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Experimental study of the Spray Pattern of a Non-Newtonian Gelled Fluid using Two Impinging Jets

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The weaknesses of liquid propellants have led to special attention to gelled propellants in the last two decades as a way to overcome the weaknesses of these propellants. Previous studies have shown that the addition of gel-forming agents to liquid propellants converts these propellants, mainly Newtonian fluids, into non-Newtonian fluids, which greatly affects the physical properties of these propellants. In order to better understand the changes occurred in the physical properties of liquid propellants due to their gelled structure, on factors such as spraying and atomization, in this study, impinging jet injectors have been used to spray and atomize a non-Newtonian gelled fluid with rheological properties similar to gelled propellants. Analysis of the results of the present study shows that the use of impinging jet injectors causes different regimes of spraying and atomization (due to the jets' high Reynolds number) for non-Newtonian gelled fluids, some of which being fundamentally different from the regimes formed for Newtonian fluids. In general, 4 regimes including stable closed rim, unstable closed rim with the formation of vermicular ligaments, open rim with successive formation of bow-shaped ligaments and a turbulent regime have been identified in this study. The properties of each of these regimes and their details will be explained in this paper.

Keywords: *Gelled Propellant, Non-Newton Fluid, Impinging Jet Injector, Atomization, Droplet*

Introduction

Continued space exploration research and advances in defense technologies require an efficient, safe and reliable vehicle. Therefore, research into technologies to improve rocket performance is always seriously pursued by aerospace scientists [1]. Choosing the best propulsion systems is based on many factors, including performance, size, reliability, cost and life of the system, as well as the use of new technologies [2]. Despite the extensive development of solid propulsion in recent decades, especially due to the simplicity of its engine system compared to the relatively complex liquid engine system, however, these propellants, due to their weaknesses, have not been able to be a good alternative to missile systems with liquid propellants. This is due to the unique advantages that liquid propulsion systems have, compared to solid propulsion systems. Advantages such as high specific impulse, thrust management capability, hypergolicity, the ability to turn the engine on and off frequently, and proper safety are of important characteristics of liquid propulsion systems [3]. Hypergolic propellants contain fuel and oxidizing

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compounds that are ignited spontaneously upon contact, without the need for an external energy source. However, some of the main weaknesses of liquid propellants are the risks associated with their possible leakage, as well as the risks of evaporation of these fuels, especially in the hypergolic propellants compounds. Because these compounds are highly toxic and suspected of carcinogenicity and can pose health risks to personnel who deal with these substances [4]. The weaknesses of liquid propellants have led to special attention to gelled propellants as a way to overcome the weaknesses of these propellants in the past two decades. Gelled propellants are made by adding gel-making materials, typically in the form of swellable polymer or particles, into liquid propellants. The use of a gelled propulsion system not only reduces the amount of vapors from the evaporation of toxic liquid propellants and thus reduces the risk of exposure to these vapors for personnel, but also it has a higher density compared to liquid propellants, so that their storage tank can be made smaller [5]. In addition, minimizing the risk of unwanted contact of hypergolic propellants with each other, both on the ground and during missions, is an important consideration because hypergolic propellants ignite spontaneously when contact with each other and cause fire. For this reason, reducing the risks of leakage and spillage resulting from the gel-making of liquid propellants is another benefit of gelled propellants. In addition, high-energy nanoparticles could potentially be suspended in gelled propellants to further enhance the performance of its propulsion systems [6]. In fact, making gelled propellants is in line with making propellants that include the advantages of both liquid and solid propulsion systems and do not have the disadvantages of both systems as much as possible. These propellants have the ability to be stored like solid propellants and also likewise, have high density impulse. On the other hand, these propellants, under pressure, have the ability to flow like liquid propellants, which has caused these propellants to have throttling restart capabilities similar to liquid propellants [7]. Due to the flexibility, safety and capabilities of gelled propellants, these propellants have found various applications. These include their use in torpedoes propulsion, airborne cruise missiles, smart propulsion missiles, satellite launch systems, advanced missile boosters and ejection seat systems. Previous studies have shown that gel-forming agents added to liquid propellants convert these propellants, which are primarily Newtonian fluids, to non-Newtonian fluids. Unlike Newtonian fluids whose viscosity is not dependent on shear stress, in non-Newtonian fluids viscosity is strongly a function of shear stress. Non-Newtonian fluids are divided into several categories, including shear- thinning and shear-thickening non-Newtonian fluids. Fluids that exhibit shear thinning properties are fluids whose viscosity decreases due to increased shear stress, while non-Newtonian shear thickening fluids exhibit the opposite property. Viscosity acts as an agent of damping during the atomization process so that the more viscous the fluid, the larger droplets are formed during the process. In addition, viscosity can affect the mass flow rate of the injector as well as how the spray is formed [8]. Larger droplets directly reduce combustion efficiency and affect combustion instability in rocket engines [9]. For this reason, gel-making materials that are added to liquid propellants must be selected in such a way as to give these propellants a shear-thinning property so that when they are ejected from the injector with high pressure, their viscosity effectively decrease in a way that they behave like a Newtonian fluid. In addition, previous studies have shown that the addition of gel-forming agents to liquid propellants and their conversion to gelled propellants alters their physical properties (viscosity, surface tension, density), and these changes in turn affect spraying, atomization and combustion of these propellants. This study has aimed for the understanding of the changes occurred in the physical properties of the propellants due to their gelled structure, on factors such as spraying and atomization, because the correct design of injectors and combustion chamber system requires better understanding of these factors.

