# Atomization of Gel Fuels using Impinging Jet Atomizers

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## Abstract

An effort was made to identify an optimal impinging-jets atomizer for gelled fluids. An injection system, based on prefixing the mass flow rate of the atomized fluid, was designed and built. Plain and gelled water were used as working fluids. Three types of impinging jet atomizers (doublet, triplet and quadruplet) at two impinging angles were utilized. The results indicate a tendency of the droplet size to decrease with the mass flow rate growth. Gels were more difficult to atomize than Newtonian fluids. The triplet was found to be superior to doublet and quadruplet atomizers. The lowest Sauter Mean Diameter values were received in the triplet injector, 8μ for water and 10μ for gel.

## 1. Introduction

There are two main requirements from current rocket/ramjet propulsion systems: adequate safety and high energetic performance. Gel propellants respond to both, 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 gellants, such that they behave as non-Newtonian, shear-thinning, and in some cases time-dependent (thixotropic), fluids. At rest, they are highly viscous with a definite yield stress value. Such a behavior allows the 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 characteristics, combined with the high density of metallized gels, their increased combustion energy and long term storage capability, make them attractive for many aerospace applications, especially for volume-limited propulsion systems.

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].

Atomization is a key issue for the achievement of high combustion efficiency. However, only a few studies have been conducted for non-Newtonian fluids, such as gels, mainly with air blast atomizers or doublet impinging jets[2-10]. Chojnacki and Feikema[2-4] investigated the atomization of water gels using a like-on-like doublet injector and the fluid injection system was transformed to a capillary viscometer to measure the viscosity of the non-Newtonian gel. In a study on the non-Newtonian liquid sheets formed by impinging jets at several impingement angles, Chojnacki and Feikema[4], indicate that the breakup radius exhibits a general trend of increasing with increasing Weber number. An attempt was made to predict the wavelength of ligaments shed from a liquid sheet using linear stability analysis, which considers the non-Newtonian effect. However the analysis over-predicted the wavelength. Mansour and Chigier[5] investigated the air-blast atomization characteristics of non-Newtonian materials using a co-axial twin fluid atomizer. They provided a rheological characterization of the fluids that included shear and extensional viscosity measurements. Moreover, they connected the rheological properties with atomization characteristics and concluded that for shear-thinning, pseudoplastic fluids with low yield stress, the SMD depends on the shear rate. They indicated that the mass averaged shear viscosity seems to be the most appropriate choice to correlate against the atomization characteristics of non-Newtonian fluids (SMD). As regards viscoelastic materials, they were more difficult to atomize than the viscoinelastic ones, and they indicate that the extensional viscosity rather than the apparent (shear) viscosity "is the most significant rheological mechanism that inhibits breakup."

Ciezki et al[6] investigated air-blast atomization of kerosene-based gel fuels using different gelling agents. They found that the gel fuels are more difficult to atomize than the Newtonian fuels. For some fuels, atomization was never

achieved and the jet was of a strongly bent shape that is rarely seen in atomization of Newtonian fluids. Rahimi and Natan[7-8] conducted experiments with water-based carbopol gels that act as gel propellant simulants and they indicate that, in general, the SMD of the gel spray is higher then the SMD of simple water spray injected under the same conditions. Chernov and Natan[10-11] succeeded to reduce the spray SMD by introducing periodic disturbances at the exit plane of the atomized fluid. The droplet size was found to decrease with increasing the frequency of the disturbances. Moreover, in an originally bimodal spray, an increasing dominance of the small droplet mode with increased frequency was observed.
Gelled fluids are non-Newtonian, shear-thinning, characterized by Power-Law. For a power-law viscous fluid, the shear stress, $\tau$, and the non-Newtonian viscosity, $\eta$, depend on shear rate, $\dot{\gamma}$:

$$\tau = k \cdot \dot{\gamma}^{n} \quad (1)$$

$$\eta = k \cdot \dot{\gamma}^{n-1} \quad (2)$$

where $k$ is the consistency index and $n$ is the power law index.
The rheological properties of the gels have a significant effect on the atomization characteristics, i.e., the spray Sauter Mean Diameter (SMD), the modal distribution etc. Viscosity affects the fluid Reynolds number and is highly influenced by the shear stress applied to the atomized fluid[5,11,12]. Weber number, defined by the fluid surface tension, also affects the atomization characteristics, however, it is very difficult to determine surface tension in gels.
The purpose of the present research was to identify an optimal impinging-jets atomizer. An injection system, based on prefixing the mass flow rate of the atomizing fluid, with multiple geometry injector heads, was designed and built. Experiments were conducted to verify the effect of the injector type and geometry on the spray.

