Development of an Imaging System and Its Application in the Study of Cutting Fluid Atomization in a Turning Process

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Airborne inhalable particulates in the workplace can represent a significant health hazard, and one of the primary sources of particles is mist produced through the application of cutting fluids in machining operations. One of the principal mechanisms associated with cutting fluid mist formation is atomization. Atomization is studied by applying cutting fluid to a rotating workpiece such as found in a turning process. In order to properly study the atomization mechanism, an imaging system was developed. This system extends the size measurement range typically achievable with aerosol sampling devices to include larger particles. Experimental observations reveal that workpiece rotation speed and cutting fluid flow rate have significant effects on the size of the droplets produced by the atomization mechanism. With respect to atomization, the technical literature describes models for fluid interaction with the rotating workpiece and droplet formation via drop, ligament, and film formation modes. Experimental measurements are compared with model predictions. For a range of rotation speeds and fluid application flow rates, the experimental data are seen to compare favorably with the model predictions.

Keywords atomization, cutting fluid mist, imaging, machining

Introduction

Cutting fluids are widely used in a broad range of machining operations for the purposes of cooling, lubrication, chip flushing, and corrosion inhibition. One of the negative aspects associated with the use of a cutting fluid is health concerns and in particular the inhalation of cutting fluid mist produced during the machining process (Hands et al., 1996). One of the principal mechanisms associated with cutting fluid mist formation is atomization. Atomization may occur when a cutting fluid stream/jet impacts a rotating or stationary object. Recently, the behavior of mist particles produced by atomization has been studied by Yue et al. (1996, 2000a, b, 2004), Chen et al. (1999), Siow et al. (2001), and Sun et al. (2004). Models have been

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Development of an Imaging System

presented by these researchers to describe droplet atomization and the resulting mist behavior. The mist behavior models have been validated by a series of experiments, but little emphasis has been placed on experimentally assessing the adequacy of the atomization models.

The droplets formed via an atomization mechanism in machining may be characterized as a sparse, polydisperse spray with a bimodal distribution (2002). Since the droplets range in size from 0 to 3000 μm, and also since standard devices for the measurement of particles larger than 500 μm, and perhaps as large as 3000 μm, are not widely available, a custom-designed droplet sizing system is needed to study the atomization mechanism. A wide range of experimental techniques have been employed to characterize droplet size distributions. Many of these are optically based and thus have the advantage of noncontact measurement. These optical techniques can be divided into several broad categories: line-of-sight diffraction measurements using low angle forward scattering diffraction patterns (e.g., the Malvern particle sizer instrument (Hirleman, 1986)), single-point measurements (e.g., phase Doppler particle anemometry (Bachalo & Houser, 1984)), and imaging techniques utilizing shadow graphs (Hay et al., 1998; Nishino et al., 2000).

Each of these techniques has its own advantages and disadvantages when measuring sparse sprays. A laser diffraction–based system has a limited size range, and for large droplets the errors tend to be larger (Lee et al., 1987). Also, experiments show that for very sparse sprays the background light will have significant effects on measurement accuracy (Lebrun et al., 1996). Phase Doppler particle anemometry is used for point measurement, and therefore a great deal of time and effort is needed to obtain the droplet size distribution. The results also suffer from errors in the sizing of large particles due to the nonlinearity in the phase-diameter relationship, which is caused by nonuniform beam intensity (Qiu & Hsu, 1998). Imaging systems have the disadvantage that the measurement accuracies are generally lower than those of the laser-based techniques due to pixel size limitation and the depth of field effect. However, an advantage of imaging systems over other systems is that particle size distribution can be measured directly. Given the above observations, for this work, it was decided to employ an imaging system to characterize the size distributions of droplets formed via atomization in machining.

As a prelude to discussing the imaging system and atomization experiments, a brief overview of the cutting fluid atomization process is provided, and some observed behaviors are compared with the theoretical predictions of Yue et al. (1996, 2000a, 2004). The particle imaging system is then described, and the experimental plan to examine the atomization process is presented. The results from a series of atomization experiments, associated with the application of a cutting fluid to a rotating workpiece, are introduced. The size of airborne particles, as measured by the imaging system, are reported as a function of workpiece rotational speed, circumferential position, cutting fluid flow rate, and radial position relative to the workpiece. For each set of experiments, the observed changes in the particle size distribution for the variable under study are noted and discussed.

