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"The Physics of Coal Liquid Slurry Atomization"

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The Physics of Coal Liquid Slurry Atomization
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Final Report

PROJECT SUMMARY

The stability of turbulent columns of liquid injected into a quiescent environment was studied. Laser Doppler Anemometry measurements of the flow patterns and turbulence characteristics in free liquid jets were made. Turbulence decay along Newtonian jets was investigated along with the effects of turbulence on the resulting droplet size distributions after breakup. The rate of decay of turbulence properties along the jet were investigated. Disintegration of liquid jets injected into a high-velocity gas stream has also been studied. Newtonian and non-Newtonian liquids were studied with particular emphasis on the non-Newtonian rheological characteristics. Determination was made of the extent that the addition of high molecular weight polymer to liquids change the breakup process. Shear thinning, extension thinning and extension thickening fluids were investigated. Shear viscosities were measured over five decades of shear rates. The contraction flow technique was also used for measurement of the extensional viscosity of non-Newtonian liquids. The die-swell technique was also used to determine the first normal stress difference. The near field produced by a co-axial airblast atomizer was investigated using the phase Doppler particle analyzer. Whether or not the classical wave mechanism and empirical models reported for airblast atomization of low viscosity liquid are applicable to airblast atomization of viscous non-Newtonian liquids was determined. The theoretical basis of several models which give the best fit to the experimental data for airblast atomization of non-Newtonian liquids was also discussed. The accuracy of the wave mechanism-based models in predicting droplets sizes after breakup of viscous non-Newtonian liquids using an airblast atomizer has also been demonstrated.

LIST OF PUBLICATIONS

The following is the list of publications. Publications 1 and 2 are currently under review. Publication 3 is in print. Publications 4 through 15 have already been published in archival journals and in conference proceedings.

1. A. MANSOUR and N. CHIGIER, "On the Use of the Contraction Flow Technique to Measure the Extensional Viscosity of Mobile Polymeric Solutions", submitted to Rheologica Acta, July, 1995.

2. A. MANSOUR and N. CHIGIER, "The Near Field of Co-Axial Airblast Atomizer Sprays ", submitted to the International Journal of Multiphase Flow, Nov. 1994.

3. A. MANSOUR and N. CHIGIER, "Air-Blast Atomization of Non-Newtonian Liquids", in print, Journal of Non-Newtonian Fluid mechanics, 1995.

4. A. MANSOUR and N. CHIGIER, "Comparison Between Rigid Sphere Drag models and Droplet Drag Coefficients Under Realistic Spray Conditions", Proceedings of the Eighth Annual Conference of Liquid Atomization and Spray Systems (ILASS- Americas, May, 95).

5. N. CHIGIER, A. MANSOUR, and U. SHAVIT, "The Separate Influences of Air and Liquid Turbulence on Atomization", International Union of Theoretical and Applied Mechanics Symposium on the Mechanics and Combustion of Droplets and Sprays, National Cheng Kung University, Tainan, Taiwan, Dec. 6-10, 1994.

6. A. MANSOUR and N. CHIGIER, "The Physics of Non-Newtonian Liquid Slurry Atomization Part II: Airblast Atomization of Viscous Non-Newtonian Liquids", Proceedings of Tenth Annual Coal Preparation, Utilization, and Environmental Control Contractors Conference, Pittsburgh, PA., July, 1994.

7. A. MANSOUR and N. CHIGIER, "Effect of Turbulence on the Stability of Liquid Jets and the Resulting Droplet Size Distributions", Atomization and Sprays, vol. 4, pp. 583-604, 1994.

8. A. MANSOUR and N. CHIGIER, "Turbulence Characteristics in Cylindrical Liquid Jets", Physics of Fluids, Vol. 6, No. 10, pp. 3380-3391, 1994.

9. A. MANSOUR and N. CHIGIER, "Turbulence Decay in Liquid Jets", Proceedings of the Sixth International Conference on Liquid Atomization and Spray Systems (ICLASS-1994), Rouen, France, July, 1994.

10. A. MANSOUR and N. CHIGIER, "Atomization of Non-Newtonian Liquids", Proceedings of the Sixth International Conference on Liquid Atomization and Spray Systems (ICLASS-1994), Rouen, France, July, 1994.

