Technical Notes

Rheological Matching of Gel Propellants

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Nomenclature

A, B	=	gellant types
f	=	fraction of gellant A defined in Eq. (1)
K	=	consistency index
m_A, m_B	=	mass fraction of gellant A or B
n	=	rate index (power-law exponent)
O/F	=	oxidizer-to-fuel ratio
T	=	temperature
$\dot{\gamma}$	=	shear rate
η	=	non-Newtonian shear viscosity
τ	=	shear stress
τ_y	=	shear yield stress

I. Introduction

A SIGNIFICANT effort has been undertaken by several research groups worldwide over the past decades to study various aspects of gel propellants. The principal objective of these basic studies is to realize a flexible energy-management propulsion system, which assures insensitive munitions compliance. In addition, their increased energy density, when metal particles are introduced in the gel matrix, in comparison to neat-liquid propellants presents a significant potential advantage. The non-Newtonian complex rheological character of these propellants and the resulting system-level implications make their use in operational rocket engines very challenging. Nevertheless, their potentially full pulse-width-modulation capabilities, combined with the ability for divert and attitude control system application, make them attractive for future rocket propulsion systems in both tactical and space applications [1–4]. Key aspects of gel-propulsion technology, propellant preparation, rheology, atomization, and combustion are presented in an extensive review by Natan and Rahimi [5]. A general rheological classification of gel propellants and simulants has been proposed in a recent study on the shear rheology of gel propellants [6].

Rheological matching of gel propellants is an intentional change in one or more relevant properties of the fluids, within specified ranges of temperatures and shear rates, to obtain a desired rheological behavior. Matching is achieved by using suitable techniques,

depending on gel composition and preparation procedure. The reasons for rheological matching can vary as follows.

1) Gel-propellant simulant matching. The use of water-based simulants in lieu of toxic and corrosive materials enables the conduction of system development tests without the difficulties inherent in the handling of such materials, allows budget savings, and enhances safety. For example, hydrazine-based gel fuels are attractive in propulsion systems because of their performance characteristics, although safety precautions make the handling of such materials a difficult task. The use of a hydrazine-gel simulant allows adequate handling and testing of the feeding system without being exposed to safety hazards. Water-based gel simulants have been used for spray flow visualization [7], thixotropy modeling [8], atomization studies [9,10], elongational behavior [11], and propellant tank expulsion performance [4].

2) Gel-propellant matching. Fuel and oxidizer can be matched for gel-feeding system design purposes. This matching provides the designer with an additional degree of freedom. In addition, certain fuel and oxidizer gels can be matched to comply with special requirements, such as a reduced temperature sensitivity of their rheological properties within a wide range of temperatures.

Shear viscosity of gel-propellant simulants has been found to be significantly affected by shear rate and gel composition (gellant type and mass fraction) [6]. On the other hand, the effects of thixotropy and temperature field were found to be insignificant in comparison to the shear-thinning and composition effects.

Rheological matching does not imply that gels of two different materials and gelling agents would have absolutely identical rheological parameters under all circumstances. However, these properties can be brought close enough, in relevant ranges of ambient conditions, such as flow rates, temperature, and external mechanical loads, to satisfy certain requirements. The gellant type and content provide a degree of freedom for the determination of the rheological properties of a gel propellant.

The scope of the present study is to demonstrate the rheological matching of fuel, oxidizer, and simulant gels using various gellants, separately or combined. An investigation of the effect of temperature on the rheological parameters of water-based, gel-propellant simulants, formulated by various gellant combinations at different ratios among them, is also presented.

II. Preparation and Testing

Various gels of hydrazine and JP-8 fuels, hydrogen peroxide oxidizer, and water-based simulant gels were prepared as described in [12]. For fuel gelation, both organic and inorganic gellants were used, whereas the oxidizer was gelled using a silica gellant. To obtain desired values of the rheological parameters K and n in the power-law model ($\tau = K \cdot \dot{\gamma}^n$) for water-based simulants, a combination of two different, polysaccharide-based gellants, designated A and B, was applied. Five samples of 1% total gellant content in a water-based simulant gel were prepared, each characterized by the mass fraction of gellant A in the total mass of gellants A and B. The fraction, f, of gellant A is defined by

$$f = m_A/[m_A + m_B] \qquad (1)$$

The values of the parameter f varied between 0 (gellant B only) to 1 (gellant A only).

