Effect of Viscoelastic Properties in Impinging Jet Sprays

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Abstract

Propellant gels are used in some rocket engines to increase safety and increase system insensitivity to external threats. The viscoelastic properties of these gels allow the propellants to be stored in tanks as if they were solids and yet to flow like liquids under pressure into the engine. However, these viscoelastic properties can also affect their atomization and consequent hypergolic ignition and combustion. Gelled propellants sometimes exhibit longer ignition delays that can lead to hard starts and catastrophic engine damage. For gelled propellants to be viable in modern engine systems, the effect of the gel phase on the ignition must be understood. This work focused on the effect of the gel phase on fuel atomization. Spray experiments and detailed rheology measurements investigated the effect of the viscoelastic properties on the formation of impinging jet sprays. A series of sprays were imaged to compare among sprays of Newtonian oil and oil gels. The injector was an impinging type typical of those in rocket engines. Varying stream velocity and gel strength enabled comparison over ranges of momentum and viscoelastic properties. The spray images show marked differences in sheet formation, rim behavior, instability propagation, and drop formation. These differences can be attributed primarily to the increased elasticity of the gels. The elastic gels require substantially more momentum to form sprays. This spray formation behavior can be classified into regimes defined by ranges of elasticity number (El) and velocity.

Introduction

In some tactical rocket engine systems, two liquid hypergolic propellants are reacted to provide propulsion for the system. In typical configurations, a stream of oxidizer and a stream of fuel impinge, form a spray, and spontaneously ignite. The hot combustion gases exhaust through the nozzle at supersonic speeds, providing thrust. While efficient, these engines pose a number of safety hazards. The fuels are generally hydrazine-based, such as monomethylhydrazine (MMH), and are carcinogens. The oxidizers are generally nitric acid-based, such as inhibited red fuming nitric acid (IRFNA), and are corrosive. The Department of Defense (DoD) mandates increasing safety of tactical systems and meeting insensitive munitions (IM) requirements. To satisfy IM, propellant tanks should not leak profusely when damaged, thus endangering personnel and other munitions. As a method to curtail tank leakage, polymers and/or particulates have been added to propellants to create propellant gels. These gels possess unique viscoelastic properties that allow them to be stored in tanks as if they were solids and yet to flow as liquids under pressure in the engine. Unfortunately these viscoelastic properties also can affect the combustion of the propellants; gelled propellants have produced longer ignition delays or “hard starts” that can potentially damage hardware. The work presented in this paper is part of ongoing research on the hypergolic ignition of gelled propellants that targets the effect of the gel phase on physical pre-ignition phenomena: atomization, vaporization, and mixing. Specifically this work aims to correlate viscoelastic properties to the formation of impinging jet sprays.

Flows of viscoelastic fluids are more complex than those of Newtonian fluids because of the development of history-dependent *normal stresses* in the fluids during flow. These normal stresses can dramatically change the character of the flow field, such as in the classic examples of recoil and die swell [1]. In sprays, these normal stresses resist elongation and drop formation and promote stability of thin filaments. The behavior of sprays of viscoelastic fluids depends on the competition among inertial, viscous, interfacial, and *elastic* forces. The interplay of these forces can be described by three independent dimensionless numbers, such as Reynolds number (Re), capillary number (Ca), and Weissenberg number (Wi). The table below defines these numbers in terms of dimensions and properties and lists the forces that they compare [2]. The rocket engine sprays fall into the (relatively) high Re, high El regime. Most current research, however, is for lower El or lower Re cases.

Table 1. Relevant Dimensionless Numbers

Re	Reynolds number	Inertial/viscous forces	$\rho Ud/\eta$
Ca	Capillary number	Viscous/interfacial forces	$\eta U/\sigma$
Wi	Weissenberg number	Elastic/viscous forces	$\lambda U/d$
El	Elasticity number	Elastic/inertial forces	$\eta\lambda/\rho d^2$
We	Weber number=ReCa	Inertial/interfacial forces	$\rho U^2 d/\sigma$