11. A. MANSOUR and N. CHIGIER, "Rayleigh Breakup of Turbulent Columns", Proceedings of the Seventh Annual Conference of Liquid Atomization and Spray Systems (ILASS- Americas 94), Bellevue, Washington, May 31-June 3, 1994.

12. A. MANSOUR and N. CHIGIER, "A Phase Doppler Investigation of Co-Axial Air-Blast Atomizers", ASME, Winter Annual Meeting, Symposium on Fluid Mechanics and Heat Transfer in Sprays, New Orleans, 1993.

13. A. MANSOUR and N. CHIGIER, "An Extensional Viscometer Atomizer for Non-Newtonian Liquids", Proceedings of Sixth ILASS- Americas 93, Worcester, MA., 1993.

14. A. MANSOUR and N. CHIGIER, "The Physics of Non-Newtonian Liquid Slurry Atomization Part I: Atomizer Design", Proceedings of Ninth Annual Coal Preparation, Utilization, and Environmental Control Contractors Conference, Pittsburgh, PA., 1993.

15. A. MANSOUR, N. CHIGIER and Hassan Eroglu, "The Physics of Coal Liquid Slurry Atomization", poster paper, Proceedings of Eighth Annual Coal Preparation, Utilization, and Environmental Control Contractors Conference, Pittsburgh, PA., 1992.

PAPER ABSTRACTS

The following are the abstracts of archival journal publications.

On the Use of the Contraction Flow Technique to Measure the Extensional Viscosity of Mobile Polymeric Solutions

Rheologica Acta

Non-Newtonian viscosities were measured over five decades of shear rates $\dot{\gamma}$ for 12 solutions of polymeric materials. By using the Brookfield viscometer and the capillary tube viscometers, the shear viscosity was determined as a function of shear rate. Both the upper and lower limiting shear viscosities were determined for all solutions. The contraction flow technique was used for the determination of the extensional viscosity. Tests were performed on 0.05, 0.10, 0.15, 0.20, 0.30% concentrations by mass of aqueous solutions of Xanthan Gum polymer, and 0.0125, 0.025, 0.05, 0.1, 0.15, 0.30, and 0.50% concentrations by mass of aqueous solutions of Polyacrilamide E10. It was found that the contraction flow technique, although successful in measuring the extensional viscosity levels of semi-dilute polymeric solutions was incapable of yielding satisfactory results for the more dilute solutions. This was true for Polyacrilamide concentrations below 0.15% and all Xanthan gum concentrations. The more dilute solutions yielded less vortex enhancement in the entry corner, thus violating some of the basic assumptions of the contraction flow technique. Vortex enhancement occurs in order to reduce the energy losses in the entry corner. When the vortex length is equal to the chamber length, no additional enhancement is possible and the flow is destabilized. When vortex enhancement is arrested by the upper wall of the chamber, the ultimate result is always destabilization of the flow. This results in a dramatic increase of the entry pressure drop in the contraction flow chamber. The increase in entry pressure after flow destabilization corroborates the basic approach taken by Binding (1988) in minimizing the energy consumption in the entry corner in his contraction flow analysis. For flows of viscoelastic materials through contractions, sufficient chamber length needs to be provided to allow for vortex enhancement and prevent flow destabilization.

The Near Field of Co-Axial Airblast Atomizer Sprays

International Journal of Multiphase Flow

This paper describes the principal flow characteristics of a co-axial airblast atomizer spray. Detailed measurements of mean drop size and velocity were made using the phase

