10.2514/6.2024-2221

Development of a Test Rig for Visualization of Gelled Propellant Simulant Atomization

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This work describes the development of an injector test rig to characterize the behaviour of rocket propellants in gelled form. The study included the design and manufacture of the test rig's propellant/simulant feed system, injector inserts, manifolds, frame, and propellant/simulant supply tank. Two converging injection orifices were used to form spray sheets at 45°, 60° and 90° impinging angles. In addition, MATLAB™ image processing tools were used to binarize spray sheet images and quantify the resulting fluid structures generated by the equipment. This work falls under a broader research program into gelled propellants conducted by the Aerospace Systems Research Institute (ASRI) at the University of KwaZulu Natal, Durban, South Africa.

I. Introduction

Gel propellants are defined as liquid propellants whose rheological properties have been altered by the addition of a gelling agent [1]. The current definition of a gelled propellant emphasizes its ability to behave like a solid at rest and to flow under shear. The transformation of liquid propellants into a solid-like gel paves the way for the development of new energetic, reliable, and possibly green propellants for rocket and ramjet propulsion systems. The addition of a gelling agent to a base fluid alters the properties of the base such that it behaves as a shear-dependent non-Newtonian, viscoelastic fluid [2]. In rocket propulsion, gelling agents are added to fuels and oxidisers, and the conduction of a gelation process changes the structural representation to a solid skeleton entrapping the liquid phase. The physical form of a gelled propellant is a soft amorphous solid with some degree of elasticity [3]. Mixing a fuel or oxidizer with a gelling agent to form a homogenous mixture imparts non-Newtonian flow behaviour to the product [4].

The research and development on different aspects of gelled propellants have been continuously expanding worldwide. Consequently, different research groups across the globe are now working on various aspects of the technology including formulation, rheological behaviour, atomization, and combustion [5].

The design of robust rocket propulsion components, mainly injectors, is crucial in the performance of a propulsion system utilizing gel propellants. The droplets created by the injector are directly correlated to the combustion efficiency. The application of computational methods for injector design is an emerging field of research with many advantages, including droplet identification and distribution. Computational methods are routinely employed for liquid propellant injector design because of the expansive experimental data from past empirical design methods [6]. The experimental database for gel propellant injectors is, however limited with respect to the designs and configurations that have been tested. This work focuses on the development of a test rig to visualize the spray generated by injector elements for image processing to obtain useful data to facilitate injector design using computational methods.

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II. Experimental Setup

The developed test rig shown in Fig. 1 is of modular design with single injection elements in a like-on-like doublet configuration. The design is of a flexible nature such that subcomponents can be changed and configured differently to broaden the range of experimental setups possible.