Overview of Cutting Fluid Atomization Process

The behavior of the cutting fluid as it impinges on a rotating workpiece is illustrated in Figure 1. Figure 1(a) demonstrates the manner in which the fluid is applied to the rotating workpiece. Figure 1(b) shows an end view of the process, where the
workpiece is rotating in a counterclockwise direction. While Figures 1(a)–(c) all show fluid atomization, the side view of Figure 1(c) clearly depicts “rims,” in which the atomization process occurs. Figure 1(d) is a sketch of the situation. As the fluid is applied to the workpiece it spreads laterally (along the workpiece axis) to form the “rims.” Yue et al. (1996, 2000a, 2004) reported that the axial positions where the flow stops and the rims form depend on the workpiece rotation speed and cutting fluid flow rate. For cutting fluid flow rates less than a critical value virtually all of the fluid applied to the rotating workpiece flows into these rims and is atomized. If the flow rate exceeds the critical value, then excess cutting fluid will drain from the workpiece. Most of the droplets produced by atomization come from the circumferential rims that are formed in the process. Depending on process parameters, the atomization mechanism associated with the rims can adopt one of the three modes identified by other researchers: drop formation mode, ligament formation mode, and film formation mode. As part of the development of a model for the atomization process Yue et al. (1996, 2000a, 2004) established a relationship for the axial spacing between the rims that are formed in the atomization process and the maximum fluid flux that a cylindrical workpiece can contain before drainage occurs.

Fluid Film Width Model Predictions and Validation

When a vertically oriented fluid stream of radius \( r_j \) and velocity \( U_j \) impinges on the top of a rotating cylinder, the high pressure generated in the stagnation region causes the fluid to spread laterally along the workpiece axis and to produce a thin film, as shown in Figure 2. The axial position at which the flow stops and rims form depends on the workpiece rotating speed, stream velocity, and the fluid properties. Yue et al. (1996, 2000a, 2004) established the following expression for the fluid film width, or alternatively, the spacing between rims:

\[
L = 3.32RFr^{0.23}e^{0.36}
\]  

(1)
where $Fr = \frac{U^2}{(gR)}$ is the Froude number, $\varepsilon = 0.5R_e^{0.5}(r_j/R)^2$, and $R_e = U_j r_j/v$ is the Reynolds number of the fluid stream.

To judge the predictive ability of the rim spacing model, the spacing between the rims was measured, via images such as that shown in Figure 1(d), for a range of workpiece rotation speeds and cutting fluid flow rates. The experiments were carried out with a 5% synthetic cutting fluid and a 6.25 mm radius nozzle. Figures 3 and 4 show the effect of rotation speed and fluid flow rate on the axial rim spacing. The figures also include the predicted spacing based on the model of Equation (1). As seen in Figure 3, increasing the workpiece rotation speed reduces the spacing between the rims. Figure 4 shows that the rim spacing increases as the cutting fluid flow rate is increased. The comparisons between the measured and model predicted rim spacing show reasonable agreement, confirming the model adequacy.

**Maximum Fluid Flux Model Prediction and Validation**

As previously discussed, as the vertically oriented cutting fluid stream impacts the cylindrical rotating workpiece, a fluid film develops on the workpiece. The amount of fluid that can be supported by the rotating cylinder is dependent on the fluid properties, system geometry, and process conditions. For instance, for very large fluid application flow rates, some of the fluid will follow the pattern illustrated in Figure 1, while much of it will simply drain off the cylinder due to gravitational

![Figure 3. Effect of workpiece spindle speed on axial rim spacing at different workpiece radii, flow rate = 0.8 L/min.](image-url)
effects. As the flow rate is reduced and the spindle speed is held constant, eventually the drainage will stop and all the fluid flow will contribute to rim formation.

