Axial velocity (m/s) with increasing bell speed for a) 100 cm$^3$/s flow rate b) 200 cm$^3$/s flow rate at 200 L/min air flow rate, 40 krpm bell speed and 60 kV volt electric potential
A four factor, full factorial DOE for flow rate, shaping air flow rate, voltage and bell speed were created by Di Domenico and Henshaw (2012) at the 95% confidence level. Basecoat application zones were maintained at 22.8 °C and 63% humidity with a coatings flow rate of 500 mL/min. They found that voltage alone had no effect on the surface waviness. They found several significant interactive effects: (flow rate) * (shaping air flow rate), (shaping air flow rate) * (bell speed), (flow rate) * (bell speed), and (flow rate) * (voltage). In this study, a regression analysis was performed using the evaporation rate as the output and the process parameters as inputs. Current process parameters include coatings flow rate, bell speed and electric potential. Figure 4.7 shows the R-squared values that resulted after eliminating variables from the regression that were not statistically significant (p<0.05). For example, evaporation shows a strong correlation to the products: flow rate, bell speed, and (flow rate) * (bell speed) as indicated by an R-squared value of 82.5%. A P=0.048 indicates a slight relation to electric potential.
4.5 Conclusion

The total evaporation of clearcoat sprayed from a rotary atomizer was measured. Evaporation of clearcoat increased with increasing bell speed. Evaporation increased with increasing flow rate from 100 cm³/s to 200 cm³/s but decreased for a further increase to 300 cm³/s. The mean diameter (D₃₂) of particles decreased with increasing bell speed, electric potential and lower flow rate. The axial velocity of particles increased with increasing bell speed.
4.6 References


CHAPTER FIVE
EVAPORATION OF BASECOAT FROM A ROTARY BELL ATOMIZER AND ITS RELATIONSHIP WITH BELL SPEED, FLOW RATE AND ELECTROSTATIC POTENTIAL

5.1 Introduction

Different types and layers of coatings are applied in the automotive coating industry. Although a variety of coating application processes are available, the basis of all coatings remains the same concept: a film-forming material is applied on the surface of a body. In automotive paint shop primer, basecoat and clearcoat are typically used as coating layers. The current trend is that basecoats contain metallic flakes to enhance sparkle. The clearcoat is a protective layer that enhances gloss.

In the automotive paint industry, appearance and cost efficiency are the two key aspects which drive improvements in technology. Appearance is directly related to automotive sales and customer satisfaction. In spite of recent advances, the industry is still fighting with the third aspect: controlling the VOC emissions, which has been a concern for decades.

Surface coating is still the most significant source of VOC emission from the automotive industry. The solvents used in the coating can easily evaporate in the air during coating application and curing. US EPA has a standard that maximum 1.40 kg of VOC/ L of applied coating solids (ACS) and 1.47 kg of VOC/ L of ACS for primer and top coat is allowable for automotive paint industry (Subpart MM, 2005). The UNECE 1999 Protocol (Gothenberg Protocol) states that the VOC emission limit values for automotive surface coating of new car plants should be 45 g/m² (Ozone Protocol, 1999; UN/ECE, 1999). According to Canadian National Pollutant Release Inventory (NPRI) 2014 report, the
Canadian paint and solvent sector accounts for around 18% (323000 tonnes) of total VOC emitted in 2012 (Environmental Canada, 2014). Almost all of this VOC comes from automotive surface coating.

A Phase Doppler Anemometer (PDA) system was used for particle diameter measurement in the spray from a Rotary Bell Atomizer (RBA) in the current study. A RBA is a special type of paint applicator where paint is pumped into the interior of a cup (the “bell”) rotating at thousands of revolutions per minute (krpm). The paint forms ligaments at the edge of the cup, and these subsequently form droplets. RBAs are normally used in high volume production environments like the automotive industry where its superior transfer efficiency and spray pattern consistency result in a smooth finish. A typical bell applicator also has a cone of shaping air flow rate, blown in the same direction as the paint, to contain the spray. RBAs produce fine droplets, and so the spray must be charged electrostatically, in order to reach the electrically-grounded target.

In a PDA system two out-of-phase laser beams create an interference pattern where they cross. Particles which pass through the measurement volume reflect the interference pattern, which is shifted, depending on the velocity of the particle. When the droplet is small and spherical, the light refracts from it, and the extent of refraction is a function of particle size. Thus, the PDA is used to calculate the size, velocity and volume flux of spherical particles, droplets or bubbles suspended in gaseous or liquid flows. A PDA and RBA are shown in Figure 5.1.
A proper investigation which correlates various paint application parameters to paint flux can increase the efficiency of the spray while decreasing the VOC emissions in the automotive paint shop. The bell speed (BS) and coating flow rate (CFR) of the paint to the RBA are two major operational controlling factors. A detailed investigation of these factors on different types of coatings can provide a better picture of coating evaporation which is important to optimize the use of coatings applied in the industry.

This research investigated the effects of BS and FR on particle Sauter mean diameter ($D_{32}$) of water and clearcoat sprayed from a rotary bell atomizer, measured using a Phase Doppler Anemometer (PDA). It also strives to calculate the effects of these parameters on metallic paint. A rotary bell atomizer (RBA) guided with a robotic arm was used to atomize the fluid. Water was used as the fluid initially to establish a method to investigate these effects, a method which was used here for clearcoat and metallic paint.

### 5.2 Literature Review

Fraser et al. conducted a range of investigations in this area in 1962 to better realize the formation of liquid sheets during atomization. A spinning cup similar to the current rotary bell was used in an air stream released vertically with the fluid spray. They figured out
that the initial drop size from the breaking of the liquid sheet was a function of sheet thicknesses. They did not find any significant impact of air containment on atomization. However, they rationalized that a good finish is highly dependent on the sheet uniformity and critically dependent on application parameters like the spinning rate of the cup, flow rate and viscosity of the fluid.

A direct relation between bell speed, flow rate and mean drop size was established by Corbeels et al. (1992). A higher bell speed, resulting in higher centrifugal and Coriolis forces accounted for a lower mean drop size, while a higher flow rate accounted for higher mean drop size when the bell speed was lower than 20 krpm. If the flow rate increases with a constant bell speed, the average drop size increases. But a higher bell speed with a constant flow rate decreases the average drop size and increases the droplet number.