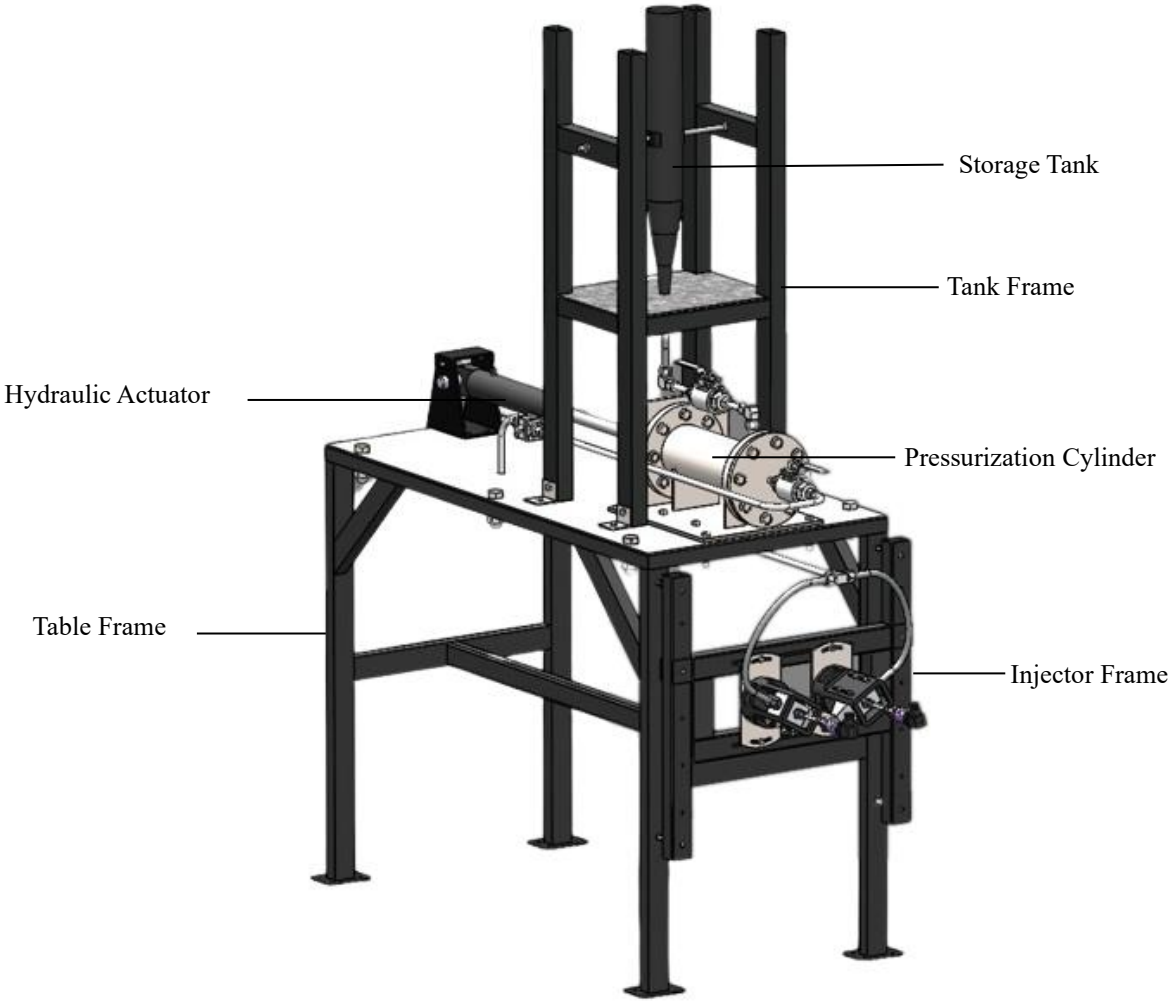


Fig. 1 Test rig assembly.

Figure 2 provides a schematic diagram of the experimental arrangement for spray sheet visualization in this study. This consists of three main systems: the gel feeding system, the injection system, and the spray visualization and data acquisition system.

The feeding system is designed to bring a continuous flow of gel to the injector manifold. The gel is stored in a cylinder with a 100 mm piston hydraulically actuated using a power pack. The cylinder and injector housing are connected by a ½ inch flexible hose. Two methods of measuring the mass flow rate were used, namely measurement of the piston displacement and measurement of the mass of gel after a test.

Water based gel simulants were used to avoid hazardous propellants for laboratory testing. Water was used as the base liquid and mixed with guar gum and xanthan gum. Simulants of 0.5, 1, and 1.5 percent by weight were used.

The injection system is designed to generate gel spray sheets for various impinging angles and allow for injection pressure measurements. The injector manifold is located on a mounting bracket that enables different angle settings and control of the impinging angle so as to make misalignment corrections. The manifold transfers the gel to the atomizer that generates the spray sheet.

The spray sheets investigated in this study were formed by two atomizers configured in the like-on-like mode. A cross sectional view of the atomizer is shown in Fig. 3. The atomizers have a 1 mm orifice with a length to diameter ratio of 10. The gel flows through 5 mm downcomers and converges to the orifice diameter.

A Chronos 1.4 highspeed camera is used to visualise and capture the generated spray sheets. The camera is capable of capturing highspeed monochrome videos from a 320 x 96 resolution at frame rates up to 40 000. Two 30 W light emitting diode lights with a soft box and diffuser were used to illuminate the spray sheets. Images

using this technique were shot at 6340 frames per second with a 12.5 mm -75 mm f/12 lens. A National Instruments™ controller (compactDAQ) is used for data acquisition and control along with a LabVIEW™ application.

Selected gels were characterized using an AR 1500ex rotational rheometer fitted with a 40 mm parallel plate geometry. Curve fitting is used to determine the relevant rheological parameters of the gelled simulants such as consistency and power law index.

