

A Study of Gelled Propellant Simulants Using Impinging Jet Injectors

J. A. Mallory^{*}, P. E. Sojka

Department of Mechanical Engineering, Purdue University, USA

jamallor@purdue.edu and sojka@purdue.edu

Abstract

The effect of liquid rheology on the flowfield resulting from non-Newtonian impinging jets was investigated experimentally and analytically. Prior to jet impingement the rheological properties of Kappa carrageenan, Agar, and several CMC water-based mixtures were obtained using a rotational rheometer. All liquids exhibited pseudoplastic behavior. Experimental impinging jet data were acquired using a unique facility. Sheet instability wavelengths, sheet breakup lengths, ligament diameters, and drop diameters were measured from high-speed video images and compared to predictions from a linear stability theory, which accounted for the Bird-Carreau pseudoplastic rheology, and to semi-empirical theories of sheet breakup length taken from the literature. Analytical results showed an improvement over previous linear stability theories in that they no longer consistently over-predict measurements.

Introduction

Gelled propellants are liquid fuels or oxidizers whose rheological properties have been altered by adding gelling agents, enhancing both their safety and performance when used in propulsion systems. This makes them attractive. These advantages stem from the non-Newtonian (shear thinning and yield stress) behavior that must be overcome when a gelled propellant flows [1].

A disadvantage of gelled propellants is their increased effective viscosity at shear rates typical of injection systems. This retards spray formation. Impinging jet atomization is typically used to surmount this obstacle. For this reason, gels for rocket propulsion systems should show shear-thinning behavior (viscosity decreases with increasing shear rate).

Most previous gelled propellant research characterized rheological properties, identified liquid sheet characteristics and related the two. The stages of atomization and observed spray patterns from a like doublet impinging jet have also been reported for various gels.

Missing from previous studies is an understanding of the flow physics underlying non-Newtonian impinging jet atomization, including, but not limited to: identifying mechanisms that transform non-Newtonian impinging jets into a sheet with waves on its surface; explaining how those waves influence sheet fragmentation and subsequent formation of ligaments; and how those ligaments break up to form drops (primary atomization). Also missing is an analytical model that accurately describes the behavior of jet impingement and primary atomization for a gelled propellant simulant.

The work presented here focuses on remedying these inadequacies by using a combination of experimental measurements and analytical predictions. This combination is unique in that it is the first to use experiments and modeling to sequentially link non-Newtonian flow physics in the sheet.

In the experimental portion of this work, sheet instability wavelengths, sheet breakup lengths, ligament diameters, and drop sizes for water-based simulants were measured from high-speed video images and compared to predictions from a newly developed linear stability theory, which accounts for the pseudoplastic rheology of the gelled propellant simulants, and to semi-empirical theories of sheet breakup length taken from the literature. The stability theory was based on the works of Dombrowski and Johns (1963) and Chojnacki (1997), but was modified to account for non-Newtonian fluid behavior using the Bird-Carreau rheological model.

Water-Based Gel Propellant Simulants

Previous results have shown that a critical factor influencing gel rheological behavior (and its atomization) is how the gelling agent interacts physically with the solvent at the molecular level. Cellulose gelling agents, for example hydroxypropylcellulose (HPC), form bonds with water creating an entangled structure, thereby inhibiting atomization. In contrast, a gelling agent like Agar absorbs the water and forms a network around it rather than bonding to it, resulting in better atomization (smaller mean drop sizes).

The shear-thinning, inelastic, solid-like gel propellant simulants used in this study were 1 wt.-% Kappa carrageenan and 1 wt.-% Agar. Due to the solid-like nature of the gel propellant simulants, accurate surface ten-

* Corresponding author: jamallor@purdue.edu

sion measurements are difficult to obtain. Therefore, several shear-thinning, inelastic, liquid-like carboxymethylcellulose (CMC) solutions were used to validate the analytical model: 0.5 wt.-% CMC-7HF, 1.4 wt.-% CMC-7MF, 0.8 wt.-% CMC-7MF, and 0.06 wt.-% CMC-7MF 75 wt.-% glycerin.