## 2. Experimental setup

### 2.1 General

The experimental system (Fig. 1) was initially designed by Rahimi[7], modified by Chernov[10] and also in the present research. Contrary to the studies of Rahimi and Natan[7-8], and Chernov and Natan[10-11], where airblast atomizers were used, in the current investigation, the spray was obtained by impinging jets of the atomized fluid. The feeding system design was based on prefixing the mass flow rate of the atomized fluid. The injection system included multiple geometry injector heads. The task of the injection system was to create a stable spray field in order to characterize the droplet size by a Malvern Mastersizer droplet-distribution measurement-system.
The experimental system components include the atomized fluid feeding system, the injection system, and the droplet size measurement and data acquisition system.

Figure.1: The Experimental System (a) general view, (b) the feeding system

### 2.2 The atomized fluid feeding system

The system is designed to bring an initially defined, continuous flow of the atomized fluid to the injector entrance with insignificant alteration to the rheological properties of the fluid.
The atomized fluid is stored in a cylinder (length 1000 mm, diameter 80 mm, gross volume 20 L, maximum working pressure 200 bar) with a piston, which causes the fluid to flow towards the injector at constant velocity, which enables a constant mass flow rate. The system is capable to control the fluid flow velocity and pressure. This is done by utilizing an additional cylinder, which contains a hydraulic fluid that pushes the atomized fluid. The piston

movement is controlled by a hydraulic pump (fluid volume 5 L) operated by a 3 HP, 1500 RPM motor, and a proportional valve. The piston can move in two directions (forward/backward) at automatic and manual operating modes. A rotating encoder allows discrete linear movement of the piston of 0.1 mm. The system repeatability is 2%. Pressures and mass flow rates were measured at a sampling rate of 5 Hz. Experimental uncertainties were estimated by the small-sample method as less than 2% for the atomized fluid mass flow rate.

## 2.3 The injection system

The task of the injection system is to convert the atomized fluid to a spray utilizing an injector head that uses different injectors with variable geometries and number of exit ports of impinging fluid jets. The system also includes a power supply unit and a command switch box that controls the opening and closing timing of the solenoid valves.

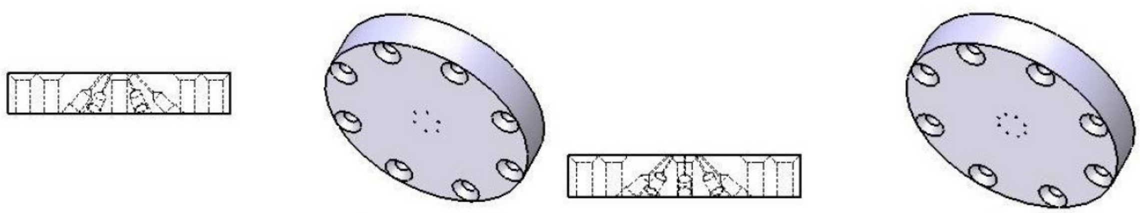
*2.3.1 The injector head*

The injector head connects the atomized fluid pipe system and the various injectors. The injector head has the option of combining two fluids from different sources, i.e., oxidizer and fuel that originate from separate cylinders. The injector head is made from stainless steel and can stand pressure up to 200 bar.
The atomized fluid is driven towards the injector through a high pressure flexible pipe connected to the center of the injector head. The injector is connected to the head by 8 bolts and it is easy to change injectors for various experiments.

*2.3.2 The injectors*

The design of the injector enables operation in experiments where two parameters can be varied: the number of the impinging jet outlets and the impinging angle. Two injectors were designed and built:

- A triplet injector, i.e., three impinging jets (Fig. 2a). The injector has 6 outlets, three of the outlets create an $80^o$ impinging angle and the other three create a $90^o$ angle. Three of the outlets were plugged to obtain the desired angle.
- A doublet/quadruplet injector with two or four impinging jets (Fig. 2b). The injector has 8 outlets, four of the outlets create an $80^o$ impinging angle and the other four create a $90^o$ angle. For each angle, four proper outlets were plugged to obtain four impinging jets and six outlets were plugged to obtain two jets.