Doppler particle analyzer (PDPA). It was found that the spray can be characterized by three distinct sub-regions. A spray breakup region is present and extends approximately to three air nozzle diameters ($3D_a$). In this region, the droplets in the central portion of the spray are subjected to secondary breakup due to high local relative velocities. The droplets around the edges have a diameter which is characteristic of the initial breakup diameter of the jet. The second sub-region, $3 < x/D_a < 8$, is a transition region to the fully developed spray, where the droplet velocity profiles develop from saddle shaped velocity profiles into those approximating Gaussian error curves. Finally there is an almost fully developed region, $x/D_a > 8$, where there are relatively small changes in flow patterns. The PDPA size classified data shows that there are significant differences between particle and gas flow velocities. The rapid deceleration of the flow beyond $x/D_a = 4$ can only be followed by small particles, generally less than 15 µm. Droplets larger than 15 µm in diameter continue to accelerate over much longer downstream distances. The drag coefficients of large droplets as a function of droplet Reynolds number were determined from the size classified velocity data. The computed drag coefficients were then compared to an empirical drag law model for rigid spheres in a uniform gas flow. At an intermediate range of droplet Reynolds number ($50 < Re < 150$), it was found that the empirical drag law model closely approximates the computed drag coefficients. At higher values of the Reynolds number ($Re > 150$) the computed drag coefficient was found to be larger than that of a sphere; the droplets are distorted into oblate shapes resulting in increases in drag coefficient over that predicted by the simple sphere model. It was also found that, at all axial locations, there are significant increases in SMD from the spray axis towards the edges of the spray. The inertia of the larger droplets allows them to penetrate the air stream with little interaction. This results in their redistribution around the spray edges.

Air-Blast Atomization of Non-Newtonian Liquids

Journal of Non-Newtonian Fluid mechanics

Air-blast atomization of viscous non-Newtonian liquids was carried out using a co-axial twin-fluid atomizer. Both Newtonian and non-Newtonian liquids were investigated with particular emphasis on the non-Newtonian rheological characteristics. Shear thinning, extension thinning and extension thickening fluids were investigated. Non-Newtonian shear viscosities were measured over five decades of shear rates $\dot{\gamma}$ for 12 solutions of polymeric materials. By using the die-swell technique, the first normal stress difference N_1 was determined for all solutions. The contraction flow technique was also used for measurement of the extensional viscosity. It was found that viscoelastic liquids are much more difficult to atomize than viscoinelastic liquids. The normal stresses developed in viscoelastic materials are much higher than their associated shear stresses. Consequently, the development of the large normal stresses appears to be the most important rheological mechanism that inhibits breakup. The accuracy of the wave mechanism-based models in predicting droplets sizes after breakup of inelastic non-Newtonian liquids has also been demonstrated. The atomized drop sizes were expressed in terms of three dimensionless groups, the liquid/air mass ratio (M_l/M_a), the Weber number (We) and the Ohnesorge (Z) number in simple forms whose exponents and coefficients were determined by least squares fit to the experimental data. The exponents of the power dependencies of the wave-mechanism based simple models were found to be comparable to their counterpart reported in the literature for air-blast atomization of Newtonian liquids with viscosities up to 10 Pa.s. For shear thinning viscoinelastic materials it was found that the atomization quality is closely related to the apparent viscosity of the fluid in the limit of infinite shear rates (η_∞). The functional dependence of the Sauter mean diameter (SMD) on η_∞ is: SMD $\alpha\, \eta_\infty^{0.42}$.

Effect of Turbulence on the Stability of Liquid Jets and the Resulting Droplet Size Distributions

Atomization and Sprays

A study has been made of laminar and turbulent columns if liquids issuing form capillary tubes in order to determine the effects of turbulence on the stability of liquid jets and to establish the influence of liquid turbulence on the droplet size distribution after breakup. For water injection into stagnant air, it was found that the stability curve is bounded by the laminar portion characterized by a very low initial disturbance amplitude [$\ln(a/\delta_{o,L}) = 22$], where a is the jet radius and δ_o is the initial disturbance amplitude, and a fully developed turbulent portion characterized by a very high initial disturbance amplitude [$\ln(a/\delta_{o,T}) \sim 4.85$]. In the transition region, $\ln(a/\delta_{o,L})$ is not single valued; it decreases with increasing Reynolds number. It was also found that, in the absence of aerodynamic effects, turbulent jets are as stable as laminar jets. For this mode of breakup the sole effect of turbulence is to propagate initial disturbances with amplitudes that are orders of magnitude larger than for laminar jets ($\delta_{o,T} = 28\text{x}10^6\, \delta_{o,L}$). The growth rates of initial disturbances are essentially the same for both laminar and turbulent columns; they are in agreement with the theoretical values derived by Weber. For laminar flow conditions, the optimum wavelength (λ_{opt}) corresponding to the fastest-growing disturbance is equal to 4.45D, which is exactly the theoretical value derived by Weber. For turbulent flow conditions, $\lambda_{opt} = 9.2D$, which is approximately 2 times the optimum wavelength calculated by using Weber's theory.