Bulk rheological properties were determined through the use of rotational and capillary rheometers. Two approaches were used to experimentally measure the surface tension of the solid-like gel propellant simulants. The first approach measured contact angles and used Young's equation and the second was based on surfactant theory [2]. All liquids exhibited pseudoplastic rheological behavior.

Experimental Apparatus

The like doublet impinging jet geometry was adopted for this study. Tests were performed using the experimental facility shown in Figure 1, which allowed the flow to be examined under a variety of conditions. The system is comprised of two positive displacement pistons driven by high pressure air, having an operating range from 0 to 6.9 MPa (0 to 1000 psi). The modular design allows easy variation of impingement angle (via rotational stages), injector length-to-diameter ratio (by substituting tip elements), impingement jet length-to-diameter ratio (by using translation stages), and jet velocity profile (by varying upstream boundary conditions). Another unique aspect is run times of up to eight minutes, depending on flow rate. Data are acquired in the form of high speed (up to 10000 fps) images (600x800 pixel resolution).

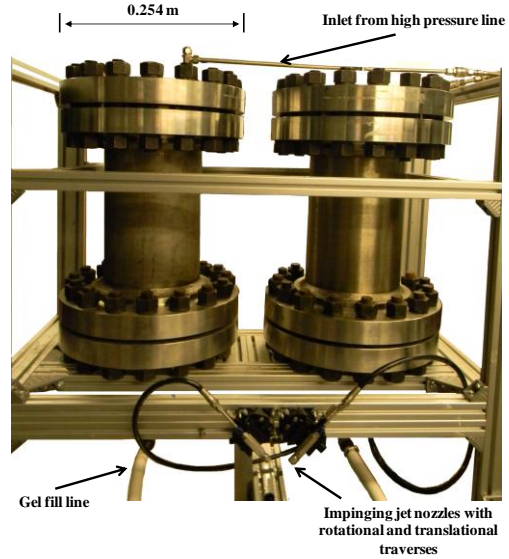


Figure 1: Experimental apparatus

Linear Stability Analysis

No analytical model exists that accurately describes the behavior of jet impingement and primary atomization for a pseudoplastic non-Newtonian liquid. Various groups have made an attempt to develop an analytical model to predict ligament diameters and drop sizes based on a maximum growth rate for Newtonian liquids. Chojnacki [3] is one of the few researchers who have attempted to create an analytical model based on the power-law rheological model due to its simplicity.

Figure 2 is a schematic of the physical system that is modeled. A flat sheet of liquid with thickness h moves with a constant velocity U_s along the x -axis. A superposition of disturbances occurs on both interfaces. The disturbance with the maximum growth rate is assumed to be responsible for the system behavior. Waves of ligaments are then shed from the edge of the liquid sheet at the troughs and crests of the fastest growing waves [7]. The ligaments break apart into drops through a subsequent mechanism.

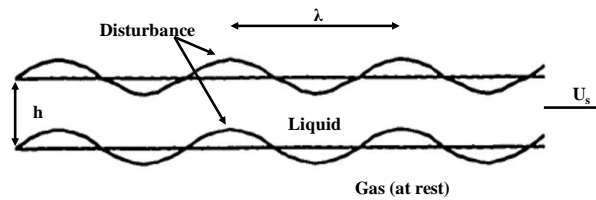


Figure 2: Geometry for linear stability analysis [3]

The analyses of Dombrowski and Johns [6] and Chojnacki [3] were modified to account for non-Newtonian fluid behavior. The Bird-Carreau rheological model was assumed to describe the relationship between shear stress and shear rate.

$$\tau_w = \left(\left[1 + (j\lambda)^2 \right]^{-1/2} (\eta_0 - \eta_\infty) + \eta_\infty \right) \cdot \dot{\gamma} \quad (1)$$

Equation (2) is derived by using Dombrowski and Johns analysis, combined with Equation (1) to account for the viscous forces acting on the non-Newtonian liquid sheet.

