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Technical Notes

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Liquid Monopropellant Combustion in Mesoscale Vortex Chamber

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I. Introduction

A WIDE variety of meso- and microscale combustion devices have been proposed and are under development to meet the power and energy density requirements of propulsion and power-generation applications [1–4]. Most of these devices employ gaseous fuels and, in particular, hydrogen, which has a fast reaction rate and high diffusivity, to demonstrate the feasibility of self-sustained combustion at millimeter scales or below. Liquid-phase storage and operations, however, are essential for taking full advantage of the high specific energy of a combustion-based power generator using hydrocarbon fuels.

At macroscales, liquid fuels are typically sprayed into a combustor in droplet form to enhance the vaporization and ensuing burning rates. If the fuel was injected as a film on the chamber wall, the liquid surface area would not be large enough to sustain the needed vaporization rate. In combustors with dimensions in the subcentimeter-size range, however, because the specific area of the wall film increases as the combustor volume decreases, a liquid film can offer a surface area for vaporization that is as large as that of a vaporizing spray. The film on the combustor surface also cools the combustor wall to create a favorably distributed temperature profile that prevents heat losses for both endothermic liquid decomposition reactions and gasification. Heat transferred to the wall, which has been considered as heat loss in most miniaturized combustor applications, can be used for fuel film vaporization. Atomizers that are capable of producing submicron-scale droplets may, therefore, not be needed for liquid-fueled combustion in meso- and microscale combustors. Sirignano et al. [5,6] concluded that a 10-mm-diam combustor has a film surface area comparable to a droplet spray with a 10 μm Sauter mean radius. The concept using wall film evaporation in small combustion chambers was demonstrated in a 3.14-cm^3-volume combustor [6] with gaseous air used as the oxidizer. Secondary air injection was recently introduced into the concept to enhance mixing and contain the reaction zone completely within the combustion chamber [7]. Furthermore, a portion of the flow residence time in the chamber was consumed by the mixing between the fuel and oxidizer.

To circumvent the problem of short flow residence time in a small-scale combustion chamber and thereby avoid the difficulties associated with the mixing of fuel and oxidizer, we studied the usage of nitromethane (CH_3NO_2), a liquid monopropellant. A mesoscale vortex combustor developed in our previous work on gaseous combustion [8] was used because of its potential to implement the concept of wall film vaporization.

II. Experimental Setup

The volume of the combustion chamber is 108 mm^3, with the chamber diameter of 5.16 mm. The injection and the exhaust ports both intersect the circumference of the cylindrical combustion chamber tangentially, but at opposite ends. The tangential positioning of the inlet creates a swirling flow that stabilizes the combustion process. Details of the combustor design, fabrication, and gaseous-fuel operation are found in [3,8]. For the present operation using a liquid monopropellant, a high-pressure syringe pump (Harvard Instruments, PHD 4400) was used for liquid injection. A 2-mm-thick sapphire window capable of withstanding pressure up to 2.758 MPa (gauge) (400 psig) was installed on the combustor to provide optical access. The window was replaced with an end cap featuring a thermocouple port when temperature measurements were conducted. The chamber pressure was monitored by a transducer (Setra Systems, Inc., Model 207) connected to a port on the side wall of the combustor.

The exhaust products were diluted with helium (99.999%) and then analyzed by an FT-IR spectrometer (ThermoNicolet 670). The gas cell of the FT-IR apparatus was equipped with ZnSe windows, and the optical path was 10 cm. The cell volume was 100 cm^3, and the temperature was kept at 130°C to avoid liquid condensation. The resolution of the spectra acquired was 1 cm^{-1}.