Research in both the propulsion and polymer communities on break-up of viscoelastic fluids provides a starting point for understanding. Propulsion research on breakup of non-Newtonian fluids targets ramjet and rocket applications. Work focuses on quantifying the atomization via typical spray metrics but only lightly treats the rheology [3-7]. The results show that the non-Newtonian sprays contain larger drops but that they follow trends similar to those Newtonian sprays: for example, the sauter mean diameter of the drops decreases with increasing ratio of atomizing gas to liquid [6] or with increased disturbance frequency [7,8]. In most of the propulsion-related work, the changes in atomization of the non-Newtonian fluids are correlated mainly to increases in apparent viscosity of the non-Newtonian liquids [6], even though the viscosities will be reduced to almost Newtonian levels at the high shear rates inside the injector. Mansour [9] shows the importance of extensional viscosity due to the normal stresses involved in elongation and atomization. The propulsion research generally neglects the effects of elasticity or relaxation times in atomization of complex fluids.

Research in the polymer community includes work on capillary-elastic flows, drops in polymer melts, and sprays of micelle solutions. In capillary-elastic flows that occur in applications such as ink jet printing, fertilizer spraying, and roll coating, unforced jets break up via capillary action. The resulting jets take on a form of spherical droplets connected by thin filaments like “beads on a string”. The capillary stresses force the fluid from the connecting ligaments into the droplets, thus thinning the ligaments and enlarging the droplets [10]. Tension along the streamlines allows these thin ligaments to persist. The same sort of streamline tension promotes existence of ligaments and hinders breaking off of droplets in viscoelastic sprays. The polymer melt studies showed that the elastic forces stabilized a submerged drop, thus requiring greater capillary forces for break-up [11-13]. In these citations, the Reynolds numbers were much smaller than one would see during atomization.

More relevant are studies of impinging jet and flat fan sprays of dilute micelle solutions done by Miller and Thompson [14, 15]. These studies used relatively dilute solutions and low flow rates but showed the effect of elasticity on spray formation. In these sprays, the sheets became unstable at increased velocity, and holes formed in the sheets. These holes grew and produced a web-like structure. This work showed that the increased elasticity stabilized the rim of the sheet while destabilizing the interior, leading to the formation of an interconnected web of ligaments. Again the presence of tension in the ligaments promoted the development of stretched structures rather than droplets.

The ORBITEC research presented in this paper studied impinging jet sprays of viscoelastic liquids in a regime, governed by both Re and El, that represents flow of elastic gelled propellants in rocket engines. The objective was to relate the rheology of the fluids to the spray behavior. A series of sprays of Newtonian oils and oil gels were imaged over a range of velocities. Detailed rheological measurements characterized the properties of the gels. These experiments demonstrated the effects of the gel phase on atomization.

Materials and Methods

The spray tests used mineral oil and mineral oil gels as propellant simulants. The objective was to study a range of viscoelastic properties bracketing those seen in current gelled propellants. Using a hydrocarbon solvent such as mineral oil instead of water was very important because of surface tension effects. In impinging jet sprays, the surface tension forces work similarly to the elastic forces in limiting sheet spread but differently than the elastic forces in promoting drop formation. Hence it is important to have the correct level of surface tension to observe the relevant interplay of forces. Figure 1 illustrates the differences in sprays of fluids with different surface tensions. These images show how different the wave disturbances are in water versus mineral oil sprays. The gellant was a SEBS (styrene – ethylene butylene – styrene) triblock polymer that was easily soluble in the mineral oil. The gel was prepared by dissolving the polymer in the mineral oil on a hot plate stirrer. To achieve reliable properties, the cooling and settling time must be closely monitored. Two formulations were used: 1% and 2% polymer. The 2% gel is about the consistency of one that would provide adequate IM properties; the 1% was chosen to produce a higher level of break-up. Measurements on a parallel plate rheometer determined the rheological properties. Figure 2 shows the rheology data. The viscosity curves (left) show that the viscosity increases with polymer concentration and that the gels are shear-thinning. Extrapolating to the shear rates of ~ 10^5 seen in atomization, the magnitudes of the viscosities will approach Newtonian levels. The plots of storage modulus, G’, (right) a measure of elasticity of the gel, show that the 2% gel is much more elastic than the 1% gel. These data also allowed estimation of material relaxation times which are useful in the dimensionless analysis. Table 2 lists some properties of these gels for comparison. Note that the G’ increases proportionally more with gellant content than the viscosity. Surface tension measurements show that the gels have the same surface tension as the mineral oil. Thus any differences among sprays of these fluids will not be caused by surface tension effects.