The rheological characterization of selected fuel, oxidizer, and simulant gels was carried out using a TA-CSL$_{100}^2$, rotational rheometer with cone-and-plate and parallel-plates configurations. The existence of no-slip conditions during all experiments was verified. Special procedures, described in detail in [13], were implemented to

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eliminate the air-friction parasitic moments and the inertia effects resulting from the rotating rheometer parts, and also the gap variations because of temperature changes.

III. Results and Discussion

The effect of temperature on the power-law indices K and n, for various values of the gellant A fraction f, is exhibited in Fig. 1 [5]. The rheological parameters obtained from the power-law constitutive model were fitted to experimental flow curves in the shear-rate range of 0.1 s^{-1} to 2000 s^{-1}, at constant temperature. The temperature varied within the range of 20–65°C. Figure 1 demonstrates the ability to modify the rheological properties, a fact that may play a very important role in the propellant selection and the propulsion system design. It shows that for a total gellant content of 1% weight, the consistency and rate indices vary significantly by changing the gellant fractions.
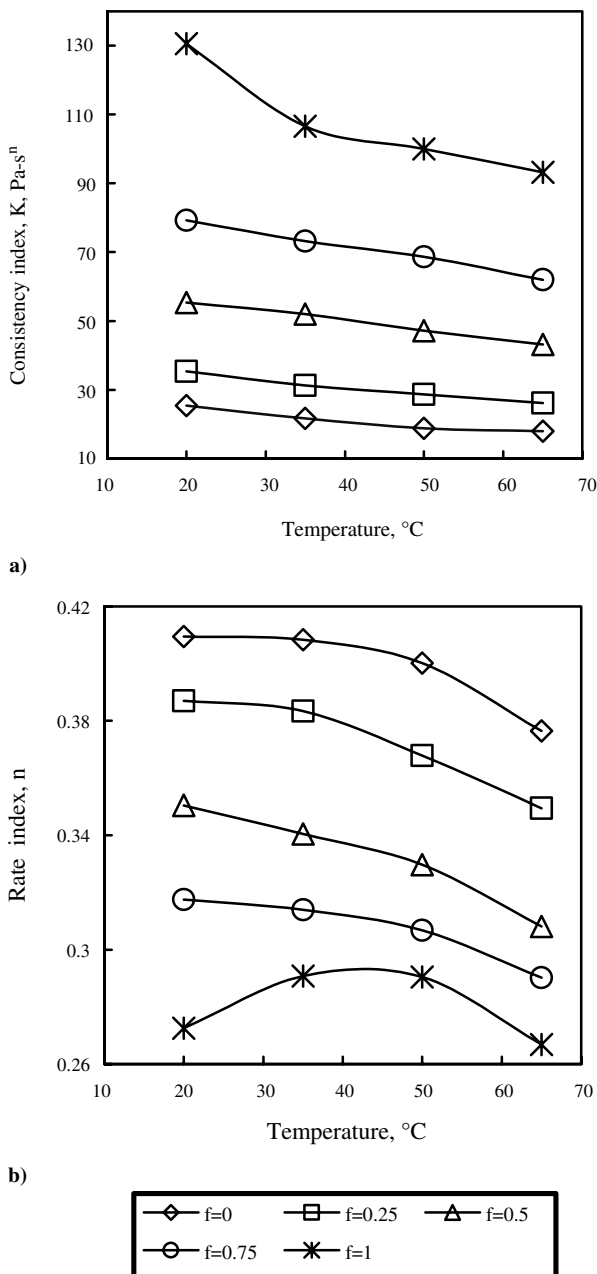
As shown in Fig. 1a, the consistency index K varies between 18 and 130 Pa-s^n for the selected temperature range. This change is attributed to the gel matrix chain dilution or thickening resulting from the use of different gellant combinations. The $K - T$ slopes change from 2.5 Pa-s^n/°C at low temperatures down to 0.03 Pa-s^n/°C at high temperatures, indicating that the sensitivity to temperature changes is higher at low temperatures, especially when a single gellant is used. The effect of temperature on the gel simulant rate index (power-law exponent) n was found to be small (Fig. 1b and [6,13,14]). However, as shown in Fig. 1b, the combination of two different gellants may result in changes of more than 50%.

