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Spray Characteristics of High Energetic Powder Added Low-Temperature Gel Fuel Using Pressure Swirl Injector

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Abstract

Hypersonic air-breathing propulsion systems primarily utilize regenerative cooling, employing endothermic fuels to cool the high temperature inflow air. However, the phenomenon of coking in the fuel due to high temperatures within the cooling channels poses a significant challenge. Adding metal particles which form organometallic compound, or gelling fuels which enhance the thermal stability of the fuel, are known to mitigate the coking issue. Therefore, application of metallized gelled fuel may be a reasonable future fuel candidate for preventing coking. However, gel type fuels are characterized by its high viscosity and also by viscosity variations with temperature. This academic study aims to investigate spray characteristics in low-temperature environments using spray visualization experiments with a pressure swirl injector. Spray angles and break-up lengths were measured from the visualization images, revealing that viscosity changes based on temperature dominantly influence the spray characteristics in low-temperature conditions.

Keywords: *Gel fuel, Low-temperature, Spray, Spray angle, Break-up length*

1. Introduction

Hypersonic air intake propulsion systems, denoting aircraft flying at speeds exceeding Mach 5, are gaining significant attention as next-generation game changers due to their extremely high speeds and maneuverability. One of the key challenges in hypersonic flight currently lies in cooling the high temperature inflow air generated during high-speed flight within atmosphere. To address this issue, solutions have been proposed including regenerative cooling through the heat-absorbing action of fuel in the air intake section [1]. However, when using hydrocarbon-based fuels such as kerosene, exposure to high temperatures while passing through the cooling channels can lead to thermal decomposition causing the precipitation of carbon excess solids, a phenomenon known as coking. Among various methods to prevent coking, there are three main approaches that focus on fuel [2]:

1. Removing aromatic components in the fuel, which are the cause of coking
2. Preventing impurities absorbed by the fuel during storage
3. Altering the type of coking deposits through the addition of metallic elements.

In this regard, NASA has made efforts to address these challenges by focusing on approaches 3, exploring the effects of doping RP-1 base fuel with added metal particles, e.g., gel type fuel [3].

Gel type fuel such as kerosene gel is manufactured by adding a gelling agent to the base liquid fuel, giving it solid properties under low shear rates whereas, as liquid properties under high shear rate. The high viscosity and yield stress of the gel prevent particle sedimentation, and therefore make it easier

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to incorporate high energetic metal particles. This advantage not only prevents coking within the cooling channels but also enhances the fuel's density-specific impulse, thereby improving the performance of long-range, high-speed guided missiles [4]. Furthermore, it is known that increasing the amount of gelling agent enhances the endothermic capability of the propellant [5], offering the prospect of additional endothermic effects due to the gelling agent during regenerative cooling. However, the viscosity of the gel fuel directly influences atomization during injection, which in turn significantly impacts combustion characteristics. To select appropriate spray system for a combustor, understanding the spray characteristics based on temperature variations is necessary.

In this study, the spray characteristics of high energetic powder added kerosene gel fuel were examined using a pressure swirl injector commonly employed in air intake propulsion systems. Spray angles and break-up lengths were measured through spray visualization using the shadowgraph technique. Experiments were performed in the low and standard temperature range (-40°C ~ 25°C) to investigate the spray characteristic variations with respect to temperature.

Table 1. Composition of gel fuels

Ingredient	Kerosene	Thixatrol ST	Micro-Al powder (13.5 ㎛)
Content (wt %)	82	8	10

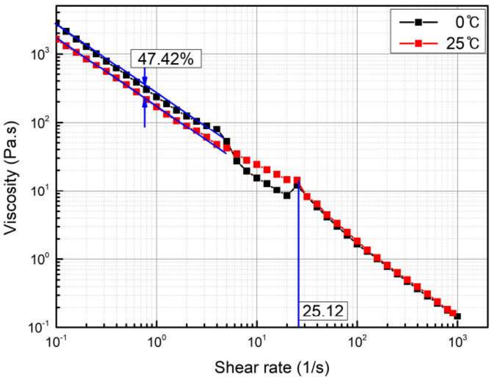

Fig 1. Shear rate vs. apparent viscosity on temperature difference

2. Experimental conditions

2.1. Gel fuel

In this study, experiments were conducted using gel fuel whose composition is shown in Table 1. Viscosity variations of the gel fuel based on shear strain can be observed in Fig. 1.

