Study of Near-Cup Water Droplet Breakup of a Rotary Bell Atomizer Using Shadowgraph and High-Speed Imaging

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Abstract
Rotary bell atomizers are used as the primary means of paint application by the automotive industry due to their high paint transfer efficiency and enhanced surface finish quality. They utilize high rotational speed of a serrated cup to provide primary atomization of the liquid, and shaping air to provide secondary atomization and to transport the subsequent droplets. In order to better understand the fluid breakup mechanisms involved in this process, an optical setup involving shadowgraph high-speed imaging was used to image the edge of a serrated rotary bell at speeds varying between 5,000 and 10,000 RPM and at a water flow rate of 250 ccm. A multi-step image processing algorithm was also developed to differentiate between ligaments and droplets during the primary atomization process. The results of this experiment showed higher bell speeds resulted in lower ligament and droplet formations. Additionally, both ligament (ranging from 40-400 μm) and droplet (ranging from 40-200 μm) hydraulic diameters formed bimodal distributions. Velocity and associated hydraulic diameter statistics were also calculated for the various cases using particle tracking velocimetry. It was found that droplet velocities did not vary with hydraulic diameter, but did vary slightly with RPM, indicating that the droplets were more driven by the rotational speed of the bell than the ligaments, whose velocities are more dependent on other factors such as liquid flow rate.

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Introduction

Rotary bell (or cup) applicators are widely used in automated paint shops, such as those in the automotive industry, as a means of transferring paint by atomization [1]. They operate by releasing fluid from the center of a rotating cup, which forms a thin liquid film over the surface of the cup. When the film reaches the edge of the cup, ligament streams are formed in which shaping air breaks the liquid to droplets and sends the fluid forward, thus resulting in application of the fluid.

Though it has been the primary method of paint application for mass manufacturers due to the increased paint transfer efficiency, the devices themselves leave room for improvement since over-coating is often necessary to ensure sufficient finish [2]. Since its inception into industry, rotating disk, and later rotary bell, applicators have been studied in a variety of ways in an attempt to understand and improve the paint application process. Improvements in application would cut costs and reduce waste in industrial paint departments.

One of the most often studied aspects of rotary bell and rotating disk applicators has been the atomization process. Early studies laid the groundwork for the physical interpretations of liquid atomization [3-5]. From these, it was found that droplet distributions tend to be Gaussian, but with a slight skew toward smaller sizes. It was also found that the atomization process comprises of droplet and ligament formation (ligaments being the term for the thin, liquid threads that form during an atomization process that eventually breakup into droplets). Various phases exist for droplet formation as well, including direct droplet formation, ligament formation and a transition region between those regions. General liquid breakup has also been described, including laminar breakup of single jet ligament length, characterizing jet breakup time, and liquid ligament detachment/elongation characterization [6-8].

In the case of spinning disks and cups, the atomization process typically involves ligaments forming at the edges of the rotating cup, which then separate into droplets. Spinning disk applicators display a simplified version of the bell spray process, showing clearly the droplet and ligament formation regions. Many studies have been conducted on the critical parameters and characteristics of spinning disk and wheel applications, such as ligament and droplet formations and droplet size distributions [9-14]. Notable conclusions from spinning disk literature include that Sauter mean diameter increases with decreased rotational speed, and that velocity slip of the liquid film flowing over a rotating wheel is significant when the wheel rotation is slow but is negligible at high Weber numbers. Additionally, in spinning disks with teeth or serrations [13], droplet evolution during the atomization process showed a bimodal size distribution, which was notably different from the typical polydispersed one for flat-rimmed rotating atomizers.

There have also been a variety of techniques used in imaging and determining droplet sizes for general sprays [15]. The imaging technique that this paper utilized is shadowgraph. Images obtained from shadowgraph typically require further processing to determine the sizes of droplets and ligaments [16-18], but provide accurate statistics after calibration from pixel dimensions. Thus, for this experiment, post-processing of the shadowgraph images was performed to gain meaningful droplet and ligament size statistics.

In addition to size data, velocities of the fluid particles in the system are of particular interest. Particle imaging velocimetry (PIV) is a technique of determining velocity fields and has been investigated in previous research to study flow fields and individual droplet velocities [19-21]. The method of PIV and particle tracking velocimetry was used to calculate the near-cup ligament and droplet velocities. In this paper, the PIV software, which utilizes time-sequenced images and cross-correlation to produce velocity fields, was used on sets of processed droplet images.

