Atomization of Gel Propellants using Pulsatile Injection

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ABSTRACT

The major mechanism of a liquid jet disintegration and atomization is the growth of disturbances on the face of the atomized jet. The atomization of water and gelled, non-Newtonian fluid using pulsatile injection was investigated. Periodic disturbances were introduced to the atomized jet and their influence on the spray character was studied. A simple triplet air-blast atomizer was used. The disturbances were introduced mechanically with periodically changing area and shape of the exit orifice. Three different methods of disturbance introduction were utilized. The spray droplet size distribution was measured using Malvern Mastersizer X. The results show that in most cases there is a reduction of Sauter Mean Diameter with the introduction of the disturbances. There are indications that increasing the disturbance frequency results in further reduction of the droplet size and in a more uniformly distributed spray.

NOMENCLATURE

E	– potential surface energy of the jet
N	– rotations per second
O/F	– oxidizer to fuel (or gas to liquid) mass ratio
SMD	– Sauter Mean Diameter
U_e	– exit velocity of the jet
We	– Weber number
Re	– Reynolds number
b_n	– constant in Fourier series expansion
d	– jet diameter
$\dot{m}$	– mass flow rate
n	– any positive integer (including 0)
r_t	– transmission ratio
γ	– dimensionless wave number
λ	– wavelength of the disturbance
σ	– surface tension force

Subscripts

f	- fluid
g	- gas
l	- liquid

INTRODUCTION

Coupled to the need for highly energetic propellants, in a wide variety of rocket motor and other applications, is the increased sensitivity to their safety features. The utilization of gel propellants provides a promising response to these requirements, although there is still a lot of ground that must 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 gellants, such that they behave as non-Newtonian time dependent fluids. This change of the rheological behavior can prevent agglomeration, aggregation and separation of a metal 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. Their performance characteristics and operational capabilities, which are similar to liquid propellants, as well as 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 state of the art was given by Natan and Rahimi [1].

This paper is concentrating on the atomization of gels, which are essentially non-Newtonian fluids. The major goal of this study is to show that small disturbances applied to atomized jet decrease the SMD of the spray. 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 first to analyze the process of jet disintegration to drops was Rayleigh [2] who investigated the disintegration of liquid jets due to initial small disturbances. The jet that he analyzed was a jet of simple, inviscid liquid, like water for example. Rayleigh calculated the potential energy due to surface tension:

$$E = \frac{p \cdot s}{2 \cdot d} \cdot \left(g^2 + n^2 - 1\right) \cdot b_n^2 \tag{1}$$

$$g = \frac{2 \cdot p \cdot d}{l} \tag{2}$$

He found out that for nonsymmetrical disturbances, n>>1 and the jet is stable. However, in the event of symmetrical disturbances, n = 0 and for $g < 1$ the potential energy E is negative, meaning that the jet is unstable. In this case the disturbances grow exponentially until the jet disintegrates. According to Rayleigh, the minimum required wavelength of the disturbance is equal to the circumference of the jet ($\lambda_{min}=\pi d_j$). The optimal wavelength for jet disintegration is $\lambda_{opt}=4.51d_j$. In this case, according to Rayleigh, the droplet diameter is going to be $1.89d_j$, and the result is a unidirectional flow of drops. Lefebvre [3] quotes Weber [4] who expanded Rayleigh's analysis to viscous jets and found that while the minimum wavelength required for disintegration is the same for any jet, the optimal wavelength grows with viscosity and it is reduced with the increase in the density and the surface tension. Weber also examined the influence of the ambient gas and found out that friction shortens both the minimum and optimum wavelengths.

Lefebvre [3] mentions that Haenlin [5] in his research has observed four regimes of jet disintegration. The transition between the regimes happens as the jet speed increases. The first one is Rayleigh regime (drop disintegration without influence of surrounding air) in which the drops are formed by the interaction of primary disturbances in the liquid and surface tension forces. The second regime is when the air influence is not negligible, and both Rayleigh mechanism and disturbances due to air friction affect the jet. In the third regime, the influence of surface tension is small and the influence of aerodynamic forces is dominant. In this case, the jet prior to breakup resembles sinuous wave. The last regime is immediate jet disintegration – atomization. Lin and Reitz [6] have identified, after examining works of Ranz [7] and Miesse [8], the conditions of different jet disintegration regimes. Rayleigh regime exists when the following conditions are satisfied:

$$We_L > 8 \text{ and } We_g < 0.4 \text{ or } We_g < 1.2 + 3.41 \cdot Z^{0.9} \tag{3}$$

where $We_i = \dfrac{r_i \cdot U^2 \cdot d}{s}$, with i notifying either liquid or ambient gas. Z is defined as $Z \equiv \dfrac{We_L^{0.5}}{\mathrm{Re}_L}$, and $\mathrm{Re}_L = \dfrac{U \cdot d}{s_L}$. The first wind induced regime exists when:

$$1.2 + 3.41 \cdot Z^{0.9} < We_g < 13 \tag{4}$$

The second wind induced regime exists when:

$$13 < We_g < 40.3 \tag{5}$$

and atomization happens when:

$$We_g > 40.3 \tag{6}$$

In the present case, $We_L < 8$. This implies that the conditions are not sufficient to allow jet disintegration and additional means should be utilized to achieve atomization.