2.2. Experimental conditions

Fig. 2 represents a schematic diagram of the spray visualization experimental setup used in the study and the pressure swirl injector. The diameters of the two tangential inlets are 1 mm each, and the converging angle of the injector is set to 90°. To supply the gel propellant at an identical mass flow rate, a motor-piston supply system was selected. A refrigerated circulating bath was installed in the middle of the gel supply pipeline to lower the supply temperature of the gel. Shadowgraph images were captured using a flat light source and a high-speed camera where the camera was triggered to operate when the temperature sensor in the manifold reached the target supply temperature.

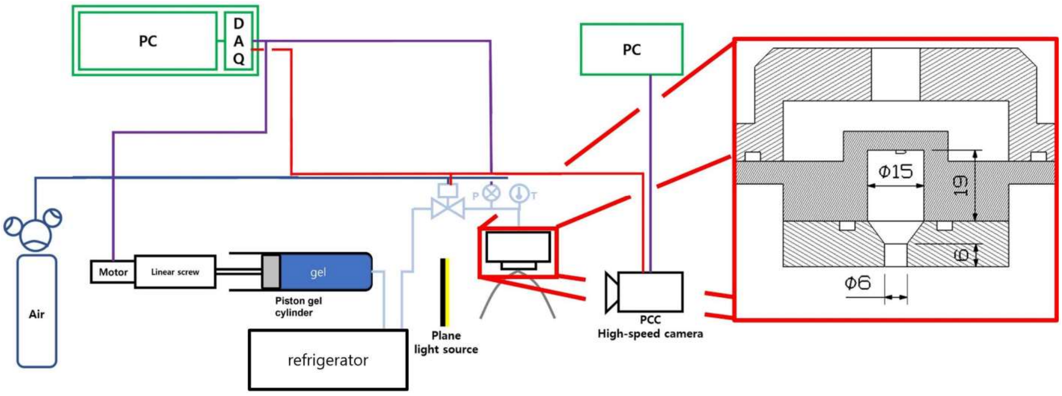

Fig. 2. Schematic diagram of the spray visualization experiment system

Table 2. Experimental conditions

Index	Value
Supply pressure	17.5 ~ 48.2 bar
Mass flow rate	16.4 ~ 99.2 g/s
Supply temperature	-40℃ ~ 25℃ (Room)

3. Experiment results

To investigate the atomization characteristics of high-energy powder additive gel fuels supplied at different temperatures, a pressure-swirl injector was utilized in this study. The atomization development process was examined based on the spray morphology at each supply temperature. Furthermore, spray angles and breakup lengths were measured through post-processing of spray images in the fully developed region.

