NON-INTRUSIVE TECHNIQUE FOR MEASURING INSTABILITY WAVE AMPLITUDES AT SIMPLEX SWIRL ATOMIZER EXIT

Viktor L. Orekhov, Dept. of Mechanical Engineering, Tennessee Tech University
Mahesh V. Panchagnula, Dept. of Mechanical Engineering, Tennessee Tech University

ABSTRACT
An optical method for non-intrusive wave amplitude measurement is examined. An experimental setup was constructed to produce sprays of various fluids including Canola oil and glycerin-water mixtures, such that precise control of pressure up to 140 psi was possible. A spray was produced by a 20 Gallon per hour oil burner nozzle at varying pressures. Initially, a smooth laminar conical sheet was noticed which eventually was found to break up into droplets. A laser was passed through the laminar conical sheet and was projected onto a surface on the other side and resulted in a vertical linear projection. This projection is postulated to be formed due to the scanning motion of the laser beam as instability waves pass through the laser. The angle of this scan was found to be a function of pressure, cone angle, and distance of laser from nozzle. High resolution images were taken of the film profile as well as the projected image and image analysis software was used to calculate cone angles and angular scan of the laser. Tests were performed with Canola Oil as well as a mixture of glycerin and water in order to evaluate the effect of viscosity and surface tension on the measurements. The resulting data was used to illustrate a principle for determining the instability wave amplitude using this technique.

INTRODUCTION
Liquid atomization is an important subject of investigation due to its many applications ranging from gas turbine combustion to spraying paint and detergents [1]. The most desirable characteristic of a spray system is the mean drop size due to its many contributions in combustion such as evaporation time, flame speed, and emissions [2]. The difficulty in predicting the breakup characteristics of these liquid films and the resulting drop size is due to the effect of many influencing factors such as nozzle geometries, air pressure, viscosity and density. Several intrusive techniques have been developed for studying the breakup characteristics of liquid films in the near nozzle region but with little quantitative success. It is therefore clear that a non-intrusive experimental technique for measuring the liquid film instability characteristics is desirable.

The general principle behind most liquid atomization systems is to form the liquid into a sheet which breaks up into ligaments and finally droplets. The breakup of the liquid sheet is usually facilitated by imparting instabilities in the form of a blast of air, rotary energy, or in the case of simplex atomizers, swirl energy. This instability is found to grow and ultimately cause the breakup of the liquid sheet. The wavelengths and wave amplitudes associated with these instabilities have been studied through the use of linear [3] and nonlinear [4] stability analyses. However, very few experimental measurements have been reported which can provide information to validate the results of these analyses. Li and Shen [5] and more recently Lanwehr et al. [6] have made measurements on annular and conical liquid sheets and were able to measure the wavelengths of instability. However, since their technique was based on image acquisition and analysis [5] or was intrusive [6], the technique could only be applied to a limited class of break up situations.

The majority of atomizer nozzles produce sprays by passing the liquid through a tiny orifice. However, this process produces spray cone angles that are too narrow to be used in gas turbines and other applications. To produce wider cone angles, simplex swirl atomizers impart a centrifugal energy to the spray. The swirling motion is produced by either using tangential slots or tangential drilled holes. A typical simplex swirl atomizer nozzle is illustrated in Figure 1. As the fluid enters the nozzle chamber, large angular velocities are imparted which produces a hollow cone within the nozzle chamber. Upon reaching the nozzle orifice, the fluid has both axial and radial velocities and is formed into a hollow conical sheet upon exit. The energy from the swirling motion is also imparted to the sheet as instability which would grow and cause it to atomize. Due to the nature of the process, the cone angle depends on both the axial and radial components of the fluid velocity which in turn are dependent on the atomizer geometry and fluid properties.
As the conical sheet expands, it becomes wavy and unstable causing it to separate into ligaments and then droplets. By measuring the wave frequencies and wavelengths along the conical sheet prior to the breakup process, the mean drop size and drop size distribution in the near nozzle region of the spray can be predicted. In the current investigation, a laser beam passing through the smooth conical sheet was utilized to measure the wave amplitude as a first step toward being able to determine frequencies and wavelengths. As a wave propagates along the conical sheet, it passes through the beam, causing the laser to diffract and produce an image on a surface on the other side of the spray. The projected image can then be related to the instability wave characteristics. This technique is in principle similar to that devised by Tropea [8] for use in measurement of drop size by laser refraction. By this technique, as a drop passes through a laser of Gaussian intensity distribution, it refracts light. The time-shift between each scattering order can then be related to drop size. We propose to use a modified version of the same technique for use with measuring instability wave characteristics on laminar conical liquid sheets.