III. Results and Discussion

To investigate film combustion using tangentially injected liquid fuels in a vortex combustor, studies were initially conducted with the combustion chamber operating on liquid nitromethane and a small amount of oxygen at atmospheric pressure (1 atm). Liquid nitromethane was injected from a port tangentially intersecting the chamber wall. A small amount of gaseous oxygen was also injected tangentially in the same direction, but on the opposite side of the combustor. Ignition was achieved by first igniting a methane–oxygen or hydrogen–oxygen pilot flame. Liquid nitromethane was then injected, while reducing the gaseous oxygen to a prespecified level. Three different mass loadings of nitromethane (80, 89, and 94% by volume) with a constant oxygen flow rate were investigated. The chemical energy imparted to the system was 70, 100, and 160 W with the three nitromethane loadings, respectively. The corresponding flame temperature and flow development were determined

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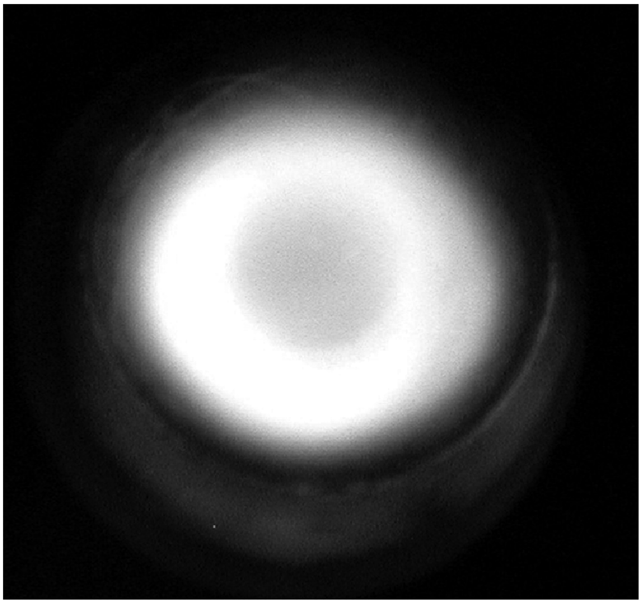

Fig. 1 Combustion of liquid nitromethane with a small amount of oxygen. The emission of the nitromethane flame is a brownish–bright-white color as compared with the bright-blue emission observed from the gaseous hydrocarbons. No carbon deposits or soot formation are observed in either case.

primarily by the amount of nitromethane. Figure 1 shows a typical flame structure, which is dominated by the combustion of nitromethane as evidenced by the yellowish–bright-white emission from the flame. No soot or carbon deposits were observed on the surfaces. Much of the liquid nitromethane appeared to be vaporized shortly after being injected into the chamber. At atmospheric pressure, combustion with nitromethane alone was found to be unachievable.

The need for a small amount of oxygen at 1 atm can be understood by comparing the nitromethane chemical kinetics to those of a hydrocarbon–oxygen system. Unlike hydrocarbon oxidation, which has significant chain branching due to the presence of molecular oxygen (via $H + O_2 \rightarrow OH + O$), no equivalent branching reactions occur in the nitromethane system. The main source of radicals is through pressure-dependent dissociation reactions, which occur rather slowly at low pressures. The flow residence time in the miniaturized combustion chamber becomes insufficient, and the reactions quench as the heat release rate cannot keep up with the enhanced heat loss rate. Nitromethane reactions accelerate dramatically, however, with increasing pressure. The acceleration effect of pressurization is compared with that of oxygen addition in Fig. 2. The figure shows the dependence of the ignition delay time on the pressure of pure nitromethane combustion, as well as on the concentration of oxygen in the reactant at atmospheric pressure. The ignition delay time was defined as the time required to reach an increase of 400 K above the initial temperature, which is set at 1000 K in the present study. It was obtained from the SENKIN [9] calculation using a nitromethane chemical-kinetics mechanism that consists of 35 species and 134 gas-phase reactions. The effect of pressure on the ignition delay time is more significant than that of the addition of oxygen at atmospheric pressure. At temperatures lower than 1000 K, the acceleration of nitromethane kinetics by oxygen addition, or an increase in pressure, is even greater.