Di Domenico and Henshaw (2012) established a full factorial two-level DOE matrix to determine the relationship between the paint finish appearance and four variable RBA parameters: flow rate, bell speed, shaping air flow rate and electrostatic potential. The appearance was categorized by evaluating the distinctness of image, surface waviness, and multi-angle color. It was hypothesized that a change of particle diameter due to the change in these important factors played an important role in the evaporation of the paint droplets in-flight, and hence affected the appearance of the cured paint.

There is a direct relation between the droplet size, surface area and evaporation. The higher the drop size, the lower the total surface area (for a given volume of paint) and the lower the total evaporation. Wang (2009) used a PDA and four types of circular nozzle to atomize a water jet sprayed upwards at a constant pressure and temperature. They found
that with increasing axial distance, the droplet diameter increased and the particle velocity decreased.

Metallic solvent-borne and water-borne paint sprayed from a RBA were used to measure the particle size characteristics by using a shadowgraphy technique (Basu et al., 2010). A CCD camera was used to calculate the particle size. For bell speeds within a 30-50 krpm range, the mean particle size ($D_{32}$) decreased with an increasing bell speed. The effect of shaping air flow rate was found insignificant for 30-50 krpm range bell speed.

In a previous investigation using water spray (Ray et al., 2015 a, b), the PDA was used to show the effect on evaporation of water by varying BS, FR, and SA. Electrostatic charging was not used. All other variables like atmospheric pressure and temperature were kept constant. The effect of shaping air flow rate was found to be statistically insignificant. The total evaporation ($cm^3/s$) between 22.5 and 37.5 cm from the atomizer was calculated from point measurements of the droplet flux. It was found that the droplet diameter decreased and hence the evaporation increased with higher bell speed or lower flow rate.

5.3 Experimental setup

Fluid (water, solvent-borne clearcoat or water-borne basecoat) was fed into a high speed bell atomizer (ABB RB1000) which was attached to a computer guided robotic arm system (ABB IRB-5500X). A PDA system (Dantec Dynamics A/S, Denmark) was used to measure the particle diameter, velocity, volume flux, and particle size distribution of the spray. The PDA system has a receiving and a transmitting optics inside the spray booth. The control and processing unit outside the booth consisted of a computer and the BSA flow software package. A nebulizer (Airlife-002002) was used to align the PDA and
robotic arm initially. The spray booth was maintained with a constant temperature of \(24\pm0.6^\circ C\) \((75\pm1^\circ F)\) and \(65\pm2\%\) humidity. The booth had a constant and uniform, mostly vertical, downward air velocity of \(2.1\) m/s. But the air had a tendency to flow towards the outer wall of the booth. In order to minimize this effect, the PDA was placed at the center of the booth. Ray et al. (2015 a,b) described the experimental setup used for this current investigation.

Measurements were taken along a traverse through the spray in an x-y plane at 22.5 cm along the axis of the bell cup rotation (z-axis). The points in the spray were sampled in 2.5 cm radial intervals by moving the robot arm holding the RBA relative to the fixed PDA probe and receiver. The shaping air flow rate was set at a constant 200 standard liters per minute (L/min), bell speed was set to 30, 40 and 50 thousand rotations per minute (krpm) and the flow rate was varied between 100, 200 or 300 cubic centimeters per minute (cm\(^3\)/min). The electrostatic charge was applied and varied for the basecoat and clearcoat. No electrostatic charge was used when spraying only water. The electrostatic change was varied between 60, 70 or 80 kV for clearcoat. Only 70 kV electrostatic charge was used for basecoat.

The PDA system was set to acquire data for a maximum of 10,000 particle counts at each position or to acquire for 5 seconds, whichever came first. This ensured a reasonable maximum number of counts at the most distal point in the spray where particle counts were lower, while not overloading the system at the center of the spray where a higher particle density existed. However, the system can only determine a statistically correct diameter or velocity with a minimum 1500 particle count. These limitations confined the spray's realistic range up to a radial distance of 7.5 cm for water and 12.5 cm for
clearcoat. It is important to note that particle counts beyond this range were low and represent less than 4% and 7% of the total flux for water and clearcoat, respectively (Ray et al., 2015a, Ray and Henshaw, 2015). Similarity in the x and y directions was assumed. Figure 5.1 shows the experimental setup in the spray booth for the current testing method.

Each test was repeated 3 times for water, clearcoat and metallic paint to estimate the variance and the variance was multiplied by 1.96 to calculate the 95% confidence limit (Dantec Dynamics, 2006; Albrecht et al., 2003). This was used to calculate the uncertainty of the PDA measurement. The static repeatability of the positioning robot is 0.15 mm (ABB, 2009). It was included to calculate the total uncertainty of the test. Ray et al. (2015a) describes a detailed calculation of uncertainty.

5.4 Results and Discussions

Particle mean diameter decreased with increasing bell speed and decreasing the axial distance when water was used as a spray fluid at 300 cm$^3$/s flow rate (Figure 5.2). Figure 5.3 shows the same trend while using clearcoat. It is noted that the initial decrease in mean diameter is steep while using water where a modest decrease was found in the case of clearcoat.
Figure 5.2: Mean diameter, $D_{32} (\mu m)$ with increasing bell speed for 300 cm$^3$/s flow rate for water

At higher bell speed, the initial sheet thickness is less, which causes a smaller initial drop diameter (Fraser et al., 1962). At the same time, the fluid particles have a higher velocity. This causes two effects: the droplets travel faster in space which increases the exposure to unsaturated air and hence evaporation, but the increased velocity means that there is less flight time for evaporation. Ultimately, the combined effect increases the evaporation and hence decreases the drop diameter. Our findings support those from previous researchers.
This research attempted to figure out if the same trend exists for basecoat. Figure 5.4 show that the results for metallic basecoat followed the same trend as clearcoat and water. However, these results should be used with caution. The basecoat droplets have a high opacity and do not refract the light so well. With water and clearcoat, the validation was more than 90% for all cases; however, it was less than 65% for basecoat. According to Dantec Dynamics, the provider of PDA system, experimental values with less than 80% validation are statistically unreliable (Dantec Dynamics, 2006). Because of this uncertainty, the flux measurement for the basecoat was considered invalid, and the evaporation rate between x-y planes was not calculated.
The trend of mean diameter decreasing with increasing bell speed that was found in water and clearcoat was also found for basecoat. However, the measurements with metallic-pigmented basecoat had a low statistical viability, and were deemed unsuitable for calculating the flux through parallel planes, which is required for calculating the evaporation.
5.6 References