The major problem of atomization in plain orifice atomizers is that in order to achieve fine atomization, high pressures are needed and the angle of the spray usually is rather small. The solution to this problem can be found in Weber's research, i.e., to increase the relative velocity between the atomized fluid and the surrounding gas. This promoted the use of airblast atomizers, where a liquid jet or a sheet is injected into an environment of a moving gas, sometimes moving in a direction parallel to the liquid jet and sometimes an angle between the two phases was introduced. Airblast atomizers proved to require lower pressures for the same results.

The present research is a continuation of the experimental work conducted by Rahimi [9] in his M.Sc. thesis. The idea for the present research is based on the theoretical results of Sadik and Zimmels [10]. 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 increases the spray is finer and the spray angle is wider. In reality, it is quite difficult to introduce several sets of disturbances. An airblast atomizer provides by definition a disturbance (the air itself), therefore a triplet airblast atomizer is chosen for the present research. The goal is to find the trend of the droplet size distribution with increasing the frequency of the disturbance. A further disturbance system is planned, but it was not been implemented yet.

EXPERIMENTAL SETUP

The basis of the experimental setup is described in detail in Reference 9. The basic injector for atomization (without the disturbances) is a triplet airblast atomizer that consists by a jet of atomized fluid, water or gel, and two jets of atomizing gas, nitrogen in the present case, which impinge at one point (Fig. 1). The experimental setup (Fig. 2) consists of the water/gel feeding system, the nitrogen feeding system, the atomizer, the disturbance system and the data acquisition setup.

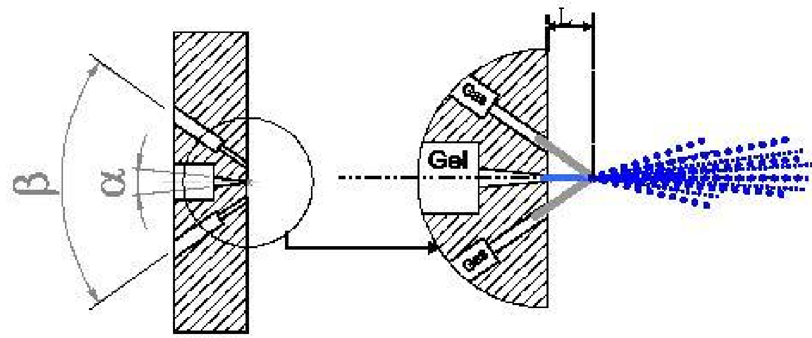


Figure 1. The injector [9]. In the present case, β=80^o, α=0^0 and L=12 mm.

Figure 2. The experimental setup: (a) nitrogen tank for the nitrogen feed system, (b) hydraulic fluid pressure tank, (c) water/gel cylinder with piston, (d) atomizer head, (e) 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 lt 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.

Nitrogen was used as an oxidizer simulant. Its mass flow rate was calculated by measuring the stagnation pressure upstream the atomizer head and assuming sonic flow at the exit.

The injector head is presented in Fig. 3.

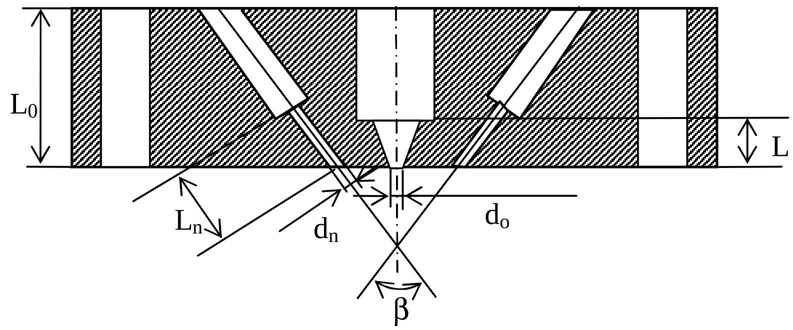


Figure 3. The injector head. $\beta=80^o$, L=10 mm, d_o=1.6 mm, d_n=2 mm, L_n=15 mm, L_0=26 mm.

Three major disturbance systems were used. The principle behind the first system was to introduce a change in the diameter of the exit orifice of the fluid. Mechanically this principle was implemented using a wheel with orifices of two different diameters. The centers of the orifices were located on a circle. There were 24 pairs of partly interlaying orifices, the big orifice had a diameter of 1.6 mm (equal to the diameter of the exit orifice of the atomizer head) and the small orifice had a diameter of 1.3 mm. The wheel was driven by a rubber transmission. The wheel was installed outside the atomizer, very close to the exit plane. The wheel is shown in Fig. 4 and the atomizer-disturbance setup is shown in Fig. 5.