This analysis indicates the necessity of operation at an elevated pressure for the combustion of liquid nitromethane monopropellant in a small chamber. Therefore, we adapted the mesoscale vortex combustor by adding a needle valve at the exhaust port of the combustor to regulate the chamber pressure. Ignition was achieved by employing a hydrogen–air pilot flame. Liquid nitromethane was then injected while the backpressure valve was closed to increase the chamber pressure to over 0.689 MPa (gauge) (100 psig). The hydrogen flow was shut off once the flame was stabilized. Air was removed gradually as the flow rate of nitromethane and the chamber pressure were increased.

The combustion of liquid nitromethane at 2.413 MPa (gauge) (350 psig) in the 107.8 mm^3 vortex chamber is shown in Fig. 3. Liquid nitromethane enters the combustor through the tube on the right side of the figure at the back end of the combustor. Exhaust products exit the chamber tangentially at the front end through the tube shown on the bottom left side of the figure. The mass flow rate of nitromethane was 0.021 g/s, which corresponded to a linear liquid feeding rate of 10.2 cm/s in the injection port. Interestingly, the continuous yellowish–bright-white flame that appeared when a small amount of oxygen was added was no longer observed. A very dim, nearly uniform white emission accompanied by a bright-red–white emission from small particles (possibly soot), which formed and rapidly disappeared, was seen. The existence of soot indicates that the temperature in the combustor might be well above 1650 K [10]. Liquid was not visually observed within the combustor under pressurized monopropellant operations, although it was in the atmospheric experiments with oxygen. The combustor body showed a reddish emission, indicating that the wall temperature may exceed the vaporization and decomposition temperatures of nitromethane at 374 and 520 K, respectively, at atmospheric pressure. Liquid nitromethane is not likely to exist in the combustor under these conditions. The tangentially injected nitromethane and its ensuing vapor and gaseous decomposition product in the vortex chamber generated a flowfield similar to that seen with gaseous reactants, in which reactions were sustained and stabilized by three recirculation zones [8].

Different flame characteristics in the mesoscale vortex combustor were observed when pressures were below 2.413 MPa (gauge). Intermittent brownish-white flames (see Fig. 4) were observed more

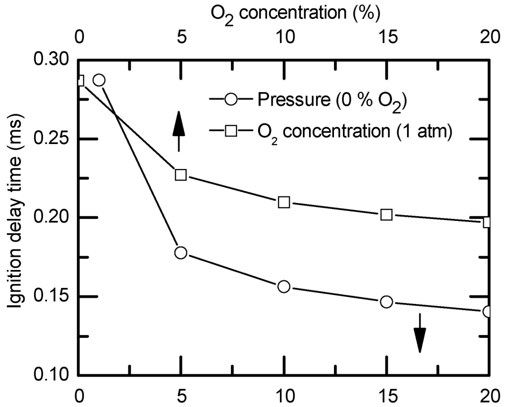

Fig. 2 Effect of pressurization and oxygen addition at 1 atm on the predicted ignition delay time of nitromethane combustion at 1000 K.

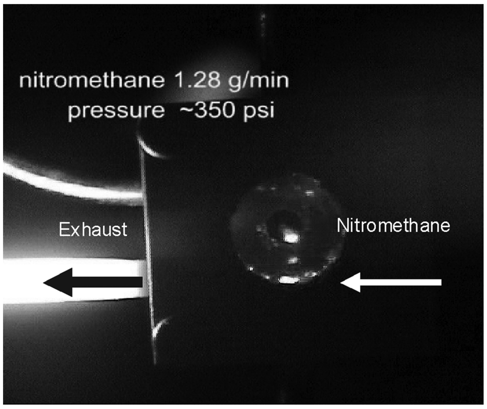

Fig. 3 Visual observation of the combustion of liquid nitromethane in the 107.8 mm^3 vortex combustor. The mass flow rate of the nitromethane was 0.021 g/s, whereas the operating pressure was 2.413 MPa (gauge).

