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Investigation of Vaporized Kerosene Injection in a Supersonic Model Combustor

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Abstract

This paper report our preliminary results of characterizing the jet structures of kerosene injection into quiescent atmosphere and a Mach 2.5 crossflow at various preheat temperature. A heating system has been designed and tested that can prepare heated kerosene of 0.8 kg up to 670 K at a pressure of 5.5 MPa. Temperature measurement near the injector shows that the temperature of pressurized kerosene can be kept constant during the experimental duration. Comparison of kerosene jet structures in the preheat temperature range of 290-550 K demonstrates that with injection pressure of 4 MPa the jet plume turns into vapor phase completely at injection temperature of 550 K, while keeping the penetration depth essentially unchanged. The results suggest that the injection of vaporized fuel would improve the performance of a liquid hydrocarbon-fueled supersonic combustor because the evaporation process is now omitted.

Introduction

Liquid hydrocarbons, such as kerosene, are attractive candidates for fueling the scramjet in the lower hypersonic flight regime due to the significant benefits in terms of energy density and handling issues, as compared to hydrogen. In general, key elements for successful operations of a liquid hydrocarbon-fueled scramjet include deeper fuel spray penetration into air stream for better mixing, generation of smaller liquid droplets for faster evaporation, and effective flameholding mechanisms with minimal drag losses.

In practical scramjet operations, the liquid hydrocarbon fuel can also be used to cool the engine flow path and absorb a part of heat imposed by the flight environment. As such, the fuel temperature would vary with different states of the flight mission [1]. In the early flight stage, since the amount of heat absorbed by the fuel is minimal, the liquid hydrocarbon fuel is expected to remain in the liquid state. However, as the flight speed increases beyond a certain value, the fuel temperature may be greater than the corresponding boiling point, leading to fuel vapor entering the combustor.

In terms of liquid hydrocarbon injection, various approaches have been proposed to achieve higher level of atomization in order to facilitate mixing and promote overall burning in a supersonic airflow. For instance, our previous investigation [2] has shown that the use of effervescent atomization can substantially increase the combustion efficiency of a supersonic model combustor. However, the question we would like to address here is as follows. For situations under which the liquid fuel

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turns into gas phase by absorbing sufficient heat, how does the injection of vaporized hydrocarbon fuel affect the performance of a supersonic combustor? A potential advantage utilizing the vaporized fuel injection is to bypass the vaporization processes, which is expected to improve the performance of a supersonic combustor. Therefore, of our particular interest is the performance comparison of vaporized fuel injection versus liquid fuel injection using effervescent atomization.

In the next section, we will sequentially present our test facility and the design, calibration, and characterization of the kerosene heater employed. This is followed by preliminary results and discussion.

Experimental Specifications

Test Facility

The test facility consisted of a Mach 2.5 vitiated air supply system, a multi-purpose supersonic combustor, and kerosene delivery and heating systems. The system was controlled by a computer and capable of supplying heated air at a range of stagnation temperature of 800-2100 K and stagnation pressure of 0.7-1.3 MPa. The supersonic combustor had an entrance cross-section area of 51 mm × 70 mm. As shown in Fig. 1, the combustor was comprised of three sections, namely one nearly constant area section and two divergent sections with total length of 1070 mm. Interchangeable integrated fuel injector/flameholder cavity modules with different configurations were used for supersonic combustion experiments. Each cavity was of 12 mm in depth and of 45 degrees in aft ramp angle [3]. For some visualization experiments of spray structure of non-reacting kerosene jets in supersonic crossflow, the cavity flameholder was replaced by a flat plate. For light access and observation, a pair of quartz windows, each was 46 mm in height and 124 mm in length, were installed on both sides of the combustor near the location of cavity module. The entire test facility was mounted upright on a platform and can be translated laterally and vertically.

Kerosene Delivery and Heating System

The aviation kerosene employed here was composed by volume of 92.5% saturated hydrocarbons, 0.5% unsaturated hydrocarbons, and 7% aromatic hydrocarbons. It was stored in a cylinder and pumped through a piston at a desired pressurized state. The piston was driven by pressurized nitrogen that was regulated through nitrogen supply, as shown in Fig. 2.