$$[2k_{ND}s] - \left[(2k_{ND}^2) \left(\frac{1}{We_L} \right) \right] - [\beta_{ND}^2] - \left[\left(\left[1 + \beta_{ND}^4 \lambda_{ND}^2 \right]^{n-3/2} (\beta_{ND}^5 k_{ND}^2 \lambda_{ND}^2) (n-1) \left(\frac{1}{Re_0} - \frac{1}{Re_\infty} \right) \right) + \left(\left[1 + \beta_{ND}^4 \lambda_{ND}^2 \right]^{n-1/2} (\beta_{ND} k_{ND}^2) \left(\frac{1}{Re_0} - \frac{1}{Re_\infty} \right) \right) + (\beta_{ND} k_{ND}^2) \left(\frac{1}{Re_\infty} \right) \right] = 0 \quad (2)$$

The non-dimensional parameters are

$$k_{ND} = kh \quad s = \frac{\rho_G}{\rho_L} \quad We_L = \frac{\rho_L U_s^2 h}{\sigma} \quad \beta_{ND} = \beta \frac{h}{U_s} \quad \lambda_{ND} = \lambda \frac{U_s}{h} \quad Re_0 = \frac{\rho_L U_s h}{\mu_0} \quad Re_\infty = \frac{\rho_L U_s h}{\mu_\infty}$$

and ρ_G is the atmospheric air density, ρ_L the liquid (gel) density, k the wave number, h the sheet thickness, β the growth rate factor, U_s the sheet velocity, σ is the surface tension, c is a time constant in the Bird-Carreau rheological model, μ_0 is the zero-shear rate viscosity, and μ_∞ is the infinite-shear rate viscosity. Parameters with a subscript 'ND' are non-dimensional.

Results and Discussion

The linear stability analysis previously described was applied to predicting the maximum instability wavelength, sheet breakup length, and drop diameter from 0.5 wt.-% CMC-7HF, 1.4 wt.-% CMC-7MF, 0.8 wt.-% CMC-7MF, 0.06 wt.-% CMC-7MF 75 wt.-% glycerin, 1 wt.-% Kappa carrageenan, and 1 wt.-% Agar impinging jet sprays. A comparison between theory and experiments for each formulation is provided. Measurements were taken on the centerline, where the thickest part of the sheet is expected.

Equation (2) is solved for the maximum growth rate factor and corresponding wave number at discrete radial locations for a spectrum of wave numbers using a MATLAB code. Since all of the tested solutions exhibited similar results, only one is presented here.

Figure 3 shows the solution to Equation (2) at five radial locations for the case of 0.06 wt.-% CMC-7MF 75 wt.-% glycerin at a 0.686 mm orifice diameter, an impingement angle of 100 degrees, an internal length-to-diameter ratio (L/d) of 20, a pre-impingement length-to-diameter ratio (x/d) of 60, and a generalized Reynolds number of $8.2E+5$. Note the peak non-dimensional growth rate factor, β_{ND} , becomes sharper near the edge of the sheet.

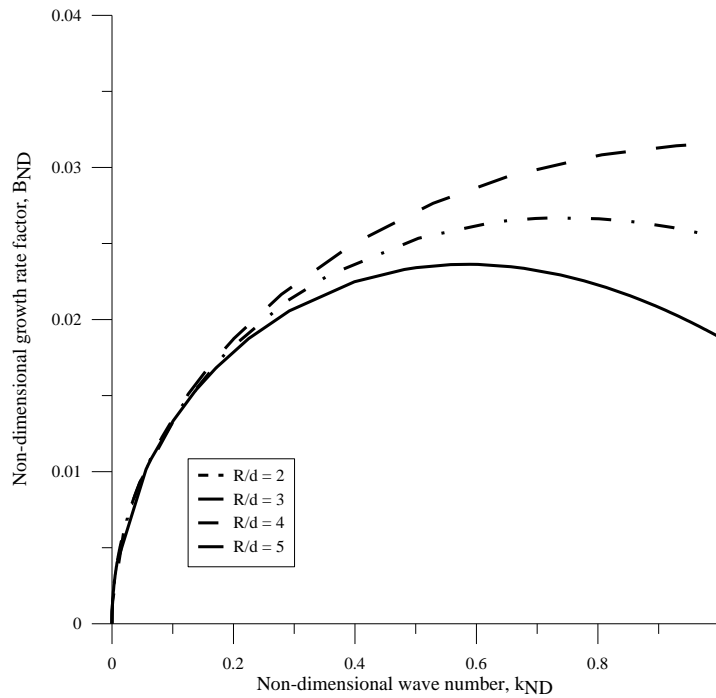


Figure 3: Solution of Equation (2) for non-dimensional growth rate factor as a function of non-dimensional wave number for 0.06 wt.-% CMC-7MF 75 wt.-% glycerin