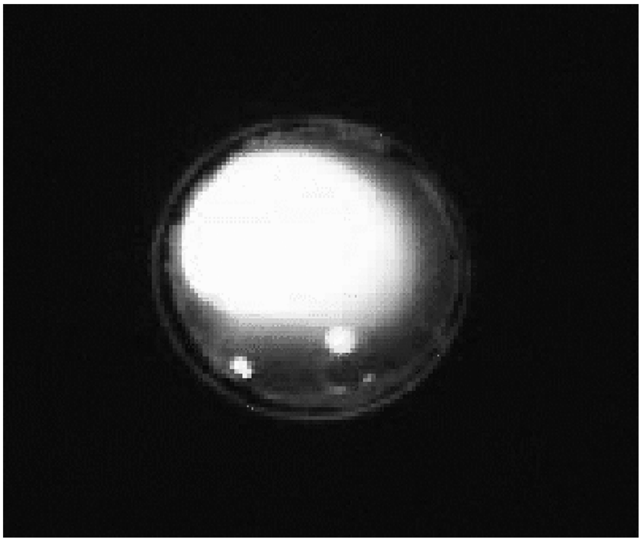

Fig. 4 Visual observation of nitromethane flame at operating pressure of 2.275 MPa (gauge). Note that the flame was oscillatory and the bright emission shown in the picture only appeared intermittently. The mass flow rate of the nitromethane was 0.0127 g/s.

frequently, finally developing into an oscillatorylike mode when the chamber pressure decreased to 2.068 MPa (gauge) (300 psig). In comparison, a low-pressure limit of approximately 3.447 MPa (gauge) (500 psig) was observed for nitromethane burning-rate measurements in a strand burner [11]. The current results show that self-sustainable combustion can be achieved in the vortex combustor at pressures as low as 1.793 MPa (gauge) (260 psig). The extended regime for stable burning may be attributed to the preheat effects of both the combustor body and the recirculation zone in the chamber created by the swirling flow. It is worth noting that the combustion of a hydroxyl-ammonium-nitrate-based liquid propellant with a burning rate at least 1-order-of-magnitude larger than nitromethane was found to be self-sustainable even at atmospheric pressure in the millimeter-size chamber [3]. The heat release rate of the propellant is, therefore, an essential factor dictating the operation of small combustors. It also determines the heat feedback for vaporizing and decomposing the liquid fuels.

The heat generated from combustion must exceed the heat required to evaporate and decompose the liquid nitromethane to achieve steady combustion, even during the oscillatory combustion of nitromethane at lower pressures. The enthalpy of vaporization of liquid nitromethane is approximately 5% of the enthalpy of reaction. The amount of energy that is available to contribute to vaporization and decomposition, however, is largely determined by the combustor configuration, as well as the temperature distributions in both the reaction zone and the combustor body. The fluctuation of the flame zone at low injection flow rates may be the result of low thermal feedback, which is insufficient to generate a steady flow of decomposed gaseous nitromethane and, consequently, causes the reaction to quench intermittently. Pressure fluctuations were recorded when the flame was in the oscillatory mode. At high input flow rates and low operating pressures, the residence time becomes too short for complete combustion, thereby resulting in less energy generation and leading to effects similar to those already discussed. In the cases in which the propellant enters the combustion chamber in the liquid phase, flame stabilization may become challenging, as the induced flow from the vaporization of the liquid propellant in the combustion chamber can alter the flow patterns. Our numerical analysis [12] revealed that, although the liquid flow travels circumferentially along the wall, due to the tangential injection, the sudden expansion of the fluid with vaporization causes the vapor to propagate normal to the interface. Consequently, all the streamlines are aligned generally along the radii due to the relatively larger radial velocity induced by liquid vaporization compared with the tangential injection velocity of the liquid monopropellant. The recirculation vortices known to be essential for flame stabilization in the small vortex combustor do not form.