Impinging Jet Injector

Atomization and spray formation in the process of spraying from injectors are important and of effective factors in efficient combustion. Injectors commonly used in rocket engines include Coaxial, Pintel, Swirl, and impinging jet injectors [4]. Impinging jet injectors are popular due to their relative simplicity in construction, high efficiency and performance, and good atomization and mixing properties, and therefore are used in liquid and gelled propulsion engines where the reactors mix is obtained easily with impinging of the fuel jets and oxidizer and moreover, due to low cost and high efficiency, these kinds of injectors are still receiving special attention today. The combustion efficiency of these engines is highly dependent on the uniformity of the mixture created by the injectors and the jet injector provides a suitable and convenient way to achieve the control of droplet size, good spray distribution and proper mixing in which the liquid jet's dynamic head is used for the instability of the impinging flow. In these types of injectors from the impingement of two identical cylindrical jets, a wide liquid sheet is formed in the plane perpendicular to the two jets, which is the bisector of the angle between the two. This sheet extends radially from the impingement area. The formed sheet then immediately becomes unstable and breaks up and due to the effect of surface tension, viscosity, inertia and aerodynamics; it turns into ligaments and droplets [10]. As a result of the impingement of liquid jets, various structures of the flow can be seen according to the Reynolds and weber number. Figure 1 shows a schematic of the impinging jet injectors and their flow. The shape and thickness of the liquid sheet depend on the angle of impingement of the two jets, the diameter of the jets, the velocity of the jets, the length to diameter ratio of the injector, the flow length of the jets before impingement and the physical properties (viscosity, surface tension, etc.) of the fluid. Most studies have used Newtonian fluid in impinging jet injectors for their research and experiments. These studies have investigated the effect of factors such as injector geometry parameters and physical properties of the fluid on different regimes resulting from jet impingements. Unfortunately, not many studies on non-Newtonian fluids have been performed to investigate the above factors, and especially very few studies have examined gelled propellants that show non-Newtonian properties. For this reason, and due to the increasing importance of gelled propellants, the purpose of this study is to experimentally investigate the atomization of non-Newtonian gelled fluids at different velocities and angles of jet impingements. The results of this study can help us better understand circumstance of spray formation in systems using hypergolic gelled propellants, which in turn helps better designing of the injectors and combustion chamber system.

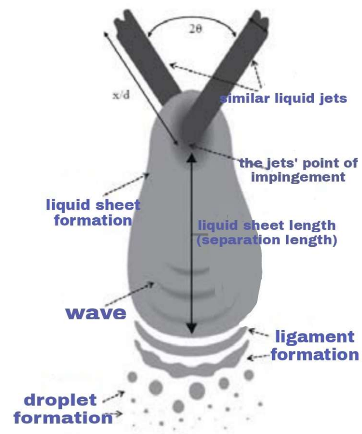


Figure1- Schematic of the impinging jet injector and the resulting flow[5]