CHAPTER SIX

SPRAY ATOMIZATION CHARACTERISTICS OF LIQUID DROPLETS: FORMATION USING A ROTARY BELL ATOMIZER AND A PARTICLE DYNAMIC ANEMOMETER

6.1 Introduction

The rotating cup has been used for atomization of liquid for the last 70 years, for numerous purposes like spray drying, heating and cooling, combustion and crystallization. In the early years, it was used in domestic heating applications (Van De Putte and Ven Den Bussche, 1947). Later, this principle was applied in agriculture, fire extinguishing and industrial painting. The rotating bell atomizer (RBA) is now a very popular device used in automotive coatings. In an RBA, the liquid coating is fed into a rotating cup, shaped like a bell. It then flows towards the edge of the cup, gains its rotating speed and forms spray drops at the edge of the cup. Shaping air flow rate is an optional measure used to control the spray. The combination of centrifugal force, angular speed of the liquid layer and droplets, shaping air flow rate, air velocity, and electrostatic charge of the liquid affect the size and velocity of the droplets, from the edge of the cup until they strike the surface (Hinze and Milborn, 1950). Considerable evaporation is expected during the flight of the droplets. These phenomena (droplet formation and evaporation) affect the efficiency with which coatings are transferred to the target and the final finish onto the surface.

Although various researchers strived to understand the basic principle of the mechanism for the disintegration of liquid occurring on and after the edge of the cup, a detailed drop size and evaporation investigation, leading to empirical formulae using data from an industrial-scale application is still pending.
6.2 Mechanism of Droplet Formation and In-flight Physical Characteristics

The lifetime of a droplet created by atomization of a liquid can be divided in two parts: the formation of droplets and the in-flight change before reaching the target surface.

6.2.1 Formation of Droplets

When a rotating cup is used for the atomization of a liquid, the liquid is supplied from a liquid cartridge which feeds into the interior of the rotating cup. Friction occurs between the liquid and the rotating cup, which results in the liquid achieving the same angular velocity as the cup. Centrifugal force causes the liquid to flow toward the edge of the cup. The length of the liquid front increases with radial distance, so by conservation of mass, the thickness of the liquid front must decrease (Hinze and Milborn, 1950). The movement of liquid through the rotating cup is shown in Figure 6.1.

Figure 6.1: Liquid and shaping air flow rate flow through a RBA
The breakup of the liquid layer into droplets is a complex phenomenon which occurs within a very short distance. The thin film of liquid faces several internal and external forces when it is separated from the edge of the cup (Dombrowski and Johns, 1963). Pressure, surface tension, and centrifugal force are the driving forces. Viscosity and initial angular velocity contribute to the formation of droplets. Several investigators observed that the liquid sheet forms an aerodynamic pattern that looks like a wave at the edge of the cup (Dombrowski and Johns, 1963; Fraser et al., 1962a). The wavy liquid breaks into a succession of circumferential ligaments when disintegration occurs. Disintegration is believed to happen when the wavy film reaches critical amplitude. The length (radial direction) of the ligaments is one half of the wave length of the liquid sheets. Upon further propagation of these unstable ligaments, they contract by surface tension and break circumferentially up into liquid droplets (Dombrowski and Johns, 1963). The formation of droplets from the liquid sheets is shown in Figure 6.2.
6.2.2 In-flight Droplet Changes

The physical model of in-flight characteristics of droplets was described by several researchers (Ranz and Marshall, 1952a, 1952b; Williamson and Threadgill, 1974). Regardless of the type of liquid, all of them evaporate when in a gaseous medium. The rate of this evaporation depends upon the ambient temperature and the vapor pressure of the liquid. When a water-borne coating is used, water is the solvent and other dissolved or suspended materials are the solute. For solvent-borne coatings, organic liquids are the solvents. For any practical spray application, the solute has a lower vapor pressure than the solvent (H.J. Holterman, 2003) and hence the solvent evaporates more rapidly than the solute. When most of the solvent (50% or more) is evaporated, the solutes start evaporating, but at a slower rate (H.J. Holterman, 2003).
When a water droplet travels through the air, it is subject to evaporation and hence a decrease in size. The droplet also cools down due to evaporation and a saturated vapor layer surrounds the droplet. At this point, the drop has reached its wet bulb temperature. The temperature of the droplet is then lower than the surrounding air temperature, which causes heat flow towards the droplet, and evaporation starts again (Ranz and Marshall, 1952a, 1952b; Holterman, 2003). Thus, the rate of evaporation is not constant and the process is not steady, so the time required for evaporation can be divided into two steps. The first is the time span from the formation of droplets to the time when droplets reach their wet bulb temperature. The second is a period of unsteady evaporation. The processes continue until the droplet reaches the target surface, or completely evaporates.

The initial angular velocity of the droplet degrades rapidly due to air friction. If any downward air velocity is present and because of centrifugal force, the droplet quickly loses its radial and tangential components and only the vertical component exists, due to gravity and drag by the ambient air. After a certain time the droplets simply have a constant axial velocity, which is called the sedimentation velocity.

Evaporation rate, $K$, which is normally termed as evaporation rate constant, and indeed is approximately constant for water in air when the droplet diameter is large enough (>300µm) (Ranz and Marshall, 1952b; Lefebvre, 1989). However, for smaller individual particles like water-borne and solvent-borne paints, the rate is not constant (Holterman, 2003; Lefebvre, 1989). The parameter $K$ is dependent on temperature, relative humidity and physical properties of the liquid (heat of vaporisation) and air (thermal conductivity). Evaporation of droplets in a spray changes the air temperature, relative humidity and
composition of the droplets and hence the change in diameter and velocity of the droplet has an effect on the evaporation rate.

6.3 Literature Review

Rayleigh (1878) was the first mathematician to investigate the properties of water droplet formation using a jet. He established a mathematical model to describe the disintegration of water jets projected into the air. He was the first to identify that the water jets form a thin layer or sheet, before forming droplets.