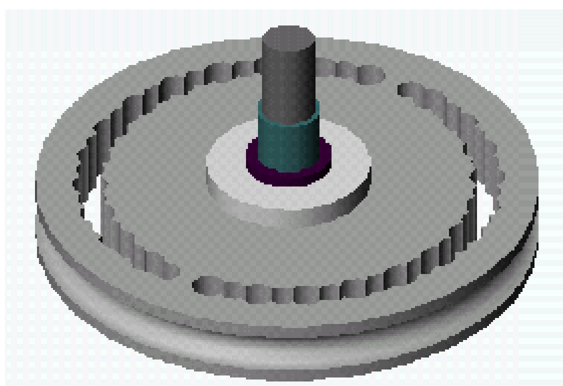


Figure 4. The first disturbance wheel.

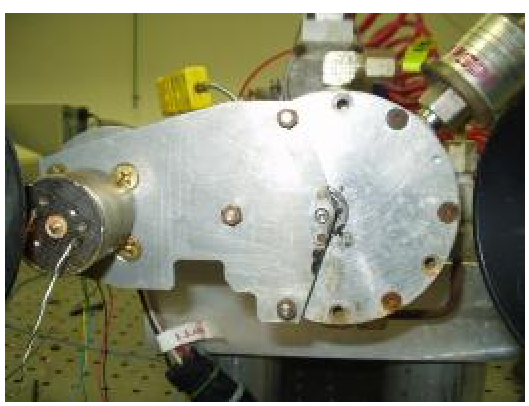


Figure 5. The first atomizer-disturbance wheel setup.

After the first disturbance system was installed, it was disqualified – the structure of the holes created a sheet. That gave higher SMD values then expected, and made much tougher the task of comparing results to static (no periodical disturbance) situation.

The second concept of introducing periodic distortions to the jet was based on the same idea, i.e., changing the orifice area, but this time the final shape of exit orifice was not circular. The idea was to introduce two identical wheels with "teeth", rotating at the same speed. In "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 "open" and the "closed" positions can be seen in Fig. 6.

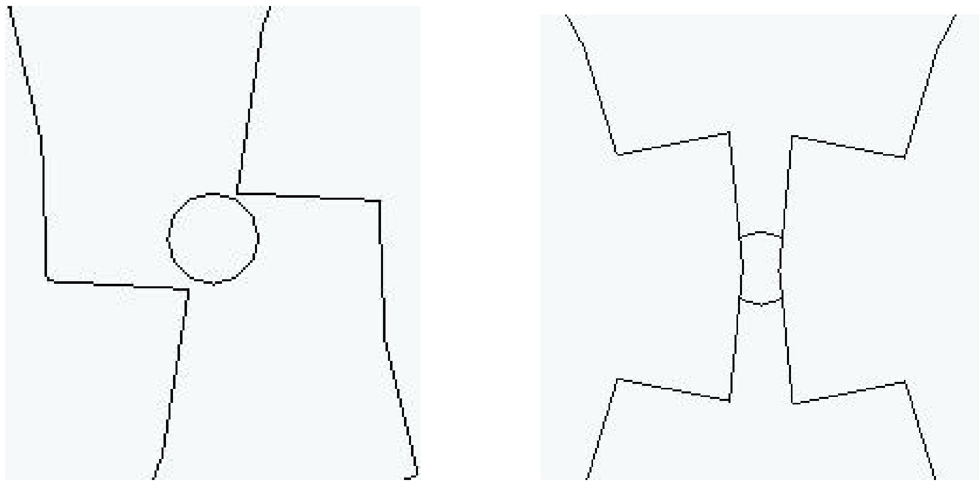


Figure 6. Open and closed positions of the wheels.

The wheels were rotated by a DC motor. The DC motor was connected by a rubber transmission to one of the wheels, and the second wheel was connected by an additional rubber transmission to the first, i.e., the motor turned the first wheel, which turned the second. The DC motor is capable of rotating at 2500 rpm. The maximum required disturbance rate at this disturbance setup was 1 kHz. Mechanical constrains limited the ratio for the transmission to 2.3:1 (which was the actual ratio of the transmission). In order to satisfy all these requirements the wheels were made with 8 "teeth". To decrease asymmetry in the transition between the "closed" and "open" modes, the wheels rotate in the same direction. The frequency of the disturbances is given by:

$$f = 8 \cdot r_t \cdot N = 18.4 \cdot N \tag{7}$$

The diameter of the driving wheel is d_m=23 mm and the diameter of the driven wheel is d_d=10 mm. The design of the wheels can be seen in Fig. 7 and the atomizer in Fig. 8. The whole disturbance system can be seen in Fig. 9.

