ABSTRACT  Gels are non-Newtonian fluids that exhibit shear thinning behavior. In general, gels are more difficult to atomize in comparison to the liquids they are based on. To improve the gel spray characteristics, one or more superimposed periodic disturbances were introduced in the exit plane of the atomized jet in a triplet impinging airblast atomizer. An experimental system, in which two kinds of periodic disturbances (low frequency–high amplitude and high frequency–small amplitude) are imposed on the spray, was designed and built. The experiments with low frequency–high amplitude disturbances showed a reduction in the Sauter mean diameter of the spray in most cases. In the originally bimodal spray, an increasing dominance of the small droplet mode with increased frequency was observed as well. Experiments with high frequency–small amplitude disturbances did not show conclusive results.

Keywords: atomization, gel, non-Newtonian, disturbances

1. INTRODUCTION

If one examines the needs of the rocket and other propulsion systems, two such needs can be identified. One is the safety of the propulsion system and the other is high energetic performance. Gel propellants are good candidates to provide a response to these requirements, although there is still a lot to be covered in order to achieve a sound understanding of their unique properties and combustion features.

Gel propellants are liquid fuels and oxidizers whose rheological properties have been altered by the addition of gellant, such that they behave as non-Newtonian, shear-thinning, and in some cases time dependent, fluids. At rest they are highly viscous with a definite yield stress value [1]. Such a behavior allows addition of high energy metal particles, and prevents agglomeration, aggregation and separation of the solid phase from the fuel during storage. Concisely, these propellants are advantageous because of their capability to provide full energy management and because of their safety benefits over conventional liquids and solid propellants. At high shear rates their viscosity is reduced, causing their performance characteristics and operational capabilities to be more similar to liquid propellants. These properties, combined with their high density, increased combustion energy and long term storage capability, make them attractive for many applications, especially for volume-limited propulsion system applications.

During the past few decades, many studies concerning different aspects of gel propulsion have been conducted. These studies focused mainly on gel propellants preparation processes, basic rheology and flow, atomization, combustion and energetic performance, applications and technological demonstrators, material compatibility and impulse intensification by metal content for space applications. A thorough review on the status of these propellants was given by Natan and Rahimi [1].

This paper is concentrating on the atomization of gels, which are essentially non-Newtonian fluids. Throughout the history of theoretical research of jet disintegration first, and atomization later, there has been a general consensus that the jet disintegration and atomization happen due to growing disturbances on the face of the atomized jet. The major goal of this study is to show that small disturbances applied to the atomized jet create a spray more suitable to combustion needs. Such properties as the Sauter Mean Diameter (SMD) and the drop size distribution are to be examined for these purposes.

Rayleigh [2] was the first to analyze the disintegration of a liquid jet due to initial small disturbances. The jet that was analyzed was an infinite inviscid jet with no surrounding gas. He examined the surface tension energy of the jet and conclusion that axisymmetric disturbances will grow with time and cause the jet to disintegrate. According to Rayleigh, the disintegration will produce a stream of identical droplets. Lefebvre [3] indicates that Rayleigh’s research was expanded by Weber [4] that examined an infinite viscous jet and the influence of the ambient gas on the disintegration of the jet.

Lefebvre [3] also mentions that Haenlin [5] observed four regimes of jet disintegration. The transition between the regimes occurs as the jet speed increases. The first one is a Rayleigh regime (drop disintegration with no influence of the surrounding air) in which the drops are formed by the interaction of primary disturbances on the liquid and surface tension forces. The second regime is when the air influence is not negligible, and both the Rayleigh mechanism and the disturbances due to friction with the air affect the jet. In the third regime, the influence of surface tension is small and the aerodynamic forces are dominant. In this case, the jet prior to breakup resembles a sinuous wave. The last regime is immediate jet disintegration – atomization. Lin and Reitz [6] have identified, after examining the works of Ranz [7] and Miesse [8], the conditions of different jet disintegration regimes. The Rayleigh regime exists when the following conditions are satisfied:

\[
\text{We}_r > 8 \quad \text{and} \quad \text{We}_g < 0.4 \text{ or } \text{We}_g < 1.2 + 3.41 \cdot \text{Ot}^{0.9} \quad (1)
\]
where \( We_i = \frac{\rho_i U_i^2 d}{\sigma} \), with \( i \) indicating either liquid (\( \ell \)) or ambient gas (\( g \)). Ohnesorge number, \( Oh \), is defined as
\[
Oh = \frac{We_i^{0.5}}{Re_i},
\]
and \( Re_i = \frac{\rho \cdot U_i \cdot d}{\mu} \). The first wind-induced regime exists when:
\[
1.2 + 3.41 \cdot Oh^{0.9} < We_i < 13
\]
The second wind induced regime exists when:
\[
13 < We_i < 40.3
\]
and atomization happens when
\[
We_i > 40.3
\]

Rayleigh was the first to analyze the temporal stability of the jet. Additional approaches regarding the jet instability were provided by Keller, Rubinow and Tu [9] that investigated the spatial stability, and Leib and Goldstein [10] that analyzed the absolute instability of a jet.

The problems of atomization by plain orifice atomizers are that in order to achieve fine atomization, high pressures are needed and that the angle of the spray is usually rather small. The solution to these problems can be found in Weber's research. One of the conclusions from his research is that higher relative velocity between the atomized fluid and the surrounding gas leads to finer sprays. This promoted the use of airblast atomizers, where a liquid jet or a sheet is injected into an environment of a moving gas. In some cases the gas is moving in a direction parallel to the liquid jet and sometimes an angle between the two phases is introduced. Airblast atomizers proved to require lower pressures for the same results. Chin, Rizk and Razdan [11] performed an extensive experimental work with several atomizers. Semibo, Andrade and Carvalho [12] provided an analysis of experimental results and suggested an empirical formula for SMD prediction. Many more researchers investigated airblast atomizers – a review of many important works was done by Lasheras and Hopfinger [13].

There is only limited information that can be found about jet disintegration of non-Newtonian fluid. Goldin et al. [14] showed that non-Newtonian fluid (polymer solutions) disintegration happens differently then in Newtonian fluids. In the beginning, the jet behaves according to the Rayleigh mechanism. However, after a while a formation of “beads-on-string” can be seen (Fig. 1). An explanation for such phenomena was provided by Yarin [15]. He suggested that in the relaxed conditions of the fluid, the polymer molecules are coiled. However, when a jet is formulated, these molecules uncoil, and their tension prevents the disintegration. The disintegration happens only after the polymer molecules break due to mechanical fatigue.

Several researchers investigated the atomization and jet disintegration of non-Newtonian fluid. Rahimi and Natan [16] studied experimentally the atomization using triplet airblast atomizers. Mansour and Chigier performed an experimental investigation where different gels and different airblast atomizers were tested, and Ciezki, Robers and Schneider [18] investigated sprays of kerosene based gel fuels using airblast and impinging atomizers.

The present research is a continuation of the experimental work conducted by Rahimi [19]. The idea for the present research is based on the theoretical results of Sadik and Zimmels [20]. They showed that introduction of superimposed disturbances to the surface of the jet creates a spray. Moreover, they claimed that if the number of the disturbances is increased, the break-up length of the jet is shorter and the spray angle is wider. In the present research, the Sadik and Zimmels idea is adopted to produce the experimental environment and the trends of spray behavior due to the introduction of periodic, superimposed disturbances are investigated.

2. EXPERIMENTAL SETUP

2.1 General Setup

The injection and atomization system is described in detail in the M.Sc. thesis of Chernov [21]. A general overview of the system is shown in Fig. 2. The system includes the following items: (a) control box, (b) atomizer head, (c) atomizer, (d) low frequency disturbance system, (e) high frequency disturbance system and (f) Malvern Mastersizer X. The water/gel feeding system carries the atomized fluid (water or gel) to the atomizer. The system consists of a 4.7 L cylinder, which can withstand pressures up to 180 atm. The diameter of the piston is 100 mm. The cylinder is connected by flexible piping to the atomizer head and the piston is driven forward by a hydraulic-fluid pressurized tank.