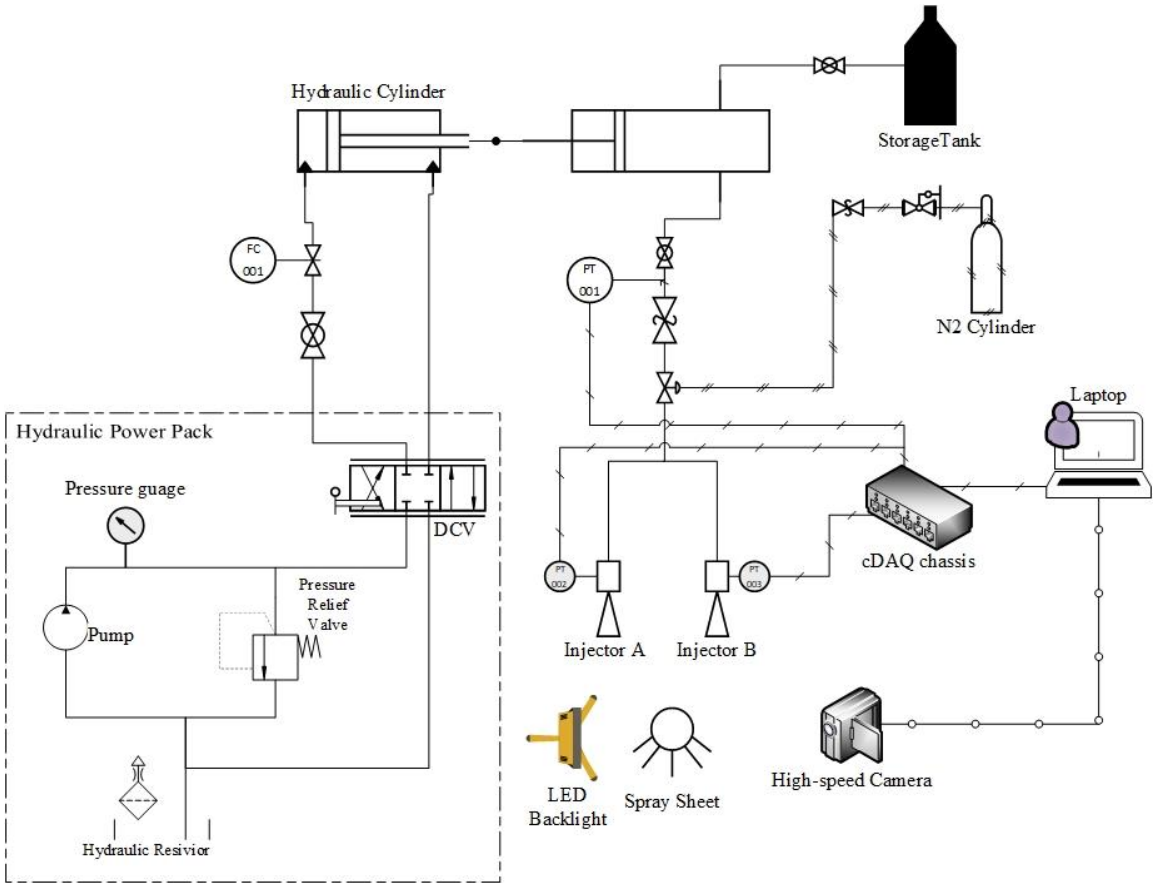


Fig. 2 Experimental setup for gel simulant spray sheet generation.

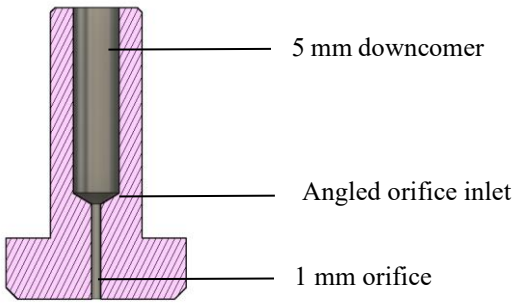


Fig. 3 Cross sectional view of atomizer.

III. Gel simulant rheological characterisation

Gel simulant characterization was carried out to verify that the prepared simulants exhibit shear thinning behaviour. This involved the use of a rheometer in controlled rate mode to detect the rheological behaviour of the simulants. A shear stress ranging from 1 to 1000 Pa was imposed on the samples to measure the shear rate and viscosity. Flow curves of two gel simulants with different gelling agent concentration are presented in Fig. 4(a) and Fig. 4(b). The compositions of analysed simulants are summarised in Table 1.

Table 1: Composition of simulants.

