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Blowout Limits of Supercritical Kerosene in Supersonic Combustors*

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Blowout limits of supercritical kerosene were experimentally studied using direct-connect supersonic model combustors at various air and fuel conditions. Effect of air stagnation temperature on the blowout limit of supercritical kerosene injected from the wall upstream of a cavity was firstly examined in Mach 2.5 airflows. Blowout limit of supercritical kerosene injected from another location, the rear part of the cavity bottom, was also investigated in Mach 2.5 airflows to study the influence of fuel injection locations. Since results demonstrate the injection from the wall upstream of the cavity is beneficial to a wider stable combustion range, the blowout limits of supercritical kerosene injected from the wall upstream of the cavity were furthermore investigated in Mach 3.0 airflows. Moreover, with fuel injected from the wall upstream of the cavity, effects of stagnation pressure on the lean-fuel blowout limit were investigated in wide stagnation pressure ranges at three air stagnation temperatures. Finally, effect of the diverging angle of the combustor on the lean-fuel blowout limit was studied.

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I. Introduction

The combustion process in a scramjet combustor includes fuel and air mixing, ignition, flame propagation, stabilization and so on. Among them, maintaining a stable flame in the combustor is crucial for the successful design of a practical scramjet. The mechanism of flame stability in supersonic flows is extremely complicated due to the strong interactions between chemical reactions, turbulent flow and shock wave. Study of the blowout limit not only can understand the flame stability mechanism by comparing the experimental measurements and the model prediction, but also provide beneficial information for the design of practical scramjet.

Through a systematic theoretical analysis, Ozawa[1] proposed that the lean and rich-fuel limits of the premixed flame could be correlated using a single non-dimensional parameter, i.e. the Damkohler number, which is the ratio of characteristic flow time to characteristic chemical reaction time. Based on these studies, Marrison *et al.*[2] further developed a theoretical model by treating the flame zone as a well-stirred reactor (WSR). The blowout limits of WSR were then calculated using a simplified reaction mechanism. But it was proved by a series of theoretical and experimental studies of Driscoll and Rasmussen *et al.*[3-6] that the correlation for the premixed flame is not applicable for the general case in the supersonic combustor. Driscoll and Rasmussen *et al.* proposed a correlation between equivalence ratio at the blowout limit and the Damkohler number for the non-premixed flame of small-molecule fuels, such as hydrogen, ethylene, methane and acetylene.[6] The correlation is not in great agreement with the experimental data, partially due to the apparent discrepancy of the experiment data. Thus it is desirable to high fidelity data with well defined facilities and experimental conditions.

Therefore, the primary goal of the present work is to acquire data on the rich/lean blowout limits of a cavity-stabilized flame of supercritical kerosene in supersonic combustors with well-defined experimental conditions. Supercritical kerosene is used as the fuel in this work due to two considerations: its potential usage in the active-cooling engine for a hypersonic flight; lack of its experimental data. In the work effects of the air stagnation temperature, the fuel injection location and air stagnation pressure on the blowout limits were experimentally studied, since the characteristic time of chemical reaction depends on the temperature of reactants, fuel equivalence ratio, and pressure of the reactant. Moreover, the model for our experimental data was preliminarily discussed. Furthermore, the effect of the inlet airflow velocity on the blowout limits was examined due to the dependence of the characteristic flow time on the airflow velocity. Finally, effect of the diverging angle of the combustor on the blowout limit was studied.

II. Experimental Specifications

A. Test Facility

The experiments were conducted in a direct–connect test facility with exchangeable convergent-divergent nozzles of Mach 2.5 and 3.0, which consisted of a vitiated air heater, a multi-purpose supersonic model combustor, and a kerosene delivery and heating system. The facility operation, control, and data acquisition were accomplished with a computer. The vitiated air heater, burning H_2 and air with replenishment of O_2, was used to supply heated airflows with stagnation temperatures of 800-2200 K and stagnation pressures of 0.7-4.0 MPa. The stagnation pressure and temperature of the vitiated air were measured using a CYB-10S pressure transducer and a Type-B thermocouple, respectively. The mass flow rates of the gases were controlled and measured by sonic nozzles. The mass flow rate coefficients of the sonic nozzles were calibrated with uncertainty < 1%.

