Blowout Limits of Cavity-Stabilized Flame of Supercritical Kerosene in Supersonic Combustors

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Blowout limits of cavity-stabilized flame of supercritical kerosene were experimentally studied by using Mach 2.5 and 3.0 direct-connect supersonic model combustors operated under various air and fuel conditions. Specifically, the effects of the stagnation temperature and the stagnation pressure on the blowout limits were investigated for supercritical kerosene injected from the wall upstream of a cavity flameholder in a Mach 2.5 combustor. Experiments were performed under the same conditions for supercritical kerosene injected from the rear part of the cavity bottom to study the influence of the location of fuel injection. The blowout limits of supercritical kerosene injected from the wall upstream of the cavity were further investigated in a Mach 3.0 combustor. Besides the effects of the stagnation temperature and stagnation pressure, the effect of the divergence angle of the combustor on the lean-fuel blowout limit was studied. Results show that there exist two blowout limits corresponding to the lean- and rich-fuel conditions for a given stagnation temperature. The location of fuel injection has substantial influence on the blowout limits, whereas the influence of the stagnation pressure and the divergence angle of the combustor can be neglected in the range of interest.

I. Introduction

As aviable solution for scramjet propulsion at high Mach numbers of $M = 4 \sim 7$, supersonic combustion of liquid hydrocarbon fuels such as aviation kerosene has been extensively studied for decades. The grand challenge of realizing stabilized combustion of liquid kerosene in supersonic flows stems from the fact that liquid kerosene must undergo a series of successive processes in a very short fuel residence time, such as the atomization into fuel droplets, the vaporization of droplets, the mixing of fuel vapor with air, and the ignition and combustion of a fuel/air mixture. With the use of regenerative cooling, the liquid fuel in wall cooling channels could be heated to a supercritical state or even cracked gas by convective heat transfer before reaching the fuel injector [1–3]. During injection, the supercritical fuel can be directly transformed to a gaseous state corresponding to the local combustor condition, bypassing the atomization and vaporization processes. As a result, the overall fuel–air mixing could be enhanced, which would promote combustion performance [4,5].

Earlier studies [6–10] have shown that a well-designed cavity is able to provide a recirculation zone in which the hot gas will act as a heat source and a radical pool to stabilize the combustion process in supersonic flow. The mechanism of flame stabilization in supersonic flows is very complicated due to the strong interaction between the chemical reaction and the turbulent flow in the combustor. The flame stabilization becomes more difficult when taking into account the actual variations in flow and fuel conditions for a practical scramjet operation. The flame stabilized at one condition might be blown out at another condition. To design a practical scramjet engine, it is

necessary to accurately determine the blowout limits of cavity-stabilized flames.

Blowout limits of premixed flames have been extensively studied [11–13]. The effects of various factors, such as flow velocity, local pressure and temperature, and flameholder geometry, were investigated. Many empirical and semi-empirical formulas were proposed to correlate the blowout limits with these influence factors. It was found that the blowout limits could be correlated using a single parameter (i.e., the Damköhler number, which is defined as the ratio of the characteristic flow time to the characteristic chemical reaction time) [13–15].

Driscoll and Rasmussen [16], Rasmussen et al. [17,18], and Chadwick et al. [19] showed that the correlations of premixed flame could not be directly applied to supersonic combustion, in which the fuel is injected into the airflow upstream or inside the cavity and the flame is actually non-premixed. Chadwick et al. [19] have proposed a theoretical model to correlate the blowout equivalence ratio with the Damköhler number for the non-premixed flames of small-molecule fuels, such as hydrogen, ethylene, methane, and acetylene. However, the agreement between the theoretical prediction and the experimental data is not satisfactory, partially due to the large variation in the data from various measurements. High-fidelity measurements of blowout limits are desirable under well-determined experimental conditions.

The primary goal in the present work is to systematically measure the blowout limits of cavity-stabilized flames for combustion of supercritical kerosene in supersonic combustors. In the following text, the test facility and supercritical fuel heating system will be first described in Sec. II. The effects of the air stagnation temperature, the air stagnation pressure, and the location of fuel injection on the blowout limits of supercritical kerosene in Mach 2.5 airflows shall be presented in Sec. III.A. The effects of the air stagnation temperature and pressure as well as that of the divergence angle of the combustor on the blowout limits in a Mach 3.0 supersonic combustor shall be presented in Sec. III.B.