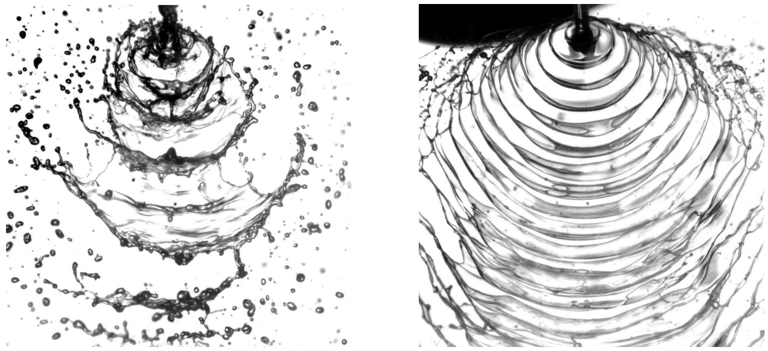

Figure 1. Images of Water (left) and Mineral Oil (right) Sprays: Stream Velocity = 20 m/s

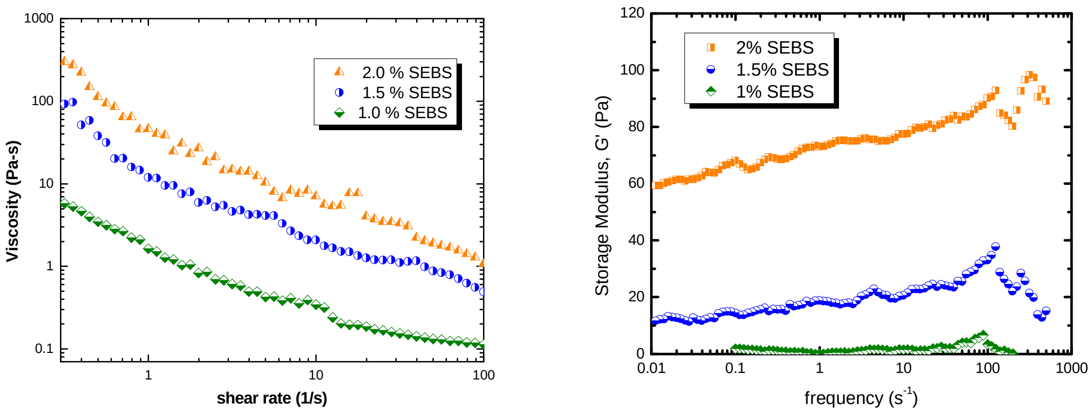

Figure 2. Viscosity Data and Storage Modulus Data for the Polymer Gels

Table 2. Summary of Viscoelastic Properties of the Gels

Symbol	η_1	η_{100}	λ	G'_1
Property	Viscosity @ 1 s^{-1}	Viscosity @ 100 s^{-1}	Relaxation time	Storage Modulus @ 1 Hz
units	Pa-s	Pa-s	s	Pa
1% polymer gel	1.63	0.1	0.5	0.16
2% polymer gel	46.3	1.1	3	73.3

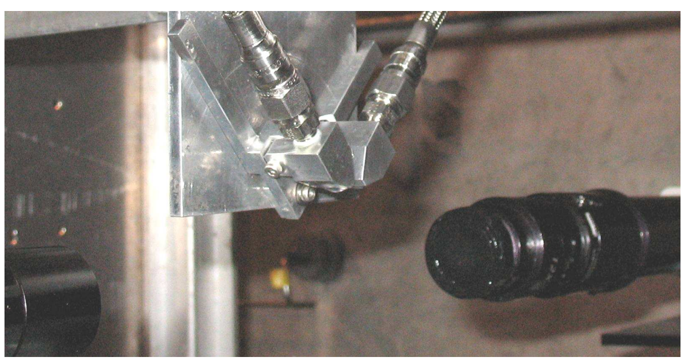

Figure 3. Impinging Injector and Camera Alignment

An impinging injector that is typical of those used in tactical rocket applications produced the sprays (Figure 3). The streams exited orifices of 0.013" (0.33 mm) and impinged at an included angle of 90°. A syringe pump provided a constant flow rate. The maximum velocity (per stream) was 35 m/s. A Nd: YAG laser illuminated the sprays from behind, and a CCD video camera captured images at 30 fps. The camera and laser were oriented to capture the sheet formed perpendicular to the plane of the impinging streams. At each set flow rate, images were acquired after the sprays had come to a quasi-steady state.