(a) (b)

Figure 2: The triplet injector (a) and the doublet/quadruplet injector (b)

## 2.4 The droplet size measurement system

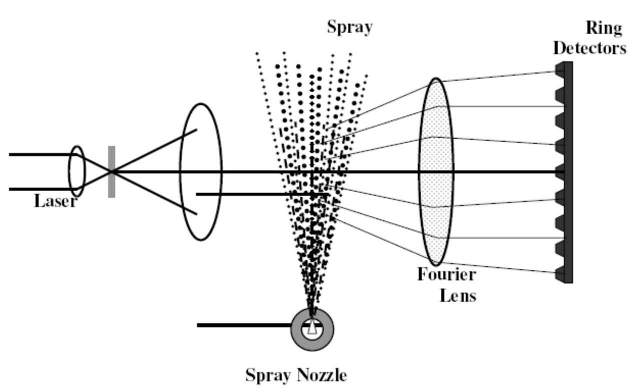
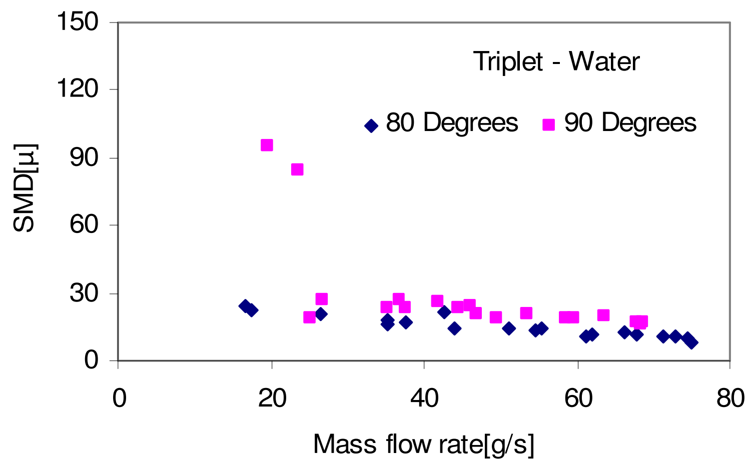



Figure 3: The droplet size measurement system

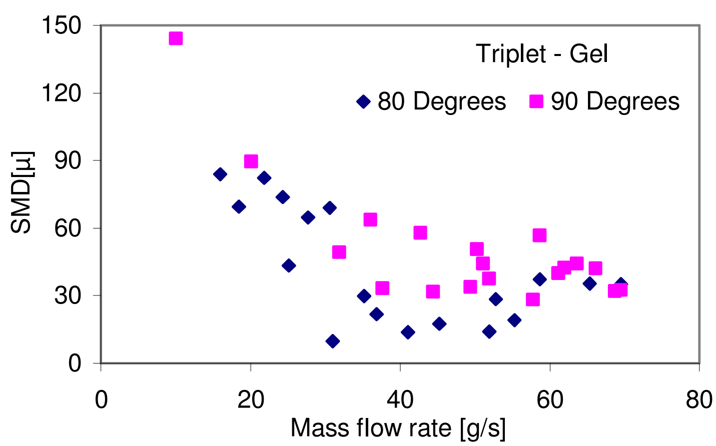
A Malvern Mastersizer X is used for the droplet size measurements (Fig. 3). The Malvern Mastersizer is located on an X-Y-Z mounting unit that allows movement by 40-50-15 cm respectively. This enables control of the measurement location whereas the injector housing stays in place. Mastersizer X is capable of measuring multi-modal droplet distributions of sizes between 1.2-600 µm. A 2-mW, He-Ne laser produces a collimated, 18 mm diameter, 0.633 µm wavelength beam of light that illuminates the droplets. The incident light is diffracted by the droplets to give a stationary diffraction pattern independent of particle position and velocity. The scattered light is focused onto a 31-element, circular photo-diode array by a Fourier transform lens. A Malvern provided Windows software based on Mie laser diffraction theory is used for the data analysis.

### 3. Results and discussion

Plain and gelled water were used as working fluids. Water was gelled with 25% wt. carbopol producing a Power-Law fluid with $n$=0.4 and $k$=8.5 Pa·s$^{0.4}$.




(a)

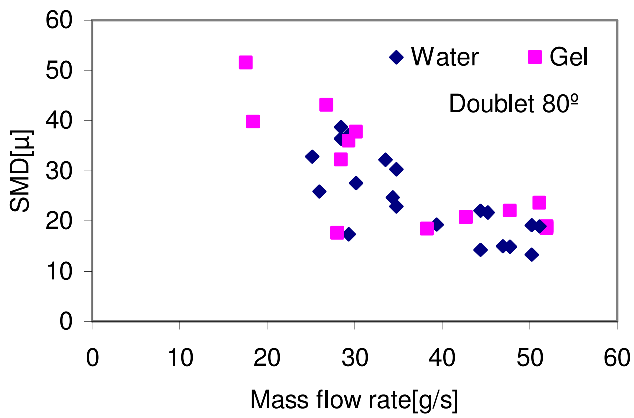



(b)