Turbulence Characteristics in Cylindrical Liquid Jets

Physics of Fluids

A study has been made of the flow patterns and turbulence characteristics in free liquid jets in order to determine the rate of decay of turbulence properties along the jet. Mean streamwise velocities and streamwise and cross-streamwise turbulence intensities were measured using laser Doppler velocimetry. The jet Reynolds number was varied between 1000 and 30000, with the diameter of the liquid jet D = 3.05 mm. Using a power law model for the time decay of turbulence kinetic energy, it was found that turbulence decays, on average with an exponent N=1, independent of the Reynolds number. A constant power for the decay implies Reynolds number similarity throughout this range. Substantial reductions in the degree of anisotropy occur downstream from the injector exit as the jet relaxes from fully developed turbulent pipe flow profile to a flat profile. For the intermediate range of Reynolds numbers (10000-20000), the relaxation distance was 20D, almost independent of the Reynolds number. At high values of Reynolds number (20000-30000), the relaxation process was very fast, generally within 3 diameters from the injector exit.

SUMMARY OF CONCLUSIONS

The major conclusions of this study are as follows:

Turbulence Characteristics in cylindrical Liquid Jets

1. Turbulent kinetic energy decays along the jet from a maximum near the nozzle exit. The velocity gradients prior to the relaxation process do not seem to influence this process appreciably. Turbulent energy generation during relaxation is very small and the relaxation process has a negligible effect on the evolution of turbulence.

2. The degree of anisotropy reduces in the downstream direction from the injector exit. For an intermediate range of Reynolds numbers (i.e., Re = 14195 and 17349), the move towards isotropy is a gradual one. The turbulence becomes almost isotropic at about x/D = 15. For the highest Reynolds numbers there is a faster approach towards isotropy. Thus, it is possible to make the approximation of isotropic flow, particularly for the high Reynolds number conditions.

3. Once the flow leaves the tube, the mean liquid velocity becomes more uniform since the gas phase cannot retard the surface velocity as effectively as the wall of the injector passage. For Re in the intermediate range, $9463 < Re < 17349$, the relaxation distance is fairly independent of the Reynolds number and is approximately 20 D. This suggests that the relaxation time is inversely proportional to the Reynolds number. At this intermediate range of Reynolds numbers, it seems plausible that both the molecular viscosity and the turbulent diffusivity are equally important in controlling the relaxation process. At higher Reynolds numbers the relaxation process is very fast, generally within the first 3 diameters from the injector exit. The relaxation process is dominated by the turbulent motion which is much more effective in transferring momentum between transverse layers within the liquid than the molecular viscosity.

4. Using a power law model for the time decay of turbulence kinetic energy it was found that turbulence decays with an exponent $N = 1$ for all Reynolds numbers considered in this study. A constant power for the decay law in this Reynolds number range implies a Reynolds number similarity throughout the range of Reynolds number studied. An exponent of 1 also implies that the decay process is mainly dominated by the decay of the energy containing eddies and that it is not possible to take one single characteristic length to make the energy spectrum self-preserving during the decay. It is possible however to

assume incomplete self-preservation during the decay, that is self-preservation of only part of the spectrum.

5. Assuming self-preservation of the turbulence energy spectrum and assuming that turbulence decay is controlled by a certain wave number (ϕ^*) that remains constant in time during the decay if the spectrum is self-similar and neglecting the interaction terms, between eddies of various wave numbers, in the differential equation for the dynamic behavior of isotropic turbulence, it was found that the non-dimensional characteristic length Λ^* ($\Lambda^* = \lambda^*/ D$) corresponding to ϕ^* scales properly with the dimensions of the injection orifice with an average value of Λ^* equal 0.383.