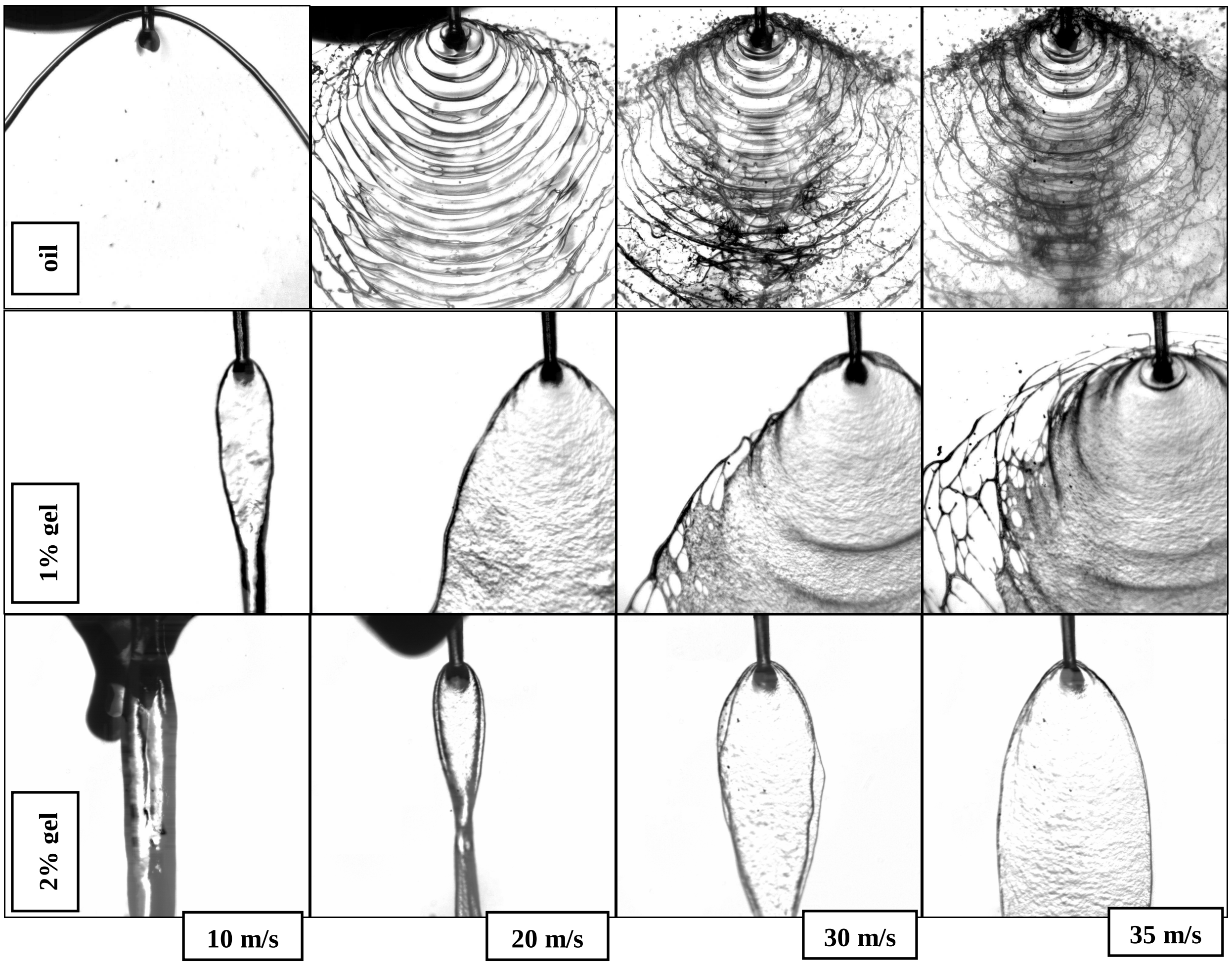

Figure 4. Comparison of Images from Mineral Oil, 1% Gel, and 2% Gel (top to bottom) at Velocities of 10, 20, 30, and 35 m/s (left to right)