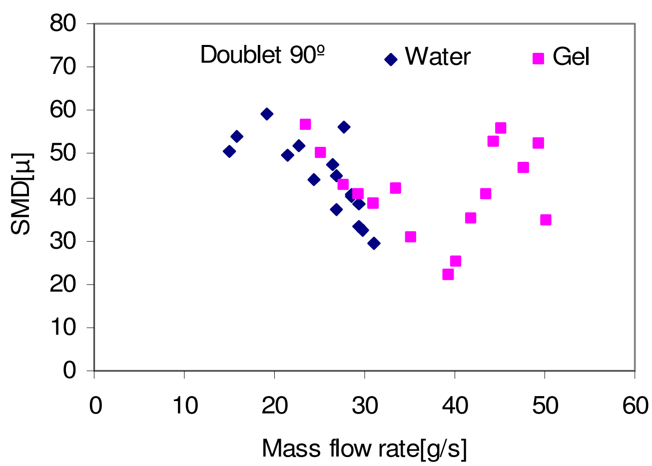
Figure 4: SMD vs. mass flow rate in a triplet injector for (a) water and (b) gel

The experimental results are presented in Figs. 4-7 (SMD vs. atomized fluid mass flow rate) for various comparisons. As also reported in previous studies[4,8], the general tendency is quite obvious; increasing the mass flow rate results in an increase in the atomized fluid Reynolds number, which decreases the spray SMD, i.e., better atomization is obtained. However, almost in all cases, increasing the mass flow rate of the atomized fluid after a certain value has no effect on the spray droplet size. This limit value is not the same for all fluids, water and gel, and injector types; yet in most cases, increasing the flow rate over 40 g/s did not produce further decrease in the SMD. For both water and gel, the limiting value was 25-30 g/s in the triplet injector, as shown in Fig. 4, and 40 g/s in the 90$^{o}$ quadruplet.

The spray resulting from doublet injectors was measured in two directions, one parallel to the exit-holes connection line and the other perpendicular to that. In general, the differences between the two measurements were minor. The mass flow rate was found to be limited in the doublet injector to approximately 50 g/s. The reason for this is the total area of the exit holes, which is the least since there are only two holes, whereas in the triplet there are three and in the quadruplet, four. As a result the pressure built inside the injection cylinder reaches its maximum value at lower mass flow rates.




(a)




(b)

Figure 5: SMD vs. mass flow rate, water and gel for (a) 80$^{o}$ and (b) 90$^{o}$ doublet injectors

*Water*

For water the minimum SMD in the quadruplet injector was 17 µ, in the triplet injector 8 µ (Fig. 4a) and in the doublet injector was 13 µ for mass flow rate of 50 g/s. Better atomization was obtained for an impinging angle of 80$^{o}$ than for 90$^{o}$, as also shown in Fig. 4. This was found to be true for all injectors.

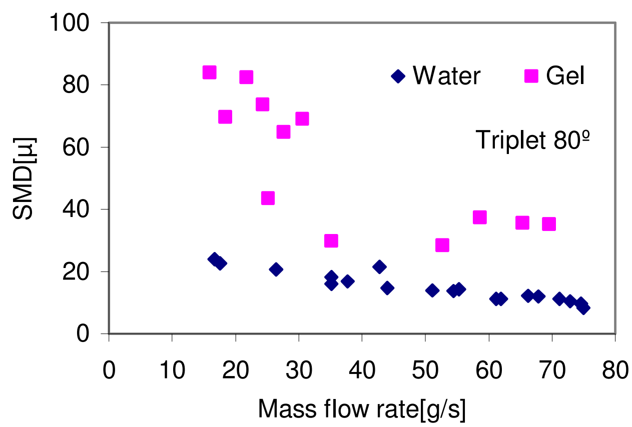
*Gel*

For gel, the minimal SMD was 10µ and it was obtained in the 80$^o$ received triplet injector (Fig 4b). For the test series with doublet and triplet injectors, lower SMD was received for impinging angles of 80$^o$ than for 90$^o$. However, in the quadruplet injector the spray with was better at 90$^o$.

