A Morphological Technique for Direct Drop Size Measurement of Cryogenic Sprays

Hrishikesh Ganu*

Research Scholar, Indian Institute of Science, Bangalore, Karnataka, 560012, India

B. N. Raghunandan†

Professor, Indian Institute of Science, Bangalore, Karnataka, 560012, India

A Morphological technique for quantifying cryogenic sprays directly from their images, has been developed. The technique has been validated with results from the laser diffraction particle analyzer for water sprays and has been shown to be effective even for dense water sprays. Morphological operations have been explained through a lucid physical analogy for the opening operation. An image of an actual cryogenic spray has been chosen to illustrate these concepts in a concrete fashion. Influence of pressure drop on the drop size distribution of an LN_2 spray, has been studied using this morphological method. This obviates the need for using simulants and extrapolation techniques. An important inference from the drop size distributions, is that evaporation effects become significant as soon as the jet leaves the injector.

I. Introduction

It is well known that the performance of combustors in all propulsive devices is critically linked to the manner in which the fuel or propellant is introduced. The computational codes dealing with the combustor performance invariably require the spray characteristics downstream of the injector as an important input in the absence of any globally accepted physical model for injectant stream breakup. Reliance on experimental data on sprays has therefore been unavoidable. While general spray features such as cone angle, intact length or overall mass distribution can be easily measured, the measurement of drop size distribution has remained a challenge. The problem becomes very acute while dealing with cryogenic fluids which have very high evaporation rates and create a mist in the spray region. This mist tends to obscure the droplets within and the well known optical instruments such as those using laser diffraction principle tend to yield erroneous data. The practice of using storable liquids, mostly water, for deducing the droplet sizes of cryogenic fluids also has serious limitations. It is not certain if the liquid jet or sheet breakup and spray formation phenomenon of a fast evaporating medium would follow the same mechanism as do the storables.

It is in this backdrop, an attempt is made to obtain frozen images of liquid nitrogen spray followed by a newly developed morphological technique to process the images and generate the drop size distribution. A great merit of this technique is its simplicity and relatively straightforward data reduction. The technique is evidently applicable to high density spray of storable liquids too.

Limitations of the Current Techniques for Drop Size Measurement of Cryogenic Sprays

A major difficulty when comparing drop size data of several investigators is the use of different measurement techniques, which often do not actually measure the same quantities. Ferrenberg and Varma,[1] described the differences in temporal and spatial distributions, obtained mainly from imaging techniques and PDPA and in some cases with the wax freezing method.

Dodge[2] indicated that the most important sources of error are obscuration and droplet number density when comparing the results of devices based on the diffracted light method and sizers based on the Phase

*Research Scholar, currently Engineer-CFD, Cummins Research and Technology, India.

†Professor, Department of Aerospace Engineering, Indian Institute of Science, Bangalore, 560012.

Doppler method, which are currently the most widely used techniques. He also indicated a way to compute overall representative average diameters from local measurements. Inversion techniques have also been developed[1]-[3] to transform line-averaged data obtained with diffraction-based devices into local values given, for instance, by the Phase Doppler technique. Glogowski et al.[4] examined shear coaxial sprays with both an air/water system and a GN_2/LN_2 system. The injector design was based on the SSME injector. They measured drop velocity and diameter with the PDPA (Phase Doppler Particle Analyzer) for both air/water and GN_2/LN_2. The GN_2/LN_2 tests examined the effect of mixture ratio and chamber pressure beyond the critical pressure of nitrogen and showed improved atomization with lower mixture ratios. The effect of chamber pressure on droplet size and mean axial velocity was found to be negligible. Under similar conditions of mass flow rate and chamber pressure, SMD was 105 μm with LN_2/GN_2 and 205 μ m with water/air.