Sample no:	Gel simulant	Composition (wt%)		
		Water	Xanthan gum	Guar gum
1	x0.5	99.5	0.5	-
2	x1.0	99	1.0	-
3	x1.5	98.5	1.5	-
4	g0.5	99.5	-	0.5
5	g1.0	99	-	1.0
6	g1.5	98.5	-	1.5

The Williamson model, described by Eq. (1) is fitted to the shear rate versus viscosity curves because the simulants are non-Newtonian. Therefore, a non-linear model is needed to describe the viscosity as a function shear rate. The Williamson Model is used because the experimental data is generated at low shear rates where the power law fails to describe the material behaviour. In the equation η is the viscosity, $\eta_0$is the zero-shear viscosity, K is the consistency, $\dot{\gamma}$ is the shear rate, and n is the power law index.

$$\eta = \frac{\eta_0}{(1 + K\dot{\gamma}^n)} \tag{1}$$

The general nature of the curves was used to confirm that samples fall within the shear thinning region of a generalised flow curve. This is the region the power law describes (straight line on the logarithmic axes). From the curves, the simulants can be described as pseudoplastic, shear thinning material.

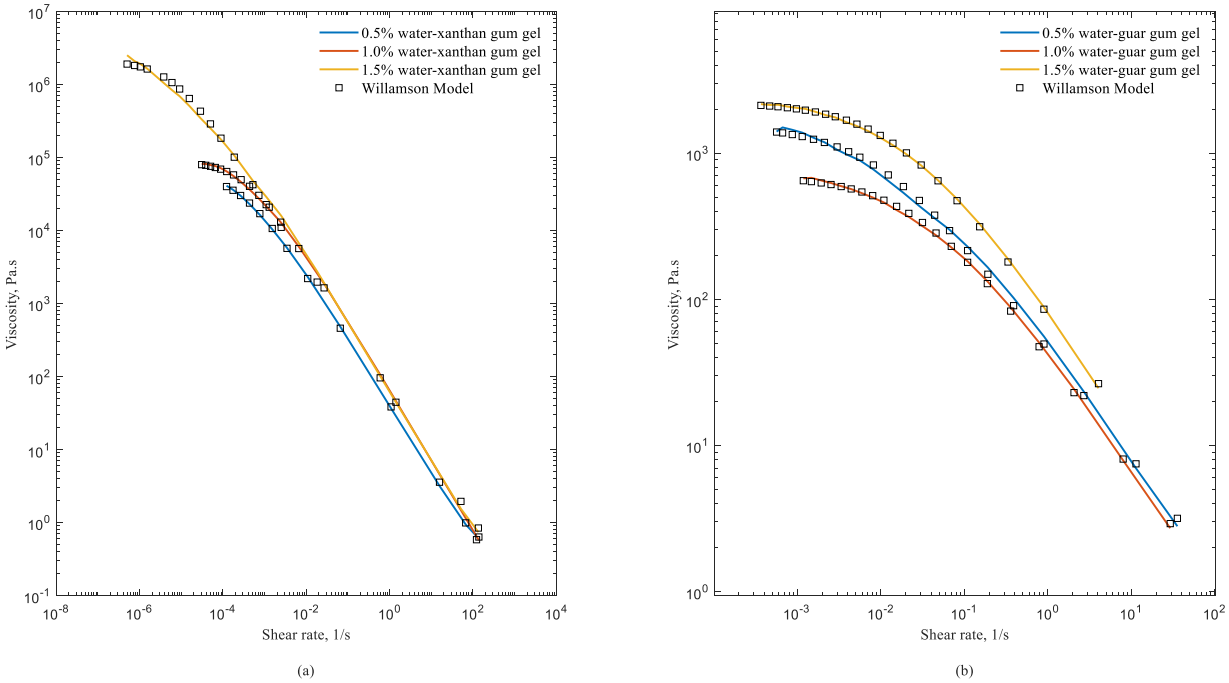


Fig. 4 Shear rate versus viscosity curves of various gel simulants.

The rheological parameters obtained from curve fitting using the Williamson model are given in Table 2. For the simulants used in this study, the gelling agent concentration did not significantly affect the rate index. The

experimental results show three distinct parallel lines for the two types of gelling agents used. Signifying that a simulant with a higher concentration features tightly linked molecules that resist deformation. Therefore, a simulant with a higher concentration requires a higher shear stress when compared to a simulant with a lower concentration to achieve the same apparent viscosity.

Table 2: Rheological parameters obtained from Williamson best-fit model.