The Effect of Turbulence on the Stability of Liquid Columns

1. The initial disturbance amplitude is not single valued; $\ln(R/\delta_o)$ is not universal for a single nozzle; it depends on the turbulence properties at the nozzle exit. In the absence of aerodynamic effects, the stability curve is bounded by the laminar portion where there is a very low initial disturbance amplitude ($\ln(R/\delta_{o,L}) = 22$) and the fully developed turbulent portion where the initial disturbance amplitude reaches its maximum ($\ln(R/\delta_{o,T}) \sim 4.85$). In the laminar portion of the stability curve, $\ln(R/\delta_{o,L})$ is single valued and the stability curve follows the straight line of unit slope which has an intercept of $\ln(R/\delta_{o,T}) =$ constant = 22. In the turbulent region the stability curve follows the straight line of unit slope which has an intercept of $\ln(R/\delta_{o,T}) =$ constant = 4.8. And finally in the transition region, $\ln(R/\delta_o)$ is not constant; it decreases with increasing Reynolds number and thus the breakup length decreases accordingly. This means that in the transition region, the reduction in the breakup length is not necessarily connected to a reduced stability of the jet, it is merely the result of the increase of the initial disturbance amplitude. Here we should make it clear that what is meant by a reduced stability is a greater growth rate and not necessarily a shorter breakup length or faster breakup time.

2. In the absence of aerodynamic effects, turbulent jets are found to be as stable as laminar jets. The sole effect of turbulence is to propagate an initial disturbance amplitude that is orders of magnitude larger than for laminar jets ($\delta_{o,T} = 28 \times 10^6\ \delta_{o,L}$). The growth rate of initial disturbances is essentially the same for both laminar and turbulent jets. Both growth rates are very close to the theoretical value derived by Weber.

3. Marked differences were found to exist between the breakup behavior and droplet formation patterns of both laminar and turbulent jets. For laminar jets, single waves were observed to detach from the liquid column in a very ordered and repeatable fashion. The

breakup length was generally unambiguous, very reproducible and readily measurable. For laminar flow conditions, the optimum wavelength (λ_{opt}) corresponding to the fastest growing disturbance is equal to $4.45D_1$ which is exactly the theoretical value derived by Rayleigh and Weber. For turbulent flow conditions, the turbulent column was observed to segment. Typically, multiple values of one wavelength were observed to detach from the liquid jet. The long ligaments contract under the action of surface tension, thus leading to increase in droplet size over that predicted by Rayleigh and Weber. Based on $d/D_1=2.4$, $\lambda_{opt} = 9.2D_1$ for this particular case, which is approximately 2 times the optimum wavelength value calculated by using Weber's theory.

4. The droplet size distribution is bi-modal; the number ratio of large ($d>D/2$) to small ($d<D/2$) droplets is equal to 3 and is independent of the Reynolds number.

The Near Field of a Co-Axial Airblast Atomizer

It has been shown that the co-axial atomizer spray can be characterized by three subregions. A spray breakup region is present and extends approximately to three air nozzle diameters ($3D_a$). In this region, the droplets in the central portion of the spray are subjected to secondary breakup due to high local relative velocities. The droplets around the edges have a diameter which is characteristic of the initial breakup diameter of the jet. The second sub-region, $3 < x/D_a < 8$, is a transition region to the fully developed spray, where the droplet velocity profiles develop from saddle shaped velocity profiles into those approximating Gaussian error curves. Finally there is an almost fully developed region, $x/D_a > 8$, where there are relatively small changes in flow patterns. In the fully developed region, the droplet velocity profiles are governed by the air jet velocity profiles and assume a Gaussian form. There are significant differences between particle and gas flow velocities. The rapid deceleration of the flow beyond $x/D_a = 4$ can only be followed by small particles, generally less than 15 µm. Droplets larger than 15 µm in diameter continue to accelerate over much longer downstream distances. Thus, when modeling this type of process, the larger droplets should be analyzed for slip effects separately. This suggests that finite interphase transport rates are very important in this particular spray particularly in the spray development region. In the fully developed region there is also evidence to show that the larger droplets maintain a relatively larger velocity than the smaller ones. The drag coefficients of large droplets as a function of droplet Reynolds number were determined from the size classified velocity data. The computed drag coefficients were then compared to an empirical drag law model for rigid spheres in a uniform gas flow. At an intermediate range of droplet Reynolds number ($50 < Re < 150$), it was found that the empirical drag law model closely approximates the computed drag coefficients. At higher values of the Reynolds number ($Re > 150$) the computed drag coefficient was found to be larger than that of a sphere; the droplets are distorted into oblate shapes resulting in increases in drag coefficient over that predicted by the simple sphere model. It was also found that, at all axial locations, there are significant increases in SMD from the spray axis towards the edges of the spray. The inertia of the larger droplets allows them to penetrate the air stream with little interaction. This results in their redistribution around the spray edges.