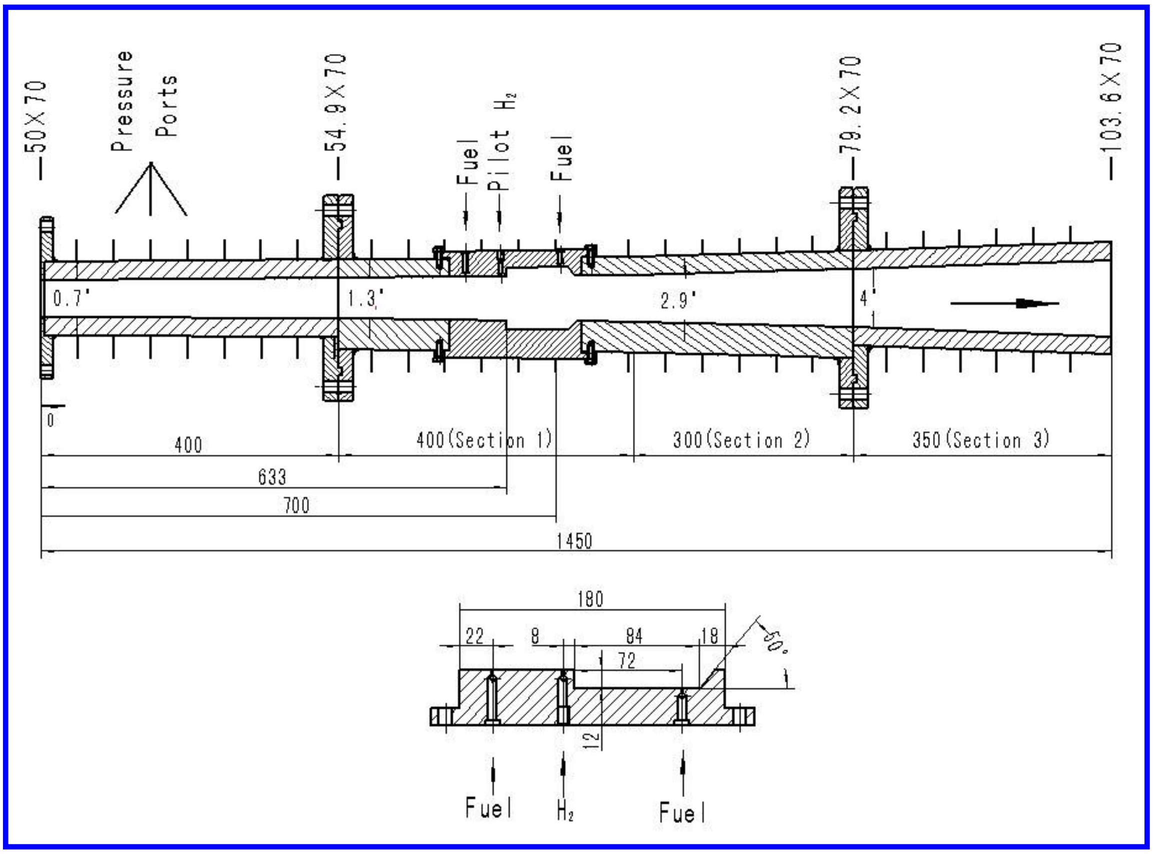

Fig. 1 Schematic of the model combustor (top) and configuration of the integrated fuel injection/flameholder module (bottom). All length dimensions are in mm.

The model combustor is shown in Fig. 1. It has a total length of 1450 mm and consists of one nearly constant area section of 400 mm and three divergent sections of 400, 300 and 350 mm with the expansion angles of 1.3, 2.9 and 4 degrees, respectively. The entry cross section of the combustor is 70 mm in height by 51 mm in width. In the figure, the "0" indicating the beginning of the constant area section represents the origin for the static pressure distribution.

