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Characterization of impinging jet sprays of gelled propellants loaded with nanoparticles in the impact wave regime

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ABSTRACT

This study presents impact wave and spray properties for sheet breakup of rheologically complex gelled propellants using high-speed visualization and image processing. Two converging high-aspect ratio nozzles formed sheets for pressure drops in the range 414–828 kPa. Metalized gelled propellants are simulated using 0–20 wt% alumina nanoparticles suspended in a gelled rocket propellant. Spatio-temporal analysis of the impact waves formed on the sheet surface is presented for the first time and wave properties are compared against other liquids undergoing sheet breakup. Impact waves propagate in primary breakup region with constant velocity much less than jets. Unlike in Newtonian liquids, wave propagation velocity smaller than jet velocity delays the breakup of gelled propellants. Breakup length of the gelled propellant sheet varied with Weber number in a similar manner to impinging water jets. However, linear instability theories describing sheet breakup of Newtonian fluids could not describe the relationship between breakup length and Weber number. Bulk jets of 0.001 m diameter broke up into droplets of Sauter mean diameters 200–400 µm. Smaller size in this range is observed in the sheet periphery and near to the impingement region. Larger size occurs in the middle regions of sheet towards downstream. Externally impinging jets must overcome the rheological resistance of gelled propellants by imparting higher kinetic energy to the sheet. This invariably results in higher velocities of the propellant jets for a given orifice diameter. Thus, a smaller injector parameter is obtained and results of this study suggest that this operational limitation could induce combustion instability.

1. Introduction

Gelled propellants are being considered in rocket propulsion due to a unique combination of advantages of liquid and solid propellants in them and many studies have been carried out on impinging jet atomization of the highly viscous non-Newtonian gelled propellants.

Multi-element impinging jets arranged on a disc are used in rocket propulsion due to their good mixing and atomization characteristics. Two fuel jets, opposed by 40–100°, impinge on each other in the doublet 'like-on-like' impinging jet configuration. Once a sheet is initiated from the impingement point in a plane perpendicular to the plane containing the jets, the kinetic energy of jets is used for stretching in downstream and lateral directions, and subsequently for breakup. Impact wave mediated breakup is important in impinging jets because droplets produced by this mode have properties required for combustion.

Notable previous studies on gelled propellant atomization were carried out at Technion [1] and DLR [2] using triplet and doublet configurations, respectively. Recent examples on impinging jet atomization of water gels include Baek et al. [3] and Rodrigues and Sojka [4]. Some studies considered the breakup regimes of gelled propellant simulants [2,3], while others report droplet sizes [1,3,4]. von Kampen et al. [2] used gelled Jet A1 propellants and micro-Al particles but have not reported droplet size measurements. Most of the studies do not use actual gelled propellants but simulate them using water gels. These studies considered jets opposed by 90°, jet diameter 0.7–1.0 mm, and jet velocities of 9–59 m/s. Under these conditions, Sauter mean diameters are 57–105 µm, depending upon nature of substance used in gelation and rheological properties of propellant.

Breakup length, sheet thickness, and droplet diameters are important parameters in impinging jet atomization. Numerous theoretical [5–9] and experimental [7–9] studies on water have been carried out for modeling of breakup length and droplet diameters. Huang [7] identified density ratio and jet Weber number ($We = \rho_l u_j^2 d_o/\sigma$) as the dimensionless groups useful in correlating the breakup length through his work on impingement of directly opposed water jets. Sheet breakup length increased linearly with $We < 500$, peaked in the transition zone in the range $We = 500–2000$, and varied thereafter as

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Nomenclature

d_c	characteristic diameter (m)
d_o	orifice diameter (m)
D_i	diameter of droplets in the i^{th} size class (μm)
$D_{0.5}$	mass median diameter (μm)
D_{10}	arithmetic mean diameter (μm)
D_{32}	Sauter mean diameter (μm)
f	frequency (Hz)
H	height of image (mm)
K	flow consistency index ($Pa.s^n$)
l	length (m)
L_b	breakup length (mm)
l_{PI}	pre-impingement length (m)
n	flow behavior index (–)
N_i	number of droplets in the i^{th} size class (–)
P_s	pressure drop (Pa)
St	Strouhal number
t	time (ms)
u	velocity (m/s)
V_p	impact wave propagation velocity (m/s)
V_{sheet}	sheet velocity (m/s)
W	width of image (mm)
We	Weber number (–)
y	coordinate direction (mm)
Y_A	weight percent of nano-Al_2O_3 (%)
z	coordinate direction (mm)