Literature Review

Rahimi and Nathan [11] have recently studied the effect of the physical properties of gelled propellants on their atomization behavior. In their study, a three-jet impinging injector was used to spray the gelled propellants. In this injector, nitrogen flow passed through two side jets with variable angles of 50 to 80 degrees and the gelled propellant passed through the middle jet. Their findings showed that the spray pattern formed is not asymmetrically axial and also the smaller angle of nitrogen jets causes better atomization and the average sauter diameter increases by increasing the viscosity of the gelled propellants (due to the increasing of the concentration of gel-making materials) and also by increasing the mass flow rate of the gelled propellants. Jayaprakash and Chakaravarthy [12] have studied the atomization properties of a gelled propellant consisting of Kerosene and Aluminum using an impingement jet injector at injection pressures of 3 to 7 bar by changing the injector diameter and the angle of impingement between them. Their findings show that with increasing injection pressure, the separation length and spray angle decreased and this trend is more evident in the smaller angles of impinging jets. Van Kampen et al. [13], As well as Madlener et al. [14], investigated the spray and combustion properties of a jet A-1 gelled fuel by adding 10 or 80 μm aluminum particles and a concentration of 0-40 wt.%. Their findings showed that the breakup length and width of the gelled sheet decreased with increasing Reynolds number, while the addition of more aluminum particles increased the above properties. They have also observed a new regime called the ray-shaped regime, which is not present in the observed regimes for Newtonian fluid spraying. Using the method of linear instability analysis and combining it with a modified experimental equation, Yang et al. [15], investigated the instability and breakup of the sheet formed by the impingement of the impinging jets of a gelled propellant. Chojnaki and Feikema [16, 17] studied the behavior of liquid sheets formed through the impingement of two jets of a gelled propellant experimentally and theoretically. Their study showed that the instability that causes the liquid sheets to break up and turn into ligaments appears in the Weber number between 400 and 500. Fakhri et al. [1٨], investigated the effect of injector inlet geometry and its dimension ratio on the liquid sheet breakup for a gelled propellant. Their study showed that longer injectors formed a more stable jet flow and delayed the process of breaking up of liquid sheet formed by the impingement of the jets in these injectors, which caused the length of the sheet formed for jets with larger lengths become greater than the length of the sheet formed for jets with smaller lengths. However, their study shows that the length of the injectors does not have a significant effect on the breakup length. The effect of fluid rheology properties on the output fluid field of non-Newtonian gelled fluids was investigated experimentally and analytically by Mallory [5]. In this study, the effect of different geometries of impinging jets and change of different fluid parameters on the instability of the sheet resulting from the impingement of the jets, its breakup length, ligaments diameter and droplets size were investigated by analyzing the images obtained from the high-speed cameras. The results of these studies showed that the viscosity of non-Newtonian fluids is not the only factor that determines how they are atomized and sprayed, but also the interaction of gel-forming agents and solvent at the molecular level plays a key role in how they are atomized and sprayed. Rodrigues [4] used the PDA (Phase Doppler Anemometry) method to measure droplet diameters and velocities in the outlet flow of impinging jet injectors for non-Newton gelled fluids. The droplet diameter was measured through the phase difference between the two signals and the droplet velocity using the Laser Doppler Anemometry method, which is based on Doppler shift. The results of this study showed that generally, by increasing the transverse distance from the centerline of the spray, droplets with larger size and lower axial velocities have been observed.