The basic injector for atomization (without the disturbances) is a triplet airblast atomizer. The jet of the atomized fluid (water or gel) and two jets of the atomizing gas, nitrogen in the present case, impinge at one point as shown in Fig. 3. There where several reasons for choosing this configuration. The first reason is that evaluation of the Weber number showed that in all cases \( We_i < 3 \) and \( Oh = 2.93 \). These numbers show that there will be no spray in pressure-only configuration and another configuration was needed. The impinging-jet configuration was chosen because it requires lower upstream pressures and also provides the accurate position of point the spray begins in order to assure accuracy and repeatability of the tests. Figure 4 shows a detailed drawing of the injector. In the present investigation the geometrical parameters were: \( \beta = 80^\circ \), \( L = 10 \text{ mm} \), \( d_1 = 1.6 \text{ mm} \), \( d = 2 \text{ mm} \), \( L_o = 15 \text{ mm} \), \( L_o = 26 \text{ mm} \). The exit diameter of the atomized fluid orifice here is relatively high. The reason is that the use of a smaller orifice would increase the complexity of disturbance system significantly.

![Figure 1. The “beads-on-string” structure [14]](image-url)
2.2 The low frequency (LF) disturbance system

The concept of introducing periodic disturbances to the jet was based on the principle of changing the orifice area and orifice shape. In such case, the exit velocity of the jet varies (hence the pulsation) and disturbances are introduced to the jet. The idea was to use two identical wheels with “teeth” rotating at the same speed. In the “open” position the atomization is the same as it would have been in a plain atomizer. In the “closed” position the exit area and shape of the atomizer is different. The wheels can be seen in Fig. 5.

The wheels were rotated by a DC motor that allowed frequencies of the disturbances to reach up to 1.1 kHz. Each wheel had 8 teeth. The wheels were rotated in the same direction to decrease asymmetry.

During the design of the atomization system one of the major considerations was separation between the moving parts and the fluid. This was especially important in the case of gel, which tends to stick on the rubber transmission and to reduce the friction to practically zero. The solution was to design a two-part atomizer head. All the driving parts (the transmissions and the driving wheels) of the wheels where located between the two parts of the atomizer. Shafts were designed to transmit the rotary motion to the front of the atomizer and the disturbance wheels were attached to the shafts. The full design of the atomizer with the wheels is presented in Fig. 6 and the disturbance wheel and shaft are shown in Fig. 7.
2.2 The high frequency (HF) disturbance system

This system is designed to introduce additional disturbances of higher frequencies at smaller amplitudes in comparison to the LF disturbance system. Theoretically, the two disturbances should be superimposed. However, application of superimposed disturbances would require the design of a micro-scale periodic disturbance system located on the wheels of the low frequency disturbance system. Such a system is highly complex and it is not realistic in the existing facility. However, a system that produces disturbances of relatively small amplitudes at high frequency and works in parallel with the low frequency disturbance system is a good simulation of a system of superimposed disturbances.

The system consists of a needle that touches the surface of the jet. The needle goes through a tube that limits its movement to one dimension, and it is attached to the membrane of a commercial speaker that is connected to a signal generator. When the signal generator is activated, the needle vibrates and creates disturbances on the surface of the jet. Both low and high frequency disturbance systems are shown in Fig. 8.

2.3 The measurement and data acquisition system

The volumetric and the mass flow rates of the atomized fluid are calculated by measuring the piston movement using a linear potentiometer mechanically attached to the piston.

The measurement of the motor revolutions was done using a rotary sine/cosine electric encoder made by Netzer Precision. The encoder accuracy was verified by other angular speed measurement methods and the maximum error was found to be less than 1%.

The droplet size distribution was measured using Malvern Mastersizer X, which is a laser-diffraction particle analyzer. The Mastersizer instrument was connected to a computer and has its own data acquisition and data analysis program.

The linear potentiometer and the rotary encoder are connected to a computer using National Instruments PCI-6023E data acquisition card and were analyzed using program written under LabView 7.0 language. Matlab was used to process part of the results.

3. RESULTS AND DISCUSSION

Experiments were conducted in three test series. The atomized fluid was water (series I) and water-based gels using carbopol as a gelling agent (0.25% and 0.5% carbopol concentration in series II and III respectively). In all cases the SMD of sprays resulted from periodic disturbances on the water/gel jet was compared to the SMD of the undisturbed spray. Water spray measurements were conducted at 2 different positions downstream the atomizer. The first (close station) was 45 mm from the atomizer and the second (far station) was 61 mm.