Pal et al.[5] also modeled their injector after the SSME rocket injector. The paper included a comparison of PDPA data from air/water and liquid-oxygen/gaseous-hydrogen experiments. Both tests were run with similar flow conditions. The author found that Sauter mean diameters from the hot-fire experiments were larger than those from the cold flow experiments, suggesting that the gas-phase velocity fields in the two cases are significantly different. The mean drop velocity was smaller for the GH_2/LOX tests than for air/water tests. Both Zaller[6] and Eroglu[7] observed similar trends in PDPA measurements of drop size in coaxial injector sprays. Yang et al.[8] compared the drop size distribution of four pairs of liquid/gas simulants, which were liquid nitrogen and liquid oxygen with room temperature nitrogen, liquid oxygen with room temperature helium and liquid oxygen with cold (around 150 K) helium. Tests were conducted with three chamber pressures (10, 5 and 1 bar), different mass flow rates of LOX and gaseous nitrogen and various positions of the PDPA probe from 15 to 80 mm downstream, in front of the LOX post. Preliminary results from the most valid tests showed a SMD between 50 and 80 microns.

These droplet sizes are not in good agreement with predictions from empirical relations taking into account the surface tension, density and viscosity of liquid oxygen. In all of the aforesaid studies, PDPA was used to make measurement of coaxial injector sprays, without and within a pressurized chamber. These studies were limited, however, by the inability of the PDPA to reliably measure drop sizes below 30 μm, handle wide droplet velocity ranges or make measurements in dense spray.

Among the current techniques, Laser diffraction is, by far, the fastest and most widely used method for determining the drop size distribution of liquid sprays. For accurate measurements with light diffraction methods, it is important to use fluids which have stable refractive indices. If the refractive index varies throughout the fluid, the pattern of the index variation will be responsible for some scattering signals, which could cause measurement errors. A major source of error, beam steering, is caused by index variation which occurs over a large scale compared to beam diameter due to temperature gradients around the cold working fluid moving in warm ambient air. For the present case, LN_2 drops are formed at a temperature very close to their boiling point i.e. 77 K, which is very low compared to the ambient gas temperature of 295 K. This not only makes small drops evaporate very quickly but also presents further difficulties through the temperature and refractive index gradients in the gas phase, surrounding the drops.

To determine the effect of dense spray, indicated by excessive obscuration, on drop size measurement by light scattering technology, Chin et al.[9] investigated a correction factor for water based on several combinations of sprays which result in high obscuration levels. The correction is required because the technique assumes that light is scattered only once in the measurement volume, whereas multiple scattering is sure to occur in sprays having a high number density. Results indicated that SMD as measured with high obscuration levels is much lower than the one measured at dilute conditions. The correct SMD was as high as twice the SMD, measured at obscuration levels exceeding 75% and resultant SMD values often appear unrealistically high.

The mode in which a jet of water breaks-up, is very much different from that of a cryogenic fluid jet. This is because, the underlying physical mechanisms are quite distinct in the two cases and cryogenic propellants exhibit peculiar trends in the variation in their thermodynamic properties like surface tension and latent heat of evaporation, close to and above the critical point. The classical modes of liquid breakup like the Rayleigh regime, wind-induced regimes etc, based on the Ohnesorge number are no longer valid in case of a cryogenic fluid. Some of the researchers[1,10,11,12] obtained spray parameters for a cryogenic spray, by performing experiments with water and then using empirical correlations to extend the results to cryogenic fluids. They tried to model the influences that properties like density, viscosity, surface tension and injection velocity, have on spray breakup, through these correlations.

Considering the disparate and inconsistent expressions given by these investigators for extrapolating the drop sizes of simulants to cryogenic fluids and the futility of using the otherwise ubiquitous technique of laser diffraction here, the need for a simple technique to measure drop sizes of cryogenic sprays was acutely felt. Conventional photography is particularly well-suited for this purpose, since it is as though the spray itself were “frozen” and a section taken for analysis. Moreover, taking a snapshot, though it calls for practical skills, requires little other than a digital camera; unlike other imaging techniques like Raman Imaging, which need complex equipment.The following section is an overview of the Morphological technique.