Using the given system geometry, fluid properties, and process conditions, Yue et al. (1996, 2000a, 2004) proposed the following relation to describe the maximum fluid flow rate (flux) that the rotating workpiece can support:

$$ q_{\text{max}} = LQ^{0.5}R^2 $$

(2)

where $L$ is the fluid rim spacing, and $Q$ is the nondimensional fluid flux across the fluid film. $Q$ can be obtained from the following equation:

$$ \Psi = \frac{288\gamma^4Q^2 + 24\gamma^2(5Q + 3) - 1}{64\gamma^3 + [1 + 16\gamma^2(1 + 3Q)^{1.5}]} < 1 $$

(3)

where $\Psi = 1$ represents the limiting condition for steady flow. The value of $Q$ associated with $\Psi = 1$ (for a given Stokes number) represents the maximum nondimensional fluid flux and can be estimated by numerically solving Equation (3).

If the actual applied fluid flow rate, $q$, is larger than the value for $q_{\text{max}}$ calculated with Equation (2), then some fluid will drain from the workpiece and the rate of fluid atomization will be $q_{\text{max}}$. On the other hand, if the fluid flow rate, $q$, is smaller than $q_{\text{max}}$, the rate of fluid atomization will be $q$. Of course, the rate of fluid atomization is important, since it affects the rate of change in the mass concentration of airborne particulates.

To examine the ability of Equation (2) to predict the maximum fluid flux (flow rate), a series of experiments was performed. The maximum flow rate that the workpiece can sustain without drainage for a given spindle speed was obtained by setting the fluid flow rate to a large value and then slowly reducing the flow rate until no drainage was observed. For each experiment, the maximum fluid flux was also predicted. Figure 5 shows measured and model-predicted maximum fluid fluxes for several workpiece diameter ($R_w$) and nozzle diameter ($R_n$) combinations. The relation of Equation (2) appears to predict the maximum sustainable flow rate well, thus supporting the adequacy of the relation. Evident from the figure is the importance of spindle speed in increasing the maximum fluid flux. Higher spindle speeds or larger
workpiece diameters can sustain higher maximum flow rates, while a larger nozzle diameter decreases the maximum flow flux.

While the equations that govern the fluid behavior are expressed in terms of the spindle speed, some meaningful conclusions can be drawn by viewing these results in terms of the cutting speed (tangential velocity of the workpiece), as shown in Figure 6. By examining these results, it is found that the nozzle diameter and cutting speed are the two primary variables that affect the maximum flow rate, with workpiece diameter having only a minor influence on the flow rate. The model proposed by Yue and the experimental data show that a higher cutting speed results in a higher maximum flow rate (i.e., the rotating workpiece can sustain a higher flow rate without drainage), while a larger nozzle diameter will result in a decrease in the maximum flow rate.

**Imaging System**

An advantage of imaging systems over other particle measurement systems is that particle size distribution can be measured directly. However, it has the disadvantage
that the measurement accuracies are generally lower than those of laser-based techniques due to pixel size limitations and depth of field effects. In this work, an imaging system was established to measure the droplets produced by atomization when a fluid stream is applied to a rotating cylindrical workpiece. To compensate for the pixel size limitation of the imaging system, two cameras were used to extend the droplet size measurement range by combining the results from both cameras. A calibration procedure was performed to minimize the depth of field effect, and empirical equations were developed based on the calibration data in order to accurately predict the droplet size.