Test Method

In order to investigate how the spray is formed in systems using gelled hypergolic propellants, it is necessary that the material used in the test to be a non-Newtonian material showing shear thinning properties. That is why the combination of water and Xanthan gum (0.4% weight of Xanthan gum + 96.6% weight of water) is used to perform this experiment, having the desired properties. Addition of Xanthan gum which is a gel-forming agent to water has increased the density of this compound compared to water and made the value of this parameter to 1050kg/m^3. Figure 2 shows a schematic of the fluid supply system to the injectors. As can be seen, this system consists of a fluid tank in which the desired fluid is poured, which is controlled by a fluid outlet valve from this tank. A pump directs the fluid to another tank called a high-pressure tank. The fluid entering the high-pressure tank is pressurized using a nitrogen gas tank with an outlet control valve and a regulator to regulate the outlet pressure. It then exits the high-pressure fluid from the high-pressure tank and after being divided into two parts, each part reaches a valve. After each valve, a pressure gauge is used to measure the pressure of the jets. After the fluid reaches the jets and the fluid test is performed, it returns to the original fluid tank to be used again to charge the high-pressure tank. During the test, the nitrogen tank is connected to the high-pressure tank, keeping the fluid pressure constant due to its reduction during the test, which means that the liquid is replaced with nitrogen gas, which allows the fluid finally to be injected at the desired pressure into the injectors. The diameter of the injectors used is 0.606 mm, their length is 43.02 mm, the pre-impingement length of the jets is 5 mm, and the angle of impingement of the jets is 80 degrees. The shadowgraphy method is used for analyzing the images captured using high-speed camera. Here, a pulsed light source called a photo freezer is used for the shadowgraphy. This light source has a minimum pulse of 125 nanoseconds and a maximum frequency of 1000 Hz. Also, a camera with a maximum capturing rate of 1000 frames per second and a minimum exposure time of 15 nanoseconds has been used to record the video of the desired phenomenon. The camera is synchronized with the light source in such a way that after each light pulse by the light source, its sensor is activated and it captures the image. This allows us to record fast-moving phenomena without blur.

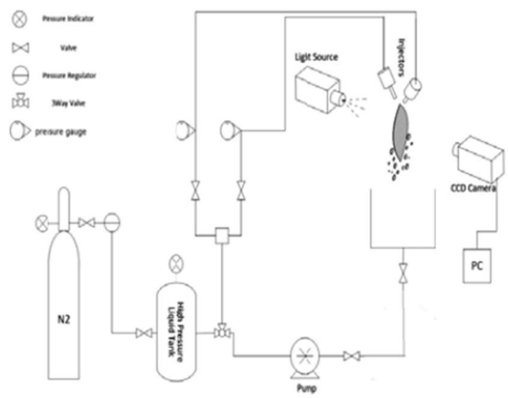


Figure 2- Schematic of the fluid supply system to the jets and how to place the light source and the camera for shading

Rheological Properties

The rheological properties of the fluid were measured using a rotary rheometer. In Figure 3, shear rheology for this fluid is shown.
The rheological behavior of non-Newtonian fluids can be described by the power law in the measured shear rate range as follows:

$$\eta = K\gamma^{n-1} \quad (1)$$

In which η is the shear viscosity, corresponding to the shear rate. K is the consistency index and n is the flow behavior index calculated as 2.5738 and 0.265 respectively from the rheological behavior diagram of the fluid (Figure 3). Describing the behavior of non-Newtonian fluids due to shear rate dependent viscosity cannot be done with the normal form of dimensionless numbers used to describe the behavior of Newtonian fluids. For this reason, their modified form should be used for calculation. In this research, an extended form of the Reynolds number formula based on the power equation proposed by Metzner and Reed (1955) [19] is used:

$$Re_{gen} = \frac{\rho u^{2-n} d^n}{K\left(\frac{3n+1}{4n}\right)^n 8^{n-1}} \quad (2)$$

In this equation, u is the jet velocity and d is the diameter of the impinging injector.

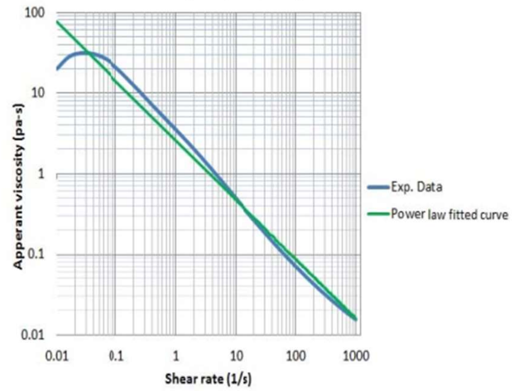


Figure 3 – Shear viscosity as a function of shear rate for the combination of water and Xanthangam (0.4%) w/w

Analysis of results

In this section, different regimes resulting from the impingement of jets at different velocities are examined. In general, the regimes of impinging jets for non-Newtonian fluid used in this research can be classified as follows:

Stable Closed Rim Regime

As can be seen in Figure 4a, when impinging jets collide at low velocities, an almost elliptical sheet of liquid forms that is surrounded by a thick rim created by the force of surface tension. This liquid sheet is relatively stable, but a little wavy, and its shape is determined based on the balance between viscous, momentum and surface tension forces at the sheet boundary. The reason for the wavy liquid sheet in this regime is the existence of hydrodynamic waves that originate from the point of impingement of two jets, however, these waves are damped downstream due to the high viscosity of the gelled fluid and disappear so that the surface of the liquid sheet becomes smooth and even at downstream. In this regime, momentum jets are not enough to overcome the surface tension at the periphery of the sheet, therefore, the rim becomes thicker than the liquid sheet by collecting the liquid in itself. Downstream of the liquid sheet (tip of the liquid sheet), the rims on either side of the liquid come together to form a jet stream, which breaks up downstream under the Rayleigh-Plateau instability, forming very large droplets. They are larger than the diameter of impinging jets, and this type of behavior is well explained in sources such as Lefebvre [8] and Ahmed [20]. In a stable closed rim regime in non-Newtonian liquids, contrary to Newtonian liquid sheets in which the inertia is balanced by surface tension forces, viscous forces also influence the equilibrium of forces in sheets and affect the size and shape of sheet. The high viscosity of the gelled fluid actively acts on the entire surface of the liquid sheet and causes damping and loss of momentum of the jets and as a result, reduces its radial expansion. Moreover, viscosity acts as a supporting force of the surface tension around the liquid sheet and reduces the instability of the rim.

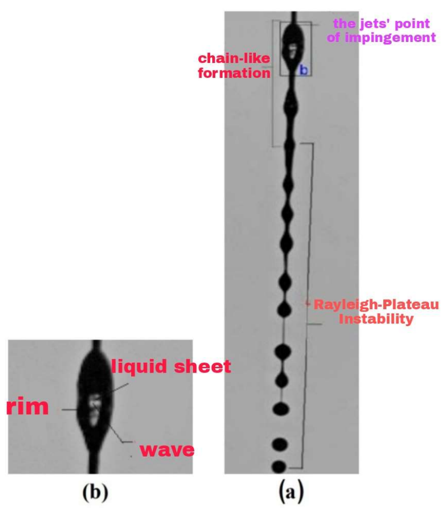


Figure 4- Liquid sheet formed from the collision of the impinging jets with Reynolds 1377 (the jets' velocity: 2.81 m/s)

Unstable Closed Rim Regime with the Formation of Vermicular Ligaments

As the velocity of the jets increases (Figure 5a), the instability of the liquid sheet due to the growth of hydrodynamic waves increases (Figure 5c) and the length and width of the liquid sheet increase quite noticeably due to the increase of the velocity of the impinging jets and consequently the jets momentum force. These waves also cause instability of the rim around the liquid sheet (Figure 5b), and as instability, which is affected by the Rayleigh-Plateau mechanism, grows in the rim , the local momentum force become greater than the local surface tension force, resulting in formation of the bead-like shapes in the rim (5b) which grow continuously throughout the rim and can cause the formation and growth of vermicular ligaments that are attached to the rim, a phenomenon that is clearly visible in Figure 5e, which is another frame from a video taken from this regime. If the velocity of the liquid sheet is low, the growth of these bead-like shapes and ligaments will not be enough to separate from the rim, and after the end point of the liquid sheet, they will merge. Downstream of the liquid sheet (liquid sheet tip), the rims on both sides of the liquid sheet come together to form a jet stream that breaks up due to Rayleigh-Plateau instability and forms droplets (figure 5d).