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II. Experimental Specifications

A. Test Facility

All the experiments in the present study were conducted on a direct-connect test facility with exchangeable convergent–divergent

nozzles for Mach 2.5 and 3.0 flows. The facility consists of an air heater, a multipurpose supersonic model combustor, and a kerosene delivery and heating system. The facility operation and data acquisition are controlled by a computer. The vitiated airflow, which is made by replenishing oxygen to the combustion products of H_2 and air, has a stagnation temperature of 800–2200 K and a stagnation pressure of 0.7–4.0 MPa. The stagnation pressure and temperature of the vitiated airflow are measured by using a CYB-10S pressure transducer with an accuracy of 0.1% and a type-B (Pt/Rh 70/30%–Pt/Rh 94/6%, by weight) thermocouple with an exposed tip, respectively. The mass flow rate of the gas flows (air, hydrogen, and oxygen) is controlled and measured by sonic nozzles. The mass flow rate coefficients of the sonic nozzles were calibrated with an uncertainty less than 1%.

Figure 1 shows the supersonic model combustor, which has a total length of 1450 mm and consists of a 400-mm-long section of nearly constant cross-sectional area and three divergent sections of 400, 300, and 350 mm in length and 1.3, 2.9, and 4 deg in expansion angle, respectively. The 0.70 deg divergence angle in the isolator is used to compensate for boundary-layer growth. The cross section of the combustor at its entrance is 70 mm in height by 51 mm in width. In Fig. 1, "0" indicates the beginning of the constant cross section and also represents the starting point for the static pressure measurement.

A pair of integrated fuel injector/flameholding cavity modules are installed in tandem on both sides of the combustor. Each of the modules has a step of 12 mm in depth, an aft ramp of 50 deg, and an overall length-to-depth ratio of 7. Two orifices of 4.0 mm in diameter are used for kerosene injection, one being located at the cavity floor and the other at the wall upstream of the cavity, as shown in Fig. 1. A pilot hydrogen of the typical equivalence ratio of 0.09, which is injected normally to the airflow from a location immediately upstream of the cavity, is used to enhance the ignition of kerosene in the supersonic combustor. The static pressure is measured by using Motorola MPX2200 pressure transducers installed along the centerline of the sidewalls of the model combustor. The experimental uncertainty of the static pressure measurement is about 3%.

The entire test facility is mounted upright on a platform. It usually takes approximately 2.5 s to establish a steady supersonic airflow and a typical total run lasts 9 second.

B. Kerosene Delivery and Heating System

A two-stage kerosene heating and delivery system, as shown in Fig. 2, was used to supply the supercritical kerosene at the stagnation temperature of 750 ± 20 K and the stagnation pressure of 3.5–6.0 MPa in the present study. The kerosene has a critical pressure and temperature of 2.4 MPa and 613 K. The first stage is a storage heater that can heat 1.5 kg of kerosene up to 570 K with negligible coking deposits, and the second stage is a continuous heater capable of rapidly heating the kerosene from the first stage to a prespecific temperature below 900 K within a few seconds.

Before each experiment, the kerosene in a storage cylinder is pumped into the first-stage heater by a piston driven by a high-pressure nitrogen gas. Two pneumatic valves (Swagelok, models SS6UM and SS10UM), which are installed at the exits of the first- and second-stage heaters, respectively, are employed to turn on/off the two heaters sequentially. When the kerosene in the first-stage heater reaches a designed temperature at a given pressure, it is driven
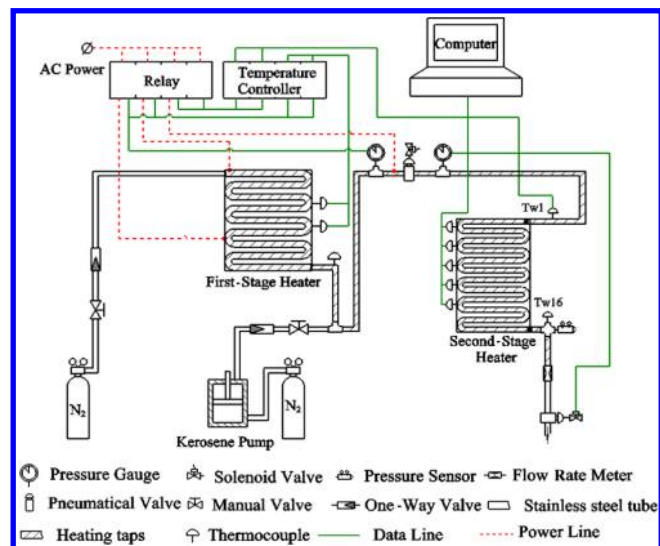