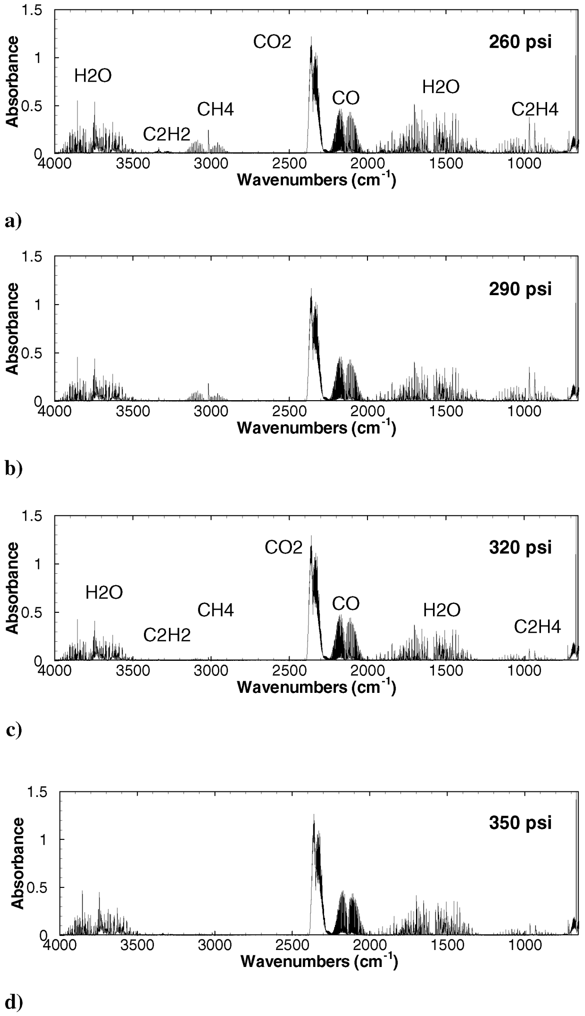

Fig. 5 FT-IR spectrum of liquid nitromethane combustion in the 107.8 mm^3 combustor: a) 1.793, b) 1.999, c) 2.206, and d) 2.413 MPa (gauge).

Absorption spectroscopy measurements of the combustion product were performed to characterize the high-pressure nitromethane combustion. Figure 5 shows the FT-IR spectra acquired at steady-state operation with chamber pressures of 1.793, 1.999, 2.206, and 2.413 MPa (gauge). The mass flow rate was maintained at 0.02 g/s. Various hydrocarbon compounds, such as CH_4, C_2H_2, and C_2H_4, are found in the exhaust gas at the lower pressures of 1.793 and 1.999 MPa (gauge) (Figs. 5a and 5b) along with the major products, CO, CO_2, and water vapor. The existence of unburned hydrocarbons indicates incomplete combustion. Nitromethane was not found in the exhaust gas. The unburned hydrocarbons were almost undetectable as the pressure exceeded 2.413 MPa (gauge) (350 psig) (Fig. 5d). Carbon in nitromethane was converted more efficiently to CO and CO_2 at higher pressures. Nitric oxide was not found in the spectra, which indicates that most of the nitrogen in the nitromethane was converted into molecular nitrogen, which is undetectable using infrared–red spectrometry due to the lack of a dipole in the diatomic molecule.

IV. Conclusions

Self-sustained liquid monopropellant combustion in a cylindrical volume of 108 mm^3 (5.16 mm in diameter) was successfully demonstrated and investigated. Pressurization of the combustion chamber was used to enhance the decomposition rate of several pressure-dependent reactions to yield the necessary radical generation and to increase the flow residence time, so that pure nitromethane operation in the miniaturized combustor was achieved. Combustion of liquid nitromethane monopropellant at atmospheric pressure was not achievable because the flow residence time was so short that the slow reaction was quenched. Oxygen was required to enhance the chemical kinetic rates of nitromethane reactions to achieve self-sustained combustion at atmospheric pressure. Although flow residence time can also be increased by lowering the injection flow rate of nitromethane, the lower chemical input power might result in insufficient heat feedback to evaporate liquid nitromethane and decompose the vaporized reactant, resulting in an oscillatory flame pattern. The study showed that stable nitromethane combustion could be reached as the chamber pressure was increased above 1.793 MPa (gauge); however, the FT-IR spectroscopic measurements revealed that estimated chemical efficiencies of over 99% were not obtained until pressurization exceeded 2.068 MPa (gauge).

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