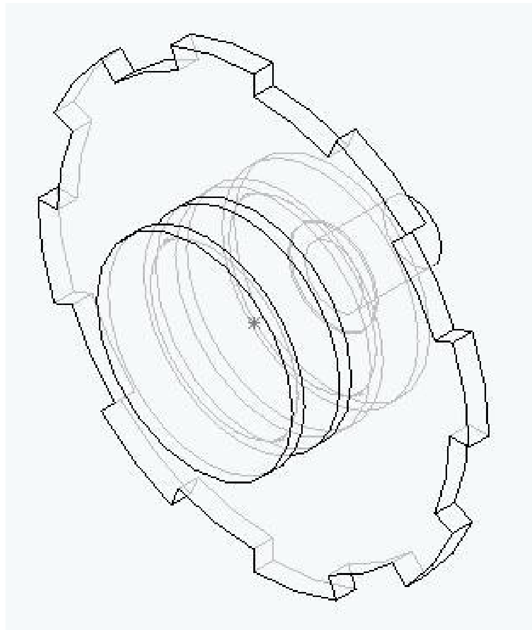


Figure 7. The second disturbance wheel.

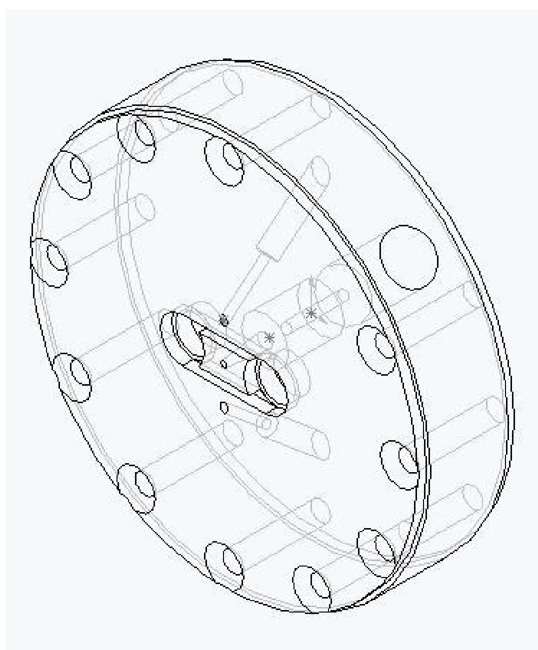
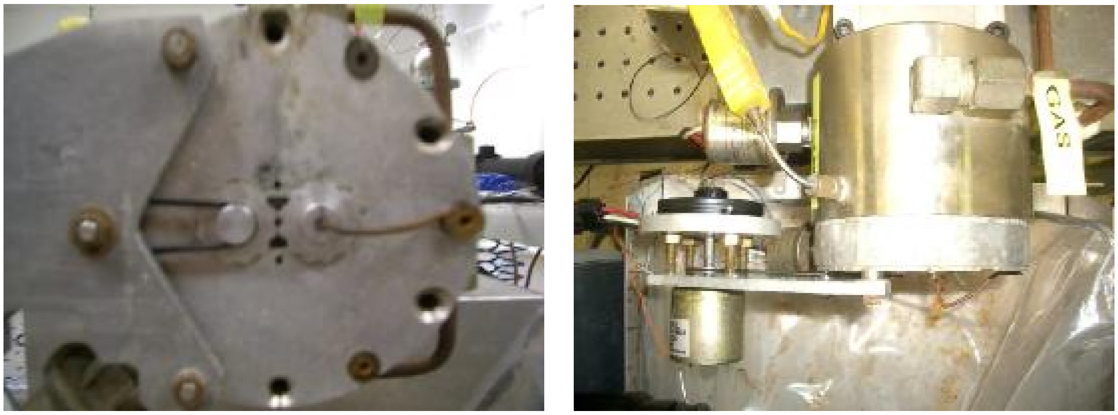


Figure 8. The second atomizer head.



(a) (b)

Figure 9. The second disturbance system, (a) – front view, (b) – top view.

During the experiments with water, the system exhibited satisfactory operation, however in the experiments with gels, mechanical problems were encountered. Gel, unlike water, stuck on the wheels and served as a lubricant reducing friction between the wheels and the transmission. The result was unsteady rotation of the wheels, even complete lack of movement.

In the third disturbance system the major challenge was to separate the moving parts from the fluid. The solution for this problem was to introduce a new atomizer, with the same flow characteristics, but with different mechanical solutions for rotating the wheels. The principle of the disturbance introduction remained the same, as shown in Fig. 6. The atomizer head was split to two parts, the rubber transmissions were transferred inside the parts and the design of the wheels was changed accordingly. The shaft of the wheel and the disturbance wheel were separated to allow changes in the disturbance wheels. The design of the third disturbance system is shown in Fig. 10. An additional disturbance system, which will introduce disturbances with smaller amplitudes and higher frequencies, will be introduced later in the future stages of the study.