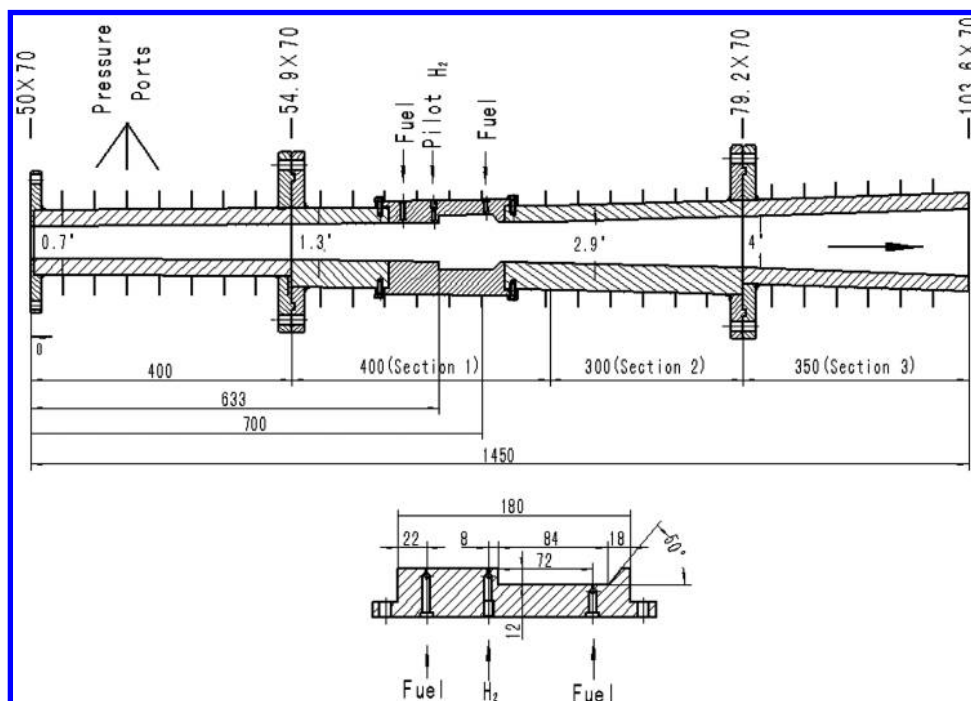Fig. 2 Schematic of kerosene delivery and heating system.

Fig. 1 Schematics of the supersonic model combustor (top) and the integrated fuel injection/flameholder module (bottom). All length dimensions are in millimeters.
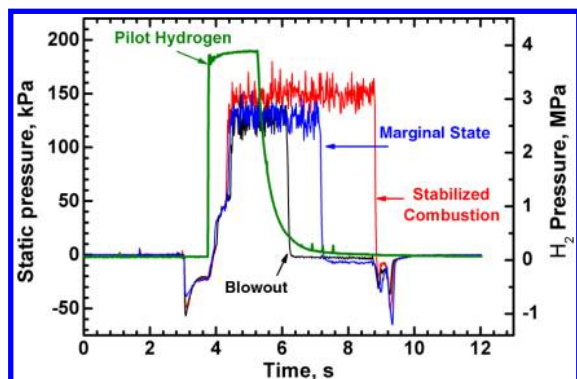
Fig. 3 Time histories of pilot hydrogen pressure (right *y* axis) and static combustion pressure (left *y* axis) at *x* = 700 mm for stabilized combustion, blowout, and marginal state.

by the nitrogen gas into the second-stage heater and heated up to the working temperature before being injected into the model combustor. Two groups of K-type thermocouples (Omega, model KMQSS-0.032E) are installed on the surface of the heater tubes or inserted into them. These thermocouples are used to monitor the fuel temperature in the heating system for its feedback control. The fuel temperature and pressure at the exit of the heating system are maintained steady during each experiment.