II. The Morphological Technique

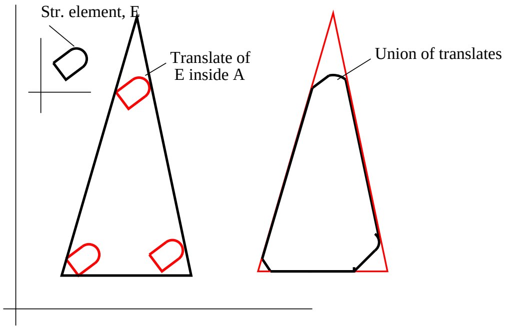


Figure 1. Opening as a Union of Translates of the Structuring Element

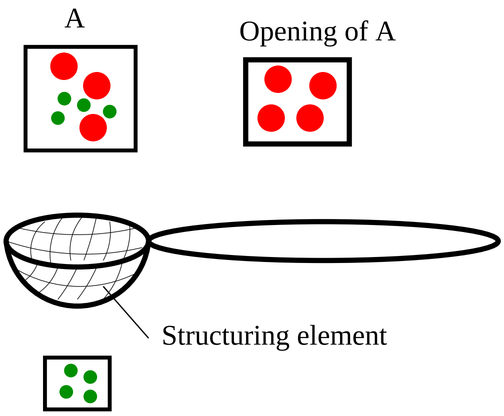


Figure 2. Physical Analogy (Sieving) for Opening

Morphology is a term commonly used in the biological sciences for describing the form or structure of an organism. In image processing morphology denotes the geometrical or textural features of the image. The techniques of morphology try to mimic the manner in which a human being perceives and processes an image. Morphological operations can help in rapidly classifying images based on the size/shape of the features they contain.These techniques derive their power from the fundamental set-theoretic operations of union, intersection and complement. Mathematical foundations for Morphology have been discussed in Ref. 17. In the present study, the ’opening’ operation, which appears in the next subsection, has been extensively used.

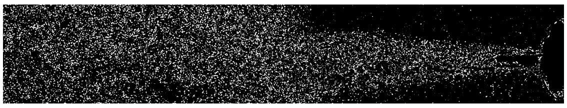
Opening is a set-theoretic operation, which is like filtering objects through a sieve of a certain size. The output from the opening consists of all objects which exceed or are equal to the mesh size of the sieve. Thus, opening by a round structuring element can be visualized as the figure generated by rolling a ball from inside the boundary of the set A, and choosing the entire interior and only those regions of the boundary which the cylinder can touch. Opening smoothes contours, breaks narrow isthmuses and eliminates sharp peaks and small islands.This effect can be seen in Figure 1 which illustrates the opening as the union of translates of a structuring element.

From Figure 2, which gives the physical analogy for opening, what exactly happens during the opening operation can be immediately observed.

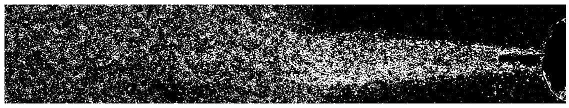
By using sieves of gradually increasing mesh sizes, and performing certain operations like taking the complement, we can obtain a sequence of images. Figure 3(a) is the black and white(binary) image of an LN_2 spray. Consider an image $\Phi_7(A)$ which is a member of this sequence of openings, derived from the same base image “A” and the image $\Phi_8(A)$ which comes next in this sequence. Here “7” and ”8” denote the sizes of the mesh used for screening. Figure 3(c) shows how $\Phi_8(A)$ has all objects smaller than “8” pixels while $\Phi_7(A)$ in Figure 3(b) holds all objects having size less than 7 pixels.The trick lies in just subtracting $\Phi_7(A)$ from $\Phi_8(A)$ to get $\Phi_{7,8}(A)$ which can be seen in Figure 3(d) and contains only those objects lying in the size class 7-8. Counting the number of droplets in images like $\Phi_{7,8}(A)$ provides data for plotting the histogram of the number of droplets against the size-class.