Kerosene heating was accomplished as follows. Prior to experiments, kerosene was stored in a ten-meter long bendable stainless steel tube of 12 mm inner diameter and 1.5 mm thickness, which was configured into a cylindrical shape. This stainless steel tube was wrapped by five heating tapes of 960 W each, which can be powered independently for achieving uniform temperature distribution along the tube. The present system was capable of heating kerosene of 0.8 kg up to 670 K at a pressure of 5.5 MPa within 15 minutes. When ready, the heated kerosene was then discharged into combustor at a desired temperature and pressure through a fuel injector. A solenoid valve was employed for quick turn-on/off. During the discharge of heated kerosene, unheated kerosene is pumped into the heater so that the system pressure can be maintained. We will demonstrate in the following section that the current heating system can provide heated kerosene at a constant temperature during the experimental duration. Figure 3 shows a photograph of this test facility.

Kerosene Temperature Measurement

As shown in Fig. 2, six K-type

thermocouples (TC1-TC6) were inserted into the tube to monitor the temperature distribution of kerosene along the tube as well as feed back signals to a controller for adjusting heating power. Figure 4 plots kerosene temperature near the fuel injector (reading of TC7) as a function of time. The typical supersonic experiment lasted 7 sec. It generally took ~2.475 sec to establish a steady Mach 2.5 airflow. It is seen from Fig. 4 that once the solenoid valve for releasing the stored hot kerosene was turned on at ~2.8 sec, it took another ~0.5 sec to reach steady-state. More importantly, the heated kerosene can maintain at constant temperature throughout the rest of test time, and in fact can last more than 4 sec.

Kerosene Flow Rate Measurement

The mass flow rate of unheated kerosene was determined using an orifice plate of 2 mm diameter, which was calibrated by the actual amount of kerosene released from the kerosene cylinder divided by the time elapsed. A pressure differential transmission sensor (Model CYB-1151, Beijing Zhong Hang Machinery and Electron Technology Corporation) was used to measure the pressure difference between upstream and downstream of the orifice plate. Figure 5(a) shows that the pressure differential signal is fairly stable during the run. In addition, it is seen from Fig. 5(b) that the correlation of kerosene mass flow rate with square root of the pressure difference across the orifice is linear. The uncertainty of the mass flow rate measurement of unheated kerosene using this orifice plate is estimated to be ~2%.

The flow rate measurement of hot pressurized kerosene is somewhat complicated because it requires knowledge of the dependence of kerosene density on temperature and pressure. Since the database of kerosene density is not readily available in the literature, the determination of kerosene density data pertinent to our test conditions was carried out using the heating system shown in Fig. 2. First, a known amount of kerosene at room temperature was stored in the heater with both inlet and outlet being closed. At constant volume, the pressure inside the heater increases with increasing temperature. A relief valve attached to the heater was set at three different pressures, namely 2.5 MPa, 4.0 MPa, and 5.5 MPa. If the pressure inside the heater is higher than the desired pressure set by the relief valve, certain amount of heated kerosene is discharged out of the heater in order to release excessive pressure. As such, the density of heated kerosene can be determined based on the remaining mass of kerosene in the heater and the known volume. At each setting pressure, the kerosene densities were measured over the temperature range of 290-570 K. Figure 6 plots the measured densities of heated kerosene, with uncertainty of ~1%.

As mentioned earlier, when kerosene is heated to the desired pressure/temperature, during the discharge the back pressure is maintained by flowing in unheated pressurized kerosene through the calibrated orifice. From the reading of the pressure difference across the orifice, the volumetric flow rate of unheated kerosene can be determined, which is assumed to be equal to the volumetric rate of the discharged heated kerosene. With the measured density of hot pressurized kerosene, its mass flow rate can then be obtained.

Results and Discussion

Since the boiling points of most of the key compounds in kerosene are below 550 K [4], the injection temperature range investigated herein is from room temperature to 550 K. It was found that when kerosene is heated up to 670 K, black coke deposits were noticed that could clog the injector orifice. In the following we shall sequentially report our preliminary characterizations of heated kerosene jet into quiescent atmosphere and a Mach 2.5 crossflow.