Mass flow rate of the supercritical kerosene is controlled and measured by sonic nozzles. The relevant calibration procedure has been described in detail in an earlier work [20]. The sonic nozzle of different sizes is selected according to the designed mass flow rate of the supercritical kerosene in each experiment. The mass flow rate of each sonic nozzle is determined based on the fuel temperature and pressure measured immediately upstream of the nozzle. The control of fuel temperature at 750 with an accuracy of 20 K ensures the accuracy of the mass flow rate, which is not sensitive to the temperature in the range. By using the measurement uncertainties of the throat area, the fuel pressure, and the fuel temperature, the overall uncertainty associated with the measured fuel mass flow rate can be determined to be less than 5%. China no. 3 kerosene [5] (similar to JP-8 jet fuel) is used in the experiments.

C. Criterion for Flame Stabilization

In each experiment, the pilot hydrogen is turned on at 3.5 s and turned off at 5.0 s. The supercritical kerosene is turned on at 4.0 s and turned off at 8.5 s. Figure 3 shows the time histories of the static combustion pressures at *x* = 700 mm (at the rear part of the cavity) for typical cases of stabilized combustion, blowout, and marginal state. The pilot hydrogen pressure is also given as a reference. Stabilized combustion is reached if the combustion pressure maintains its level to the end of kerosene injection at 8.5 s after the pilot hydrogen is turned off at 5.0 s. Flame blowout occurs if the combustion pressure drops immediately when the pilot hydrogen is turned off. Marginal state is defined when the combustion pressure drops at an intermediate moment between the two states. The time sequences of the pressures measured at other locations, such as *x* = 600, 800, and 900 mm are given in the supporting material, indicating that the criterion for flame stabilization is independent of the location of pressure measurement.

III. Results and Discussions

A. Mach 2.5 Experiments

1. Effect of Air Stagnation Temperature

Figure 4 presents the combustion regimes of the supercritical kerosene injected from the wall upstream of the cavity in terms of the fuel equivalence ratio and the stagnation temperature of the inlet airflows. Symbols in the figure denote the experimental data, and lines are fitted to separate different combustion regimes. The experiments were conducted in the stagnation temperature range of 1000–1800 K, the air mass flow rate range of 1100–2000 g/s, and the
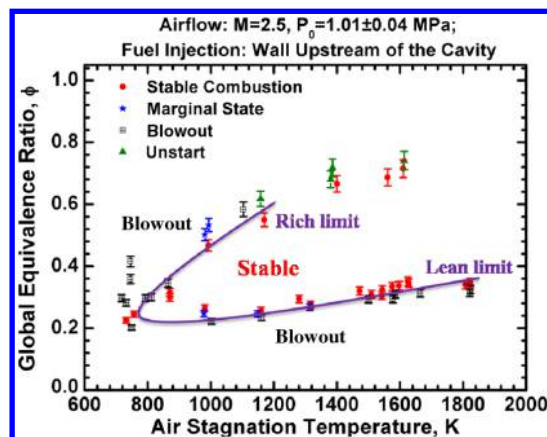

Fig. 4 Combustion regimes of supercritical kerosene injected from the wall upstream of the cavity in Mach 2.5 airflows at different air stagnation temperatures.

kerosene mass flow rate range of 25–60 g/s. The overall equivalence ratio [16] defined by using the total flow rates of fuel and inlet air is in the range of 0.2–0.8 in the experiments shown in Fig. 4. The relative error for the overall equivalence ratio is determined to be about ±3%, considering that the uncertainties associated with the mass flow rates of fuel and airflow are within 5 and 1%, respectively. The air stagnation pressure was fixed at 1.02 ± 0.04 MPa.

Several observations can be made of the combustion regimes shown in Fig. 4. There exist two branches of blowout limits, namely, the lean branch and the rich branch. The two branches stop at a critical turning point corresponding to an overall equivalence ratio of approximately 0.24 and a stagnation temperature of approximately 750 K. This critical temperature is the limit case in which the characteristic times of chemical reaction and flow can balance. Below this temperature, no stable combustion can be found. It was experimentally observed that the critical turning point is very sensitive to the temperature. Considering that the temperature uncertainty is about ±50 K in the present experiment, the critical temperature should be in the range of 750 ± 50 K. The lean and rich blowout limits both increase almost linearly with the stagnation temperature, but the slope of the lean limit is much lower than that of the rich limit.