The nature of the gels that were used dictated several factors and conditions of the experiments. The gel used in this research is a sticky, viscous substance. This leads to fast contamination of the lenses of Malvern Mastersizer X. In order to solve that problem, the number of sweeps performed during drop size measurement was reduced from a maximum 2000 down to 50. During that small time period it was possible to get in many cases a good reading, but
only at the far station. However, in several cases, it was not possible to acquire good readings. Accurate readings became more difficult to obtain as the gellant content increased and experiments had to be repeated many times to assure repeatability.

3.1 Low frequency periodic disturbances
Experimental results for the LF disturbance system are presented in Figs. 9-14 for various ALR ratios. It can be seen that in most cases there is a significant reduction of the SMD when disturbances are introduced and in most cases the SMD decreases with increasing frequency. In some cases, a peak of higher SMD can be observed at low frequencies. Vaguely speaking, the disturbances cause a reduction between 25%-60%, depending on the gellant content, mass flow rate and ALR. However, in certain cases there is no significant decrease in SMD with the increase of the frequency of the disturbance, especially for relatively low ALR ratios (in a couple of cases, it was observed that increasing the frequency the SMD even increased).

Figure 9. The SMD as a function of frequency for water injected at close station, at \( m_1 = 5.16 \text{ g/s} \)

Figure 10. The SMD as a function of frequency for water injected at far station, at \( m_1 = 5.16 \text{ g/s} \)

Figure 11. The SMD as a function of frequency for 0.25% water based gel injected at \( m_1 = 8 \text{ g/s} \)

Figure 12. The SMD as a function of frequency for 0.25% water based gel injected at \( m_1 = 16 \text{ g/s} \)

Figure 13. The SMD as a function of frequency for 0.5% water based gel injected at \( m_1 = 21.6 \text{ g/s} \)
Figures 15-18 show the histograms of some of the sprays. It can be seen that most of the sprays are bi-modal. The first mode (small) includes droplets of 10-20 µm in diameter. The second mode (large) occurs at droplets of several hundreds µm in diameter. It can be seen that the influence of the disturbances is to reduce the “large” mode and to increase the “small” mode. In some cases, the size of the droplets of the “small” mode is increased, but the mode still stays in the area of desirable droplet diameters. Another interesting observation can be seen in Fig. 14. The SMD of the spray with disturbances at 156 Hz (red line) is 23.25 µm and the SMD of the spray with disturbances at 391 Hz (green line) is 29.62 µm. As it can be seen, even though the SMD of the latter spray is higher, the trend of reduction of the “large” mode and growth of the “small” mode continues.
3.2 High frequency periodic disturbances

Even though a significant experimental effort was invested with high frequency disturbances, no conclusive results have been obtained. In most cases the influence of the disturbances was small and no clear trend was observed. Such an outcome does not necessarily imply that there is a flaw in the theory, but it does show the practical difficulties with its implementation. There are some possible explanations for the results:

- Sadik and Zimmels [20] did not consider the effects of viscosity on the propagation of the disturbances. It is possible that viscosity plays an important part in restraining the influence of small amplitude disturbances.
- It was practically impossible to make sure that the needle was moving during the injection of the fluid. It was moving when there is no flow, but it is possible that the speaker that moved it was not powerful enough to overcome the drag of the fluid and there was no feasible way to verify this.

4. CONCLUSIONS

(1) The introduction of disturbances to the jet prior to atomization leads in most cases to a decrease in the spray SMD. In general, the SMD decreases with increasing ALR.
(2) The introduction of periodic disturbances reduces the mode of large droplets and increases the mode of small droplets. This behavior can be observed even when the SMD of the spray is not reduced with increased frequency of the disturbances.
(3) No conclusive results were obtained from experiments with high frequency-small amplitude disturbances.
(4) Additional research on the disturbance introduction techniques is required, such as system of true superimposed disturbances. As can be seen from the present study, disturbance introduction is a challenging task and significant results can be obtained if the technical problems are solved.

5. NOMENCLATURE

\[ \text{Subscripts} \]
- \( g \) \quad \text{gas}
- \( l \) \quad \text{liquid}

6. NOMENCLATURE


