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Burn rate characterization of desensitized isopropyl nitrate blends

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ABSTRACT

A study regarding the linear burning rates of strands of blended liquid monopropellants was conducted in a pressurized vessel. The blends consisted of the monopropellant isopropyl nitrate (IPN) and the desensitizer dibutyl sebacate (DBS) while an established monopropellant Otto fuel II (OF-II) was also tested. Additional experiments were performed to determine and compare the temperature profiles in the liquid and gas phases of the propellants under study using S-type thermocouples. The study was conducted in a quiescent atmosphere of air with the ambient pressure varying within the range of 10–100 bar. The liquid strands were created using quartz tubes with an inner diameter of 5 mm and a thickness 1 mm. Profiles of regressing surfaces and the derived burning rates were plotted with pressures varying from atmospheric to 100 bar for IPN-DBS blends and OF-II. Furthermore, the experimental results of IPN-DBS blends have been compared against the theoretical predictions of a semi-empirical model, with a reasonable match between the two. A blend of 90% IPN with 10% DBS (by mass) was found to be an excellent candidate to replace OF-II.

1. Introduction

Multicomponent monopropellant formulations are amongst the prime candidates for replacing hydrazine as the mainstream propellant. These next generations of green monopropellants are intended to mitigate the various hazards posed by hydrazine and its derivatives. Various ionic liquid propellant formulations based on hydroxylammonium nitrate (HAN) as well as ammonium dinitramide (ADN) are at the forefront of this effort. Heterogeneous monopropellant formulations containing nanoparticles are also being explored. Although monopropellants were originally used for space-propulsion, they have also been envisioned in various other applications such as underwater power sources, high-altitude unmanned aerial vehicles, robotic actuators, liquid fuelled guns, and as fuels in conventional reciprocating engines. Historically, Otto fuel II (OF-II) has been a well-known liquid monopropellant formulation which was successfully utilized for several applications [1]. OF-II is based on the monopropellant propylene glycol dinitrate (PGDN) and the desensitizer dibutyl sebacate (DBS).

The combustion characteristics of these liquid monopropellants are routinely extracted by conducting strand combustion studies in order to elucidate the variation of linear burning rates with ambient pressure, composition, and temperature. Strand combustion studies of various multi-component liquid monopropellants such as OF-II [2,3], numerous HAN-based propellants [4–6], and heterogeneous propellant formulations [7] as well as pure liquid monopropellants such as hydrazine [8], various alkyl nitrates [9–11], and nitromethane [12–14] have been reported in the literature.

The motivation of the current study stems from an ongoing investigation which focuses on alkyl nitrates and nitroalkanes as green alternatives to hydrazine. Particularly, isopropyl nitrate (IPN) is envisaged as a potential candidate owing to its widespread usage prior to the advent of hydrazine. The known safety issue with IPN involving adiabatic compression-ignition of fuel vapor bubbles can be mitigated by de-aerating the fuel before storage and blanketing it with nitrogen [15]. Furthermore, the safety characteristics of IPN may be improved by creating a blend with a known desensitizer such as DBS. A novel propellant formulation based on IPN could be envisioned where a blending scheme similar to OF-II is followed. However, fundamental combustion characteristics of any such a blend must be elucidated prior to the utilization in an application.

The addition of DBS to IPN is expected to cause desensitization of IPN from adiabatic compression of vapor bubbles, thus mitigating detonation. However, the precise quantity of DBS required to desensitize IPN must be determined by a concerted study of detonation of such mixtures. The upper bound for the

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mixing ratio would be the minimum amount of DBS required for desensitization of IPN, while the pressure exponent of the resulting formulation would determine the lower limit. Furthermore, the specific impulse generated by the formulation may be used as a criterion for selection. In order to arrive at a candidate formulation based on IPN, the formulation of OF-II was followed, consisting of 76% PGDN as the monopropellant, 22.5% DBS as the desensitizer, and 1.5% 2-nitrodiphenylamine as the stabilizer by weight.

The theoretical performance of a rocket utilizing IPN or the IPN-DBS blend was estimated using NASA CEA code [16]. The chamber pressure for this hypothetical rocket was assumed to be 20 bar and expansion ratio 50. The vacuum specific impulse for a rocket operating on OF-II was found to be 256.6 s, while the 75:25 (by mass) IPN-DBS blend yielded a vacuum specific impulse of 230.5 s which indicating a lower performance compared to OF-II. In order to match the performance of OF-II rocket, a 90:10 IPN-DBS blend (by mass) was selected, resulting in a vacuum specific impulse of 242.9 s. Although the 90:10 IPN-DBS blend results in similar theoretical performance as that of OF-II, as the practical formulation may be different due to undetermined detonation characteristics, the study of a range of blends may be necessary. Thus, the objective of the current study was to elucidate the burning characteristics of IPN-DBS blends consisting of 75% IPN and 25% DBS (ID7525) as well as 90% IPN and 10% DBS (ID9010).