The algorithm for generating a granulometry is represented by the flowchart shown in Figure 4 below. It accepts the raw image A as the input and delivers a sequence of images.It can be seen that there will be an image corresponding to the smallest mesh size at which nothing will pass through the sieve.

(a) Black and White (Binary) Image "A"of an LN_2 spray



(b) Image $\Phi_7(A)$



(c) Image $\Phi_8(A)$

(d) Image $\Phi_{7-8}(A)$

Figure 3. Two consecutive images $\Phi_7(A)$ and $\Phi_8(A)$ in the morphological sequence and the resulting Φ_{7-8}

III. Results and Discussion

A. Coaxial Injector Using Water:Air as Simulants

Trials were carried out on a coaxial injector using water and air as simulants for LOX and LH_2 respectively. The water spray emerging from this injector is seen in Figure 5. While Malvern Mastersizer was used to measure the drop size distribution, analyzing the same spray using the morphological method was an interesting proposition that would further validate this technique. With a pressure drop of 0.26 bar for the water jet and a drop of 1.26 bar in the pressure across the co-flowing air stream, several images were captured under identical conditions, and were processed through the morphological technique. There was almost an imperceptible variation in the SMD across runs on three different photographs. This is also reflected in the histogram of Figure 6.

Once the the repeatability of the technique was proven, the fractional and cumulative volume distributions were plotted. Figure 7 shows these plots, alongwith the results given by Malvern Mastersizer. Though the obscuration levels were within acceptable limits, laser diffraction shows a bimodal distribution with a second peak around 1400μ m. The presence of this second peak cannot be substantiated and this indicates that obscuration is not the only limiting factor while using laser diffraction. Under the same conditions, morphological analysis as in Figure 6 reveals the presence of a very large number of droplets in the lower size class and hence, multiple scattering might be the culprit in this case. This view is supported by the cumulative volume distribution curves: that from the morphological method rapidly saturates at 700μ m, as in Figure 7 whereas that from Malvern Mastersizer continues to accumulate volume from size classes even beyond 1000μ m. The photographic method, clearly, suffers from no such limitations, as regards the droplet number density.

B. Cryogenic Sprays

1. Jet Breakup Length and Spray Divergence Angle

The experiments are conducted with liquid nitrogen at a pressure of 300-350 kPa injected into ambient air. The LN_2 jet in air at Δ p of $3kg/cm^2$, corresponds to a Reynolds number of 10^5 and an Ohnesorge number (Oh) of around 10^{-3}. Hence in our experiments, the jet was always in the atomization regime of the stability theory of Reitz[13] at all pressure drops.

Our results using a plain atomizer discharging LN_2 into ambient air echo the trends reported earlier as reviewed by Reitz[13] for change in the breakup length with velocity, in the atomization regime. Thus, the

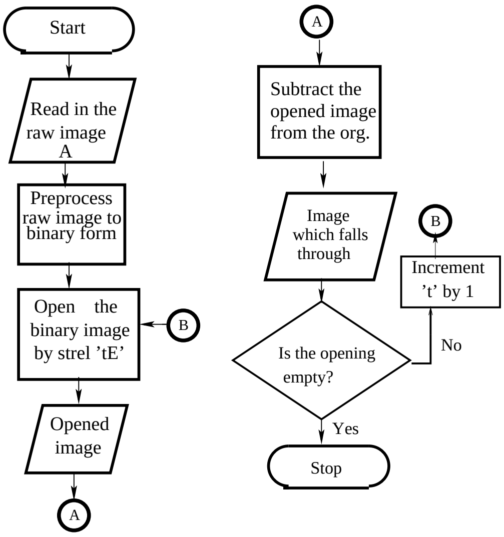


Figure 4. Flowchart for generating a granulometry

Figure 5. Coaxial injector using water/air as simulants

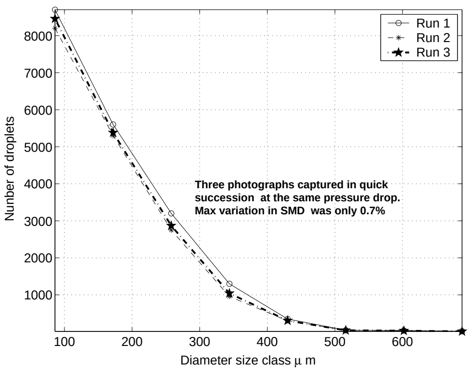


Figure 6. Testing the Repeatability based on three photographs captured in quick succession