The consistency index K can be controlled by varying: a) the total mass fraction of gellant content [6], b) the gellant type mass fraction f, and c) the ambient temperature. All the experimental data of the investigated water-based gel simulants were correlated and the indices K and n can be expressed as a function of temperature (in K) and the gellant combination fraction f by the relations

$$K = 192.6 \exp^{1.65 \cdot f - 7.1 \times 10^{-3} \cdot T}$$

$$n = (-1.94 + 0.011 \cdot T - 1.6 \cdot 10^{-5} \cdot T^2) \cdot f + (8.5 \cdot 10^{-3} + 0.011 \cdot T - 1.5 \cdot 10^{-5} \cdot T^2) \quad (2)$$

The correlations in Eq. (2) agree well with experimental data as shown in Fig. 2.

The capability of changing the rheological properties of the water-based simulants, as shown in Fig. 1, led to the preparation of a hydrazine-gel simulant. In the present work, hydrazine fuels, gelled with polysaccharide gellants, were rheologically characterized as shear-thinning pseudoplastic fluid with low τ_y. Figure 3 shows the variation of the shear viscosity as a function of the shear rate for a hydrazine gel and its water-based simulant, as further described in the following section. For this hydrazine gel, the exponent n and the consistency index K were found to be 0.39 and 11.8 Pa $\cdot$ s$^{0.39}$, respectively.

Furthermore, Fig. 3 shows the capability to prepare an inert simulant, which is rheologically matched with the hydrazine gel, with respect to the viscosity vs shear-rate dependency, throughout 3 orders of magnitude of the shear rate. For both hydrazine and its water-based simulant, the same power-law exponent n was obtained ($n = 0.61$), whereas the consistency index K was 11.8 and 11.4 Pa $\cdot$ s^n, respectively. In addition, it has been demonstrated [11] that the rheological parameters for these types of gels obtained in simple shear measurements agree fairly closely to those obtained in uniaxial elongation measurements. Moreover, the power-law model was found suitable for gel fuels based on hydrazine derivatives such as mono-methyl-hydrazine (MMH), which has low freezing
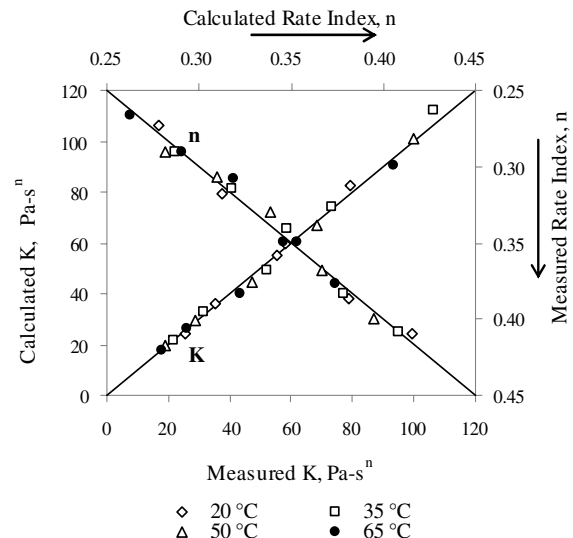

Fig. 1   Variation of the power-law model parameters of a water-based simulant gel with temperature for various combinations of gellants, A and B: a) consistency index, and b) rate index [5].