As discussed in the Introduction, a few empirical or semi-empirical formulas have been proposed to correlate the blowout limits with various influencing factors. However, it is difficult to directly compare the present experimental results with the predictions based on those correlations, which were established for distinctively different experimental conditions. Figure 5 shows an illustrative comparison between the present experimental data and previous correlations. Following Driscoll and Rasmussen [16], the global equivalence ratio was scaled so that the rich and lean limits converge at an equivalence ratio of unity. It is not surprising to observe substantial difference between the present results and Driscoll and
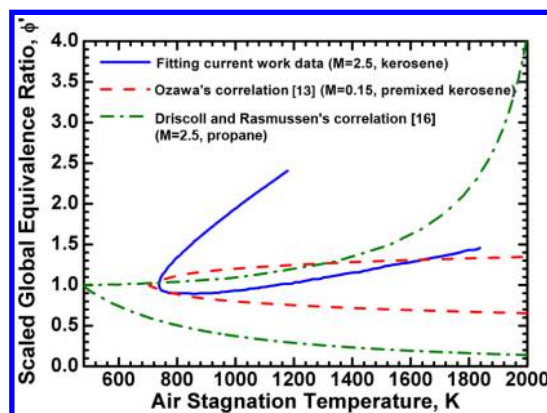

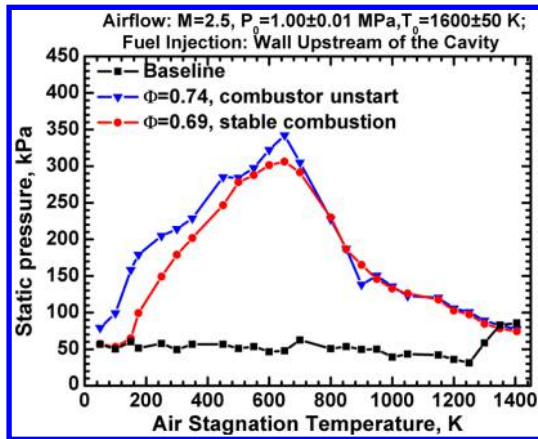**Fig. 5 Comparison of experimental data with the previous correlations.**

Fig. 6 Static combustion pressure distributions of two typical states: combustor unstart and stable combustion.

Rasmussen's correlation, which was derived for non-premixed supersonic combustion of small-molecule fuels. In the present experiments, the combustion was partially premixed to a large extent because kerosene was injected to the combustor from upstream of the cavity and hence can be sufficiently mixed with air before burning. However, the comparison indicates that injection at the wall upstream of the cavity benefits the rich limit, whereas direct injection into the cavity broadens the lean limit. Compared with the critical temperature of 750 K of kerosene, the smaller critical temperature of about 500 K predicted by Driscoll and Rasmussen's correlation may be due to the shorter ignition delay time of propane. Figure 5 also shows Ozawa's correlation [13], which was derived for subsonic combustion of kerosene and therefore cannot be directly compared with the present results.

It is also noted that, for the rich branch, when the temperature is higher than approximately 1200 K, the combustor "unstart" would occur before the rich blowout limit is reached, as shown in Fig. 4. When the precombustion shock train propagates out of the isolator due to high combustion pressure, the inlet airflow condition is accordingly changed, which may cause engine unstart. Similarly, combustor unstart used in a direct-connect test to stand for the inlet condition is changed due to excessively high combustion pressure, such as the case of kerosene $\Phi = 0.74$ at stagnation temperature of 1610 K in Fig. 6. It can be seen from Fig. 4 that the combustor unstart narrows the regime of stable combustion.

2. Effect of Air Stagnation Pressure

Figure 7 shows the lean blowout limit of supercritical kerosene in Mach 2.5 airflows at a fixed stagnation temperature of 1590 ± 50 K and varying stagnation pressures of 1.0–1.8 MPa. The transition
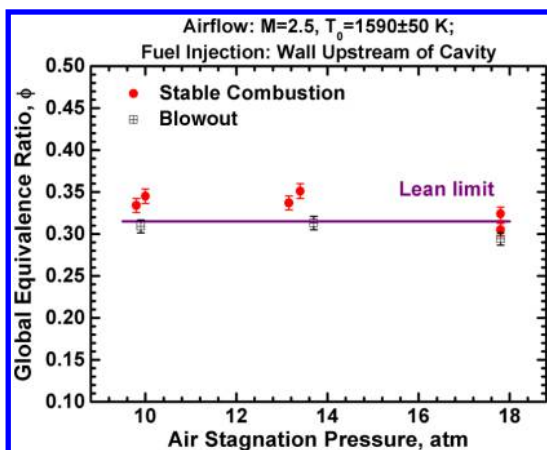