Simulant	Zero-rate viscosity	Consistency	Rate index	Std error	Flow type
0.5% xanthan	16040	15.78	0.8976	5.553	Shear thinning
1.0% xanthan	28660	14.96	0.9379	8.414	Shear thinning
1.5% xanthan	3.45E+05	14.1	0.909	6.209	Shear thinning
0.5% guar	535.6	13.09	0.8422	4.662	Shear thinning
1.0% guar	587	15.44	0.8484	5.158	Shear thinning
1.5% guar	908.8	14.10	0.8916	3.624	Shear thinning

IV. Spray Characterisation

Characterization of the spray sheets was carried out using image analysis. The time-resolved imagery of the spray sheet was recorded with a Chronos 1.4 highspeed camera. Typical settings used for the camera are summarized in Table 3. Spray sheet images were obtained at different injection pressures. The injection pressure was regulated between 1.4 bar and 14 bar and injected into an ambient field. Spray sheets were captured for three operating conditions, namely low, medium, and high injection pressure conditions. For each condition, the spray sheets were visualized at 45-, 60-, and 90-degrees impinging angles.

Images were taken per operating condition at each impinging angle and processed using MATLAB™'s image processing tools. In this process, an image was extracted from the high-speed video footage and converted into an 8-bit grayscale image. The grayscale image was then binarized to minimise the variance of black and white pixel values. Lastly, regions of interest containing ligaments and droplets were created and analysed. Figure 5 shows the process for measurements by image processing.

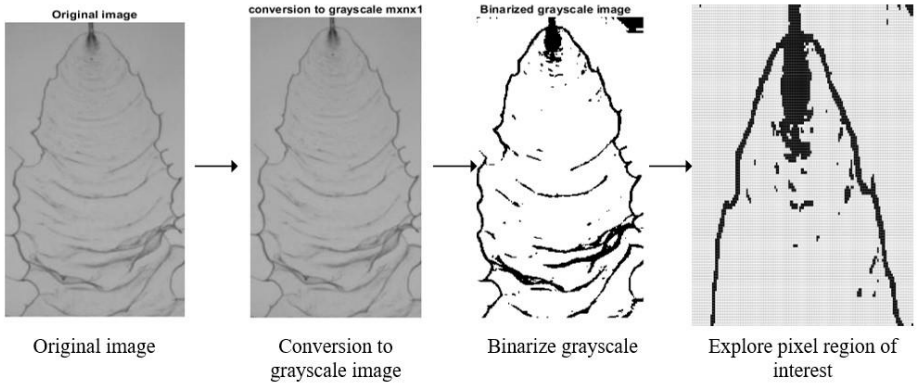


Fig. 5 Process for measurement by image processing.

Table 3 Highspeed camera settings.

Parameter	Setting
Frame rate	6340
Resolution	320 x 640
Exposure	152.16 μs
Field of view	0.331 m
Sheet to lens distance	1.4 m

V. Results and Discussion

The sheets formed at different injection pressures were observed and the resulting features were identified. The breakup length which is defined as the distance from the impinging point to the location where the sheet becomes disconnected was also determined. Breakup characteristics are named after physical structures observed in the images, similarly to work done by Manisha et al [1] and Jejurkar et al [5].

Figures 6 and 7 show spray sheets of 45 degrees impinging doublets for 0.5 wt% xanthan and guar simulants at different operating conditions. The left image shows the low injection pressure condition, the middle image shows the medium injection pressure condition, and the right image shows the high injection pressure condition.

Spray sheets involving rims were observed on simulants with low concentrations (0.5 wt%), for xanthan and guar gum simulants an unstable wavy rim was observed at low injection pressures. This pattern is suggested by Ramasubramanian et al [7]. When the injection pressure increases the rim becomes unstable and fishbone structures are observed. These structures eventually develop into fishbone patterns of symmetric distribution [8]. It was also observed that the spray sheets with unstable rims have holes that nucleate on the sheet and produce ligaments. The breakup mechanisms of the gels with respect to concentration are non-uniform. For example, 1.5 wt% xanthan gum sprays illustrated in Fig. 8 and 0.5 wt% guar gum sprays suggest that fishbone instability is a mechanism of atomization when there is a rim at the periphery of the sheet.