3.1. Spray development

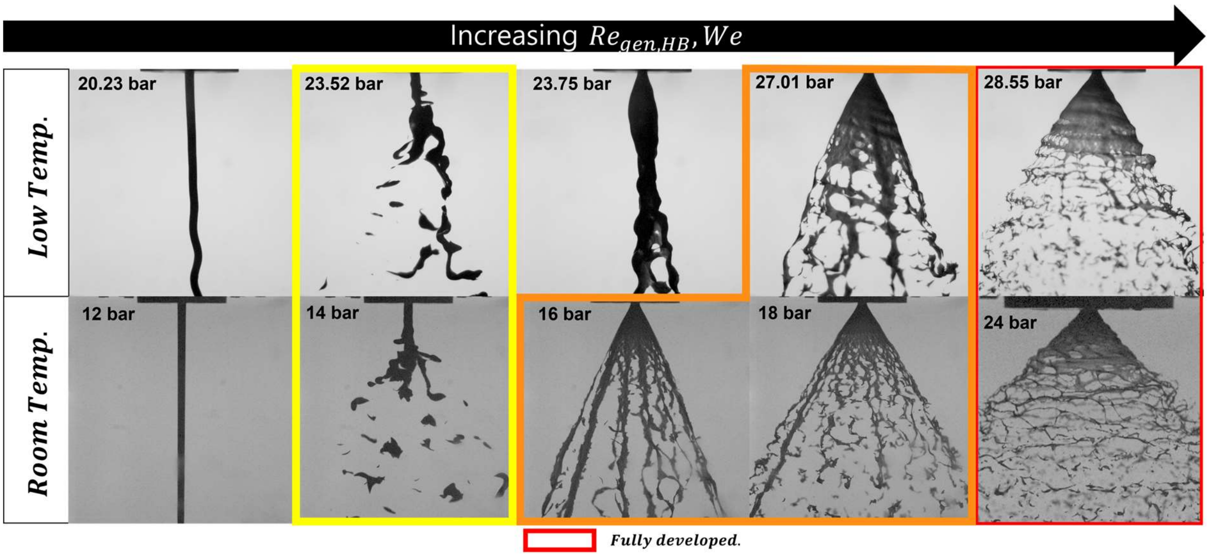

Fig. 3. Spray development process of metalized kerosene gel due to the gel supply temperature

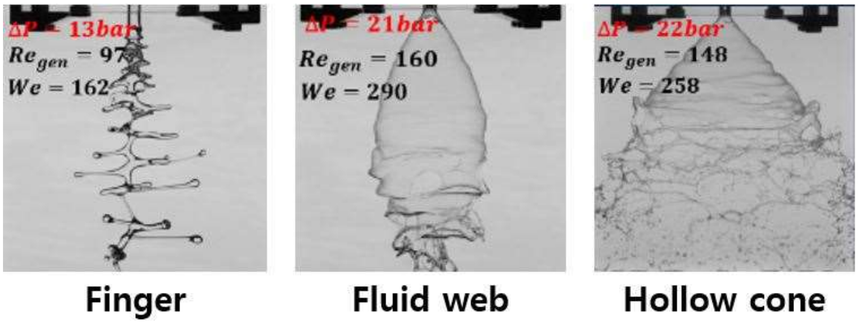

Fig. 4. Pressure swirl spray shape using simulant gel (water/Carbopol)

Fig. 3 depicts the development process of pressure-swirl spray shape of metal particle additive kerosene gel fuel at low (-40°C) and room (25°C) temperatures with varying supply pressures. It can be observed that the spray shape gradually evolves as the supply pressure increases. Additionally, due to the viscosity of the gel fuel at low (-40°C) temperatures, it is noted that the supply pressure appears to be approximately 10 bar higher at the onset of spray shape changes, and approximately 5 bar pressure difference is observed when fully developed.

Fig. 4 illustrates the general spray shape observed during the spraying process with a pressure-swirl injector using water/Carbopol simulant gel [6,7]. Generally, it is distinguished by a hollow cone shape in the fully developed state, as indicated in the red box in Fig. 3, which exhibits a similar form. However, in the case of the morphology appearing next to the liquid core, referred to as "finger," it appeared in a separated form without a connection to the central axis, as depicted in the yellow box in Fig. 3. Furthermore, unlike the fluid web form where the cone re-contracts or splits transversely, or the hollow cone where the cone splits transversely to form ligaments and droplets, a unique form was observed where the liquid film splits longitudinally immediately after the cone formation. Therefore, it is suggested that different criteria for distinguishing the breakup regions need to be established for high energetic powder additive gel fuels.

3.2. Spray angle

To evaluate spray performance, images obtained under various experimental conditions were post-processed to measure spray angles and break-up length, as shown in Fig. 4.