**Experimental Setup**

The setup of the imaging system is illustrated in Figure 7. A cutting fluid stream is delivered to the top of a rotating workpiece mounted in the headstock of an engine lathe. Two nozzle geometries, having radii of 3.25 and 6.25 mm, were used in the experiments. For a given experimental trial, the cutting fluid nozzle was positioned to achieve a 10 mm or smaller clearance with the workpiece, to minimize the amount of fluid splattering (Siow et al., 2001). A strobe light source, with an adjustable frequency, was placed near the lathe headstock and directed at the droplet formation region. Shielding was constructed about the light to control the area of illumination and to protect the light from stray airborne mist particulates. A diffusing screen was employed to provide an even illuminating light source. Since the droplets or mist particulates produced during the atomization process are opaque, backlit illumination was used. Two CCD cameras (A and B) were placed near the tailstock of the lathe and were focused on the droplet formation region. Camera A is a JVC model KY-F30BU whose CCD sensor size is 6.4 mm $\times$ 4.8 mm with 512 $\times$ 480 pixels. It gives an imaging area of 54 mm $\times$ 40 mm and was used to measure droplet sizes larger than 500 $\mu$m. Camera B is a ScienceScope with the same CCD sensor size, has an imaging area of 6.8 mm $\times$ 5.1 mm, and was used to measure droplet sizes in the range of 50 to 500 $\mu$m. The cameras were connected to a PC that includes a frame grabber (Foresighting-Image I60) and image analysis software (Scion Image). Special purpose C++ programs were employed to post-process the images and integrate the results from the two cameras to produce a single droplet distribution.

![Figure 7. Setup of imaging system.](image-url)
Image Processing

A typical captured image is composed of an array of pixels (512 horizontal \times 480 vertical). Associated with each pixel is an intensity value or gray level ranging from 0 (black) to 255 (white). The image acquisition procedure begins by collecting a reference image. This reference image is acquired when no droplets are present in the workspace. Variations in pixel intensities within the reference image reflect both deterministic and stochastic trends in the imaging system. Once a droplet image has been obtained during the operation, the following algorithm is applied to the array of pixels of the droplet image:

\[ I_{\text{mod}}(x, y) = I(x, y) - I_{\text{ref}}(x, y) \]  \hspace{1cm} (4)

where \( I(x, y) \) and \( I_{\text{ref}}(x, y) \) denote the intensity levels in the droplet and reference images respectively, and \( I_{\text{mod}}(x, y) \) denotes the intensity of the modified image. It may be noted that this transformation produces a negative of the original image. The resulting modified image may be further enhanced to obtain a satisfactory spread in the intensity level. Figure 8 displays the initial and modified (preprocessed) images.

With the preprocessing of the image completed, attention shifts to the extraction of droplet information from the image. A chief challenge of the image analysis is to extract only those droplets that are “in focus.” Figure 9 shows hypothetical intensity profiles for two droplets in the modified image. Ideally, an optimum, in-focus droplet should display a “square-wave” profile (as exemplified by the droplet on the right in the figure), with nearly a discontinuous change in the intensity at the edge of the droplet. Unfortunately, virtually no droplets display this behavior. Therefore, a typical intensity profile, like the one on the left in the figure, must be interpreted. From the intensity profiles, it can be seen that the gradient at the edge of the droplet reflects the degree of focus (with a larger gradient implying a more “in-focus” droplet), and, thus, the gradient can be used as a criterion for droplet interpretation (Yule et al., 1978). Two intensity levels that define a “halo” can be selected between the white light droplet core and the black background. One could envision setting the level \( I_0 \) such that it yields the actual diameter of the droplet, and then level \( I_n \) could be used to determine a halo whose width can be used as a rejection criterion for out-of-focus droplets. The halo width can also be used to correct for out-of-focus effects on measured droplet size. Out-of-focus droplets must be rejected to preserve the integrity of the droplet density within a thin imaging volume. Halo size and the droplet rejection/acceptance method will be further examined in the next subsection.

Figure 8. Original and preprocessed images.
The intensity values \( I_a \) and \( I_b \) were selected based on the expressions displayed in Equations (5) and (6):

\[
\frac{I_b - I_{\min}}{I_{\max} - I_{\min}} = 0.5 
\]

\[
\frac{I_b - I_a}{I_{\max} - I_{\min}} = 0.15 
\]

where \( I_{\max} \) and \( I_{\min} \) are the maximum and minimum light intensity levels in the image. The choice of the dimensionless values 0.5 and 0.15 in Equations (5) and (6) is not critical, but they are usually set at values such that \( I_a \) and \( I_b \) lie in the region where the light intensity gradient is high at the edge of the droplet image (Chigier, 1991).