Fig. 7 Lean-fuel blowout limit of supercritical kerosene in Mach 2.5 airflows at a stagnation temperature of 1590 ± 50 K and stagnation pressures of 10–18 atm.
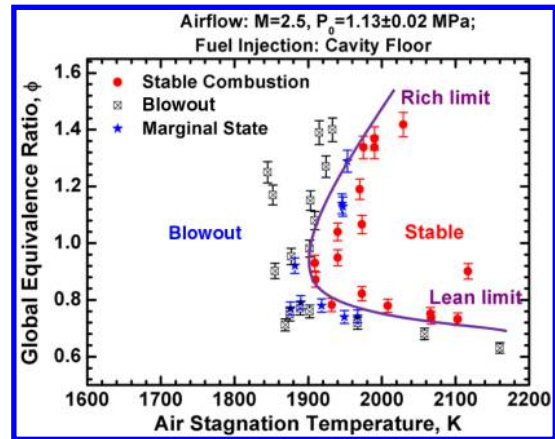
equivalence ratio for stable combustion is about 0.315 ± 0.02 over the whole range of the stagnation pressure studied. The variation of the stagnation pressure has a negligible influence on the lean blowout limits. A possible reason is discussed in Sec. III.B.1.

3. Effect of Fuel Injection Location

To study the effect of fuel injection location on the blowout limits, experiments with fuel injected from the rear bottom of the cavity floor (as shown in Fig. 1) have been carried out.

Figure 8 shows the experimental results obtained at stagnation temperatures of 1800–2200 K and a fixed stagnation pressure of 1.13 ± 0.02 MPa. The air mass flow rate is in the range of 1200–1500 g/s, the fuel mass flow rate is 65–140 g/s, and the corresponding equivalence ratio is 0.6–1.5. It is noted that the absolute error for the overall equivalence ratio is dependent on the mass flow rate. The larger global equivalence ratio shown in Fig. 8 makes the error bar larger than those in other figures. This is the reason for the larger data scattering in Fig. 8. Compared with the case with fuel injected from the upstream of the cavity in Fig. 4, the required stagnation temperature for stable combustion becomes much higher. The lowest stagnation temperature is approximately 1900 K. This is probably due to the deterioration of the fuel–air mixing level for fuel injected inside the cavity, which will slow down chemical reactions. The equivalence ratios of both lean and rich blowout limits are higher than those with fuel injected upstream of the cavity. A possible explanation is that a large portion of the fuel is convected directly out of the cavity when injected inside the cavity. Mixing of a supercritical fuel with surrounding gas exhibits similar behavior to actual gas–gas mixing [21,22], which significantly benefits the mixing for the case with fuel injected upstream of the cavity. It is concluded that it is much easier to stabilize the combustion if fuel is injected upstream of the cavity than from the rear bottom of the cavity, because the mixing level is relatively higher in the former situation.

It is noted that the trend of lean-fuel blowout limit shown in Fig. 8 is different from that shown in Fig. 4. Detailed flow and reaction simulations may be necessary to fully understand this phenomenon. Finally, no combustor unstart was found in this case even at the equivalence ratio as high as 1.4.

B. Mach 3.0 Experiments

1. Effect of Stagnation Temperature and Stagnation Pressure

Figure 9 shows the combustion regimes of supercritical kerosene in Mach 3.0 airflows. Because the fuel injection from upstream of the cavity has been proved to be a much more effective injection location than that from the rear bottom of the cavity, only the former injection scheme was used for Mach 3.0 experiments. The experiments were carried out at stagnation temperatures of 900–2000 K and a fixed stagnation pressure of 1.72 ± 0.03 MPa. The combustion regimes are similar to those for Mach 2.5 airflows shown in Fig. 4. Several differences can be identified by comparing Figs. 4 and 9. First, the
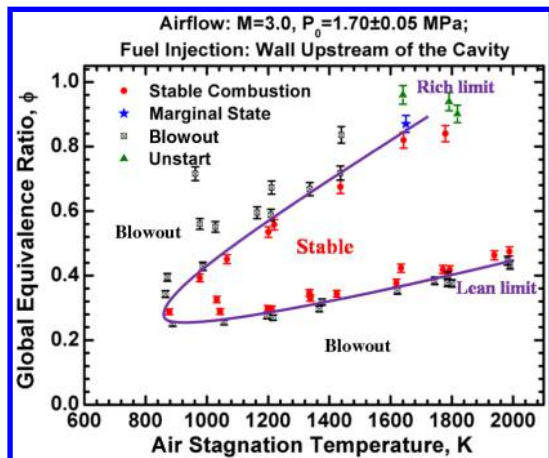