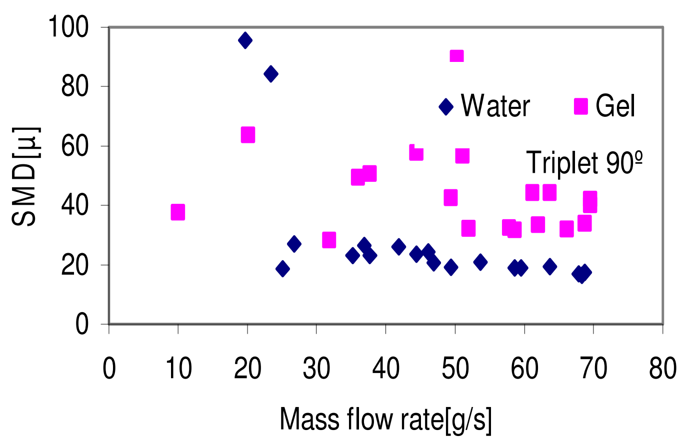
*Comparison between water and gel*

Comparative results between water and gel spray are shown in Figs. 5-7. It is quite clear that in gel spray the droplet size is larger for the same mass flow rate range. This is reasonable because gel is non-Newtonian fluid, viscous and it is much harder to atomize gel than water.

The experimental results for water exhibit a more consistent tendency whereas the gel results are scattered. There are two possible reasons for that. A. The lack of surface tension; B. The lenses of the Malvern are getting dirty from gel droplets, resulting in measurement inaccuracies.

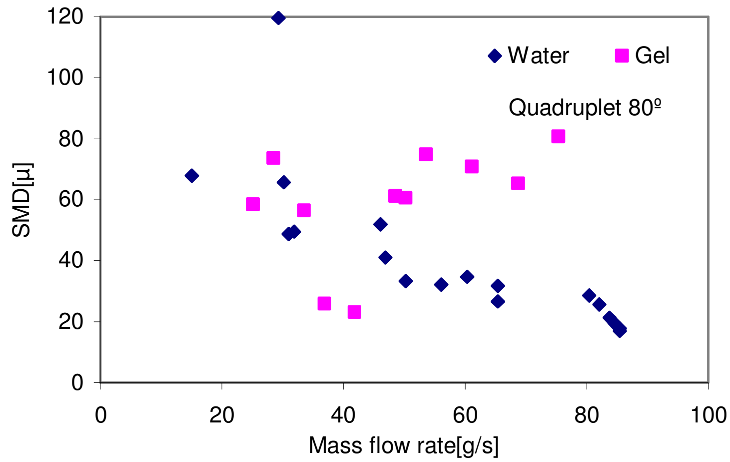



(a)

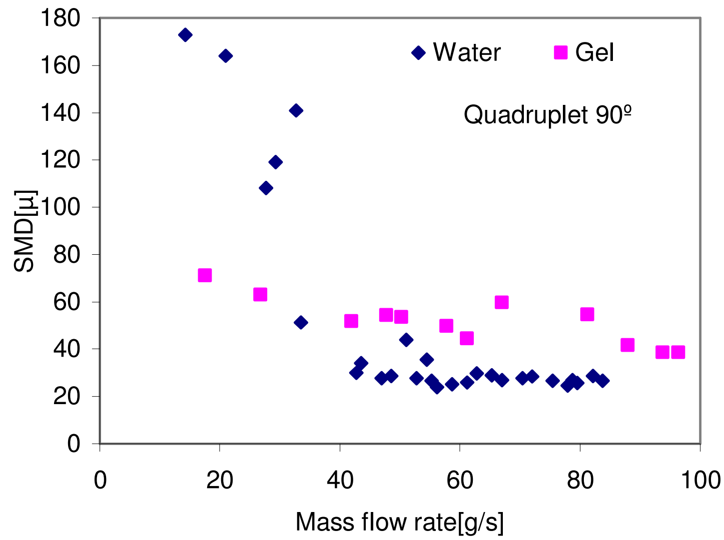



(b)

Figure 6: SMD vs. mass flow rate, water and gel for (a) 80$^o$ and (b) 90$^o$ triplet injectors




(a)




(b)

Figure 7: SMD vs. mass flow rate, water and gel for (a) 80$^o$ and (b) 90$^o$ quadruplet injectors

## 4. Conclusions

In the present study, an effort was made to identify an optimal impinging-jets atomizer for gelled fluids. Plain and gelled water were used as working fluids. Three types of impinging jet atomizers (doublet, triplet and quadruplet) at two impinging angles (80$^o$ and 90$^o$) were utilized.

The results indicate a tendency of the droplet size to decrease with the mass flow rate growth. Gels were found to be more difficult to atomize than Newtonian fluids. The triplet was found to be superior to doublet and quadruplet atomizers. The lowest Sauter Mean Diameter values were received in the 80$^o$ impinging-angle triplet injector, 8μ for water and 10μ for gel. In general, lower SMD was received for impinging angles of 80$^o$ than for 90$^o$.

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