Hinze and Milborn (1950) did an initial investigation of the atomization of liquids using a rotating cup. They divided the occurrence of atomization into three possible “stages” depending on the supply rate of the liquid. In the first stage, a liquid torus is formed at a very low flow rate, which eventually deforms by centrifugal forces and drops are formed. If the flow is increased, the second stage kicks in, in which the torus becomes ligaments of liquid. Increasing the flow rate increases the thickness and number of ligaments, which at their end become droplets due to disturbances caused by external forces. A further increase in flow rate results in the maximum thickness of ligaments where an extending film is formed from the edge of the cup which later forms circumferential ligaments and breaks down into droplets. In this third stage, the thickness of the liquid film just outside and inside of the edge of the cup is practically the same. They used this assumption to calculate the thickness of the liquid layer, which was later used by most researchers to calculate the diameter of the droplets.

Dombrowski and Johns (1963) investigated the aerodynamic instability and disintegration of viscous liquid sheets. They discussed the characteristic change of the
liquid layer after it is ejected from the rotating cup and acted on by the surrounding atmosphere. Though different operating conditions affect the method of disintegration of the liquid layer to droplets, the major cause of the disintegration is the interaction of liquid layers with surrounding conditions and the forces that work on them. They considered only a Newtonian fluid where the liquid sheet disintegrates to droplets. During the growth of aerodynamic waves, forces caused by gas pressure, surface tension, liquid inertia and viscosity of the liquid sheet were considered in deriving the initial drop size equation (Dombrowski and Johns, 1963).

A thorough investigation of the formation of a liquid sheet with a rotating cup was performed by Fraser et al. (1962). They considered the shaping air flow rate in their series of studies. Formation of a uniform liquid sheet is important for a uniform spray of liquids over a wide range of operating conditions. In their first study (Fraser et al., 1962a) they showed the importance of an uninterrupted supply of liquids into the rotating cup wall for the production of uniform liquid sheets. In their second study (Fraser et al., 1962b), they showed the influence of various factors: rotating cup dimension, speed, flow rate and viscosity on the thickness of liquid films. The sheet thickness increased with an increase in the liquid flow rate and liquid viscosity. The sheet thickness decreased with an increase in rotating cup speed and cup diameter. In their third study (Fraser et al., 1962c), they considered the shaping air flow rate to increase the air-liquid contact, which was believed to decrease the liquid sheet thickness at higher air flow rates. Shaping air flow rate ensures better energy transfer efficiency and finer droplet size, of which the latter is important in creating a better finish on the coated surface. The same concept is true for the relation between droplet diameter, rotating cup speed and flow rate. By
increasing the shaping air flow rate from 100 to 400 ft/s, a sharp decrease in mean droplet diameter was found at all liquid flow rates. However, any further increase of shaping air flow rate had little or no effect on droplet diameter.

Dominick (2012) considered Weber number (We) and critical flow number to postulate a non-dimensional correlation with the Sauter mean diameter of droplets for both Newtonian and non-Newtonian fluids in a high speed rotary bell atomizer. They found that Sauter mean diameter increased with decreasing bell speed for both the fluids. However, no considerable effect on Sauter mean diameter for change of Weber number and critical flow number was found.

A detailed investigation of the kinetics and evaporation of in-flight water droplets was described by Holterman (2003). He described the physical phenomenon which occurs during the flight path of a droplet. He used the classic equation of Williamson and Threadgill (1974), who developed an equation for evaporation rate and used it to find the droplet diameter anytime during the flight.

Di Domenico and Henshaw (2012) used a full factorial DOE matrix to find a relationship between the operating parameters: flow rate, bell speed, shaping air flow rate, electrostatic potential with the appearance of cured paint. Prior to their investigation, it was believed that small particles experience greater evaporation in flight (compared to large droplets) ensuing lower solvent content, greater viscosity during surface contact and hence are less amenable to surface tension induced leveling (Overdiep, 1986). However, they found contradictory results, where drier films had fewer wrinkles. They postulated that, surface tension gradient driven solvent flow results in an uneven thickness of the
coating resin, so that after the solvent has evaporated the waviness in the film is higher. Thus, films from a drier spray would end up flatter. Ray and Henshaw (2015) confirmed that decreased flow rate and increased bell speed decreased the spray droplet size and they measured more in-flight evaporation of solvent from smaller droplets. Accordingly, greater in-flight evaporation causes drier films, which have less solvent-driven migration and result in a smoother finish, especially in the lower wavelengths of surface undulation (< 1 mm). Since Ray and Henshaw (2015) confirmed that evaporation was greater in clearcoat under the conditions that lead to smaller droplets (higher bell speed, lower flow rate), it is inferred that the surface tension driven solvent flow is likely the reason for the previous observations by Di Domenico and Henshaw (2012).

Ray et al. (2015a, b) and Ray and Henshaw (2015) published a series of experimental studies where water and clearcoat were used and the effects of different RBA parameters on the evaporation and characteristics of droplets. They found that the droplet diameter and evaporation were dependent on bell speed and flow rate of liquid. However, no significant effect due to shaping air flow rate was found during these investigations.

6.4 Experimental Procedure

The measured droplet diameters and velocities for different bell speeds and flow rates used in this analysis were taken from the experiments by the same authors (Ray et al., 2015a,b; Ray and Henshaw, 2015). A high speed rotary bell atomizer (RB1000 WSC; ABB K.K., Shimada-Shi, Japan) was connected to and maneuvered by a robotic arm system (IRB-5500X; ABB K.K., Shimada-Shi, Japan). A Particle Dynamic Anemometer (PDA; Dantec Dynamics, Skovlunde, Denmark) - also known as a Phase Doppler
Anemometer - was used to measure the particle diameter and velocity of the particles. The PDA system consists of transmitting optics, receiving optics and a processing unit. The spray booth was maintained with a constant temperature of 24±0.6°C (75±1°F) and 65±2% humidity.

An orthogonal coordinate system was chosen such that the axis of rotation of the RBA was the z-axis. Measurements were taken along the x-axis at 2.5 cm intervals on both sides of the z-axis. Data were collected in x-y planes at 22.5 and 30.0 cm axial distances from the bell cup, while the spraying was performed in the downward direction (positive z-axis direction). A constant 200 standard liters per minute (L/min) shaping air flow rate was used, the bell speed was set to 30, 40 or 50 thousand rotations per minute (krpm) and the flow rate was varied between 100, 200 or 300 cubic centimeters per minute (cm³/min). An electrostatic charge of 60, 70 or 80 kV was applied for the clearcoat only.