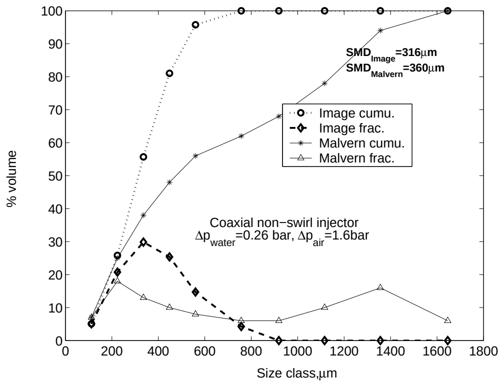


Figure 7. Coaxial injector with water/air as simulants: Fractional and cumulative volume distributions

breakup-length displays almost a linear decrease with increasing pressures as in Figure 8.

From Figure 9, it is seen that the spray divergence angle increases with increasing pressure drops. However, the aerodynamic surface wave growth theory[13] predicts a different trend. This confusion can be resolved if one takes into account the effects of vaporization of the cryogenic jet. Then the classical theory for breakup of a liquid jet is no longer applicable, and the droplet gasification time (τ_g) and the droplet bulge formation time (τ_b) become important. This also means that the equation proposed by Chehroudi[14]

$$\theta_{Ch} = 0.27[\tau_b/(\tau_b + \tau_g) + (\rho_g/\rho_l)^{1/2}]$$

is more relevant than the spray growth equation due to Ranz,[13] in the case of cryogenic sprays.

2. Drop Size Distributions at Δ *p=350 kPa*

The "global" drop size distribution, (based on the entire spray) is shown in Figure 10(a).

Similarly, Figure 10(b) gives the "local" drop size distribution in the vicinity of the atomizer exit (0-25 mm from injector face).The SMD based on the global spray was 313μm. This value is close to the value obtained by other workers[15] who used photographs and manual counting to quantify LN_2 sprays.