The Rheology of Mobile Polymeric Solutions

Non-Newtonian viscosities were measured over five decades of shear rates $\dot{\gamma}$ for 12 solutions of polymeric materials. By using the Brookfield viscometer and the capillary tube viscometers, the shear viscosity was determined as a function of shear rate. Both the upper and lower limiting shear viscosities were determined for all solutions. By using the die-swell technique, the first normal stress difference was determined for all solutions. The contraction flow technique was also used for the determination of the extensional viscosity. The Non-Newtonian liquids selected for the experiment were aqueous solutions of Xanthan Gum and Polyacrilamide E10 polymers. Tests were performed on 0.05, 0.10, 0.15, 0.20, 0.30% concentrations by mass for the Xanthan Gum polymer, and 0.0125, 0.025, 0.05, 0.1, 0.15, 0.30, and 0.50% concentrations by mass for the Polyacrilamide E10. The following conclusions follow directly from the rheological measurements.

1. The single most important difference between the Xanthan gum solutions and the Polyacrilamide E10 solutions is the much higher levels of normal stresses developed in the E10 solutions when compared to the Xanthan gum solutions. Despite the fact that all polymeric solutions exhibit a more conventional shear dependent viscosity (i.e., shear thinning), die-swell measurements indicate that Polyacrilamide solutions develop large normal stresses at high shear rates. The die-swell that has been observed for the Polyacrilamide solutions in the capillary tube experiments suggests that the extensional viscosity levels for the E10 solutions are large and that the extensional viscosity is probably the most significant rheological mechanism that inhibits breakup.

2. The contraction flow technique, although successful in measuring the extensional viscosity levels of semi-dilute polymeric solutions was incapable of yielding satisfactory results for the more dilute solutions. This was true for Polyacrilamide concentrations

below 0.15% and all Xanthan gum concentrations. The success of the extensional viscosity measurements for the semi-dilute solutions (0.3% and 0.5% solutions) is weakened since at these high concentrations the liquid did not atomize. Thus the contraction flow technique is of little value for the rheological control of extensional viscosity particularly when applied to atomization.

3. The Trouton ratio, which is the ratio of the extensional viscosity to the shear viscosity, can reach 10^3 times the shear viscosity in the limit of the highest shear rates considered in these experiments. It is therefore of importance to consider the extensional viscosity levels of non-Newtonian liquids when describing breakup behavior of these liquids. Unfortunately, the contraction flow technique was shown to be inadequate for the rheological control of the extensional behavior of dilute polymeric materials. The success of extensional viscosity measurements for semi-dilute solutions is eclipsed by their unusual capability to resist breakup. It was not possible to assess the atomization quality of the more concentrated solutions.

5. For flows of viscoelastic materials through contractions, sufficient chamber length needs to be provided to allow for vortex enhancement. Vortex enhancement occurs in order to reduce the energy losses in the entry corner. When the vortex length is equal to the chamber length, no additional enhancement is possible and the flow is destabilized. This results in a dramatic increase of the entry pressure drop in the contraction flow chamber. The increase in entry pressure after flow destabilization corroborates the contraction flow analysis basic approach of minimizing the energy consumption in the entry corner. It can be concluded that vortex enhancement occurs in order to reduce the viscous dissipation in the entry corner. When vortex enhancement is arrested by the upper wall of the chamber, the ultimate result is always destabilization of the flow and relatively large increases in the entry pressure result.