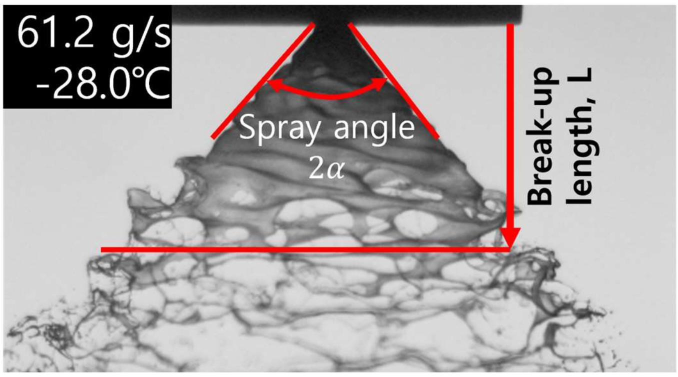

Fig. 4. Sample of spray angle and break-up length measurement

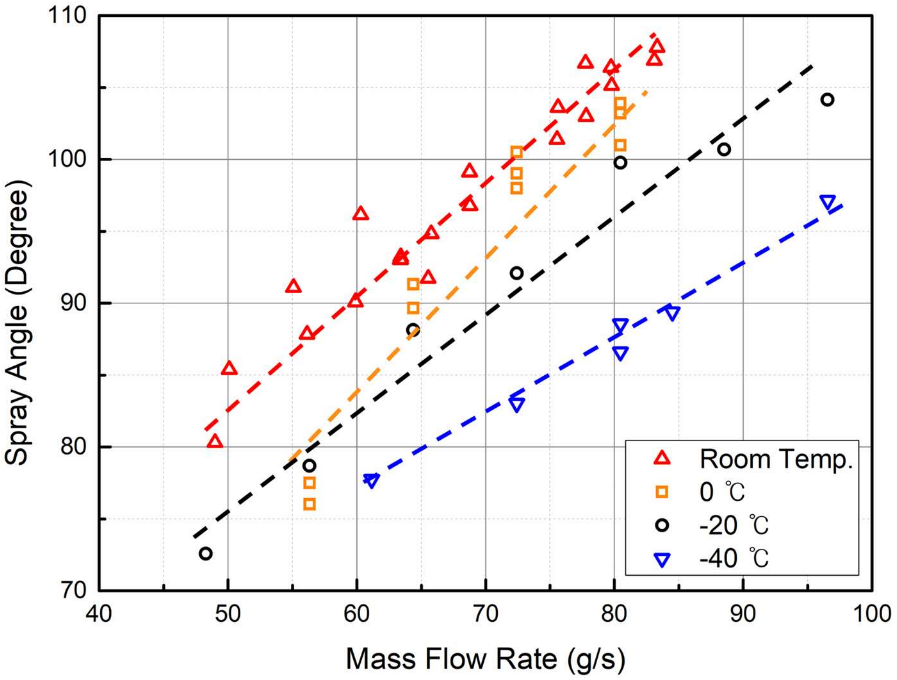

Fig. 5. Mass flow rate vs. spray angle for different temperature

Fig. 5 illustrates the variation in spray angles with respect to the mass flow rate for several values of temperature. The spray angle was measured by extracting the edges of post-processed spray images and summing the angles derived from linear fitting of the edges on both sides. It is observed that lower temperature results in smaller spray angles under the same mass flow conditions. These results are attributed to the increase in viscosity of the chilled gel propellant, which manifests as changes in spray angles [8]. The spray angles tend to increase with the gel mass flow rate while a higher supply temperature leads to a more significant gradient in spray angle. At a supply temperature of 0°C, the gradient of the spray angle appears to be significantly different from the other conditions, indicating a distinct trend. However, it is inferred that an error occurred in the experiment or measurement, as the spray angle at a flow rate of approximately 56 g/s is observed to be smaller than that at a supply temperature of -20°C.