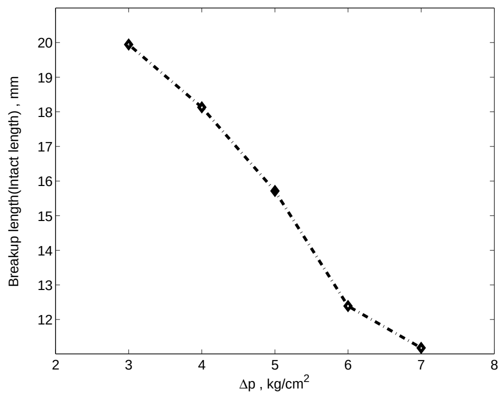


Figure 8. Liquid core breakup length with change in Δp

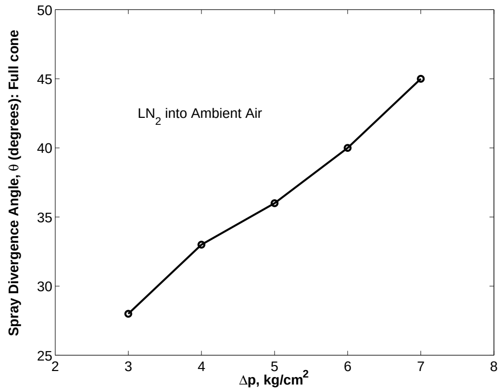
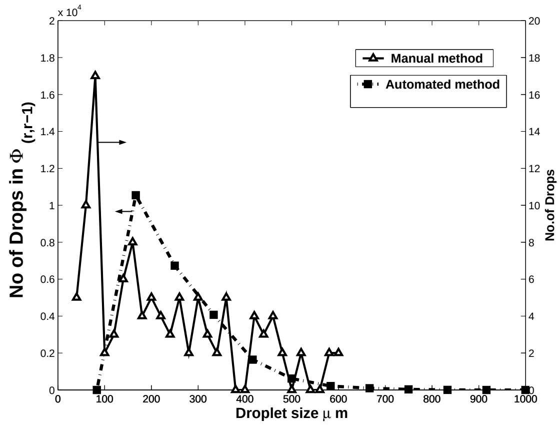
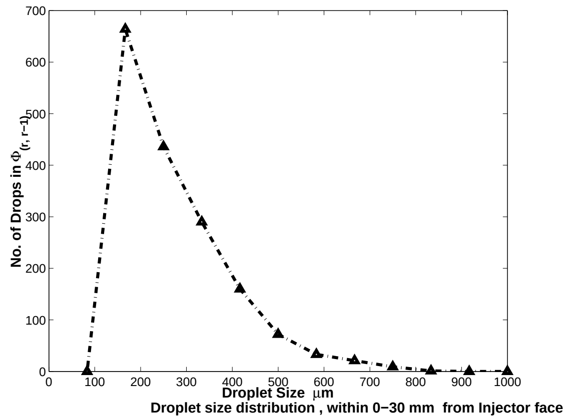


Figure 9. Spray Divergence Angle: variation with Δp



(a) Global Distributions at Δp 350kPa: Manual and Automated methods



(b) Local Drop Size Distribution by Automated method(Δ p 350kPa)

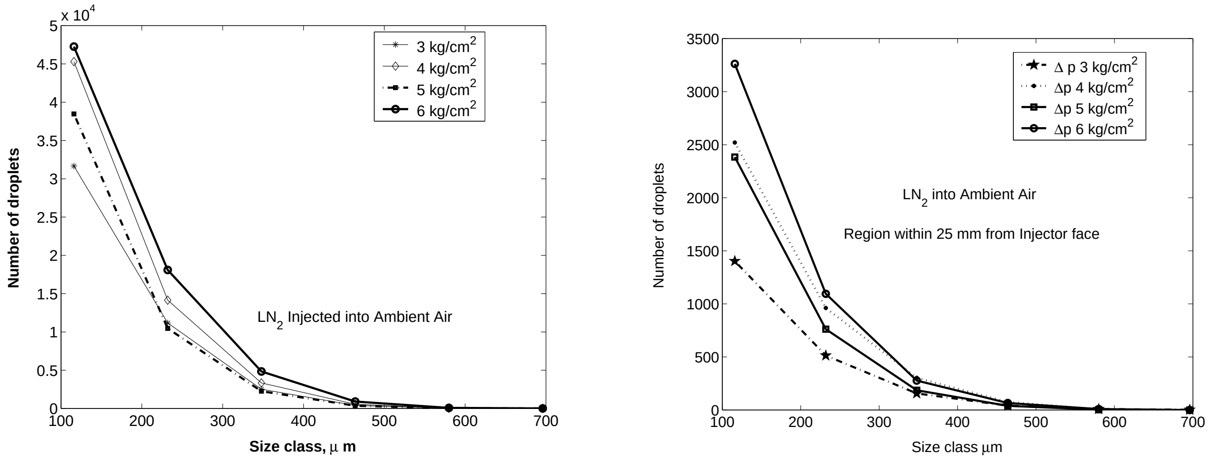
Figure 10. Global and local drop size distributions at $Delta$p=350 kPa

3. Effect of Pressure Drop on the Drop Size Distribution

From the global drop-size distribution at various pressure drops from 3 to 6 kg/cm^2 in Figure 11(a), one is tempted to conclude that the droplets in the smallest size class at $100\mu m$ influence the SMD the most. This is however, not true because the medium sized droplets at 350μm by being thrice as large, contribute almost equally to the volume and a bit less to the area of the entire spray, as compared with the smallest droplets. Secondly, though the absolute difference between the number of droplets seen at $3kg/cm^2$ and at $6kg/cm^2$ varies across different size classes, their relative proportions remain the same throughout. It is generally believed, that large droplets are a result of primary atomization and the smaller ones are due to secondary atomization. Then, it appears that the relative strengths of these mechanisms are independent of the pressure drop and hence the jet velocity.