Airblast Atomization of Non-Newtonian Liquids

Airblast atomization of viscous non-Newtonian liquids is carried out using the Co-Axial twin-fluid atomizer. As the atomizing air interacts with the liquid jet downstream from the nozzle exit, waves form on the surface of the liquid jet. As a result, the liquid jet sheds ligaments which rapidly collapse into droplets. The atomized drop sizes can be described in terms of three dimensionless groups, namely (M_l/M_a), Weber (We) and Ohnesorge (Z) numbers in simple forms whose exponents and coefficients are determined by least squares fit to the experimental data using non-linear curve fitting. The following conclusions follow from the study of airblast atomization of non-Newtonian liquids:

1. The effects of solution rheology on the atomization are first examined in order to determine which viscosity should be used in the Ohnesorge number. For shear thinning viscoinelastic materials the power-dependency (X_Z) of the SMD on the Ohnesorge number was shown to be a function of the shear rate in the injection tube. The power-dependency X_Z of the Sauter mean diameter on viscosity, in the limit of infinite shear rates, is not constant and is a function of the shear rate. At the low end of shear rates ($8V/D < 3600\ s^{-1}$), the exponent X_Z decreases with shear rate. Beyond $8V/D = 3600\ s^{-1}$, X_Z remains sensibly constant. The variations of X_Z with respect to the shear rate is relatively simple to explain in terms of the apparent shear viscosity of the fluid. At the low end of shear rates, the liquid inside the injection tube is sheared to a consistency which is intermediate between η_o and η_∞. The use of η_∞ to correlate the SMD data is not appropriate. At shear rates above $3600\ S^{-1}$, the liquid inside the atomizer is sheared to a consistency η_∞ for all concentrations and the use of η_∞ to correlate the SMD data is the most appropriate choice. The average value of X_Z at shear rates greater than $3600\ s^{-1}$ is $X_{Z,av} = 0.417$, is not far removed from the previous results with Newtonian liquids. Thus, the use of η_∞ as the viscosity value to correlate the SMD seems to be the most appropriate choice particularly at high liquid flow rates.

2. The accuracy of the wave mechanism-based models in predicting droplets sizes after breakup of viscous non-Newtonian liquids using an airblast atomizer has also been demonstrated. The exponents of the power dependencies of the wave-mechanism based simple models are comparable to their counterpart reported in the literature for airblast atomization of Newtonian liquids with viscosities up to 10 P.

3. The power-dependency of $(1+M_l/M_a)$ in the SMD equation is unity.

4. The average value of the Weber number-dependency X_W is $X_{W,av} = 0.503$.

5. The atomized drop sizes can be described in terms of three dimensionless groups, namely (M_l/M_a), Weber (We) and Ohnesorge (Z) numbers in simple forms whose exponents and coefficients are determined by least squares fits to the experimental data using non-linear curve fitting. When the aerodynamic pressure force predominates, waves propagate as acceleration waves which are governed by $(Z/We)^{2/3}$. In contrast, when the surface tension predominates, waves propagate as capillary waves which are governed by (Z^2/We). Therefore, both We and Z, with exponents of the Z number equal to or twice

that of the We-dependency, were included in the modeling of drop sizes for airblast atomization.

Five different models were used for the non-linear curve fitting procedure. The coefficients of correlation were found to be in the range 0.933 to 0.972. The best correlations were found for the equations involving the exponent of the Z-dependency equal to the exponent of the We-dependency. This verifies the basic hypothesis that at the conditions of this study the waves propagate as acceleration waves. It should be stressed that in the computation of the Z-number, the viscosity in the limit of infinite shear rates (η_∞) was used.

6. Viscoelastic liquids are much more difficult to atomize than viscoinelastic liquids. Viscoinelastic liquids showed breakup patterns similar to that of water sprays. Viscoelastic materials showed remarkably different breakup patterns. The ligaments were seen to undergo a very large stretching motion before they breakup, resulting in long threads of liquid attached to droplets. The normal stresses developed in viscoelastic materials are much higher than their associated shear stresses. Consequently, the development of the large normal stresses appears to be the most important rheological mechanism that inhibits breakup. The ability of viscoelastic materials to resist breakup in these contexts is caused by the molecular orientation that arises when the ligaments are extended. This extension leads to large increases of the extensional viscosity compared to that of the pure solvent. As the liquid between drops contracts to form a neck, the extension rate increases. If the extensional viscosity increases as the rate of extension increases, the neck will be strengthened, inhibiting breakup.