Stable-rimmed spray sheets were observed for guar gum simulants with a concentration of 1.5 wt%. Figure 9 presents an illustration of these spray sheets. The sheets observed at low-range injection pressure have stable rims, and their surface is smooth near the impinging point. Sprays involving rimless sheets were observed at 90 degrees for a given gel simulant. At 90 degrees impinging angle, bow-shaped impact waves were observed. These waves were the main observed feature on these rimless sheets as illustrated by Fig. 10. Bow-shaped ligaments were generated and observed in these sheets when the liquid connecting two impact waves receded. The ligaments gradually break up into smaller fragments, and in some cases, droplets. For xanthan simulants shown in Fig. 11 the resulting ligaments were continuous and created tangled webs.

Variations of breakup length with injection pressure indicate that the breakup length decreases with increasing pressure drop for a given concentration. Trends with respect to concentration for xanthan gum show that the breakup length generally increases with increasing gelling agent concentration. Thus, the breakup is delayed suggesting that gels or injectors producing high concentration rimmed spray sheets are not ideal for rocket engine applications because highly effective atomization is needed to improve propulsion performance. The opposite was observed for guar gum. Given that both gelling agents are similar, their different intermolecular interaction with the base liquid (water) is clearly different and leads to dissimilar breakup.

Spray sheets at an impinging angle of 90 degrees have a larger spray cone but this configuration features breakup of the liquid sheet into ligaments and droplets. Large spray angles can cause a wide flame within a combustion chamber resulting in hotspots that could lead to material degradation. A wider spray angle could also increase thermal loads on the combustion chamber, which in turn, may require additional cooling to the combustion chamber walls. The atomization performance of gels is greatly influenced by viscosity meaning that the type of gelling agent used has a significant impact on the size of droplets in the spray. In this study, the spray sheets investigated feature ligaments which must still undergo breakup into droplets. This delayed breakup is because of the gel's viscosity and the process of ligament breakup into large droplets. Droplets of large size take longer to evaporate in the combustion chamber, which may lead to incomplete combustion and decreased performance of the motor.

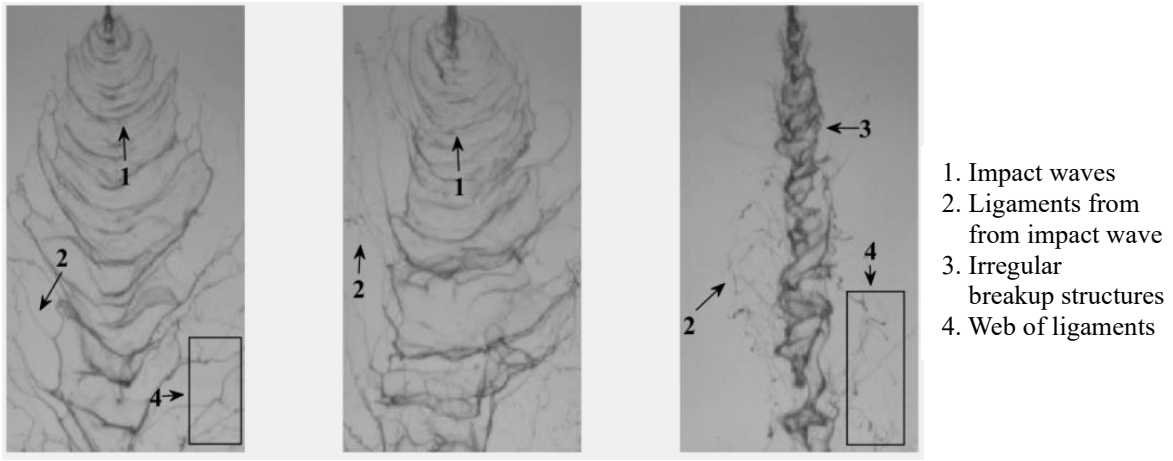


Fig. 6 Spray sheet images of 60 degrees impinging doublets for 0.5% xanthan for different injection pressures.