This is evident from Figure 12, which shows the number of droplets due to secondary atomization, relative to that due to primary atomization at various pressure drops. If aerodynamic effects alone were the mechanism responsible for breakup, the number of droplets in the higher size class (produced due to primary atomization) should not have increased with pressure drop. One can then infer, that evaporation claims a fairly large share of primary as well as secondary breakup.

The local SMD (in the region within 0-25mm from injector exit)is throughout, greater than the global SMD in Figure 13 which compares the global and local distributions.This means that coalescence even if present is not dominant, and the large droplets which appear in the global distribution, are mostly due to primary atomization. Ruling out coalescence as a candidate mechanism for producing large droplets enables



(a) Global Distribution LN_2 into Ambient Air at Various Pressure Drops

(b) Local Distribution: LN_2 into Ambient Air at Various Pressure Drops

Figure 11. Effect of pressure drop on drop size distribution

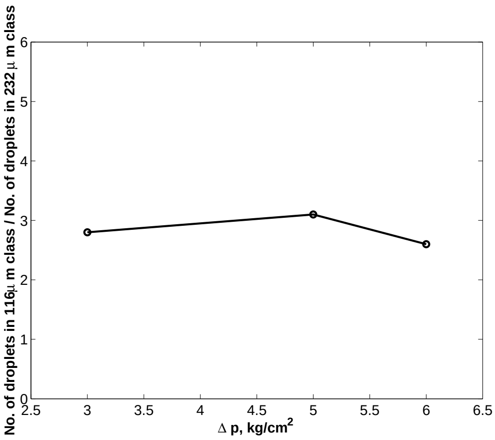


Figure 12. Relative Influences of Primary and Secondary Atomization at Various Pressure Drops

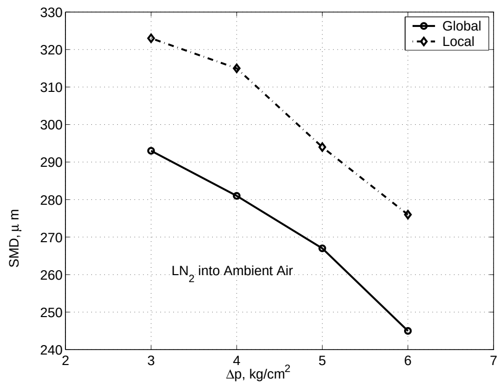


Figure 13. Variation of SMD with Pressure Drop(LN_2 into Ambient Air)

us to compare the strengths of primary and secondary breakup.

The droplet size distributions in the local region within 25mm from the injector, show a trend similar to that of the global distribution at various pressure drops.The local distributions, of Figure 11(b) thus, differ from the global distributions of Figure 11(a) only in the number and SMD (see Figure 13) of particles present in the image.

IV. Conclusions

The present study has demonstrated how a simple photographic technique can be used to study cryogenic spray breakup. Though qualitative results giving the trends in breakup length and spray divergence angle, using photographs, have been available for some time now, the significance of the morphological technique lies in its ability to provide "quantitative data" in the form of the drop size distribution. Another outcome is that evaporation effects are dominant in case of cryogenic sprays and hence classical breakup theories, which do not consider effects of evaporation, are bound to produce inaccurate predictions.