A detailed description of the experimental procedure can be found in Ray et al. (2015a, b).

Measurements at each location were repeated 3 times for water and clearcoat in order to estimate the variance. The variance was multiplied by 1.96 to attain the 95% confidence limit of the test (Dantac Dynamics, 2006; Albrecht et al., 2003). The uncertainty of the PDA measurement was less than 10% of the calculated evaporation (Ray et al., 2015a). The static repeatability of the positioning robot is 0.15 mm (ABB, 2009). This value was included in calculating the total uncertainty of the test. Ray et al. (2015a) described a detailed calculation of uncertainty.
6.5 Results and Discussions

Using the dimensional analysis method of Hinze and Milborn (1950), two dimensionless parameters $\omega D \sqrt{\left(\frac{\rho D}{\sigma}\right)}$ and $\frac{Q}{D} \sqrt{\left(\frac{\rho}{\sigma D}\right)}$ were used to identify three stages which characterize the type of droplet formation phenomenon that occur. Here, $\omega$ is the angular speed of the rotating cup (rad/s), $D$ is the maximum diameter of the cup (m), $\rho$ is the density of the liquid (kg/m$^3$), $\sigma$ is the surface tension of the liquid (N/m) and $Q$ is the flow rate of liquid supplied to the cup (m$^3$/s). It is noted that the physical properties of the liquid, the dimensions and the velocity of the rotating cup, and the flow rate are the important factors which determine the type of disintegration that will occur. These dimensionless parameters were plotted on a logarithmic graph (Figure 6.3) to identify which of the three stages is appropriate for these water and clearcoat tests. It is noted that both water and clearcoat are well inside of Stage III. Based on their categorization as Stage III, both liquids formed a liquid film, which then disintegrated into ligaments and droplets.
Ray *et al.* (2015 a, b) investigated the change in water droplet diameter for different bell speeds and flow rate conditions between 22.5 cm and 30 cm axial distance from the spray. The decrease in drop diameter was calculated and it was at most 15%, which was relatively small considering the magnitude of the diameter. Also, the evaporation rate was almost steady throughout the droplet flight (flux at an axial distance of 27 cm was also measured). Holterman (2003) proposed that if the decrease of drop size is relatively small and the evaporation rate does not change much, the classic equation for change in droplet diameter by Williamson and Threadgill (1974) can be re-written as:

\[ d_{p2}^2 = d_{p1}^2 - 2Kt \]  \hspace{1cm} \text{(m}^2) \hspace{1cm} \text{[Eqn. 6.1]} \]

where

\[ K = 2a \left( 1 + b \sqrt{\left( \frac{d_{p1} V_s}{\rho} \right)} \right) \]  \hspace{1cm} \text{(m}^2/\text{s)}
\[ a = \frac{(4YM_LD_V \Delta T)}{\rho_LRT} \quad \text{(m}^2\text{/s)} \]

\[ b = 0.276 \left( \frac{\rho_a}{\eta_a D^2} \right)^{1.6} \quad \text{(m}^{-1}\cdot\text{s}^{0.5}) \]

\[ \Delta T = T - T_w \]

\( T_w \) = wet bulb temperature (°C)

\[ = T - (5.1055 + 0.4295 T) + (-0.04703 + 0.0000466) \times \text{RH} \]

\[ V_s = \frac{\rho_L g D p_1^2}{18 \eta_a} \quad \text{(m/s)} \]

\( d_{p_2} \) = droplet diameter after evaporation (m)

\( d_{p_1} \) = initial droplet diameter (m)

\( K \) = evaporation rate (m\(^2\)/s)

\( t \) = time required to travel the distance (s)

\( T \) = temperature (°C)

\( Y \) = function of atmospheric pressure and wet-bulb temperature (Pa/K)

\( B = 0.000660 \times (1 + 0.00115 T_w) \times \text{atmospheric pressure (Pa)} \)

\( M_L \) = molecular weight of evaporating liquid (kg/mole)

\( D \) = average diffusion co-efficient of vapor molecules in the saturated films around the drop (m\(^2\)/s)

\( \rho_L \) = liquid density at temperature T and pressure (kg/m\(^3\))

\( \rho_a \) = air density at temperature, T, and pressure (kg/m\(^3\))

\( R \) = gas constant (8314 J/mol·K)

\( \eta_a \) = air viscosity at temperature, T, and pressure (kg/m·s)

Equation 6.1 can be re-written as

\[ d_{p_1} = \sqrt{\left( d_{p_2}^2 + 2Kt \right)} \quad \text{(m)} \quad \text{[Eqn.6. 2]} \]

Equation 6.2 can be used to calculate the droplet diameter at the \( z = 22.5 \) cm plane from the measured droplet diameter at the \( z = 30 \) cm plane (z-axis is the rotational axis of the
RBA) at the same radial distance. The measured and calculated droplet diameters at $z = 22.5$ cm for different bell speeds and flow rates are plotted in Figure 6.4. It can be seen that the equations predict $d_{p1}$ within 3%, which is less than the uncertainty of the measurement (below 10%).

![Figure 6.4: Relation between measured and calculated water drop diameter at an axial distance of 22.5 cm at 0, 2.5, 5, 7.5 cm radial distance](image)

Ray and Henshaw (2015) investigated the change in clearcoat droplet diameter due to evaporation under the same conditions as just described for water. For the clearcoat tests, an electrostatic charge was applied. The electrostatic charge creates repulsion between droplets and increases droplet velocity (Snarski and Dunn, 1991). However, no known effects on evaporation have been reported. As discussed before, the solvent starts evaporating before the co-solvents in solvent-borne coatings (Holterman, 2003). When all the solvent is evaporated, the co-solvents start to evaporate and the evaporation rate needs to be adjusted for the co-solvents in Equation 6.1. The clearcoat used in these experiments contains 74% solvent by volume. Thus, the evaporation rate of clearcoat
follows Equation 6.1 until the droplet diameter reaches 50% of its initial diameter. However, from the experimental measurements only a maximum of 10% of the diameter is lost between in-flight distances of 22.5 cm and 30 cm of the clearcoat droplet. Thus, it can be safely assumed that the change in diameter measured in these experiments is due to the evaporation of solvent only. So, Equation 6.1 should be valid for the calculation of droplet diameter for clearcoat. The measured and calculated droplet diameters for clearcoat at \( z = 22.5 \) cm for different bell speeds and flow rates are plotted in Figure 6.5. It can be seen that the Williamson and Threadgill equations predict the droplet size within 1%, which is less than the uncertainty of the measurement (below 10%).