In summary, for rotary bell specific research, much has already been done to attempt to characterize the process. Direct droplet and ligament formation, as well as droplet sizing, have been investigated in various capacities for rotary bell applicators [22-24]. However, many of these studies were not characterized with the inclusion of shaping airflow, which is used in the automotive rotary bell. Both general research into pulsed airflow breakup effects [25] and specific study of rotary bell atomization characteristics with shaping air [26] have also been conducted. This paper examines a rotary bell applicator with shaping air in an attempt to gain further knowledge and aid in efficient paint transfer.

Methodology

An Asea Brown Boveri Ltd. (ABB) rotary bell atomizer equipped with a 65 mm diameter serrated bell-cup was used in this experiment. The rotary bell was operated at speeds of 5,000 and 10,000 RPM. Liquid water was used as the atomization fluid and was sent through the bell at a flowrate of 250 ccm. The water released from the bell was contained within a large metal hood with a single opening port facing the bell.

A high intensity 500 W lamp was used as the illumination source for shadowgraph imaging and placed on the opposite side of the rotary bell as the camera, shown in Fig. 1. A Phantom V611 CMOS camera equipped with an f = 105 mm Sigma lens was used to image the liquid. The repetition rate of the camera was set to 340 kHz with a spatial resolution of 40 μm/pixel.
and an overall field of view of 5 x 2.5 mm due to the chip sensor being limited at high frame rates.

High-speed shadowgraph imaging was performed at the near field of the cup edge with the camera placed at an angle behind the cup to capture the ligament formation. Shadowgraph imaging allowed the edges of the water droplets to be identified. For each flowrate and bell speed case, 100,000 images were taken. The images were then processed to determine size and velocity distributions. Each image from the high-speed data set was first processed to define a binary image where each pixel represented either liquid or gas, as described in the next section.

**Size Measurements**

With the images processed to a binarized format, fluid size statistics were calculated. Fluid size was measured in terms of hydraulic diameter, calculated using (1), where

\[ D_h = \frac{4A}{P} \]  

(1)

\( D_h \) is the hydraulic diameter, \( A \) is the area of the object and \( P \) is the perimeter.

Groups of connected liquid pixels were first found in each image to define each separate droplet. The area of each droplet was then defined as the pixel count of that group, and the perimeter as the number of pixels bordering the inscribing area for each individual droplet. The area and perimeter in pixels were converted into physical distance using a calibration measurement to characterize the optical resolution (pixel/mm).

**Velocity Measurements**

LaVision Davis 8.3 was used to process the images and obtain velocity information of the individual ligaments and droplets using combined PIV and particle tracking velocimetry (PTV). From the large number of high-speed images, 250 evenly spaced sets of two sequential images in time were used for velocity analysis. First using PIV, a multi-pass cross-correlation algorithm was applied, which successively worked down from 64 x 64 to 4 x 4 pixel interrogation window sizes with 50% overlap. The PTV option subsequently detected droplets in the image and reoriented the interrogation window to obtain a single vector for each droplet. Using the combination of the PIV and PTV capabilities, not only were droplet and ligament velocities able to be obtained, but those velocity vectors could be correlated to the droplet and ligament sizes.

**Results**

**Image Processing**

In processing the images for droplet and ligament size statistics, a processing algorithm was first used to identify liquid and binarize the image, then connected liquid pixels were formed into droplet groups, and finally these groups were segmented into either ligaments or droplets. Using MATLAB, each image was first corrected for variations in the background light intensity by creating a pseudo background image. This background was computed by dilating the original image to remove individual liquid droplet, as shown in Fig. 2. This background image was then subtracted from the original image in order to enhance the contrast of the liquid ligament and droplets. Finally, the image was binarized using a thresholding method to give an image of liquid (consisting of both ligaments and droplets). Afterwards, the outline of the processed image was superimposed on the original to check the accuracy of the processing, shown in Fig. 2. Once it was determined that the accuracy of the threshold was satisfactory, that threshold was used for the remaining images automatically.