EXPERIMENTAL APPARATUS

The test setup was designed to provide a steady vertical spray. The experimental fluid was poured into a three gallon pressure vessel equipped with an internal dip tube and was pressurized to a constant pressure of 140 psi. The two fluids under consideration were Canola Oil and mixtures of glycerin and distilled water. Canola oil is an ideal fluid due to its ability to form a uniform sheet relatively easily which allows for a greater experimental pressure range. It is also non-hazardous, cheap, and readily obtainable which provides for long run times. The main benefit of the glycerin is its miscibility with water and the ability to form mixtures at varying viscosities.

<table>
<thead>
<tr>
<th>Glycerin</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$, Density (kg/m$^3$)</td>
<td>1,260</td>
</tr>
<tr>
<td>$\eta$, Viscosity (cSt) @ 21°C</td>
<td>1,190</td>
</tr>
<tr>
<td>$\mu$, Viscosity (cP) @ 21°C</td>
<td>1,500</td>
</tr>
<tr>
<td>$\sigma$, Surface Tension (N/m)</td>
<td>0.063</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Canola Oil</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$, Density (kg/m$^3$)</td>
<td>0.90</td>
</tr>
<tr>
<td>$\eta$, Viscosity (cSt) @ 21°C</td>
<td>57.4</td>
</tr>
<tr>
<td>$\mu$, Viscosity (cP) @ 21°C</td>
<td>51.5</td>
</tr>
<tr>
<td>$\sigma$, Surface Tension (N/m)</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 1: Properties of Fluids

Figure 2 illustrates the experimental setup used. While the tank was maintained at a constant pressure, a regulating stem needle valve (Swagelok B-1RM4) allowed for accurate control of final pressure at the nozzle tip, which was measured using a pressure gage. The nozzle was a 20 gal/hr 60° cone angle simplex swirl atomizer and provided a uniform continuous spray at pressures above approximately 40 psi. The spray was collected in a five gallon collection tank to be recycled for subsequent trials. A shutoff valve allowed for the flow to easily be turned off to make adjustments in the regulation valve and setup.

A 5mW He-Ne laser (Hughes 3222H-PC) was positioned to pass through the spray horizontally at a specific vertical distance from the nozzle. The distance was maintained constant at .16 in for all trials except data in figure 9. The laser was positioned so that upon passing through the conical sheet, it was projected onto a vertical surface that was perpendicular to the laser beam. A ruler was placed on this surface to provide a reference for distances. A Nikon D70 digital SLR camera equipped with a Nikkor 18-70mm lens was set up to capture side images of the spray.

Figure 3: Detail of spray at nozzle tip
An incandescent lamp was used as a back light to provide a clear contrasted image of the spray at each pressure setting for accurate measurement of the cone angle of the spray. The camera was also used to capture the projected laser image for post-processing.

Figure 3 shows a schematic of the mechanism underlying the current proposed technique. When the conical sheet is smooth and laminar, the laser beam passes through the sheet with little scatter and is imaged on the imaging plane as a single laser point. This case is illustrated in the top portion of the schematic. However, when a traveling wave propagates along the sheet, it refracts the light from the laser eventually causing it scan through an angle $\alpha$. It can be noted that $\alpha$ is a function of wave amplitude and possibly the wavelength. Since the phenomenon of refraction depends on second derivative of the surface profile (curvature), small changes in surface amplitude result in a measurable change in the laser scan angle.