After the values for \( I_a \) and \( I_b \) have been set, the threshold \( I_a \) is applied to the preprocessed image; intensity values that exceed this value are assigned a white level (255), and intensity values less than \( I_a \) are assigned a black (0) level. This binarization process generates a black-and-white image. An erosion algorithm embedded within the software is then employed to identify the neighboring pixels that define each droplet and the number of pixels for each droplet. After the number of pixels for each droplet has been obtained, the droplet diameter can be estimated with the following equation:

\[
d_a = \sqrt{\frac{4NA_p}{\pi}} 
\]

where \( d_a \) is the estimated droplet diameter, \( N \) is the number of pixels in the droplet, and \( A_p \) is the area associated with a pixel. Similarly, \( I_b \) is applied to the preprocessed image to produce another, smaller droplet diameter \( d_b \); the two calculated diameters
associated with a droplet can then be used to estimate the halo width for a droplet, \( h = (d_\text{a} - d_\text{b})/2 \). So, once an image has been captured and processed, the diameter \( d_\text{a} \) and halo width \( h \) for all droplets in the image are available.

As noted above, two cameras were employed to capture droplet size information. Camera A principally considers the larger droplets and camera B the smaller droplets. As will be described shortly, the size distribution information collected from the two cameras may be combined to produce a single distribution across a wide range of droplet sizes. The droplet size distribution is established by subdividing the range \([d_\text{min}, d_\text{max}]\) of the droplet diameters into \( N \) classes of equal width given by:

\[
\Delta d = \frac{d_\text{max} - d_\text{min}}{N}
\]

(8)

For each size range, the number of droplets in the size class is counted to produce a droplet size histogram.

For a large particle size range, the image edge effect has to be considered because a droplet that lies partially outside the captured image will not be counted when determining the size distribution. For a field of view of size \( H \times V \) (horizontal \( \times \) vertical), a droplet of diameter \( d \) will have the following probability of intersecting the edge of the image:

\[
P = \frac{V + H - 2d}{VH}
\]

(9)

Failure to compensate for the image edge effect will lead to a droplet size distribution that is biased towards smaller droplets. With this in mind, a correction coefficient (Oxford Lasers, 2001), \( 1/(1 - P) \), may be applied to each size range within an experimentally acquired size distribution.

From Figure 10, it can be seen that the correction coefficient for camera B becomes significant when \( d \) is greater than one-tenth of the imaged region. So, for a small field of view, the spatial resolution is high, but the probability of a droplet intersecting the image edge is large. On the other hand, for a large field of view, a droplet has a small probability of intersecting the edge, but the image has a low spatial resolution. A balance must be achieved between the resolution and the droplet image-edge intersection issues. In the present work, a high resolution and a small probability of droplet-edge intersection were achieved through the use of two cameras. The transition or cutoff point between the two cameras was selected to be

![Figure 10. Droplet size distribution obtained from two cameras and the correction coefficients.](image-url)
500 µm, approximately one-tenth of the field of view for camera B. The distributions secured by the two cameras may then be combined by matching the particle count numbers at the cutoff point. In Figure 10, a typical droplet size distribution, which is a combination of those obtained from each camera, is shown. For camera A, which has a large field of view but low resolution, only droplets larger than 500 µm are counted, and for camera B, droplets with diameters between 50 and 500 µm are counted.

For a given droplet size distribution, the mean diameter is calculated based on the following equation:

$$d_{p,q} = \left( \frac{\sum_{k=1}^{N} n_k d_k^p}{\sum_{k=1}^{N} n_k d_k^q} \right)^{\frac{1}{q-p}}$$

(10)

where \(d_k\) is the diameter associated with the \(k\)th size class, and \(n_k\) is the number of particles in the \(k\)th size class. The calculated mean diameter is referred to as the count mean diameter when \(p = 1\) and \(q = 0\). Other widely used diameters may also be calculated: surface mean diameter \((p = 2, q = 0)\), volumetric mean diameter \((p = 3, q = 0)\), and Sauter mean diameter \((p = 3, q = 2)\).