![Figure 6.5: Relation between measured and calculated clearcoat drop diameter at an axial distance of 22.5 cm at 0, 2.5, 5, 7.5 cm radial distance](image)

The evaporation rate, \( K \), was calculated and reported in Figure 6.6 for water and Figure 6.7 for clearcoat for different flow rates and bell speeds. \( K \) is dependent on the initial droplet diameter and settling (terminal) velocity of the droplet (Holterman, 2003). It was found that \( K \) decreased with increasing bell speed and increased with increasing flow rate. For the same bell speed and flow rate, \( K \) was higher for clearcoat than for water,
meaning that the inter-molecular attraction force for clearcoat is lower than water. It should be noted that K will vary for different types of clearcoat according to its solvent composition. However, K is also dependent on temperature and pressure, which were constant in these experiments. At 10°C, K was reported to be between 963-986 μm²/s for water where the initial droplet diameter was between 20-30 μm (Holterman, 2003). For the same range of droplet diameters, the value of K was found to be between 860-1270 μm²/s for the current experiments (T=24±.6°C).

Figure 6.6: Evaporation rate, K for different bell speeds and flow rates for water
Dombrowski and Johns (1961) established an equation between droplet diameter and fluid ligament diameter based on fluid properties. The relation holds true for viscous fluids which form droplets as in Stage 3 of the zoning chart by Hinze and Milborn (1950). The relation is described by the following equation:

\[ d_p = \left[ \frac{3 \pi}{\sqrt{2}} \right]^{\frac{1}{3}} d_L \left[ 1 + \frac{3 \mu}{(\rho L \sigma d_L)^{\frac{1}{2}}} \right]^{\frac{1}{3}} \]  
[Eqn. 6.3]

where,

\[ d_L = 0.9614 \left[ \frac{K_1 \sigma^2}{\rho \rho_L U^4} \right]^{\frac{1}{6}} \left[ 1 + 2.6 \mu \left( \frac{K_1 \rho^4 U^7}{\tau_2 \rho_L \sigma^5} \right)^{\frac{1}{2}} \right] \]  
[Eqn. 6.4]

- \( d_p \) = droplet diameter in (m)
- \( d_L \) = ligament diameter (m)
- \( \mu \) = liquid viscosity (kg/m.s)
- \( \rho \) = air density (g/m^3 at specific pressure and temperature)
- \( \rho_L \) = liquid density (kg/m^3 at specific pressure and temperature)
\[\sigma = \text{surface tension of liquid (kg/s}^2)\]
\[U = \text{mean liquid velocity in air (m/s)} = \sqrt{\frac{2p}{\rho_l}}\]
\[K_1 = hL = \text{nozzle parameter (m}^2)\]
\[h = \text{sheet thickness (m)}\]
\[L = \text{sheet propagation distance (m)}\]
\[p = \text{Liquid ejection pressure (kg/m}^2) = \frac{mV}{tA}\]
\[m/t = \text{liquid mass flow rate (kg/s)}\]
\[V = \text{Tangential velocity at the edge of the bell (m/s)}\]
\[A = \text{Liquid and surface contact area (m}^2)\]

It is noted that since the physical properties for liquid and gas (air) are constant, the mean droplet diameter depends upon the mean liquid velocity in the air and \(K_1\), which differs according to the type and size of the rotating cup and the flow rate of the liquid. The value of \(K_1\) can be determined for each specific bell type and is constant for a rotary (and associated mean liquid) velocity (Dombrowski and Johns, 1963). The formation of droplets from the liquid film happens within a fraction of a second for a high speed rotary atomizer. The droplets which are found at the center of the spray (radial distance), have the maximum diameter with the minimum distance travelled. Also, the distance travelled by the liquid film before the formation of droplets is negligible compared to the total distance traveled. So, it can be assumed that the newly formed droplet has the same velocity as the air. In fact, the velocity calculated at zero axial distance based on the measured velocity at 22.5 cm axial distance is within 85% of the settling velocity, which indicates that settling velocity is attained within very short distance of droplet formation.

At different bell speeds and flow rates, the initial droplet diameter \((d_o)\) was back calculated from the measured droplet diameter in the 22.5 cm plane, using Equation 6.1.
$d_0$ was then used in Equation 6.4 to determine the value of $K_1$. It was noted that $K_1$ decreases with increasing bell speed and increases with the flow rate for water (Figure 6.8). However, for clearcoat no variation was reported for different bell speeds and flow rates ($K_1=0.0018 \text{ cm}^2$ in Figure 6.9). Hasson and Mizrahi (1961) estimated the value of $K_1$ to be $0.00315 \text{ cm}^2$ for fan-spray nozzles over the range of operating conditions employed.

Figure 6.8: Nozzle parameter, $K_1$ for different bell speeds and flow rates for water

Figure 6.9: Nozzle parameter, $K_1$ for different bell speeds and flow rates for clearcoat
It should be noted that the viscosity ($\mu$) of clearcoat is much higher than water (0.1605 kg/m-s for clearcoat and 0.000911 kg/m-s for water at 24±0.6°C), which allows water to have a variable $K_1$ for different flow rates and bell speeds. In Equation 6.3, a very low viscosity makes the ligament diameter ($d_L$) directly proportional to the droplet diameter, which eventually makes it directly related to bell speed and flow rate. In Equation 6.4, if the viscosity ($\mu$) is very small, $K_1$ is almost proportional to the third root of ligament diameter ($d_L$). So, bell speed and flow rate have a very significant effect on the value of $K_1$ for water. However, in the case of clearcoat, viscosity ($\mu$) is comparatively high and the effect of bell speed and flow rate are insignificant. Ligament diameter for various flow rates and bell speeds (both water and clearcoat), using the calculated values of $K_1$, are shown in Table 6.3. Wax spray, which has a higher average viscosity (0.01 kg/m.s) than water but lower than clearcoat, was used by Hasson and Mizrahi (1961) to estimate the value of $K_1$ to be 0.00315 cm$^2$ for fan-spray nozzles.