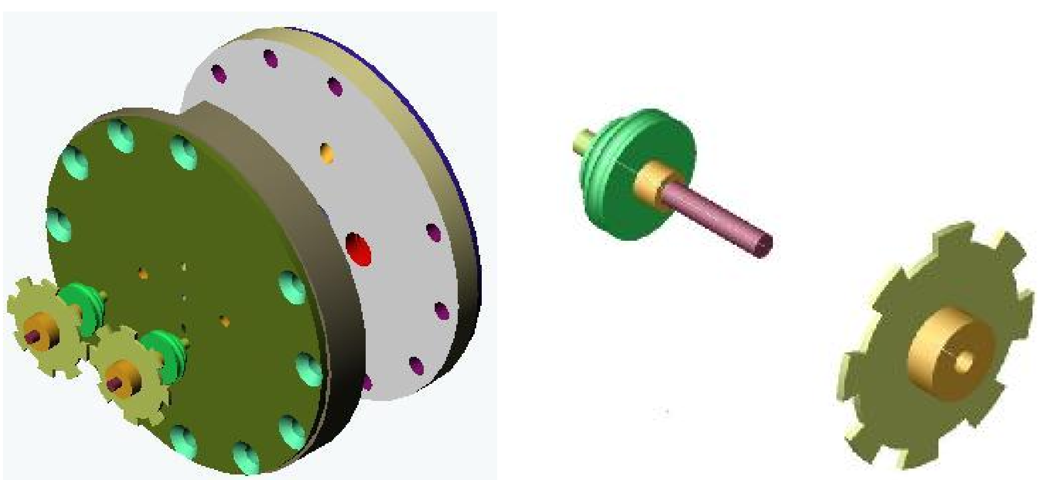


Figure 10. The third atomizer head and the wheel.

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 by Netzer Precision. The encoder accuracy was verified by other angular speed measurement methods and the maximum error was found to be less then 1%.

The most important measurement is the measurement of the droplet sizes. The droplet sizes were 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 also used to process part of the results.

RESULTS AND DISCUSSION

Experiments were conducted in two test series. The atomized fluid was water in the first case, and water based gel (0.25% concentration of the gellant) in the second case. 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. The results can be seen in Figs. 10-13 for various O/F (oxidizer to fuel or gas to liquid) ratios. It can be seen that in most cases there have been a significant reduction of the SMD when the disturbances were introduced.

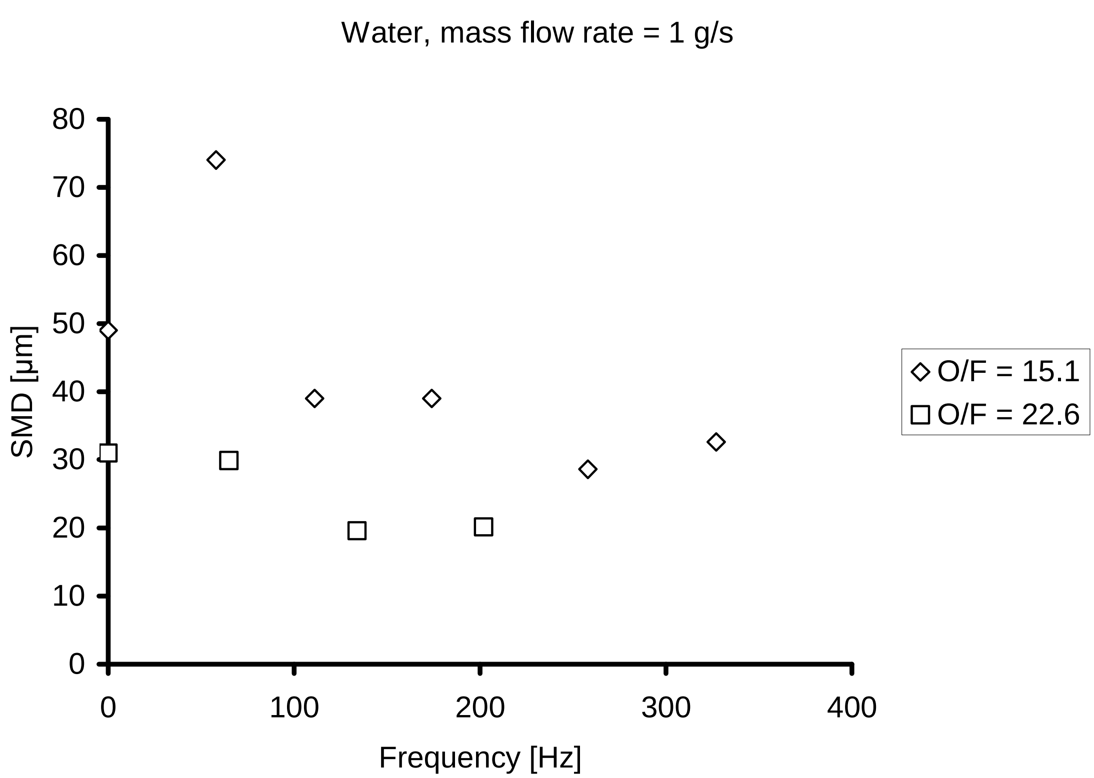


Figure 10. The SMD as a function of frequency for water injected at $\dot{m}_f = 1 \ {}^{g}\!/\!_{s}$ for two O/F ratios.