**Calibration**

Many imaging techniques use backlighting for particle illumination (actually all areas except for the droplets are illuminated) and acquire shadow graphs, from which a variety of particle features can be extracted. The advantages of this technique are the simplicity of the measurement principle and the ease with which the captured image and associated object(s) can be understood. However, an accurate measurement of droplet size is limited by many factors such as light diffraction and lens aberrations, depth of field, effect of shutter, and illumination conditions (Olsen & Adrian, 2000; Bongiovanni et al., 1997; Lee, 1990). Of these factors, the depth-of-field effect associated with backlighting represents the major limitation on measurement accuracy. Chigier (1991) stated that there are two possible sources of measurement errors originating from the depth-of-field effect. One is the ambiguity in defining the perimeter of a droplet when it is out of focus. The difficulty lies in the fact that the uncertainty will increase as the distance of the droplet from the focus plane increases. The other error source is the dependence of apparent particle size on the distance of the particle from the focus plane. Oberdier (1984) has shown that the degree of focus depends not only on the distance from the focal plane, but also on the droplet size. Small droplets away from the focal plane are less focused than larger droplets at the same position. The impact of this effect will be a bias toward larger droplet sizes. A calibration procedure is therefore needed to reduce these errors.

The calibration procedure was initiated for the low magnification camera (camera A) by creating a set of opaque black circle artifacts of precisely known diameters from 200 to 3000 µm. These circles were then imaged at various positions relative to the focus plane of the camera and the halo width and imaged circle diameter were recorded. Figure 11 shows the measured diameter as a function of halo width for a few of the black circle artifacts. For each artifact diameter, the relationship between the halo width and the measured diameter is linear. Based on this behavior,
Fantini et al. (1990) suggested that an empirical relationship could be established for predicting actual droplet size based on the halo width and imaged (apparent) diameter:

\[ d_n = (A \ln(d) + B)h + Cd + D \]  \hspace{1cm} (11)

where \( h \) is the halo width, \( d_n \) is the measured (apparent) diameter from the image, and \( d \) is the predicted diameter of the droplet. Using the calibration data collected in this study, the empirical coefficients were estimated as \( A = 8.276, B = -78.02, C = 0.929, \) and \( D = 102.52 \). The model behavior is represented by the lines in Figure 11.

The empirical relationship of Equation (11) addresses the measurement error caused by a droplet being out of focus, i.e., the first error source noted above. The other error source is that measurement results could be biased toward larger droplets because a larger droplet is more likely to intersect the thin imaging “plane” and thus be captured in the image. Since it is desired to measure only the droplets within a fixed volume, droplets lying primarily outside the region must be rejected. To solve this problem a fixed depth of field, in which the droplets are assessed and counted, must be employed. Using Equation (11) the actual diameters of droplets lying well outside of the focal plane may be determined even though they are significantly out of focus and have large halos. Therefore, critical halo widths were defined as a function of artifact diameter. Droplets with halo widths above this critical value for a given diameter are then rejected as lying too far from the focal plane. The behavior of the critical halo width is shown as a curve in Figure 11. The depth of field was defined as 15 mm for camera A, and the halo widths at both edges of the image collection volume in the optical axis direction were used to generate the empirical relationship for the critical halo width. The relationship is given by:

\[ h_c = E \ln(d) + F \]  \hspace{1cm} (12)

where \( E = -4.85 \) and \( F = 50.16 \). The same calibration process was performed for the high magnification camera.
**Atomization Experiments**

The work of Yue et al. (1996, 2000a,b, 2004) and Chen et al. (1999) studied the atomization mechanism for the case of a fluid stream applied to a rotating cylindrical workpiece such as considered herein. They predicted droplet size to be a function of the following variables: workpiece rotation speed, fluid flow rate, workpiece diameter, and nozzle radius. However, as mentioned previously, their work did not directly measure the size of the droplets produced by atomization, but rather the characteristics of the airborne particulates in the workspace surrounding the lathe. The efforts described in this article employed the imaging system to directly assess the size of the atomized droplets. To investigate the effects of the variables noted above four sets of atomization tests were performed. The test results may also be used to assess the adequacy of the analytical models that have been proposed in the technical literature to describe the atomization process.