Fig. 8 Combustion regimes of supercritical kerosene injected from the cavity floor in Mach 2.5 airflows.

Fig. 9   Combustion regimes of supercritical kerosene injected from upstream wall of the cavity in Mach 3.0 airflows.

Fig. 11   Lean-fuel blowout limits of supercritical kerosene in Mach 3.0 airflows at the stagnation temperature of 1780 ± 40 K and the stagnation pressures of 16–30 atm.

blowout limit branches increase with the stagnation temperature slightly faster in the Mach 3.0 airflow than in the Mach 2.5 airflow because more fuel is burnt to maintain stabilized combustion in higher Mach number flow, which has a smaller flow residence time. Second, the critical stagnation temperature for maintaining the stable combustion in the Mach 3.0 airflow is about 150 K higher than that in the Mach 2.5 airflow. That is because a shorter characteristic chemical reaction time is needed by increasing the temperature to match the smaller flow residence time for the Mach 3.0 airflow. Third, it is more difficult to cause combustor unstart in the Mach 3.0 airflow than in the Mach 2.5 airflow, as it should be. As shown in Figs. 4 and 9, combustor unstart starts occurring at a much smaller equivalence ratio and stagnation temperature in the Mach 2.5 than in the Mach 3.0 airflow.

The effect of the stagnation pressure on the blowout limits was further investigated for Mach 3.0 airflows. Figure 10 shows the lean-fuel blowout limit at the varying stagnation pressure of 1.1–2.4 MPa and the fixed stagnation temperature of 1370 ± 50 K. Figure 11 shows the lean-fuel blowout limit at the stagnation pressure of 1.6–3.0 MPa and the fixed stagnation temperature of 1780 ± 40 K. Similar to the case of Mach 2.5 flows, no apparent variation of transition equivalence ratio was found for these two cases for Mach 3.0 flows. It can be therefore concluded that the influence of inlet airflow stagnation pressure on the lean-fuel blowout limit of supercritical kerosene injected from the wall upstream of the cavity is negligible in the experimental conditions presented here.

In comparison with Ozawa's correlation [13], the different pressure dependence of blowout limits in the present experiment can be understood in the following. Because combustion in the present experimental condition is premixed to a large extent, blowout limits
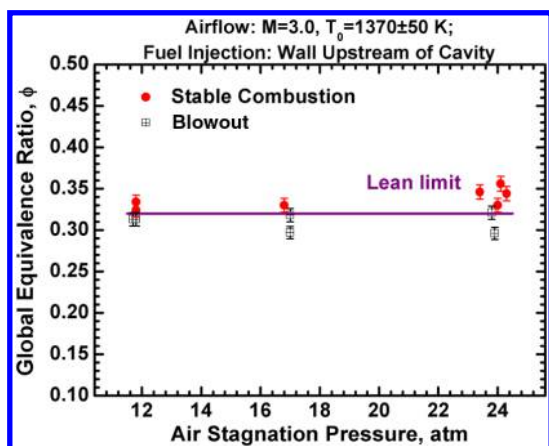
can be approximately determined by the balance between the local flame speed and the local flow speed. It is well known that the pressure dependence of laminar flame speed of hydrocarbon fuel is weak [23]. Recent studies on turbulent flame speed at different pressures show that increasing pressure does enhance the flame propagation, but the pressure dependence is not significant [24]. This is consistent with the present experimental observations. Moreover, Ozawa's classic correlation [13] was obtained by fitting the blowout limits for premixed combustion in subsonic flows, which are distinctively different from the present flow conditions. Consequently, a direct comparison between these two studies is unlikely meaningful.