Results and Discussion

The imaged obtained from the experiments were quite interesting and allowed some interpretation of the spray formation. The array of images shown in Figure 4 compares the sprays from mineral oil, 1% gel, and 2% gel. The images represent an 8 mm x 8 mm field of view the top of which is just above the intersection point of the two streams. The location allows viewing the early sheet formation behavior. The sprays are compared at fixed velocities of 10, 20, 30, and 35 m/s. Matched velocities rather than Re were chosen because the viscosity and hence the Re vary with the velocity. The viscometry data was taken at fairly low shear rates, and extrapolating the data to the shear rates seen in the injector (~10^5 s^{-1}) would be inaccurate. At the shear rates shown in Figure 2, the viscosity is decreasing in approximately a power-law relation, but at higher shear rates it will asymptote to a fixed value. Among the fluids the sprays show marked differences in spread of the sheet, behavior of the rim, and disturbances within the sheet.

As the two fast-moving streams impinge, their momentum induces formation and spreading of a flat sheet perpendicular to their plane. The surface tension and elasticity forces oppose and limit the spreading of this sheet. Here the surface tensions are uniform, but the elasticity increases with gel strength. The images show decreasing sheet width with increasing gel strength. This trend illustrates the effect of the elastic forces in limiting the momentum-driven spreading of the sheet.

The behavior of the rim surrounding the sheet varies significantly due to the fluid properties. In a high surface tension fluid such as water, distinct droplet shedding occurs along the rim. In the mineral oil, the droplet shedding is less visible. In the gel sprays, the rim forms thin ligaments that extend from the rim. This is an example of the ligament stability seen in viscoelastic fluids. The capillary forces that might pinch off drops cannot overcome the elastic forces, and the ligaments remain stable and stretchy.

The fluid properties affect the type of disturbance seen in the sheets. In the impinging jet sprays, disturbances propagate down the sheet and ultimately lead to it breaking apart. In the mineral oil sprays, the sheet is initially very smooth and then shows a set of smooth, even, organized waves. In the gel sprays, a few different kinds of disturbances occur. The interiors of initial sheets are not smooth but instead show small-scale, disorganized disturbances. As the velocity rises, waves start propagating down the sheets. In the gel sprays, the wave trains are generally unsteady in time. The high viscosity likely damps the propagation of the waves; the elasticity may hinder or even distort the propagation. Two types of unique disturbances occur near the periphery. As stated earlier, ligaments form due to instabilities in the rim. Also, as noted in [12], holes form in the sheet and stretch in size. These instabilities lead to the eventual breaking of the sheet into webbed structures unique to elastic sprays.

In these sprays, the dominant forces are the elastic forces and the inertial forces, both within the jet and between the jet and the surrounding air. Levels of elasticity number, El, and velocity can be used to define some regimes for spray behavior. Figure 5 shows a plot of El vs. velocity with data points for each of the images shown. Annotated on each data point is the Re. The viscosity measured at 100 s^{-1} shear rate estimates the viscosity level for the gels; the actual viscosity is somewhat smaller. Lines drawn on the chart divide it into regimes. In the first region, there is insufficient momentum for a sheet to be formed, and the spray is merely a stream. In the second region a sheet forms and spreads due to increased momentum. In the mineral oil case, the sheet is almost instantly wide and smooth; in the 2% gel case the sheet spreads slowly with increased velocity. In the third region, disturbances appear in the sheet. The type of the disturbance varies quite a bit among the fluids. In the mineral oil, the disturbances lead quickly to breakup into drops. In contrast, the 1% gel sheet shows waves, holes, and ligaments. At the velocity levels in these experiments, the 2% gel does not begin to show disturbances. Note that the sheet formation actually starts at lower Reynolds numbers in the 2% gel. Because of the high viscosity of the 2% gel, very high velocities would be required to match the Re of the mineral oil. This plot demonstrates how a fluid with high elasticity requires much higher velocities to break up a spray, because the momentum has to overcome the elastic forces.