Figure 4 is a representative image of the laser scan on the projection plane as produced in a typical experiment (nozzle pressure = 80 psi). Firstly, the edges of the image produced were of a very high contrast, allowing us to measure the scan heights and the resultant scan angles very accurately. $\alpha$ is calculated from this measured height and from the knowledge of the distance of the projection plane from the center of the spray. It can be noted from figure 4 that the projected image is not perfectly vertical as would be expected if purely axisymmetric waves were to be generated on the sheet. It is therefore postulated that this non-vertical motion could be caused by non-axisymmetric waves that may be present on the conical sheet.

Figure 4: Laser passing through conical sheet and the resulting projected image

A typical experiment began with pouring the Canola Oil into the pressure tank. The tank was then sealed and pressurized to 140 psi. The regulation valve was opened enough to allow a cylindrical jet of oil to flow out of the nozzle. This jet was utilized to align the laser to pass through the center of the spray cone and remain perpendicular to the projection surface. As the laser beam passed through the stream, it refracted and projected a horizontal line that had a Gaussian intensity distribution. The most intense area of the line was aligned with the center of the projection surface. The regulation valve was then opened such that the nozzle pressure was increased to 40 psi. The camera was used to capture the cone angle as well as the projected image from the laser scan. The pressure was then increased in increments of 5 psi until the laser beam was in the sheet breakup region. The captured images were then processed to calculate the angle of the spray cone and height of the projected image.

The spray cone angle was calculated from the captured images in a MATLAB program which used the Sobel method of edge detection to generate an edge profile. Adobe Photoshop was used to crop the images to a 512x480 resolution and convert them into bitmap format as required by the program. The resulting images were then printed and manually measured to find the angle. Figure 5 shows a representative image (obtained at a nozzle pressure of 60 psi) along with the length scale associated with the measurement process. The projected image height was calculated using the ruler in the captured image as a reference. This process was repeated for each of the captured images at the different nozzle pressures.

Figure 5: Cone angle Pre and Post-Processed image from the edge detection program

Two fluids were tested during the course of this project – Canola oil and approximately 80:20 by volume glycerin/water mixture. The dynamic viscosity of the Canola oil used was tested at room temperature to be 55 mPa-s. The glycerin and water were mixed to match the viscosity of the Canola oil at room temperature. This fluid was used to primarily investigate the effect of surface tension on our measurements. All viscosity measurements were made using a Brookfield Synchro-lectric Viscometer Model LVF with standard spindles with an accuracy of ±2.5 mPa-s. The same procedure was repeated with the glycerin/water mixture and the resulting images and calculations were compared with the Canola oil data.

RESULTS AND DISCUSSION

Figure 6 shows the change in spray cone angle as a function of pressure for each fluid. Angle values were calculated at pressure increments of 5 psi on a pressure range that ensured the laser beam passed through a laminar sheet as seen in figure 3. As can be seen from the figure, the cone angle decreases as the pressure is increased. It is also clear that the cone angles for Canola oil are higher at any given pressure than the cone angles obtained using glycerin. Both of these observations are consistent with previous observations [2], in that as the nozzle pressure increases, the ratio of the axial momentum to the angular momentum increases causing a narrower spray. Moreover, as the surface tension decreases, the cone angle is found to increase slightly.

The linear relationship between cone angle and pressure is due to the axial and radial velocities intrinsic to the conical sheet formed by swirl atomizers. As the pressure is increased, the axial velocity increase is more significant than the radial velocity increase causing a decrease in cone angle. Since the Canola oil and glycerin mixture have the same viscosities, the wider angles obtained with Canola oil were due to surface tension. As the oil exits the nozzle orifice, two forces are acting...
on it radially, the centrifugal force imparted by the nozzle and surface tension. Since the surface tension in Canola oil is less than the glycerin/water mixture, the effect that it has on the spray cone angle is significantly less as seen in the figure.