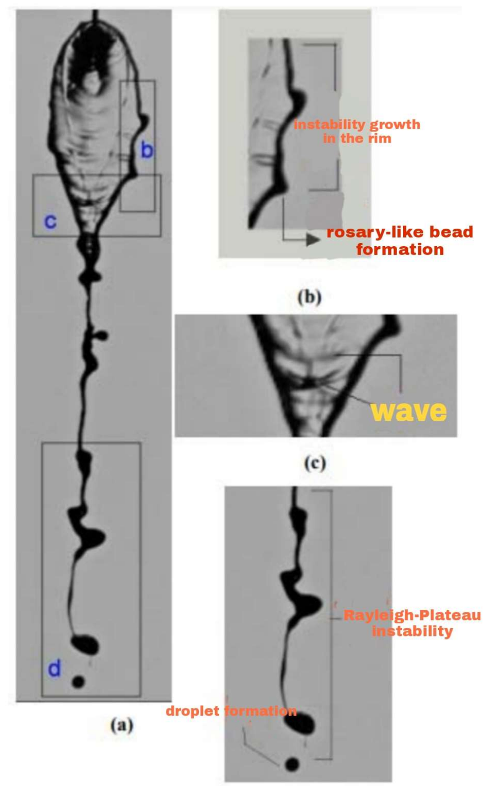


Figure 5- Liquid sheet formed form the collision of the impinging jets Reynols 3524 (the jets' velocity: 4.83 m/s)

As can be seen in Figure 6a, in this regime the increase in the velocity of the impinging jets causes the rim to become more unstable and its wavy form to become more intense, and the formation of bead-like shapes accelerate so that the formed liquid sheet cannot carry these relatively large bead-shaped drops. For this reason, thin vermicular ligaments are formed that connects these bead-shaped droplets to the liquid sheet (Figure 6b), which then become unstable due to Rayleigh-Plateau instability and breaks up into droplets (Figure 6c). Downstream of the liquid sheet, the rims on both sides of the liquid sheet come together to form a jet stream that is affected by the Rayleigh-Plateau instability (Figure 6c). In addition, in this regime, the liquid sheet is considerably thinner due to the radial expansion caused by the increase in momentum force of the jets and also due to the instability caused by the presence of waves on the surface, which leads to the formation of holes near the rim and between two consecutive hydrodynamic waves. This phenomenon can be clearly seen in the Figure 6d, which is another frame of the video taken from this regime.

Open Rim Regime with Successive Formation of Bow-shaped Ligaments

As the velocity of the impinging jets increases, as seen in Figure 7a, the open-rim regime is observed with successive ligament formation. Unlike the closed rim regime, in this regime the rims do not reach each other downstream of the liquid sheet, however, Rayleigh-Plateau instabilities, the formation of bead-like droplets, and thin vermicular ligaments that connect these droplets to the liquid sheet, can still be observed in the rim.

In this regime, the liquid sheet, due to the growth of hydrodynamic waves caused by the impingement of two jets and also the growth of Kelvin-Helmoltz aerodynamic waves which are formed due to the difference in velocity between the liquid sheet and ambient air, becomes unstable and wavy and breaks up into bow-shaped ligaments. These ligaments are then broken up into droplets due to Rayleigh-Plateau instability, and the breakup of the liquid sheet as a ligament causes its length to shrink and becomes smaller compared to the closed rim regime.

In this regime, in addition to transverse bow-shaped ligaments, longitudinal ligaments also can be observed due to the merger of adjacent holes and network structure between two adjacent waves which these longitudinal ligaments themselves are a separate source for the production of droplets in the impinging atomization of gelled propellants. This phenomenon can be seen in Figure 7b, which is another frame of the video taken from this regime. Longitudinal ligaments need more time to collapse and high production of this type of ligament reduces the atomization efficiency. The structure of longitudinal ligaments is not observed in the sheet breakup regimes resulting from the impingement of Newtonian liquid jets. As shown in Figure 7c and 7d, increasing the velocity of the jets increases the instability of the liquid sheet and the frequency of production of bow-shaped ligaments increases, and more droplets of different sizes are separated from the separated ligaments. However, except at the two sides of ligaments, these ligaments do not break and turn into drops due to the high viscosity of the fluid used in the test.

Figure 5e- Growth of vermicular ligaments attached to the rim in the unstable closed rim regime

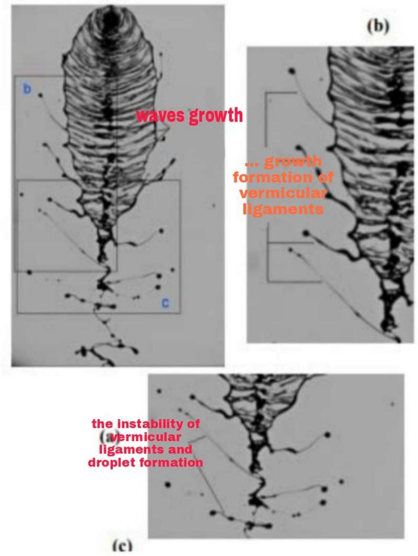


Figure 6- The regime generated from the collision of implinging jets with Reynolds 8258 (the jets' velocity: 7.89 m/s)