Fig. 2   Correlations for the consistency (left and bottom axes) and rate (right and top axes) indices.
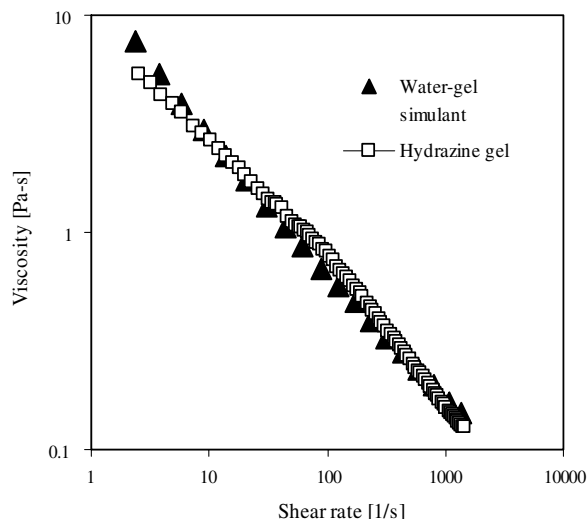
Fig. 3　Rheological matching of a water-based simulant gel and a hydrazine gel.
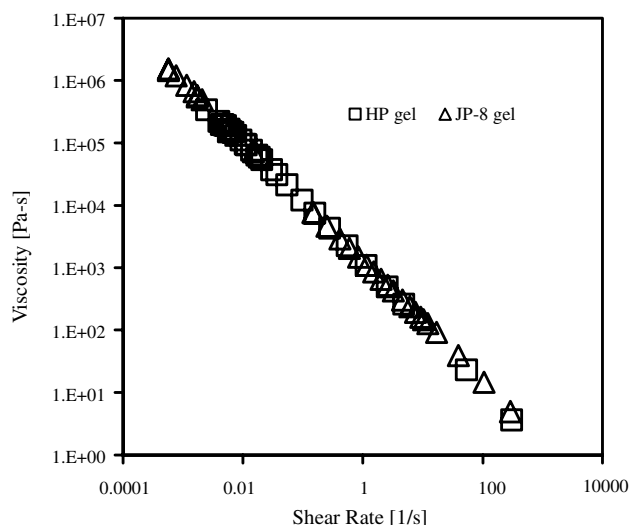

Fig. 4　Rheological matching of a fuel gel and an oxidizer gel.

temperature. These fuels were also gelled with polysaccharide gellants. Their rheological characterization yielded exponents n in the range of 0.3–0.5, with consistency indices K in the range of 5 to 15 Pa · s^n (these results are consistent with the values obtained by Varghese et al. [14]). Accordingly, it is possible to match a suitable water-based simulant with the MMH-based fuel gels as well.

The matching of water-based simulant gels with actual-propellant gels requires adequate selection of gellants and their concentrations, as well as the procedures of preparation. It becomes more difficult when different gellants have to be used. However, matching for particular needs is possible by identifying the process or operation to be simulated. For example, for a predominantly laminar shear-flow in a pipe, the simulant matching is carried out by fitting the behavior of the shear viscosity η as a function of shear rate $\dot{\gamma}$ of the propellant to that of the water-based simulant gel in the relevant range of shear rate. Such a simulant gel can be used for evaluation of pressure losses in the feeding system and to assure the desired O/F ratios under various conditions. Investigations of the spray characteristics were carried out by Rahimi and Natan [9] using similar Carbopol-type simulant gels with gellant mass fraction between 0.3 and 1%, as well as by Chojnacki and Feikema [10]. The rheological matching of a JP-8 fuel

gel with a hydrogen peroxide (HP) gel, shown in Fig. 4, demonstrates the capability of fuel and oxidizer matching for adequate design of the gel-feeding system. The exponent n is 0.97 and 0.95 and the consistency index K is 1164 and 1286 Pa · s^n for the gelled H_2O_2 oxidizer and the JP-8 fuel, respectively.

IV.　Conclusions

The paper demonstrates the capability to manufacture gelled fuels, oxidizers, and inert simulants with desired rheological properties in the relevant range of operating temperatures, using a combination of different gellants. This capability allows rheological matching of gel fuels to gel oxidizers or matching of gelled water-based simulants to actual gel propellants to reduce hazards and cost during experimentation for propellant development.

Acknowledgments

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