Characterization of Heated Kerosene Jet into Quiescent Atmosphere

With a given injection pressure of 4 MPa, Fig. 7 compares the direct images of four kerosene jets into quiescent atmosphere at injection temperatures of 290, 480, 510, and 550 K, respectively. The orifice diameter of injector was 0.8 mm. It is seen that the heated kerosene jet first exhibited mixed liquid/vapor plume at injection temperature of 480 K, as shown in Fig. 7(b). However, at this condition the amount of kerosene vapor was much smaller than that of liquid phase. Further increasing the injection temperature to 510 K, Fig. 7(c) illustrates that vaporized kerosene dominates the jet structure, while little amount of liquid kerosene spray was still noted.

Figure 7(d) clearly shows that the heated kerosene completely turns into vapor phase at 550 K injection temperature. Especially, "white smoke" was observed even right at the injector exit. We note that the critical conditions of common kerosene are of 680 K and 22 atm. Due to the complex injection process, it is unclear regarding the actual state of this hot pressurized kerosene prior to discharging.

Characterization of Heated Kerosene Jet into a Supersonic Crossflow

Four kerosene jets with the same conditions as those of Fig. 7 were visualized by injecting into a Mach 2.5 crossflow, with local static conditions of 570 K and 0.07 MPa. Again, the orifice diameter of injector was 0.8 mm. Figure 8 shows the corresponding Schlieren images.

It is seen that the heated kerosene jet structure was severely bent by the Mach 2.5 crossflow and the bow shock ahead of the jet was evident. It is also of interest to note that the penetration depth of four kerosene jets was approximately the same in the temperature range of 290-550 K, implying the resulting jet momenta were quite similar.

For the case of pure liquid atomization shown in Fig. 8(a), the spray structure in the Schlieren image appears to be dark owing to the blockage of incident light by the fine droplets. As the temperature of kerosene is increased to 480 K, the blockage of incident light by kerosene spray, while still noticeable, is substantially reduced, as seen in Fig. 8(b). Further increasing kerosene temperature beyond 500 K, Figs. 8(c)-(d) clearly show that the heated kerosene jet structures become more and more transparent to the incident light. Obviously, this transparency is indicative of the extent of kerosene gasification, which is expected to be enhanced with increasing temperature. The present results demonstrate that it is feasible to achieve complete vaporization of kerosene and to inject the vaporized kerosene into a supersonic combustor with comparable penetration depth as the liquid jet. Since the use of vaporized kerosene bypasses the vaporization process, the performance of a supersonic combustor is expected to be improved.

Work in Progress

Experimental investigation of vaporized kerosene combustion in a supersonic model combustor is underway. Ignition characteristics and combustion performance using vaporized kerosene injection are of particular interest. The results will be compared to those obtained with liquid kerosene injection and effervescent atomization. In addition, a new system capable of heating kerosene and delivering it continuously at a steady, controllable flow rate is currently under design and test.

Summary

Injection of pressurized kerosene into quiescent atmosphere and a Mach 2.5 crossflow was experimentally characterized at various preheat temperatures. The heating system was shown to be capable of providing constant high-pressure, high temperature kerosene up to 550 K during the typical 7-sec test run. Using the present heating system, the variation of kerosene density as functions of pressure and temperature was also measured. Both direct and Schlieren images illustrate that the amount of kerosene vapor increases with increasing preheat temperature. For injection pressure of 4 MPa, it was found that the kerosene jet plume is completely in vapor phase at injection temperature of 550 K. Furthermore, the supersonic experiments show that with a fixed injection pressure the penetration depth is approximately the same for the range of injection temperatures investigated. The present results suggest that the use of vaporized kerosene injection would enhance global combustion in a supersonic combustor, as compared to liquid kerosene atomization. Further study in this regard is warranted.