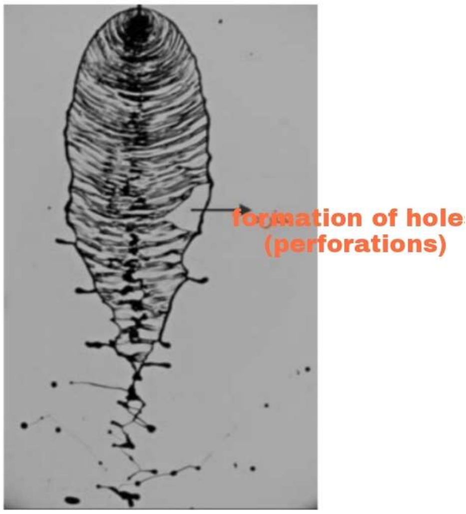


Figure 6d- Formation of holes (perforations) by the rim in the unstable closed rim regime

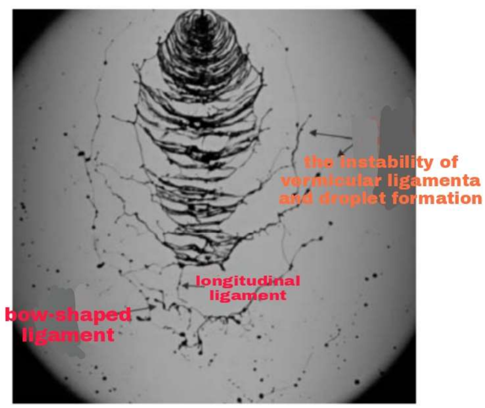
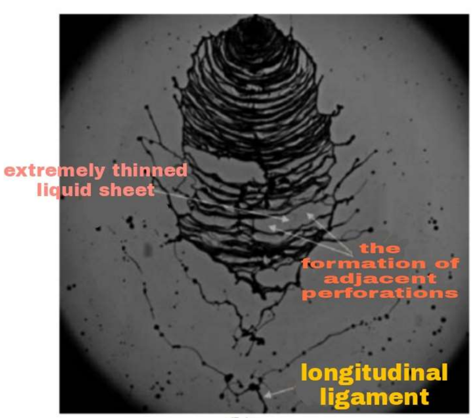
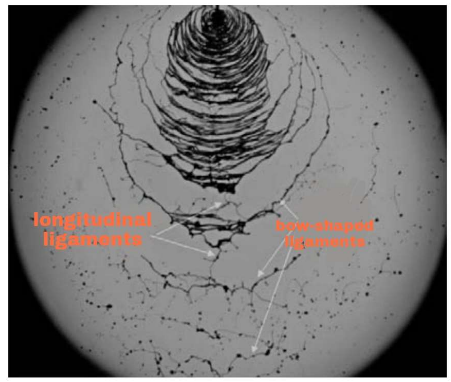


Figure 7a- The regime generated from the collision of impinging jets with Reynolds 11986 (the jets' velocity: 9.78 m/s)

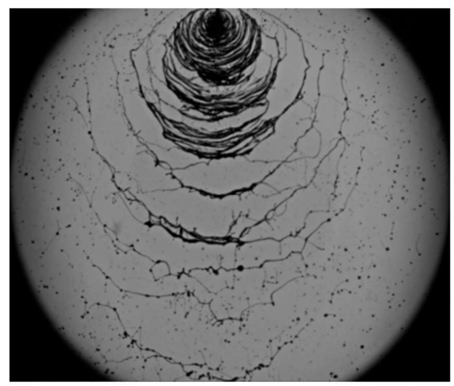


(b)

Figure 7b- The integration of adjacent perforations and formation of longitudinal ligaments



(c)



(d)

Figure 7c,7d- The regime generated from the collision of impinging jets with Reynolds (c): 16675 (the jets' velocity: 11.83 m/s), (d): 24797 (the jets' velocity: 14.87 m/s)

Turbulent Regime

As can be seen in Figure 8, by increasing the inertial force of the jets, a turbulent regime is generated. In this regime, it is generally difficult to determine the exact length of liquid sheet breakup, and the process of liquid sheet breakup is through the spread of hydrodynamic waves that form at the point of impingement of the jets and move downstream, which lead to formation of ligaments. These bow-shaped ligaments have network structure, and eventually break up into droplets. This regime is suitable for use in engines with gelled propulsion due to the fine atomization it offers, and the atomization process in this regime is improved by increasing the velocity of the impinging jets.