The images were further processed to separate the ligaments from the droplets. To do this, ligaments were defined as continuous fluid elements that were attached to the cup, and droplets as every other liquid group in the image. The connected components in the binarized image were calculated and the largest connected component was removed from the image, leaving only the droplets in the image. The component was then placed in its own separate image, and the cup edge was removed by using a circular fit from the original image. This left two images, one with ligaments only and the other with droplets only, shown in Fig. 3.

**Statistical Distributions**

The number and volume distributions for the ligaments and droplets both separately and combined can be seen in Fig 4. The number distributions show a shift for both droplets and ligaments to smaller hydraulic diameters with increasing RPM. They also appear to show a bimodal distribution of hydraulic diameters across each of the cases. The volumetric distributions appear to have bimodal distributions as well. In the case of ligaments only, a notable single peak shifts towards lower hydraulic diameters with higher RPM. These results collectively indicate that both ligament and droplet size decrease with increasing RPM. They also indicate, as evidenced by the bimodal distribution, that there are two regimes of droplet size in the near-cup field of view.

The velocity measurement results can be seen in Fig. 5. The velocity number distributions show a few trends. The first is that the ligaments and droplets have their distribution peaks at different locations and that the peak of the droplets distribution is approximately centered about the tangential cup velocity. Also, as the
bell speed increases, the ligament distribution begins to approach the droplet distribution. The average velocity versus hydraulic diameter, shown in Fig. 6, indicates similar trends. The droplets are again approximately centered about the tangential cup velocity while the ligament velocities differ slightly, but ultimately begin to converge to the droplet velocities as RPM increases.

These velocity results indicate that as the bell speed increases, ligament speeds approach droplet speeds. This makes physical sense because the ligament size approaches droplet size, or ligaments begin to disperse and essentially become droplets. The velocity results also indicate that droplet velocities are dependent on the cup velocity. Conversely, ligament velocities appear to have another velocity influencing their magnitudes, which could be due to the momentum from the liquid flow rate. Future work will be conducted to understand these effects.

Conclusions

Using high-speed shadowgraph imaging, droplet and ligament sizes were measured for a rotary bell atomizer, with the inclusion of shaping air, near its cup edge for two separate operational bell speeds. Those imaging techniques, combined with the inclusion of image post-processing techniques, allowed for a large sampling of droplet and ligament sizes. The size distributions showed that both ligament and droplet hydraulic diameters decrease with increased RPM. The distributions also illustrated that droplets have a bimodal distribution, indicating two separate regimes of droplet formation that separately evolve over time.

The post-processed images were also examined using PIV and PTV to determine droplet and ligament velocities. The raw velocity magnitude distributions indicate that the droplet velocities center on the tangential cup velocity, while the ligament velocities center near a velocity that is slightly higher than the tangential cup speed, likely an effect of the liquid flow rate. The velocity magnitude distributions also show that as cup speed increases, the ligament velocity distribution begins to approach the tangential cup speed, indicating that the flowrate of the liquid becomes less important, if bell speed is sufficiently increased. These results are reaffirmed by the hydraulic diameter relation to average velocity that show the same trend for ligament and droplet velocities with respect to the tangential cup speed.

References


Figures

**Figure 1.** Experimental setup diagram with lamp (A), rotary bell (B), camera (C), hood (D) and computer (E).

**Figure 2.** Image processing steps visualization, which includes the original image (A), dilated image (B), subtraction (C), binarization (D) and edges of binarization imposed on the original image (E).

**Figure 3.** Ligament and droplet separation process, which includes the original binarized image (A), largest connected component (B), subtraction of the cup (C) and the components of the original image that were not the largest (D).
Figure 4. Number (left) and volumetric (right) distributions of droplets (top), ligaments (middle) and both (bottom) for the 5,000 RPM (blue) and 10,000 RPM (orange) bell speeds.

Figure 5. Velocity number distributions of ligaments (blue), droplets (orange), both (yellow) and the associated tangential cup velocity (vertical dotted line) for the 5,000 RPM (top) and 10,000 RPM (bottom) bell speeds.

Figure 6. Velocity vs. size distributions of ligaments (triangles), droplets (circles), both (squares) and the associated tangential cup velocity (horizontal dotted line) for the 5,000 RPM (top) and 10,000 RPM (bottom) bell speeds.