Acknowledgements

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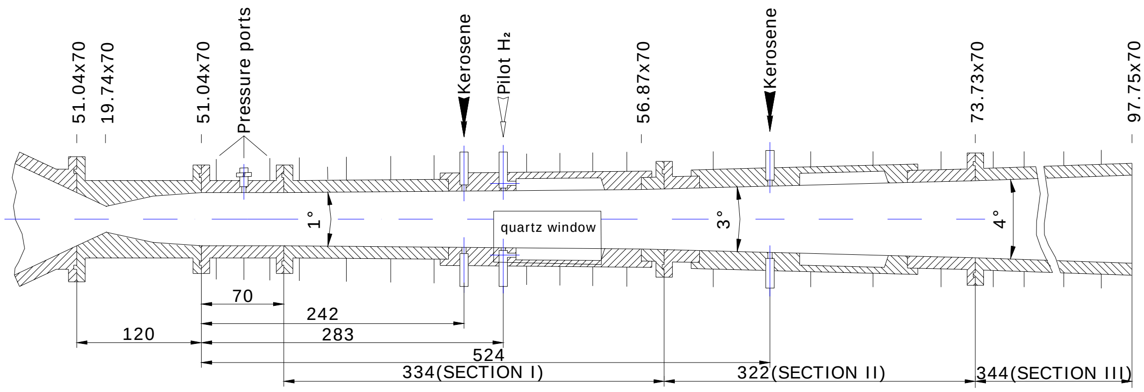

Figure 1 Schematic of kerosene/pilot hydrogen supersonic model combustor. All length dimensions are in mm.

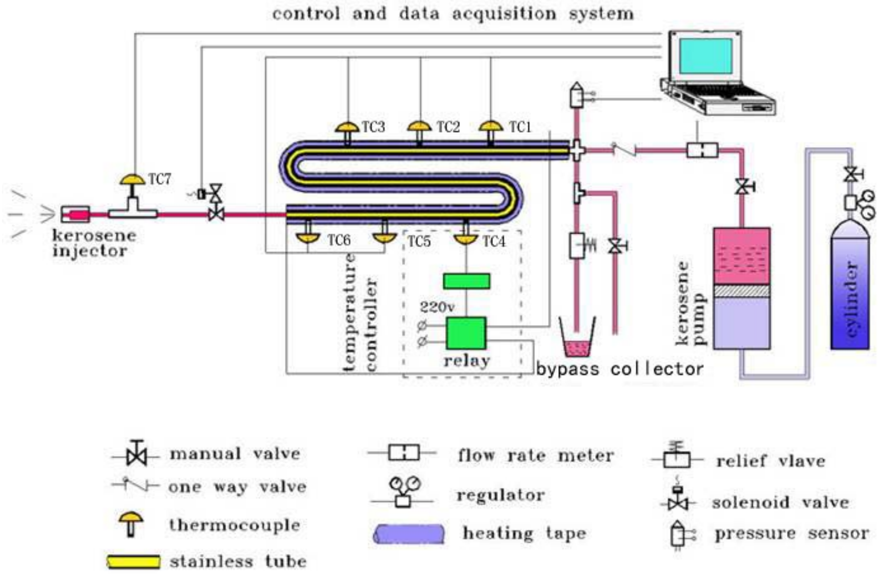

Figure 2 Schematic of kerosene delivery and heating system.

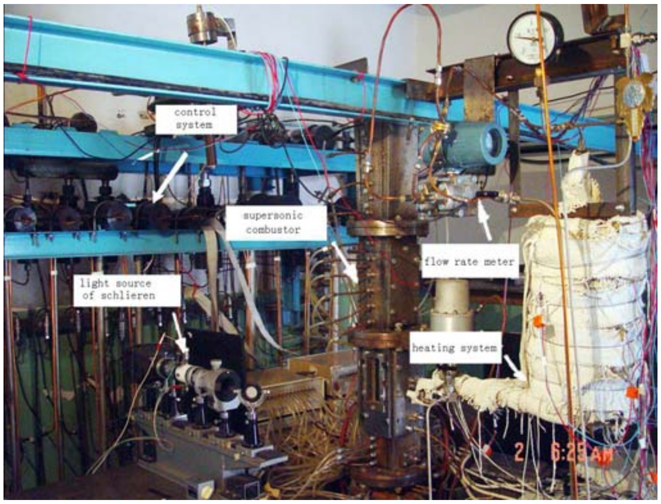

Figure 3 Photograph of test facility.