A general rule of thumb of scramjet designers is that 0.5 atm of static pressure is required to burn, because static pressure less than 0.5 atm reduces the chemical reaction rate too much. In the present work, the fuel vertical injection upstream of the cavity into supersonic flow forms a bow shock, which makes the local static pressure of the cavity much larger than that at the entrance of the isolator. This is the possible reason that the flame can still be stabilized when the static pressure at the entrance of the isolator is less than 0.5 atm.

2. Effect of Combustor's Divergence Angle

Previous studies have shown that the divergence angle of the combustor has a significant influence on the thermal choking and ignition in the supersonic combustor [25,26]. Thus, it is of interest to investigate its influence on the blowout limit. Figure 12 shows the lean-fuel blowout limits of supercritical kerosene in Mach 3.0 airflows with two combustor divergence angles, 1.3 and 1.6 deg of section 1 in Fig. 1. The experiments were carried out at stagnation

Fig. 10   Lean-fuel blowout limits of supercritical kerosene in Mach 3.0 airflows at the stagnation temperature of 1370 ± 50 K and the stagnation pressures of 11–24 atm.
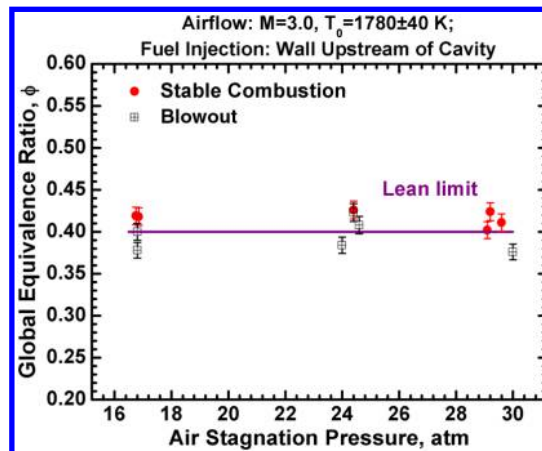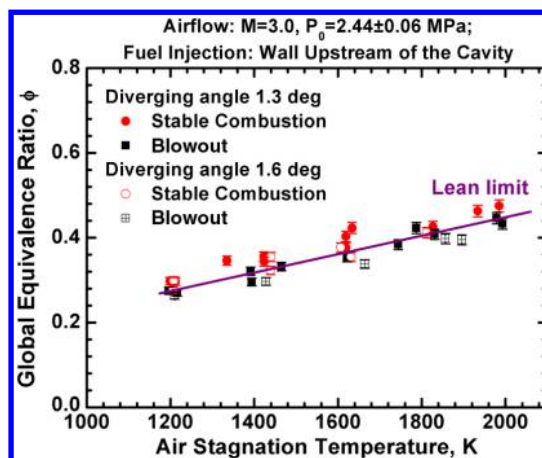

Fig. 12   Lean-fuel blowout limits of supercritical kerosene injected from the wall upstream of the cavity in a Mach 3.0 airflow with different combustor diverging angles.

temperatures of 1200–2000 K and stagnation pressures of 2.44 ± 0.06 MPa. Figure 12 shows that the difference in lean blowout limits is negligible for the two cases. Thermal choking downstream of the cavity can decrease the flow speed and increase the pressure around the cavity, enhancing the flame stability. The one-dimensional analysis of the supersonic combustor indicates that there is no thermal choking in all the cases of this work, and so the divergence angle does not have a significant effect on blowout limits under the present experimental conditions.

IV. Conclusions

The blowout limits of supercritical kerosene in Mach 2.5 and 3.0 supersonic combustors were experimentally studied. The effects of the air stagnation temperature, air stagnation pressure, fuel injection location, and divergence angle of the combustor on the blowout limits have been investigated. The following important conclusions can be drawn from the present study.

The air stagnation temperature and fuel injection location have substantial influence on the blowout limits, whereas the stagnation pressure and the combustor divergence angle have negligible influence.

Rich blowout limits increase with the stagnation temperature regardless of the fuel injection location, whereas the lean blowout limits strongly depend on the fuel injection location. The lean blowout limit increases with increasing stagnation temperature for fuel injected upstream of the cavity but decreases with fuel injected from the rear bottom of the cavity, which is possibly due to the change of the local mixing level inside the cavity. Further study is necessary to clarify this finding.

Acknowledgments

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