Maximum Instability Wavelength

Experimental maximum instability wavelengths, λ_{\max} , were compared to predicted values using the developed viscous linear stability theory, Equation (2), to solve for the wave number, k_{\max} , corresponding to the maximum growth rate. The maximum instability wavelength is calculated from Equation (3).

$$\lambda_{\max} = \frac{2\pi}{k_{\max}} \quad (3)$$

Experimental data were also compared with predictions from a maximum instability wavelength expression based on inviscid linear stability theory developed by Squire [4]. Although this expression lacks a viscous term, Ryan *et al.* [5] concluded inviscid and viscous liquids up to a certain limit will exhibit the same behavior.

Comparing the predicted viscous λ_{\max} and experiment λ_{\max} shows better agreement for all solutions than the predicted inviscid λ_{\max} . An example of typical observed behavior for all solutions is shown in Figure 4 for 1 wt.-% Agar.

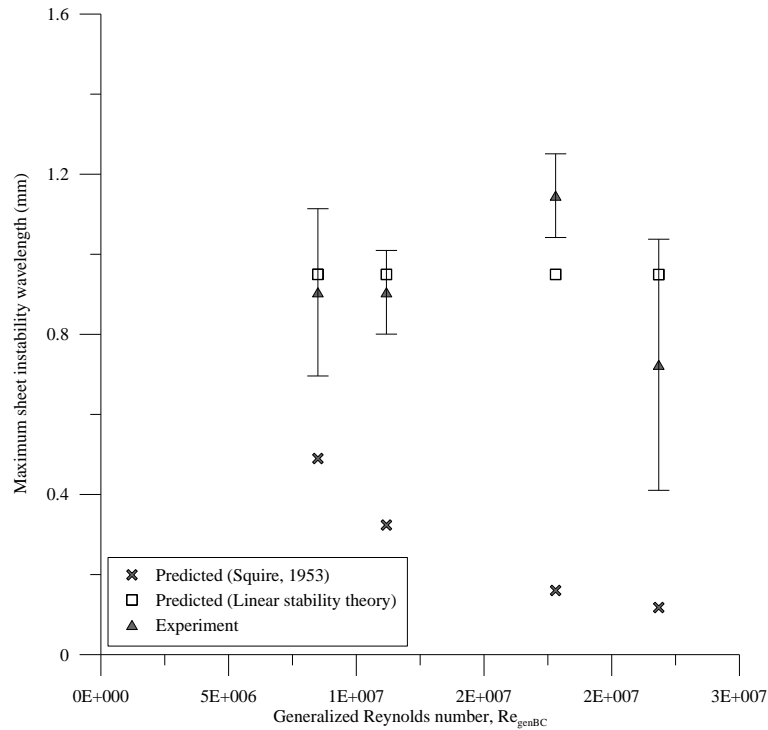


Figure 4: Comparison of predicted maximum instability wavelengths and experiments for 1 wt.-% Agar

Sheet breakup length

Experimental sheet breakup length, x_b , data were compared to predicted results by combining results from Equation (2) with two equations, one from Dombrowski and Johns [6] and one from Huang [7]. Linear stability theory cannot be directly used to predict the breakup of liquid sheets. However, the empirical relation based on maximum growth rate factor of Dombrowski and Johns [6] in conjunction with linear stability theory can be used to predict when breakup occurs.