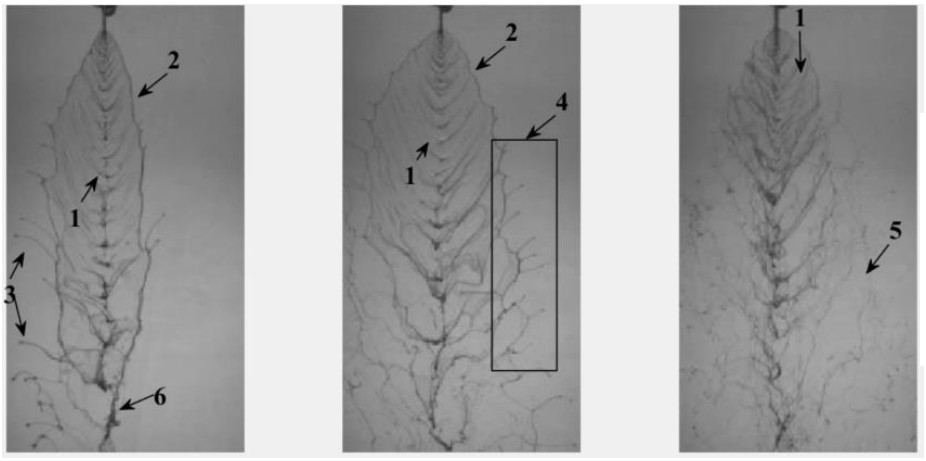


Fig. 7 Spray sheet images of 60 degrees impinging doublets for 0.5% guar for different injection pressures.

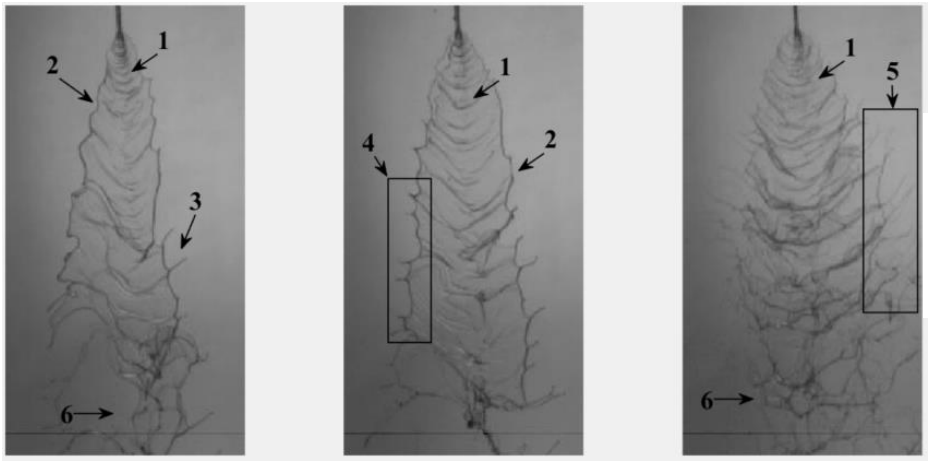


Fig. 8 Spray sheet images of 45 degrees impinging doublets for 1.5% xanthan for different injection pressures.