Table 6.3: Ligament diameter for various flow rates and bell speeds

<table>
<thead>
<tr>
<th>Liquid Type</th>
<th>BS (krpm)</th>
<th>FR or CFR (m$^3$/s)</th>
<th>Mean liquid velocity in air, $U$ (m/s)</th>
<th>Term 1 ($\mu$m)</th>
<th>Term 2 ($\mu$m)</th>
<th>Ligament diameter, $d_L$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>30</td>
<td>100</td>
<td>15.71</td>
<td>21.8039</td>
<td>0.08431</td>
<td>21.88</td>
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<tr>
<td></td>
<td>50</td>
<td>200</td>
<td>26.18</td>
<td>19.5302</td>
<td>0.01538</td>
<td>19.54</td>
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<tr>
<td>Clearcoat</td>
<td>30</td>
<td>100</td>
<td>15.71</td>
<td>18.4269</td>
<td>2.28312</td>
<td>20.71</td>
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<td></td>
<td>50</td>
<td>200</td>
<td>26.18</td>
<td>13.2136</td>
<td>3.72361</td>
<td>16.94</td>
</tr>
</tbody>
</table>

Where, Term 1 = $0.9614\left(\frac{K_1^2 \sigma^3}{\rho L U^5}\right)$ and Term 2 = $2.6\mu\left(\frac{K_1 \rho^7 U^7}{72 \rho L^2 \sigma^5}\right)^{\frac{1}{2}}$
6.6 Conclusions

The nozzle parameter $K_1$, varies widely with different bell speeds and flow rates for water, but is a constant for clearcoat. The initial particle diameter for different bell speed and flow rates can be calculated using this nozzle constant. The equations reported by Holterman (2003) for evaporation of the droplets can be used to calculate the diameter of a droplet at any distance along the flight path. Both $K$ and $K_1$ are close to the numbers reported by the respective authors, which verifies their models and can be used for similar equipment setups. The combination of these two models can be used to determine the particle diameter and respective evaporation at any distance in the spray. This prediction can be used to improve finish in a paint spray or atomization of the spray. This will also allow designers to control evaporation where air pollution is a major concern.
6.7 References


CHAPTER SEVEN
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

The PDA method was successfully used with water to estimate evaporation and the relation of evaporation with different operating parameters; the tests were repeated with clearcoat. The total evaporation of liquid sprayed from a rotary atomizer was based on the difference between liquid flow rates measured at two planes. In contrast to the experiments with water, electrostatic voltage was applied to the clearcoat spray and a metal target plate was used for clearcoat to provide a point of attraction for the electrostatically-charged spray. The PDA was able to determine the volume flux up to 10 cm from the axis of the spray for water and 12.5 cm for clearcoat. With the same flow rate and bell speed, this difference indicates more spread of the spray for paints compared to water. There are two possible reasons for the difference in spread between solvent-borne clearcoat and water. Clearcoat is less dense than water, hence has less vertical terminal velocity and therefore the droplet trajectories are more horizontal. In addition, the electrostatically-charged particles may have repelled each other, resulting in a wider spray.

In water-borne and solvent-borne cases, the maximum flux was found at 2.5 cm from the axis. Normally, the spray pattern is assumed to be shaped like a hollow cone. The fact that the peak number of particles occurred at 2.5 cm from the centreline indicates that the spray pattern changed to a cylinder when the radial velocity dissipated due to friction.
The trend for base coat shows the same 12.5 cm axial distance limitation for flux. However, an exact calculation for neglected flux was not possible for base coat.

Evaporation increased with an increasing bell speed and flow rate for both water and clearcoat. However, the rate of increase was highest between 100 cm$^3$/min and 200 cm$^3$/min and comparatively much lower between 200 cm$^3$/min and 300 cm$^3$/min. The rate of increase was also higher between 30 krpm and 40 krpm bell speed compared to between 40 krpm and 50 krpm. The evaporation rate, K, decreased with increasing bell speed (30 krpm to 50 krpm) and increased for increasing flow rate (100 cm$^3$/min to 200 cm$^3$/min) for both water and clear coat (Figure 6.6 and 6.7). The measured evaporation of clearcoat followed the same trend as water where the evaporation increased with increasing bell speed and coating flow rate, except that the evaporation decreased at the highest CFR (300 cm$^3$/min). The mean diameter ($d_{32}$) of particles decreased with increasing bell speed, electric potential and flow rate. The axial velocity of the particles increased with increasing bell speed. At 30 krpm the mean particle size ($d_{32}$) was around 38 µm for a 30 krpm bell speed with 200 L/min shaping air flow rate and decreased to 32 µm for a 50 krpm bell speed under the same conditions. With 100 cm$^3$/s flow rate, 200 L/min shaping air flow rate, 70 kV electric potential and at $z$=22.5 cm, the mean diameter at the center of the spray was around 30 µm for a 30 krpm bell speed, and decreased to 25.5 µm for a 50 krpm bell speed. The effect of shaping air flow rate was ignored as it was found insignificant, as in the case of water sprays.

Increasing the flow rate and/or bell speed also increased the number of smaller particles and decreased the number of larger particles. The velocity of the particles also increased with an increase in bell speed. These combined actions contributed to the increase of
evaporation for both water and clearcoat. This also provides evidence that the postulation of possible evaporation and increase in surface waviness by Di Domenico and Henshaw (2012) was correct. As the droplet diameter decreases, solvent evaporation increases, therefore the droplets are drier when they strike the target surface. The fact that the wave scan number increases with a drier spray, must therefore be explained by phenomena that occur during drying and curing of the film.