The expression given by Huang [7] is used for high Weber number flows ($We > 2000$) and is based on sheet shape and fluid properties. In general, the predicted and experiment data exhibited an expected relationship between sheet breakup length, x_b , and generalized Reynolds number, Re_{genBC} . As Re_{genBC} increases, the sheet breakup length decreases. With the exception of 1 wt.-% Agar, the linear stability theory developed here is more accurate than previous theories [3], which consistently over-predicted experiment data.

Figures 5 and 6 compare predictions to experiment data for 1 wt.-% Kappa carrageenan and 1 wt.-% Agar, respectively. Figure 5 shows the developed linear stability theory accurately predicted 1 wt.-% Kappa carrageenan experiment data. Unlike the other investigated solutions, Figure 6 shows the developed linear stability theory did not accurately predicted 1 wt.-% Agar experiment data.

Given both gelling agents are similar in rheological nature, i.e. polysaccharides extracted from red seaweed, hydrocolloids, inelastic, weak, and form a double helical structure when gelled; their dissimilar intermolecular chemical structure was enough to cause a different atomization behavior.

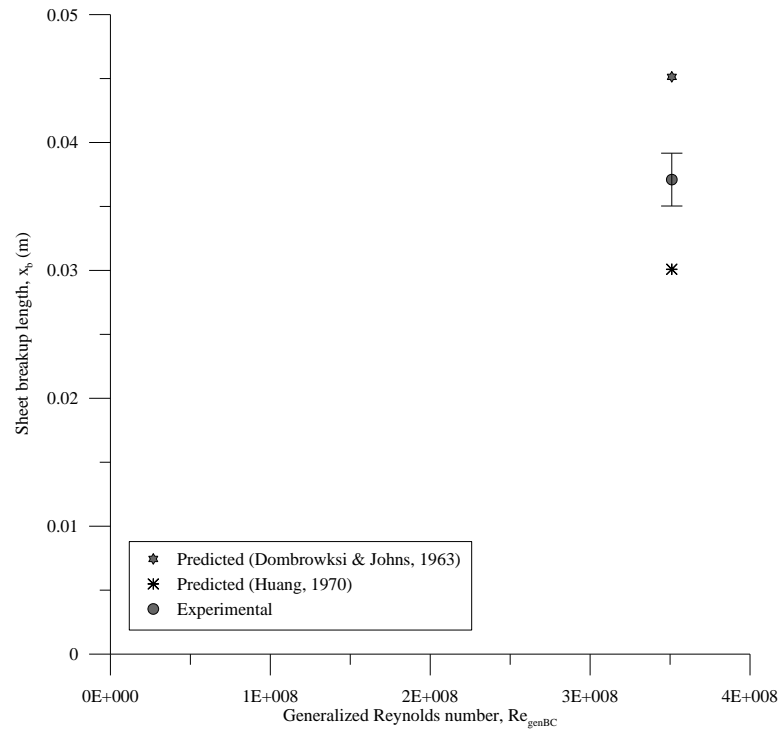


Figure 5: Comparison of predicted sheet breakup lengths and experiments for 1 wt.-% Kappa carrageenan