**Atomization Test Conditions**

The imaging system was employed to study the atomization process associated with the application of a cutting fluid to a rotating cylindrical workpiece such as found in a turning process (see Figure 1). The conditions considered in the four sets of experimental trials are shown in Table I. For all trials, a synthetic fluid, mixed at 5% concentration with water, was applied to the workpiece, images of the droplets were collected, and the images were analyzed to determine particle diameters. Based on the particle diameter information, particle size and mass distributions were established, and values for the mean droplet size were calculated. Generally, more than five thousand droplets were collected for each experimental condition to form the droplet distribution.

Table 1 summarizes the conditions considered in the four sets of experimental trials for the five key variables: fluid flow rate, workpiece rotation speed, radial position, angular position, and nozzle radius. A sixth key variable, workpiece diameter, was fixed at a value of 100 mm for all tests. The manner in which the fluid was

<table>
<thead>
<tr>
<th>Test Set 1</th>
<th>Flow rate (L/min)</th>
<th>Spindle speed (rpm)</th>
<th>Normalized radial position</th>
<th>Angular position (°)</th>
<th>Nozzle radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.35, 0.5, 0.75, 0.8, 1.1, 1.3, 1.6, 1.9, 1.95, 2.2, 2.25, 2.52</td>
<td>700</td>
<td>2.0</td>
<td>90</td>
<td>3.25</td>
</tr>
<tr>
<td>Test Set 2</td>
<td>0.8</td>
<td>700, 1700</td>
<td>2.0</td>
<td>22.5 to 337.5 in 22.5 increments</td>
<td>3.25</td>
</tr>
<tr>
<td>Test Set 3</td>
<td>2.2</td>
<td>500, 700, 950, 1250, 1700</td>
<td>2.0</td>
<td>90</td>
<td>6.25</td>
</tr>
<tr>
<td>Test Set 4</td>
<td>0.75</td>
<td>500</td>
<td>2.6, 4, 5, 5.4, 6, 6.5, 8.4, 9.2</td>
<td>90</td>
<td>3.25</td>
</tr>
</tbody>
</table>
applied to the rotating workpiece is illustrated in Figure 12(a), which shows the position of the nozzle relative to the workpiece for the experiments. Figure 12(b) shows the droplet atomization resulting from the fluid application. As has been noted previously, and as the figure demonstrates, multiple atomization modes are possible, and it is to be expected that the droplet size distribution may be dependent on the angular position and the radial position at which the droplet image is collected. The angular position is defined in the counterclockwise direction, with the top of the workpiece corresponding to 0°. The normalized radial position is defined as $r/R$, where $r$ is the radial distance from the workpiece axis and $R$ is the workpiece radius. The minimum normalized radial position considered was 2.0, since for radial positions smaller than this, images may also capture fluid ligaments.

**Effect of Flow Rate (Test Set 1)**

Model predictions by Yue et al. (1996, 2000a, 2004) have shown that flow rate has an effect on the mean droplet diameter. To examine this effect, a set of experiments was performed. These experiments, Test Set 1, considered varying flow rates as shown in Table 1. Figure 13 shows the particle count distributions for three of the fluid flow rates from the experiment. The particle count distributions in the figure show that for the low fluid flow rate of 0.35 L/min, the majority of the droplets are centered near 200 μm. The particle count distributions for the two larger flow rates have similar shapes, and they appear to have most of their droplets close to 300 μm. The count distributions also show another mode near 1000 μm for each flow rate. Yue et al. (1996, 2000a, 2004) suggested that larger droplets (in this case those near 1000 μm) may be the primary droplets associated with ligament breakup, with the smaller droplets (those associated with the 300 μm mode) being satellites of the main droplets.
Figure 14. Effect of fluid flow rate on droplet size.

In examining the particle count distributions of Figure 13, it is evident that while the modes are in the 200–300 μm and 900–1200 μm ranges, the count mean diameter (CMD) will lie somewhere in between these modes. For example, the mean diameter associated with the 0.35 L/min fluid flow rate was determined to be 360.1 μm. The behavior of the mean diameter as a function of flow rate is shown in Figure 14. As is evident, the diameter increases with increasing flow rate up to some critical value.