The model developed by Williamson and Threadgill (1974) and later verified by Holterman (2003) to calculate the change in diameter of a water droplet at any distance along the flight path was used to calculate the evaporation rate $K$ (m$^2$/s) for water and clearcoat. For water, the value of $K$ was between 860-1270 $\mu$m$^2$/s for the current experiments ($T=24\pm0.6^\circ$C). The value of $K$ was between 1300-2000 $\mu$m$^2$/s for clearcoat. These values of $K$ were found to overlap with the numbers reported by the respective authors. Values of $K_1$ for clearcoat were within a factor of two with those reported in the literature, where a different type of nozzle was used. In most of the conditions, solids start evaporating after all the water is evaporated but the evaporation of solids is very low under standard temperature and pressure (Holterman, 2003). This implies that the current model can be used for water-borne basecoat as well. Holterman, 2003 found that their model works for water droplets 10 $\mu$m to 1000 $\mu$m at 20°C. So the current model would work for the water-borne basecoat sprays studies. This remains to be confirmed with proper instrumentation. The current study found that the models for evaporation and droplet formation work for water and solvent based clearcoat within certain operating conditions and assumptions. Dombrowski and Johns, 1963 reported that their model of droplet formation is valid for a wide variation of water-borne and solvent-borne paints.
For water-borne paint sprays, water starts evaporating first, unless a steady state condition is achieved. From an environmental perspective, one major scope of this research was to reduce the solvent evaporation during the spray application of coatings. In a paint shop, the spraying and curing processes account for most of the VOC emissions. Evaporation rate and its effect on various operation parameters can be used as a tool to control the solvent evaporation in new paint formulation and existing paint spray, which can result in reduction of surface waviness. Control and optimization of the spray process can decrease the amount of paint use, which eventually decreases the VOC emission. Improving the efficiency of the spray also ensures optimum use of raw materials which reduces the production pollution footprint.

7.2 Conclusions

Water was initially used as a surrogate for clearcoat and basecoat to mimic the situation in a industrial paint shop, while avoiding potential hazards and cost associated with experiments using paints. The droplet fluxes through different planes were measured using a PDA. The evaporation was calculated by subtracting the water flow rate between two horizontal planes. The uncertainty was found to be under 10% of the total estimated evaporation and hence the calculated evaporation is considered valid. But due to the uncertainty, it was difficult to predict the actual change in evaporation rate in the axial direction.

The effects on evaporation of water by varying bell parameters: shaping air flow rate, bell speed and liquid flow rate, were observed. Temperature and pressure were kept constant in the spray booth. Although the effect of shaping air flow rate was found to be
statistically insignificant, the other parameters were significant. Evaporation increased with increasing bell speed for a constant liquid flow rate and shaping air flow rate. The particle concentration increased with increasing bell speed but particle diameter (d_{32}) decreased at the same time so the total surface area for evaporation increased with increasing bell speed at a constant flow rate and shaping air flow rate. Higher bell speeds also increased the initial vertical droplet velocity. However, the measurements with both the metallic-pigmented or non-metallic-pigmented (straight shade) basecoat had a low statistical viability, and were deemed unsuitable for calculating the flux through parallel planes, which is required for calculation of the evaporation.

The combination of these two models was used to determine the particle diameter and evaporation at any distance in the spray. This prediction can be used to improve the finishing of paint spray or atomization of spray. The model developed by Dombrowski and Johns (1961) to represent the relation between droplet diameter and fluid ligament diameter based on fluid properties was used to find the nozzle parameter K_1(m^2) for a RBA for both water and clearcoat. The parameter K_1 (m^2) for water was found to depend on water flow rate and bell speed. But, a constant value (0.0018 cm^2) was found for clearcoat.

7.3 Future Recommendations

The current method was unable to estimate the evaporation using a PDA for basecoat. Shadowgraphy or ultrasonography techniques can be used for this estimation. However, both of these measurement techniques involve a high uncertainty. Pressure, temperature and humidity were kept constant during current investigations in order to mimic the
current industry situation. Further investigation is required to understand the effects of these parameters on evaporation. Composition of the clearcoat was also kept constant and a fixed type of atomizer was used during this investigation. However, use of a wide variety of clearcoat and other liquids, and with other types of RBAs can explore a great range of scenarios and lead to a better understanding of the formation and evaporation of sprays.

7.4 References


## APPENDICES

### Appendix A: Configuration of properties in PDA

<table>
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<tr>
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<th>Properties</th>
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Appendix B: Total Evaporation (cm$^3$/s) for various values of bell speed, flow rate and shaping air flow rate

<table>
<thead>
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<th>FR (cm$^3$/min)</th>
<th>SA = 200 L/min</th>
<th>SA = 300 L/min</th>
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<tr>
<td></td>
<td>BS = 30 (krpm)</td>
<td>BS = 40 (krpm)</td>
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<tr>
<td>100</td>
<td>0.611 ± 0.031</td>
<td>0.762 ± 0.042</td>
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<td>200</td>
<td>1.327 ± 0.031</td>
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<tr>
<td>300</td>
<td>1.499 ± 0.023</td>
<td>1.715 ± 0.039</td>
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To estimate the uncertainty of the measurement, each test was repeated 3 times in order to calculate the variance. The variance was multiplied by 1.96 to calculate the 95% confidence limit of the measurement (BSA flow soft manual v.4.10, 2006; Albrecht H.-E. et al., 2003) and this values were used to calculate the uncertainty.
Appendix C: Configuration of properties in PDA

<table>
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Figure A1: Mean diameter $D_{32}(\mu m)$ with different bell speed for 300 cm$^3$/s flow rate, and 80 kV electrostatic potential of basecoat (straight shade, white)
Appendix E

Table B1: Increasing total surface area at 200 cm³/s water flow rate for increasing bell speed

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Appendix F

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Birgitte Moltke <bme@dantecdynamics.com>  May 11 (1 day ago)

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Birgitte Moltke
Marketing Assistant

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Sent: Sunday, May 10, 2015 5:31 PM
To: US - Dantecdynamics
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Tonsbakken 16-18, P.O. Box-121,
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found on the following link
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Sincerely,

Rajan Ray
Ph.D. Candidate,
Department of Civil and Environmental Engineering,
University Windsor, Windsor, Ontario, Canada

Attachments
FCA US LLC

To: Rajan Ray
    Nihar Biswas
    Chris Sak

From: Ralph E. Smith

December 19, 2014

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AUTHOR(S) OR PRESENTER(S):
Rajan Ray, Paul Hensaw, Nihar Biswas and Chris Sak

FOR PUBLICATION IN OR PRESENTATION AT:
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