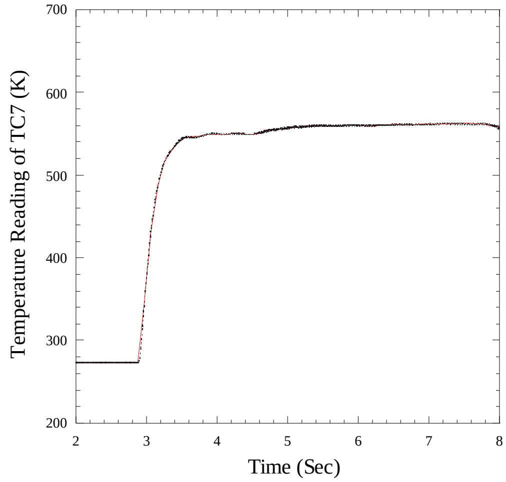

Figure 4 Time variation of kerosene temperature near the fuel injector.

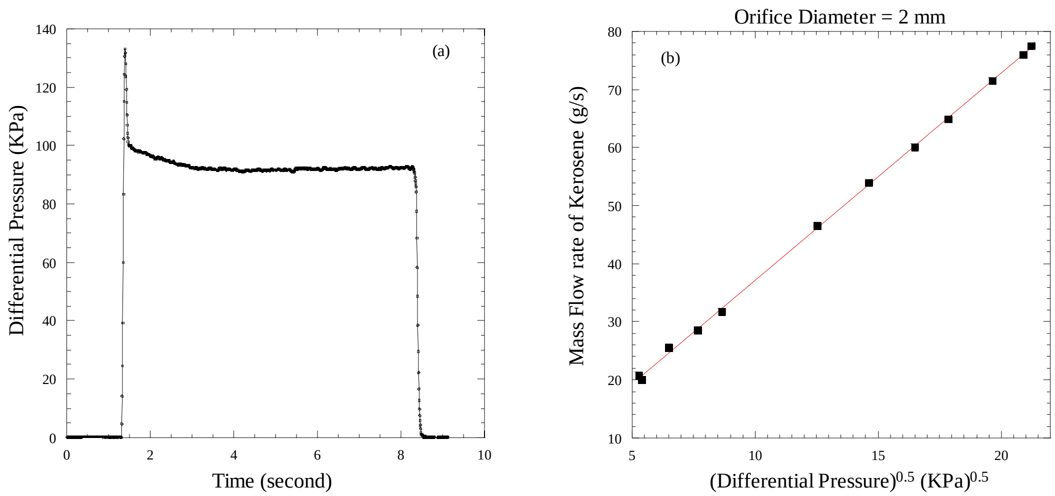

Figure 5 (a) Differential pressure across an orifice plate as a function of time. (b) Calibration of kerosene mass flow rate with an orifice plate flow meter.

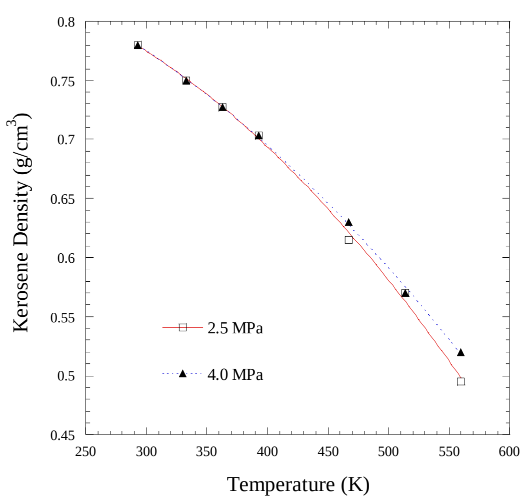

Figure 6 Variation of kerosene density in terms of pressure and temperature.