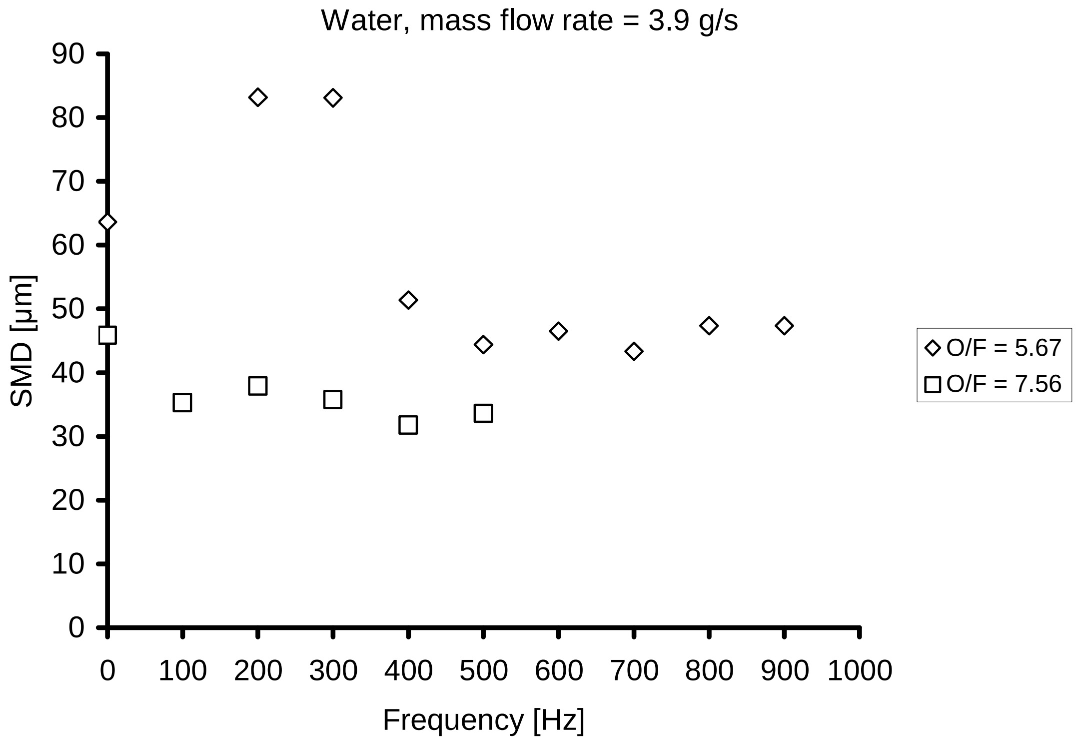


Figure 11. The SMD as a function of frequency for water injected at $\dot{m}_f = 3.9\ {}^{g}\!/_{s}$ for two O/F ratios.

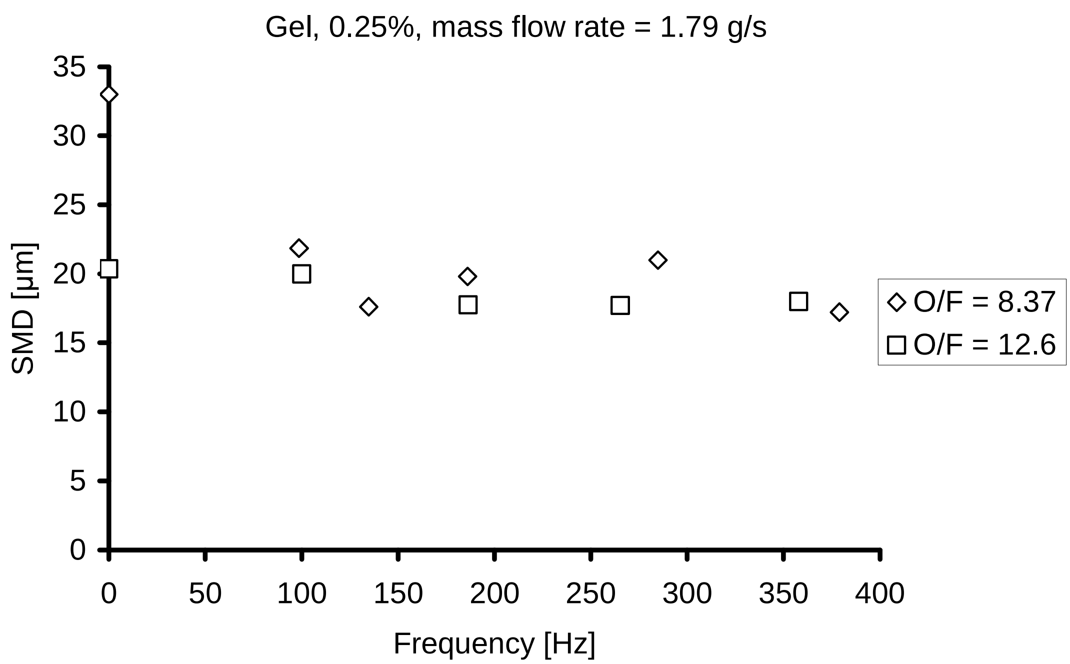


Figure 12. The SMD as a function of frequency for 0.25 water based gel injected at $\dot{m}_f = 1.79\ {}^{g}\!/_{s}$ for two O/F ratios.