Subscripts

a	air
j	jet
l	gelled propellant

Greek Letters

$\dot{\gamma}$	shear rate (s^{-1})
η	shear viscosity (Pa.s)
θ	impingement half-angle (°)
λ	wavelength (mm)
ρ	density (kg/m^3)
σ	surface tension (N/m)
φ	azimuthal angle (°)

$\propto (\rho_a/\rho_l)^{-2/3}We^{-1/3}$. Santoro and coworkers [8,9] performed experiments on obliquely impinging water jets. They scaled the jet Weber number by $f(\theta) = (1-\cos\theta)^2/\sin^3\theta$, otherwise retaining essentially the same dependence on density ratio and *We*. The dependence on *We* has been subsequently also considered by above studies on water gels.

Impact waves produced after impingement of jets are characterized by their propagation velocity, frequency, and wavelength; quantities, which are associated with the combustion instability in liquid rocket engines. Therefore, estimation of these parameters has received attention [8,9], although only in case of Newtonian fluids like water. However, little experimental data on these properties is available for gelled propellants. Recently, Ramasubramanian et al. [10] reported limited data on the wavelength of impact waves for gelled ethanol-water but did not consider other properties of waves and their association with combustion instability.

Yang et al. [11] analyzed the sheet of a power law fluid within the framework of linear stability theory by modifying the dispersion relation to account for the shear thinning effects. Their analysis verified the experimental observations that sheet becomes more and more unstable and the distance between waves reduces as pressure drop and sheet Weber number are increased. In terms of the stability theory, maximum growth rate and dominant wave number increase under such conditions. Further, opposite effect is predicted when viscosity is increased. However, applicability of such analyses for gelled propellants remains to be verified because multiple studies show that gelled propellants show yield stress, thixotropy, and viscoelasticity [12–15]. These properties are likely to introduce nonlinear effects not treated in linear stability theories. Recent studies on the behavior of particulate gels of the same type considered in this work [16] show that the nanoparticles present in these gels also affect the local properties of the waves.

Therefore, before these analyses can be taken up, it is necessary to provide quantitative data on breakup of gelled propellants in the impact wave regime. Lack of knowledge about impact wave properties is a major hurdle for development of models and empirical correlations for gelled propellant atomization using impinging jets. Therefore, major goal of our investigation is to provide and describe impact wave properties with reference to gelled propellants. Second goal is to compare and discuss breakup length and impact wave properties with existing theories. As part of the investigation, droplet size data are also presented and discussed. This paper is organized as below.

First, experimental methods for formulation of gelled propellants, impinging jets facility, and spray characterization are briefly described. In the results and discussion section, first, the instantaneous shear viscosity data is used to show that gelled propellants are non-Newtonian and shear thinning. Thereafter, overall features of impact wave regime are considered. Then, properties of impact waves, sheet breakup length, and droplet sizes are presented and discussed with reference to nanoparticle concentration and pressure drop across injector. Finally, major conclusions of this investigation are presented.

2. Experimental methods

2.1. Formulation and characterization of gels

ISROsene (ISRO, India) is a kerosene-based liquid hydrocarbon rocket propellant. It was gelled in this investigation by an organic non-polymeric castor oil derivative, Thixatrol ST® (Elementis Specialties). Average size of the gellant particles is 23 μm. Xylene acts as a vehicle solvent for the gellant. The solid phases were dispersed in ISROsene by mixing at 1900–2200 rpm using an impeller. Procedure for gelation, which involves heating the mixture of chemicals at approx. 63 °C, is same as the previous study on gelation of Jet A1 [17]. Duration of heating and mixing was optimized for ISROsene. To ensure safe handling in laboratory, α-alumina nanoparticles (Nano Wings) of average particle size ∼50–150 nm were used with oleic acid surfactant as simulant for energetic metal nanoparticles. Oleic acid was 10% of the alumina particle concentration to reduce agglomeration during mixing. Gelled propellant consists of a gellant matrix that traps liquid propellant within and nanoparticles remain suspended in and around the matrix structure. Compositions are summarized in Table 1. Henceforth, a propellant is identified by concentration of alumina nanoparticles

Table 1
Composition of gelled ISROsene propellants.

Gelled Propellant	Components (wt%)			
	Liquid Propellant	Xylene	Thixatrol ST®	Alumina
A0	85	7.5	7.5	0
nA5	80	7.5	7.5	5
nA10	75	7.5	7.5	10
nA20	65	7.5	7.5	20