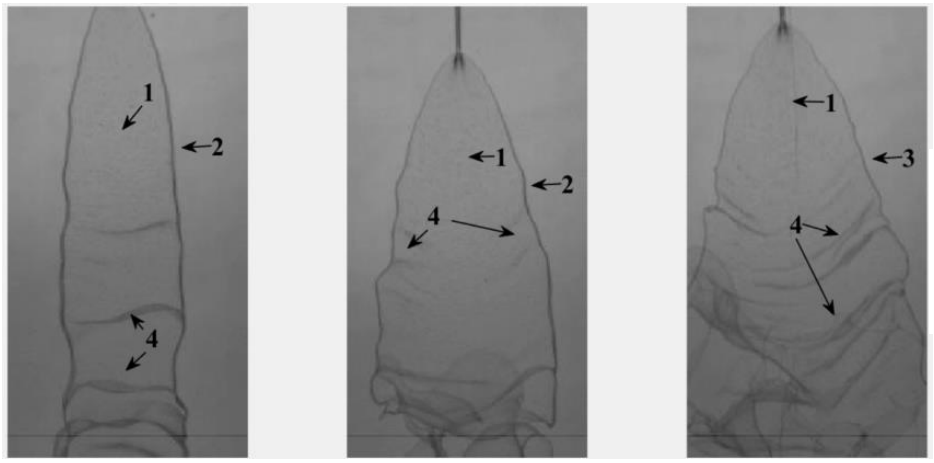
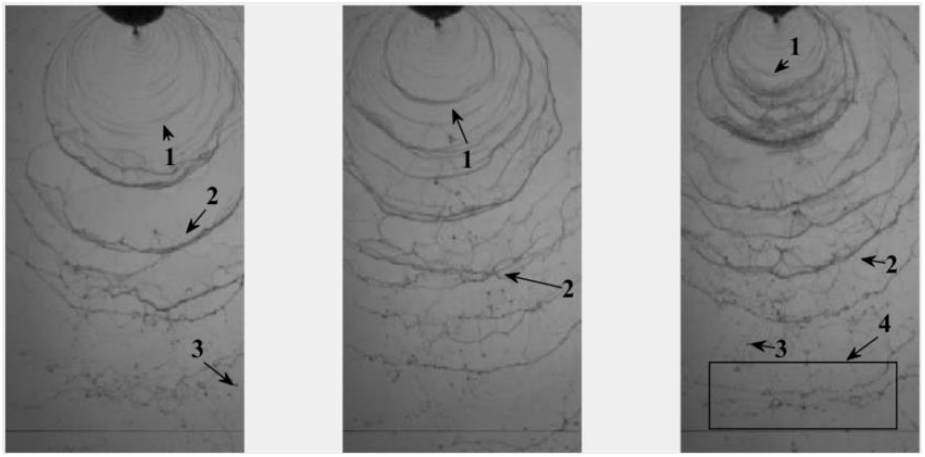
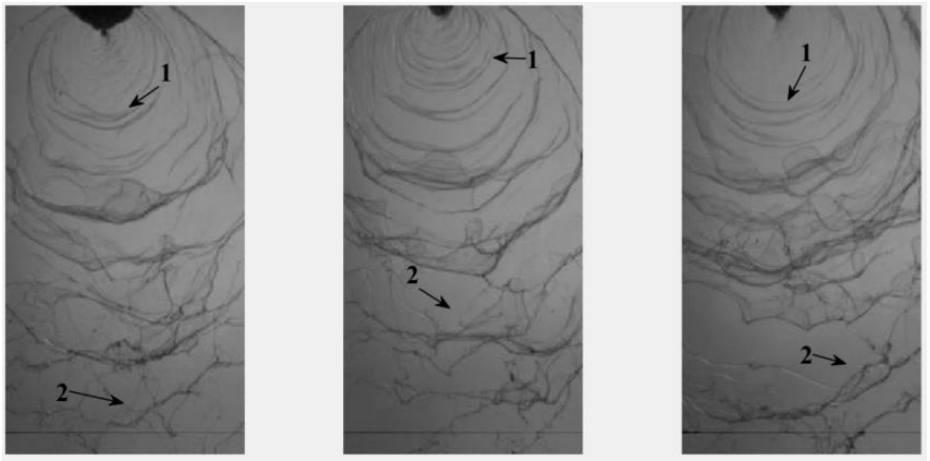


Fig. 9 Spray sheet images of 45 degrees impinging doublets for 1.5% guar for different injection pressures.



1.Impact surface wave
2. Ligaments
3. Droplets
4. Cluster of ligaments and droplets

Fig. 10 Spray sheet images of 90 degrees impinging doublets for 1.5% guar for different injection pressures.



1. Impact surface wave
2. Web of ligaments

Fig. 11 Spray sheet images of 90 degrees impinging doublets for 1.5% xanthan for different injection pressures.

The test rig provided a controlled environment for studying gel propellant spray characteristics and behaviour. Visualising the spray sheets enabled the assessment of important parameters such as spray angle, breakup length, and sheet breakup. By understanding how gel propellants behave during the spraying process, their formulation for enhanced ignition, combustion efficiency, and stability can be optimized. The results obtained mark a primary milestone in advancing the understanding and development of gel propellants. The next step involves conducting a comprehensive analysis of spray patterns of green gel propellants. Amongst those considered include ammonium dinitramide (ADN) and hydroxylammonium nitrate (HAN).

VI. Conclusion

Spray sheet images have been captured for a single element injector in a like-on-like impinging doublet configuration using a number of gelled propellant simulants as the working fluid. These were formulated at gellant percentages analogous to real propellant formulations, giving insight to the likely behaviour of spray sheets inside a rocket engine chamber with similarly configured injector elements.

The study comprises the initial step in the development and implementation of gel propulsion technology for rocket application by ASRI. The test rig is intended to facilitate advancement of gel injector design methodologies by providing experimental data against which simulation results derived from computational methods can be compared. The test rig's commissioning has enabled the generation of qualitative and quantitative data that can be used to validate CFD results as the development of propulsion systems utilizing gelled propellants progresses.

Acknowledgments

This research is supported by the Department of Science and Innovation and the South African National Space Agency (SANSA). The authors are grateful for the support of the DSI Space Science and Technology directorate.

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