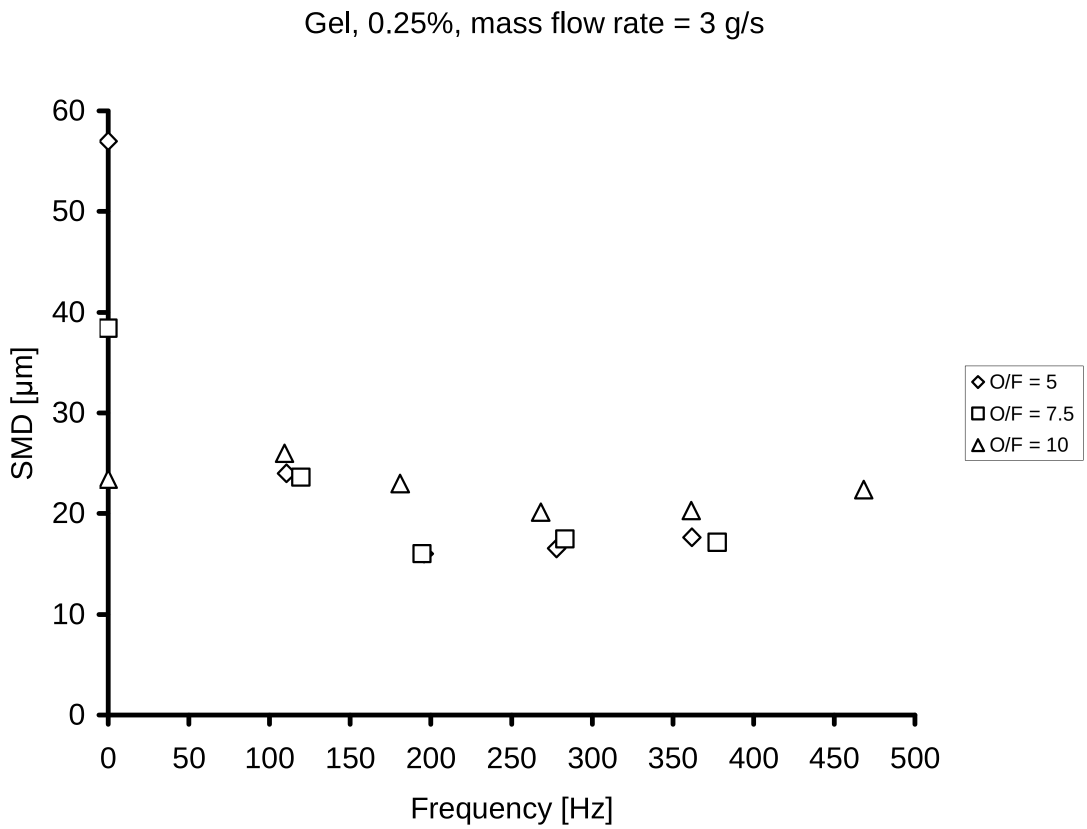


Figure 13. The SMD as a function of frequency for 0.25 water based gel injected at $\dot{m}_f = 3\ {}^{g}\!/\!{}_{s}$ for three O/F ratios.

SMD is a good indicator for comparing spray quality. Another important parameter in spray analysis is the droplet size distribution. Several spray size distributions are presented in Figs. 14 and 15.

A few quite important points can be raised from the results presented. First, it is clear that the SMD decreases when the frequency is increased. However, in certain cases there is no significant decrease in SMD with the increase of the frequency of the disturbance. This phenomenon happens mostly at high O/F ratios, which leads to the conclusion that at some stage the effect of the gaseous atomizing jets is the dominant one and the effect of the disturbances is of lesser importance.

The reason for the SMD decrease can be seen in Figs. 14 and 15. It can be seen that a spray without disturbances is bimodal, the first mode occurs at small diameters (10µm) and the second at large diameters (150-200µm). When disturbances are introduced, the spray tends to become monomodal, the number of large droplets decreases, and in some cases they disappear completely.