Traditionally,only scientists associated in only a few well funded institutions have had access to advanced techniques for cryogenic spray studies and the others had to rely upon extrapolation techniques, in absence of a cost-effective and simple alternative. The advent of direct techniques like the morphological method, presents a strong case for doing away with such extrapolation techniques,which do not capture the physics of cryogenic spray breakup.The morphological technique, thus, it is hoped, will make cryogenic spray breakup studies accessible to a much wider range of users.

V. Acknowledgments

Hrishikesh Ganu wishes to thank Cummins Research and Technology India, for permission to use their resources for typesetting this paper. Discussions with research scholars Amit Lal and Hrishikesh Gadgil were of great help in crystallizing the concepts.

References

[1]Ferrenberg, A.J., and Varma, M.S., *Atomization Data for Spray Combustion Modeling*, AIAA/ASME/SAE/ASEE 21^{st} Joint Propulsion Conf., Monterey, CA-July 1985.

[2]Dodge, L.G., *Comparison of Performance of Drop Sizing Instruments*, Applied Optics, Vol. 26, No. 11, June 1987.

[3]Dodge, L.G., *Representation of Average Drop Sizes in Spray*, Journal of Propulsion and Power, Vol. 4, No. 6, 490-496,1988.

[4]Glogowski, M., Bar-Gill, M., Puissant. C., and Micci, M., *Shear Coaxial Injector Instability Mechanisms*, AIAA Paper 94-2774, 1994.

[5]Pal, S., Moser, M.D., Ryan, H.M., and Foust, M.J., *Shear Coaxial Injector Atomization Phenomena for Combusting And Non Combusting Conditions*, Atomization and Sprays, Vol.6, No. 2, 227-244, 1996.

[6]Zaller, M.M., and Klem, M.D., *Coaxial Injector Spray Characterization using Water/Air As Simulants*, NASA-TM-105322, November 1991.

[7]Eroglu, H. and Chigier, N.A., *Initial Drop Size and Velocity Distribution for Airblast Coaxial Atomizers*, Journal Of Fluids Engg., Vol. 113, 453-459, 1991.

[8]Yang, V., and Anderson, W.E, *Combustion Instability in Liquid Rockets*, Vol. 169, Progress In Astronautics and Aeronautics, Chapter 7, 1995.

[9]Chin, J. S., And Zhang, Y., *Experimental Study Of The Effect Of Dense Spray on Drop Size Measurement by Light Scattering Technology*, ASME J. Eng. Power, Vol.114, 82-88, January 1992.

[10]Jasuja, A.K., *Atomization of Crude and Residual Fuel Oil*, ASME J. Eng. Power, Vol. 101, No. 2, 250-258, 1979.

[11]Lefebvre, A.H., *Atomization and Sprays*, Hemisphere, Washington, D.C. 1989.

[12]Radcliffe, A., *Fuel Injection, High Speed Aerodynamics and Jet Propulsion*, Vol. 11, Sect D, Princeton University Press, 1960.

[13]Reitz et.al, *Mechanisms of Breakup of Round Liquid Jets*, The Encyclopedia of Fluid Mechanics, ed.N Cheremisnoff 3:233-49. Houston:Gulf, 1986.

[14]B. Chehroudi, D. Talley, and E. Coy, *Fractal Geometry and Growth Rate Changes of Cryogenic Jets Near the Critical Point*, AIAA 99-2489, 35^{th} AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit 20-24 June 1999, Los Angeles, California.

[15]Santosh Kumar Sahoo, *Spray Characteristics of A Cryogenic Liquid Jet*, MSc(Engg.) Thesis, Dept. of Aerospace Engg., IISc, January 2003.

[16]J.Bellan, *Supercritical (and subcritical) fluid behavior and modeling: drops, streams, shear and mixing layers, jets and sprays*, Progress in Energy and Combustion Science, 26 (2000), pp 329-366, 2000.

[17]Hrishikesh Ganu, *A Morphological Technique for Direct Drop Size Measurement of Cryogenic Sprays* MSc(Engg.) Thesis, Department of Aerospace Engineering,IISc, Bangalore, 2005.