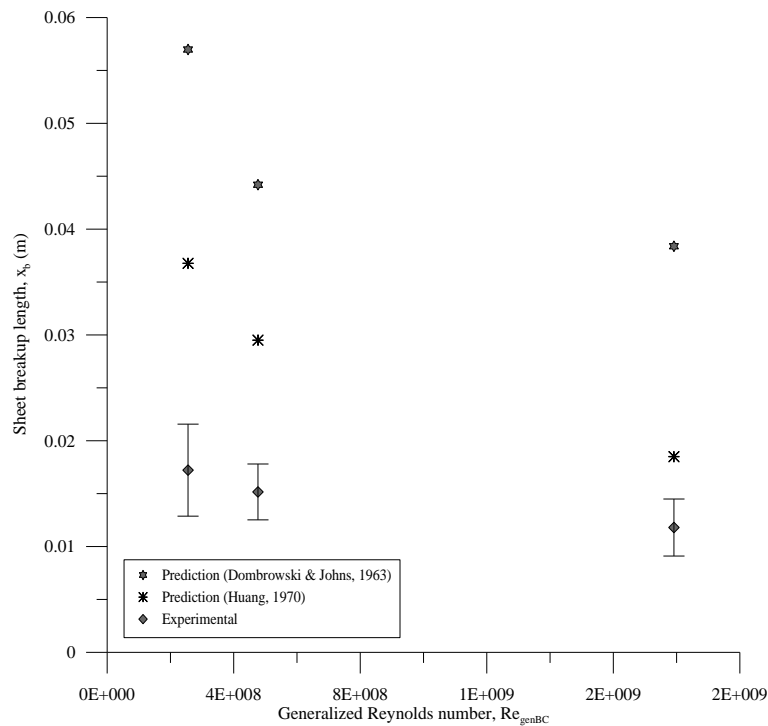


Figure 6: Comparison of predicted sheet breakup lengths and experiments for 1 wt.-% Agar

Ligament diameters

Dombrowski [6] concluded the drop size for water in air is equivalent to 1.89 times the ligament diameter, Equation (2.19). The ligament diameters of 0.5 wt.-% CMC-7HF, 1.4 wt.-% CMC-7MF, 0.8 wt.-% CMC-7MF, 0.06 wt.-% CMC-7MF 75 wt.-% glycerin, 1 wt.-% Kappa carrageenan, and 1 wt.-% Agar were experimentally measured and compared to experimental drop size measurements.

Comparing the measured drop to ligament diameters, all of the investigated solutions had a drop to ligament diameter ratio below the observed Newtonian value ($d_D/d_L = 1.89$).

The drop to ligament diameter ratio of the CMC-water solutions (0.5 wt.-% CMC-7HF, 1.4 wt.-% CMC-7MF, and 0.8 wt.-% CMC-7MF) was nearly one, Table 1, indicating ligaments breaking directly up into drops. However, the drop to ligament diameter ratio of the 0.06 wt.-% CMC-7MF 75 wt.-% glycerin, 1 wt.-% Kappa carrageenan, and 1 wt.-% Agar, Table 2, was between the value measured for CMC-water solutions and the value of water drops in the literature.

Table 1: Comparison of ligament and drop diameters for 0.5 wt.-% CMC-7HF

Re_{genBC}	Drop diameter d_D (mm)	d_D STD (mm)	Ligament diameter d_L (mm)	d_L STD (mm)	d_D/d_L
8.50E+06	0.24	0.02	0.21	0.03	1.14
1.12E+07	0.24	0.03	0.19	0.02	1.21
1.78E+07	0.23	0.03	0.21	0.04	1.14
2.18E+07	0.18	0.03	0.20	0.03	0.91

Table 2: Comparison of ligament and drop diameters for 1 wt.-% Agar

Re_{genBC}	Drop diameter d_D (mm)	d_D STD (mm)	Ligament diameter d_L (mm)	d_L STD (mm)	d_D/d_L
8.70E+05	0.41	0.06	0.34	0.06	1.20
1.21E+06	0.35	0.11	0.26	0.08	1.38
2.44E+06	0.32	0.08	0.25	0.04	1.29

Drop diameters

Drop diameter experimental results were compared to predicted results utilizing three expressions, one from Dombrowski and Johns [6], one from Ibrahim and Przekwas [8], and one from Ryan *et al.* [5]. Dombrowski and Johns' expression is based on the assumption that the wave grows until the disturbance amplitude is equal to the ligament radius, thus resulting in one drop per wavelength. They related ligament diameter to sheet thickness, and maximum wave number k_{max} , so in turn drop diameter becomes a function of these parameters [6].

The expression from Ibrahim and Przekwas [8] is based on a Kelvin-Helmholtz type of instability leading to sheet destruction. They argued if sheet breakup is assumed to be due to the growth of the waves of maximum disturbance, then resulting drop sizes are half the wavelength of the fastest growing waves with wave number.

Lastly, Ryan *et al.* [5] based their expression on the work of Dombrowski and Johns [6], but incorporated influence of fluid properties.