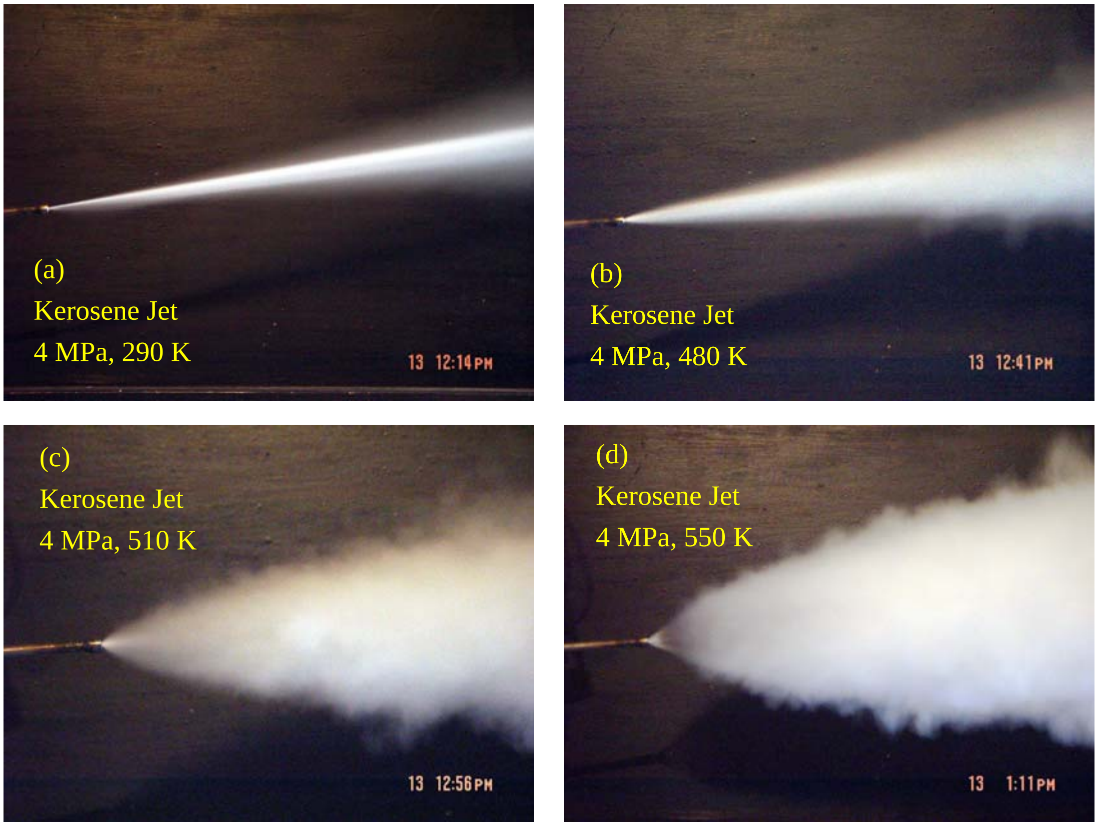

Figure 7 Direct images of pressurized kerosene jet into quiescent atmosphere at different injection temperatures.

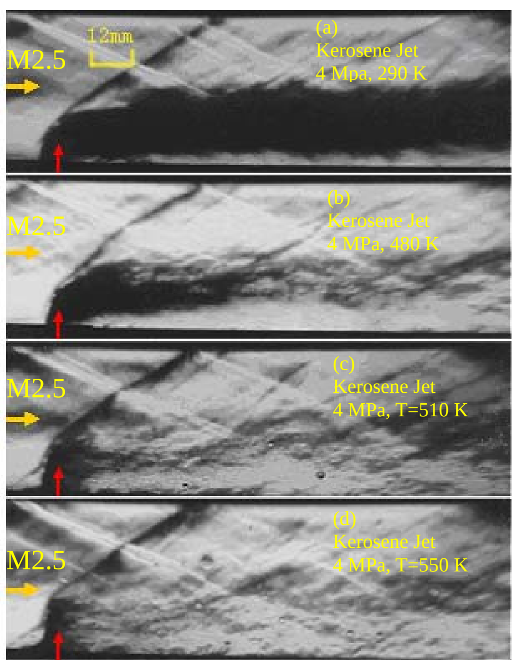

Figure 8 Schlieren images of pressurized kerosene jet into a Mach 2.5 crossflow at different injection temperatures. The local static conditions are of 570 K and 0.07 MPa.