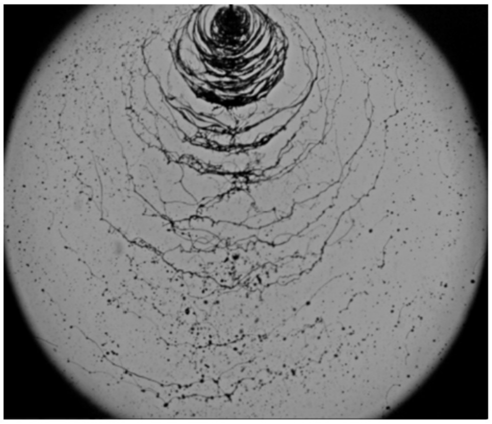


Figure 8- The regime generated from the collision of impinging jets with Reynolds 41830 (the jets' velocity: 20.1 m/s)

Conclusion

The weaknesses of liquid propellants have led to reconsideration of gelled propellants as a way to overcome the weaknesses of these propellants. In fact, making gelled propellants is in line with making propellants that include the advantages of both liquid and solid propulsion systems and do not have the disadvantages of either systems as much as possible. Previous studies have shown that the addition of gel-forming agents to liquid propellants converts these propellants, which are mainly Newtonian fluids, into non-Newtonian fluids, which greatly affects the physical properties (viscosity, surface tension, density) of these propellants. In order to better understand the changes occurred in the physical properties of liquid propellants due to their gel forming, on factors such as spraying and atomization, in this study, impinging jet injectors have been used to spray and atomize a non-Newtonian gelled liquid with rheological properties similar to gelled propellants.

Analysis of the results of the present study shows that the use of impinging jet injectors has led to different regimes of spraying and atomization (based on Reynolds number of jets) for non-Newtonian gelled fluids, some of which are fundamentally different from the regimes formed for Newtonian liquids. In general, 4 regimes including stable closed rim, unstable closed rim with the formation of vermicular ligaments, open rim with successive formation of bow-shaped ligaments and turbulent regime have been identified in this study. In a stable closed-rim regime, impinging jets collide at low velocities, forming an almost elliptical liquid sheet surrounded by a thick rim. This liquid sheet is relatively stable however wavy and its shape is determined based on the balance between viscous forces, momentum forces and surface tension at the sheet boundary. Increasing the velocity of the jets causes the formation of an unstable closed-rim regime with the formation of vermicular ligaments, in which the instability of the liquid sheet is increased due to the growth of hydrodynamic waves and the length and width of the liquid sheet increase noticeably under the influence of the momentum force of the jets. These waves also cause instability of the rim around the liquid sheet and the formation of bead-like shapes in the rim that grow continuously along the rim, creating vermicular ligaments that are attached to the rim. With increasing velocity of impinging jets, the open-rim regime is observed with the successive formation of bow-shaped ligaments. Unlike the closed rim regime, in this regime the rims do not reach each other downstream of the liquid sheet. In this regime, the liquid sheet becomes unstable due to the growth of hydrodynamic waves and aerodynamic waves and becomes wavy and breaks up in the form of bow-shaped ligaments. In this regime, in addition to transverse bow-shaped ligaments, longitudinal ligaments are also observed due to the merger of adjacent holes and network structure between two adjacent waves. The structure of longitudinal ligaments is not observed in the sheet breakup regimes resulting from the impingement of Newtonian liquid jets. With the increase of the inertial force of the jets, a turbulent regime is generated. In this regimen, the exact length of the liquid sheet breakup is basically difficult to be determined and the process of liquid sheet breakup is through the hydrodynamic waves which are formed in the impinging point of the jets and moves downstream, resulting in the formation of ligament. These bow-shaped ligaments having a network structure and eventually break up into droplets.

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