For all tested solutions, comparing the difference between predicted and experimental results lead to the same observed trend. The linear stability theory developed here accurately predicts experimental data when comparing it to the expression of Ryan *et al.* (less than 1% difference) for all solutions with the exception of 1 wt.-% Agar. An example of this behavior is shown in Figure 7 for 0.06 wt.-% CMC-7MF 75 wt.-% glycerin and Figure 8 for 1 wt.-% Agar. Although the expression of Ryan *et al.* is not as accurate for 1 wt.-% Agar, the experimental results are still bracketed by this prediction. This decrease in accuracy is again attributed to the slight difference in chemical molecular nature of Agar.

This leads to the conclusion that utilizing an expression that considers both geometric and fluid parameters will improve accuracy of predictions. Additionally, considering both the physical and chemical molecular structure of a gelling agent would increase accuracy.

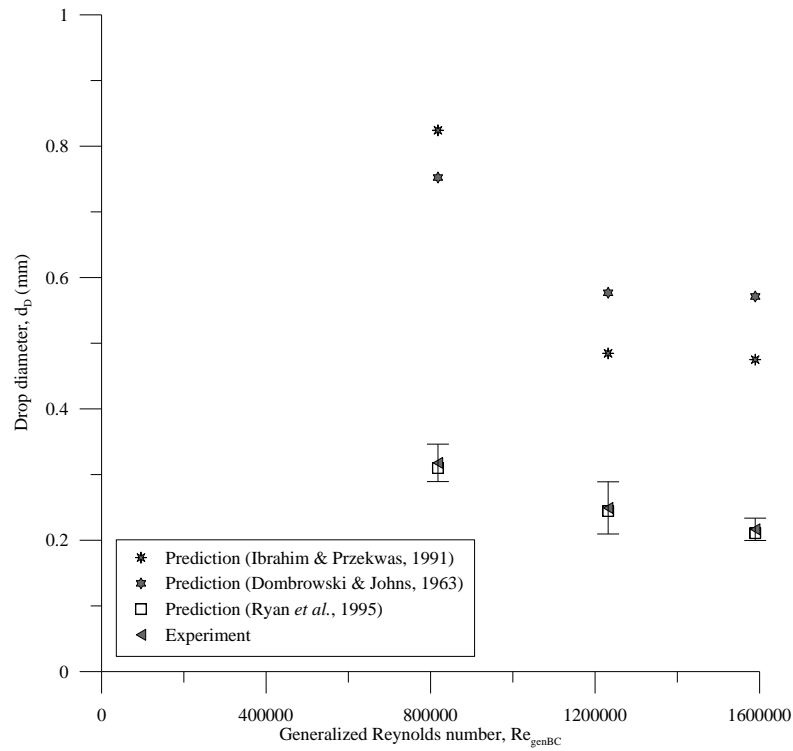


Figure 7: Comparison of predicted drop diameters and experiments for 0.06 wt.-% CMC-7MF 75 wt.-% glycerin