The effect of ambient pressure on the combustion of IPN-DBS blends was investigated with ambient pressures starting from 10 bar, as at lower ambient pressures the IPN-DBS blends neither could be ignited nor be combusted in a repeatable fashion. Furthermore, this allows the investigation into the monopropellant nature of the blend as it has been established that IPN decomposition reactions occur significantly only beyond 10 bar [11]. The linear burning rates for these formulations were investigated with ambient pressures varying up to 100 bar. The burning rates extracted would be important for the design of torpedo propulsion systems, as well as power sources, such as internal combustion engines operating at high altitudes, where the combustion chamber operates at much lower pressures. An internal combustion engine with a compression ratio of 10, when operated at an altitude of 15,000 m, achieves a peak compression pressure of 3 bar, which may be increased further by utilizing higher compression ratios or through turbochargers. Furthermore, the experimental study has been augmented by utilizing a semi-empirical model [11] for predicting the burning rate constants for IPN-DBS blends.

2. Experimental approach

The experimental setup utilized for analyzing the strand combustion of liquid monopropellants has been described in detail previously [11]. The current study utilized transparent quartz tubes of 5 mm internal diameter and a thickness of 1 mm to create the liquid strands. The burning rates of the monopropellants were measured optically within a chamber pressure range of 10–100 bar. Ignition was achieved by electrically heating a nichrome wire dipped in the liquid strand. Immediately after ignition, the nichrome wire was removed from the vicinity of the tube using a servo-motor-driven mechanism. The energy deposited by the heated nichrome wire was found to be insufficient for the experiments with OF-II strands. In these experiments, the nichrome wire was threaded through a small piece of composite solid propellant comprised of an approximately stoichiometric mixture of ammonium perchlorate (AP) and hydroxyl–terminated polybutadiene (HTPB), with a square base of approximately 2 and 1 mm height.

Temperature measurement of the liquid phase as well as the flame zone was conducted for ID9010 and OF-II strands using S-type thermocouples with a wire diameter of 100 μm. ID7525 blends were excluded as their burning rates were considerably lower than that of ID9010 and OF-II. The thermocouples were placed at a distance of approximately 6 mm below the tip of the tube center and fixed throughout the experiments. The 100 μm S-type thermocouples were calibrated with an oil bath in the temperature range of 373–873 K. The measured values were found to deviate by 3.4% with a confidence level of 99.97%. Unfortunately, the lack of calibration devices beyond this range prevented us from estimating the uncertainty at higher temperatures. However, we expect the actual values to lie within 10% of the measured values reported in Tables 4 and 5, owing to the non-luminous nature of the monopropellant flames. The errors may be augmented by radiative losses from the thermocouple bead once the luminous flames in the LPR and IPR region collapse within the tube.

3. Results and discussions

3.1. Phenomenology of blended liquid propellant combustion

A range of factors determine the behavior of the combustion process and the burning rate of liquid strands consisting of monopropellant blends, including the overall oxygen balance, proportion of the monopropellant in the blend, the relative ease of vaporization of the components, the ambient pressure and composition, and the thermodynamic critical pressures and temperatures of the constituents. Furthermore, the low-pressure deflagration limit (LPDL), beyond which the monopropellants are known to exhibit self-sustained combustion, is a significant property of the monopropellants. High-pressure combustion of monopropellants may encounter the phenomenon of critical mixing point pressures beyond which the combustion process becomes similar to a flame propagating through a dense gas as no liquid surface can be distinguished. The strand combustion studies by Faeth [10] as well as Kounalakis and Faeth [4] have reported the value of the critical combustion pressure to be significantly higher than the thermodynamic critical pressure of the pure propellants. This effect was attributed to the increased quantity of dissolved gases in the liquid phase leading to the surface temperature being significantly less than the corresponding boiling point at the ambient pressure. Although a clearly distinguished liquid surface is maintained even beyond the thermodynamic critical pressure, the enthalpy of vaporization of the liquid may be considered to be zero [17]. Furthermore, blended monopropellants often have constituents with widely different boiling points and enthalpies of vaporization which has a significant effect on the combustion process below the critical pressure. Table 1 shows the boiling points and thermodynamic critical points of various components of the blends considered in the current study. Based on the thermodynamic criticality of the components, a binary blend may be envisaged to display three combustion regimes. The first regime where none of the components are in the supercritical state may be termed as the low-pressure regime (LPR). The second regime where one component is in supercritical condition may be dubbed as the intermediate pressure regime (IPR). The high pressure regime (HPR) may be defined when both the components are in the supercritical state. Hence, we recommend that the design pressure is in the HPR for a practical combustor.

Owing to these factors, the binary blend may demonstrate a significantly different combustion behavior than the individual components. Four distinct processes may be outlined which must occur as the binary blend combusts in an atmosphere of air. The first process was the preferential evaporation of the lower boiling point liquid and a corresponding rise in the concentration of the higher boiling point component in the solution. A typical blend of miscible liquids with a difference in boiling points experiences distillation when subjected to heating. In such a scenario, the vapor phase above the liquid is enriched by the lower boiling point