3.3. Break-up length

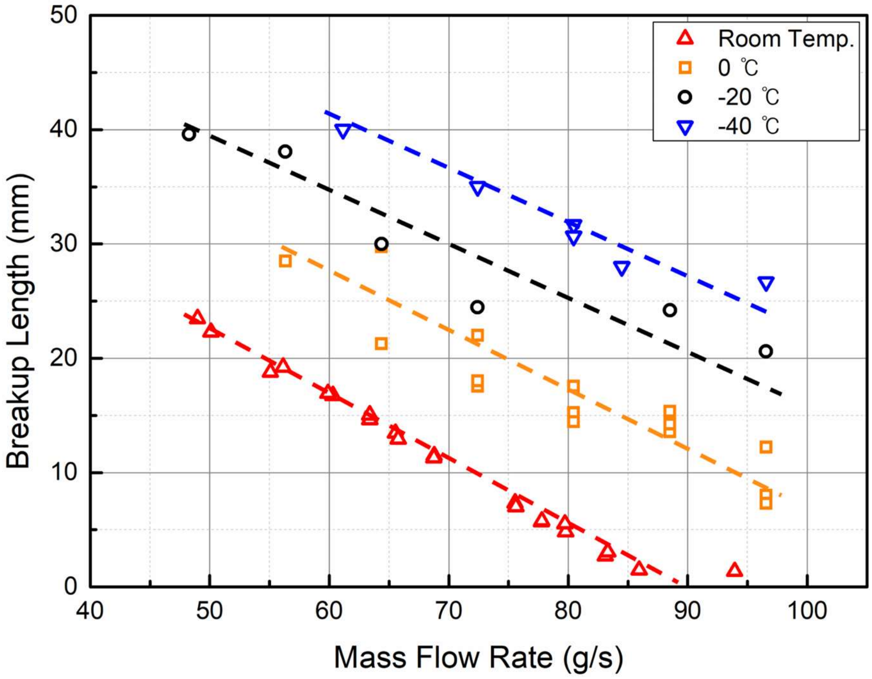

Fig 2. Fig. 6. Mass flow rate vs. break-up length for different temperature

Fig. 6 presents the variation in break-up length with respect the mass flow rate for several values of temperature. The break-up length was determined by measuring the break-up length of each frame in the spray visualization images and then averaging them. In each frame, the break-up length was measured by extracting the image intensity values longitudinally from the injector's central axis, identifying inflection points, and measuring them. A total of 1,000 images were used for each experimental condition. As the gel fuel supply temperature decreases to -40°C, the break-up length increases. This effect is due to the increased viscosity resulting from the decrease in supply temperature. With an increase in gel mass flow rate, there is a tendency for the spray length to decrease. At room temperature, when the flow rate over 85 g/s, the liquid film forms at the injector outlet and immediately splits thereafter. The measured result consistently showed approximately 1.4 mm. While variations in spray length exist on different temperature, the gradient of break-up length remains constant for all supply temperature used in the study.

4. Conclusion

In this study, spray shapes and characteristics of high energetic metal particle added gel fuel were investigated for different supply temperature range (-40°C to 25°C) with a pressure swirl injector. The gel fuel with high energetic powder additive required higher supply pressure for spray development under low-temperature conditions. Furthermore, the spray shape appeared differently from previous studies, suggesting the need for establishing separate morphology criteria. It was observed that the spray angle decreased due to the increase in viscosity caused by the decrease in supply temperature while, as expected, break-up length increased when the viscosity is higher.

It is found that at a higher supply temperature, the gradient of the spray angle increased. At the contrary, there was no variation of the gradient of the break-up length irrespective of temperature change. In addition, it is seen that spray angles (as well as break-up length) variation with respect to the mass flow rate has a monotonic trend despite variations in supply temperature. This fact implies that factors other than viscosity do not play a significant role to the spray angles and break-up length. In other words, besides viscosity variation, factors such as freezing event or alteration of gel internal structure did not occur.

Gel spray characteristics investigation for the high-temperature environment will be followed during the next phase of the study.

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