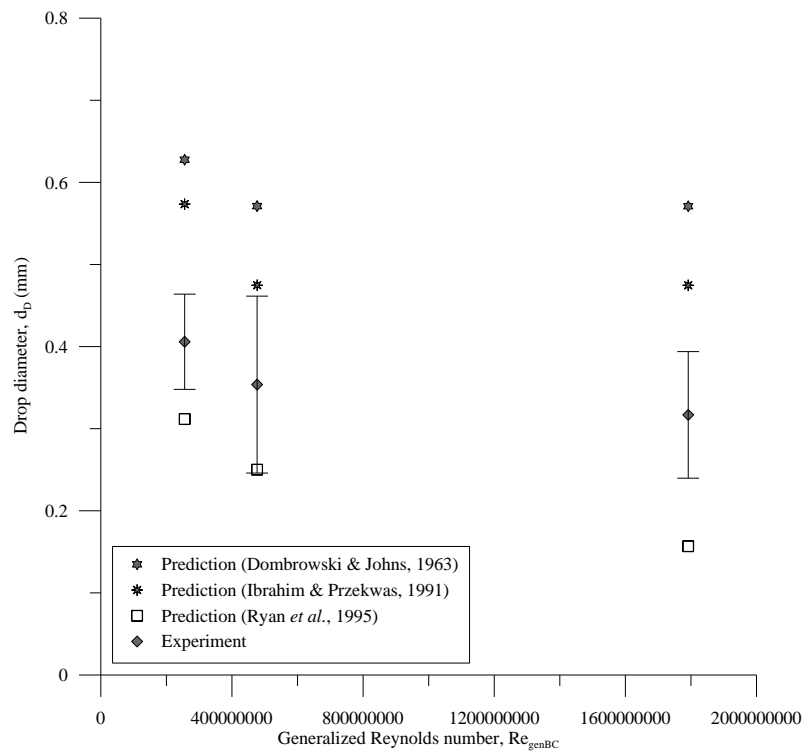


Figure 8: Comparison of predicted drop diameters and experiments for 1 wt.-% Agar

Summary and Conclusions

A novel experimental apparatus that allows variation of numerous spray parameters was used to perform measurements of sheet evolution using a high-speed camera system. Gelled propellant rheology was characterized for water-based simulants using Kappa carrageenan, Agar, and CMC.

The first linear stability analysis using a nonlinear rheological model for non-Newtonian liquids was developed to predict the maximum instability wavelengths, sheet breakup lengths, ligament diameters, and drop diameters. The developed theory either accurately predicted or bracketed experimental results, with the exception of 1 wt.-% Agar. As a result, it is more precise than previous theories [3], which consistently over-predicted experiment data.

An investigation was also conducted comparing measured ligament and drop diameter ratios. It was found non-Newtonian liquids have a ligament to drop diameter ratio of roughly one. As viscosity is increased, this ratio becomes larger. However, the ligament to drop diameter ratio is consistently lower than the Newtonian value of 1.89 regardless of what non-Newtonian liquid was tested.

Comparison studies between Kappa carrageenan and Agar gelling agents lead the conclusion that molecular structure may have a greater affect on atomization behavior than investigated spray parameters and needs to be considered in predictive models for improved accuracy. A preliminary demonstration of this concept is the drop diameter equation of Ryan *et al.* [5], which incorporates both sheet and fluid property characteristics. Comparing the three investigated drop diameter expressions, the one of Ryan *et al.* consistently accurately predicted drop diameter more than the others. This shows the importance of incorporating both fluid and sheet characteristics into a predictive analytical model.

Future work should focus on introducing chemical parameters, in addition to, current rheological and atomizer geometric parameters used in predictive models.

Acknowledgements

The research presented in this paper was made possible with the financial support of the U.S. Army Research Office under the Multi-University Research Initiative (MURI) grant number W911NF-08-1-0171. JAM also thanks the National Science Foundation for a Graduate Research Fellowship.

References

- [1] Pein, R., 2005. "Gel Propellants and Propulsion," 5th *International High Energy Materials Conference and Exhibit DRDL*, Hyderabad, India.
- [2] Mallory, J. A. *Jet Impingement and Primary Atomization of Non-Newtonian Liquids*. Ph.D. Thesis, Purdue University, West Lafayette, Indiana.
- [3] Chojnacki, K., 1997. *Atomization and Mixing of Impinging Non-Newtonian Jets*, Ph.D. Dissertation, The University of Alabama, Huntsville.
- [4] Squire, H. B. (1953). Investigation of the Instability of a Moving Liquid Film. *British Journal of Applied Physics*, 4(June), 167-169.
- [5] Ryan, H., Anderson, W., Pal, S., and Santoro, R. (1995). Atomization Characteristics of Impinging Liquid Jets. *Journal of Propulsion and Power*, 11(1), 135-145.
- [6] Dombrowski, N. and Johns, W.R., 1963. "The Aerodynamic Instability and Disintegration of Viscous Liquid Sheets." *Chemical Engineering Science*, 18, pp. 203-218.
- [7] Huang, J. C. P. (1970). The Break-Up of Axisymmetric Liquid Sheets. *Journal of Fluid Mechanics*, 3(2), 305-319.
- [8] Ibrahim, E. A., and Przekwas, A. J. (1991). Impinging Jets Atomization. *Physics of Fluids*, A(3), 2981-2988.