Figure 6: Spray Cone Angle verses Pressure

Figure 7 shows the change in $\alpha$ as a function of pressure. $\alpha$ is a measure of the angle that the laser beam sweeps as the wave passes and is related to the wave amplitude. Alpha is found by calculating the arctangent of the height of the projected image divided by the distance from the nozzle to the projection surface. This method allows for a more general approach of representing the data. As can be seen from this figure, the scan angle for the glycerin/water mixture increases with increasing pressure initially. At approximately 65 psi pressure, the scan angle is found to decrease drastically. As the pressure is increased, the intact length of the conical liquid sheet is decreased owing to increased instability. Therefore, as the pressure increased, at some point the intact length of the conical sheet will become shorter than the height where the laser is positioned w.r.t. the nozzle. It was noticed that this transition occurred at 65 psi which shows a sudden decrease in the scan angle. It is clear from the figure that the range of alpha for Canola oil is much narrower than that of the glycerin mixture. The data for Canola oil shows that the scan angle is relatively constant with increasing pressure. This could point to the possibility that the wave amplitude remains approximately constant over the range of pressures tested. This hypothesis is however yet to be tested.

Figure 7: Alpha verses Pressure

Figure 8 shows the spray cone angle as a function of alpha for Canola Oil. It is seen from the figure that there is a linear relationship between the two variables. The linearity is increased if the last data points from the three highest pressures are discarded. These three points appear as the lowest three in the figure. At higher pressures, it is more feasible that the laser beam had begun to pass through the wavy disintegrating portion on the spray which would introduce errors.

Figure 8: Spray Cone Angle verses Alpha for Canola Oil

It is postulated that the projected height is a function of both the cone angle and the wave amplitude. It is also noted that a change in cone angle alone will not change the projected height or alpha since a smooth conical liquid sheet will only produce a single laser point. This case was tested by allowing the laser to pass through a conical glass bulb wherein we only observed a single laser point with no scan angle. Figure 8 shows that there is clearly a linear relationship between the cone angle and alpha which can be used to determine the contribution that cone angle has on the projected height. Once this is known, the only remaining variable is the wave amplitude which can then be calculated.

Figure 9 shows two sets of data, both of which were obtained using Canola oil. The difference between the two is that one was performed with the laser beam at .34 inches from the nozzle and the other at a distance of .19. As illustrated in the figure, as distance from the nozzle increases, the height of the projected image increases. This is in agreement with intuition since the sheet becomes increasingly unstable as distance increases and would produce larger amplitudes.

Figure 9: Height verses pressure at two distances from nozzle
CONTINUING WORK

Work is in progress to utilize this technique to measure other useful parameters related to the waves on a conical sheet. The first objective is to quantitatively measure wave amplitudes and relate them to literature values. Once this technique is established quantitatively, three photo diodes will be arranged in an array along the projection surface. By accurately calculating the time it takes the laser beam to move from one photo diode to another, we will be able to calculate the wave velocity. A third photo diode is used for the sake of redundancy, and will aid in checking for constant velocity. The same setup is also going to be used to measure the oscillation frequency which is directly related to the wave frequency. The pauses between pulses produced in the photo diodes will also be useful in determining wavelengths. Finally this data will be compared with literature values to determine the reliability of this technique.

CONCLUSION

In conclusion, we have developed a technique based on laser refraction that can be utilized for making instability wave amplitude measurements on conical liquid sheets in the near nozzle region of a pressure swirl atomizer. We have tested the technique on Canola oil and glycerin/water mixtures both of the same viscosity. It was observed that the instability wave amplitude for glycerin/water increases with increasing pressure but for Canola oil, it was noticed that the instability wave amplitude remained relatively constant with pressure. The spray cone angle for both of these cases was observed to decrease with increasing pressure which is consistent with previous observations.

ACKNOWLEDGMENTS

We acknowledge help from Goodrich for providing some of the equipment that was used in this study. Thanks are also due to Mr. Wayne Kimsey for help with the software analysis.

REFERENCES