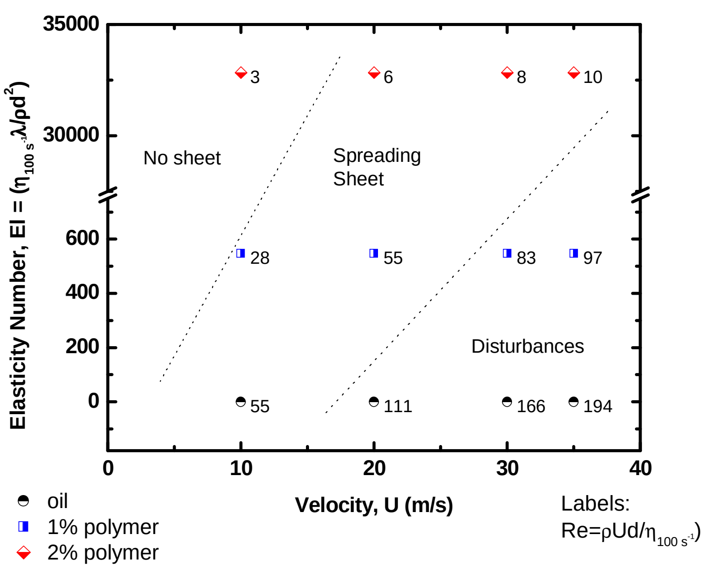

Figure 5. Regimes of Spray Behavior

Due to the elasticity and normal stresses seen in these gels, the ultimate form of the spray is much different than in a Newtonian fluid. The formation of ligaments along the periphery of these sheets, discussed above, produces very interesting web structures downstream of the sheet. Figure 6 shows an example of ligaments forming along the rim and two examples of webbed structures downstream of these sprays. As the velocity of the spray increases, these ligament structures become increasingly long and thin. These long, skinny shapes complicate the assessment of the quality of the atomization, because standard metrics apply only to drops. These ligaments have high ratios of surface area to volume, and will likely evaporate quickly, but they have larger mass.

These experiments demonstrated how the increase of elasticity in a fluid hinders its ability to be atomized in a standard impinging jet. Future work will cover more levels of velocity, look at gels with different composition and viscoelastic properties, and acquire high-speed images with a larger field of view. Applying frequency analysis to the sprays and developing specific image processing techniques will enable quantitative results.

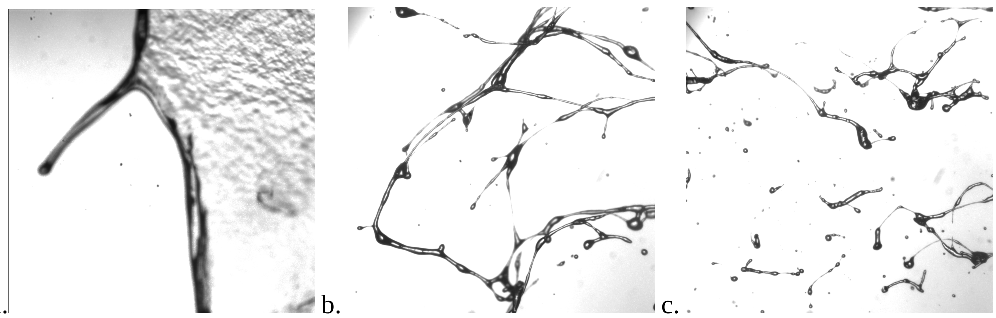

Figure 6. Examples of ligament and web formation in mineral oil gel sprays:
a. 1% gel, 17 m/s, b. 1% gel, 20 m/s, c. 1% gel, 35 m/s

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Nomenclature

d	diameter or orifice
G'	storage modulus
U	velocity
R	density
η	apparent viscosity
σ	surface tension
λ	relaxation time

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