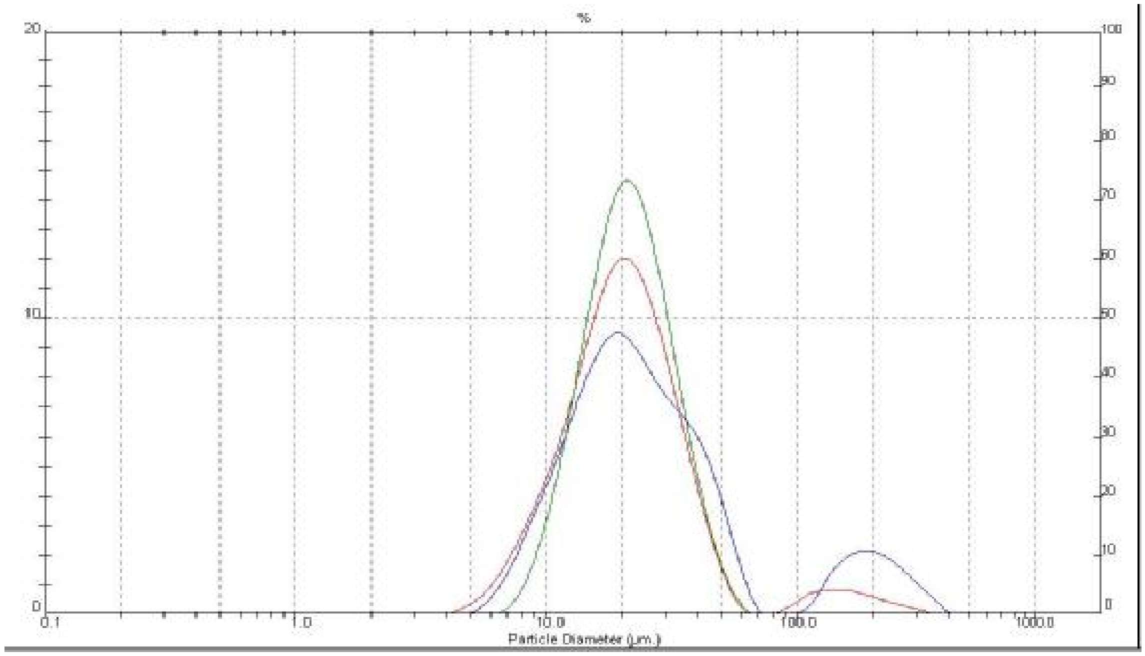


Figure 14. Three different gel sprays under the same flow conditions ($\dot{m}_f = 1.79\ g/s$, O/F=12.6), with different disturbance frequency. The blue line corresponds to no disturbances introduced, the red line – 99 Hz and the green line – 135 Hz.

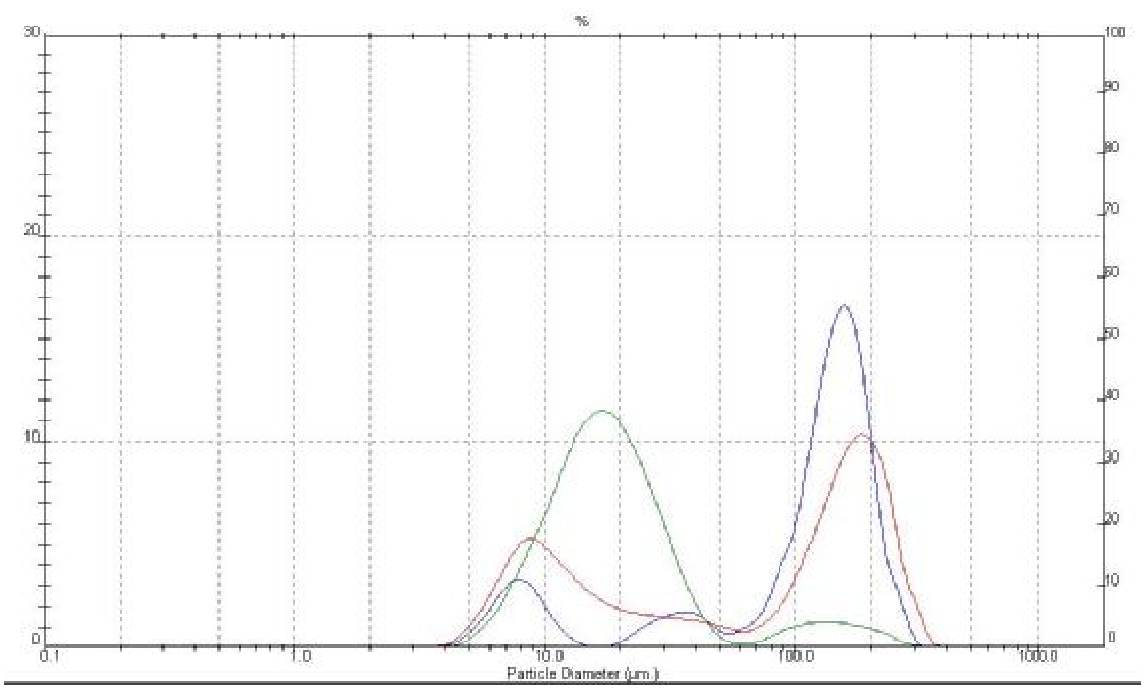


Figure 15. Three different gel sprays under the same flow conditions ($\dot{m}_f = 3\ g/s$, O/F=7.5), with different disturbance frequency. The blue line corresponds to no disturbances introduced, the red line – 120 Hz and the green line – 195 Hz.

CONCLUSIONS

The introduction of disturbances to the jet prior to atomization leads to a decrease in the spray SMD. It is especially important in sprays with relatively low O/F ratios, where the momentum flux of the atomizing jet is not large enough to produce fine atomization.

The introduction of these disturbances can produce a monomodal spray, or at least it reduces the number of the large droplets.

Additional research on the disturbance introduction techniques is required. As can be seen from the present study, disturbance introduction is a challenging task and significant results can be obtained.

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