Yue et al. (1996, 2000a, 2004) made predictions for this critical flow rate, above which some of the fluid drains from the workpiece, and only a portion of the fluid is atomized. The data obtained from the experimental trials of Test Set 1 were used to assess the adequacy of the model proposed by Yue et al. Figure 14 displays the model-predicted critical flow rate for the conditions examined. It is observed that the droplet size increases until the critical flow rate and that for flow rates above this value the droplet diameter remains relatively constant. Observations made during the experiments indicated that for flow rates above the critical flow rate, significant fluid drainage occurred. For flow rates below the critical flow rate, virtually all the fluid applied to the workpiece was atomized.

Effect of Angular Position (Test Set 2)

Test Set 2 was performed to examine how the atomization process changes as a function of angular position. The experimental conditions for Test Set 2 are shown in Table 1. Figures 15 and 16 present the behavior of the droplet size as a function of angular position for spindle speeds of 700 and 1700 rpm. The figures show that as the angular position increases, the drop size is reduced. Also shown in the figures are the drop diameters predicted by Sun et al. (2004). An examination of
Figures 15 and 16 reveals that the model predictions agree very well with the experimental data. The reduction in the drop size as a function of angular position corresponds to the change from film to ligament to drop mode. Also evident from a comparison of the figures is that an increase in the spindle speed dramatically reduces the droplet size.

**Effect of Speed (Test Set 3)**

A series of experiments was performed with varying workpiece rotation speeds to explore the effect of speed on droplet size (refer to Test Set 3 in Table 1). The effect of workpiece rotation speed on droplet size is shown in Figure 17. The figure shows that as the workpiece rotation speed increases the droplet size decreases exponentially. The figure also demonstrates the same general behavior of drop size as a function of speed for several different mean diameter types (e.g., count mean, surface mean, and volume mean). The effect of the rotation speed on the dominant droplet

![Diagram](image_url)
diameter is consistent with trends predicted by atomization model of Yue et al. (1996, 2000a, 2004), e.g., a higher rotation speed produces smaller droplets.

**Effect of Radial Position (Test Set 4)**

The particle size as a function of radial position was studied using Test Set 4 in Table 1. The changes in the size distributions are summarized in Figure 18, which displays the count mean diameter as a function of radial position. The changes in the distribution shapes and in the observed mean diameter as a function of radial position appear to indicate that the small droplet diameters are less and less evident as the radial position increases. This behavior could be due to small droplet entrapment within the airflow very near the rotating workpiece. It could also be attributed to large droplets produced at angular positions between 270° and 360° that are pulled through the measurement region by gravity.

**Summary and Conclusions**

Cutting fluid mist can represent an inhalation hazard in the workplace, and atomization is one of the principal mechanisms in mist formation. An imaging system has been developed to study the atomization mechanism associated with the application.
of a cutting fluid stream to a rotating workpiece. The imaging system utilizes back-light illumination and two cameras to measure droplets between 50 and 3000 μm. Multiple images are combined to produce droplet size distributions (particle count, mass, etc.), from which distribution mean diameters may be calculated. A series of experiments has been conducted to explore the effect of workpiece rotation speed and fluid flow rate on the mean diameter. Also investigated was the impact of radial positions relative to the workpiece on droplet characteristics. Based on the experiments that were conducted, the following conclusions can be drawn:

- An increase in the rotational (spindle) speed reduces the droplet size.
- Larger droplet sizes are produced as the flow rate is increased, until some critical value is reached. For flow rates above the critical flow rate, drainage occurs. For flow rates lower than the critical value, virtually all fluid is atomized.
- Three atomization modes, film mode, ligament mode, and drop mode, occur along the workpiece circumference based on the amount of fluid available for atomization.
- At larger radial positions the mean droplet size is much larger than that at smaller radial positions.

While the principal emphasis of this article has been the experimental investigation of the atomization process associated with application of a cutting fluid to a rotating cylinder, the experimentally acquired data do provide some evidence of the adequacy of atomization models reported in the technical literature.

References


Development of an Imaging System and Its Application in the Study of Cutting Fluid Atomization in a Turning Process

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