A pairs of integrated fuel injector/flame holder cavity modules in tandem were installed on both sides of the combustor, each of with a step of 12 mm in depth and a 50º aft ramp and an overall length-and-depth ratio of 7. Two orifices of 4.0 mm in diameter are available for kerosene injections, one at the cavity floor and the other at the wall upstream of the cavity as shown in Fig. 1. A small amount of pilot hydrogen was used to facilitate the ignition of kerosene in the supersonic combustor, which was injected normal to the airflow just upstream of the cavity. The typical equivalence ratio of pilot hydrogen was 0.09. Distribution of the static pressure in the axial direction was determined using Motorola MPX2200 pressure transducers installed along the centerline of the model combustor sidewalls. The experimental uncertainty in the static pressure measurement was approximately 3%.

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

B. Kerosene Delivery and Heating System

Supercritical kerosene used in this work was at stagnation temperatures of 750±20 K and stagnation pressures of 3.5-6.0 MPa, which was prepared using a two-stage kerosene heating and delivery system. A schematic of this system is shown in Fig. 2. The first stage is a storage heater that can heat kerosene of 1.5 kg up to 570 K with negligible coking deposits and the second stage is a continuous heater, which is capable of rapidly heating kerosene to a desired temperature below 900 K within a few seconds.

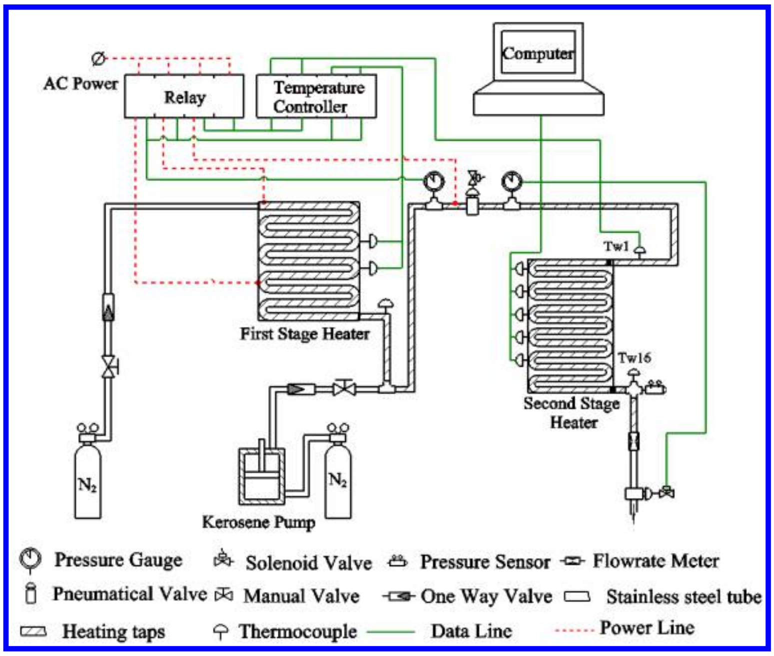

Fig. 2 Schematic of kerosene delivery and heating system.

Prior to each experiment, the kerosene in a storage cylinder was pumped into the first-stage heater by a piston driven by high-pressure nitrogen gas. Two pneumatic valves (Swagelok, Model No. SS6UM and SS10UM) installed, respectively, at the exits of the first- and second-stage heaters were employed to turn on/off the two heaters sequentially. When kerosene in the first-stage heater reached a desired temperature at a given pressure, it was pressed into the second-stage heater and heated up to the working temperature before injected into the model combustor. Two groups of K-type thermocouples (Omega, Model No. KMQSS-0.032E), denoted in Fig. 2, were installed on the surface of or inserted into the heater tubes. These thermocouples were used to monitor the fuel temperature distribution along the heating system and achieved the feedback control of the heating system. Steady fuel temperature and pressure at the exit of the heating system were accomplished and maintained during each experiment.

Mass flow rates of the supercritical kerosene were controlled and measured by sonic nozzles. The associated calibration procedure has been documented in ref. 7. The different size of the sonic nozzle was chosen according to the desired mass flow rate of the supercritical kerosene in the experiment. It was installed at the exit of the second-stage heater, as shown in Fig. 2. The mass flow rate of each sonic nozzle was determined on the base of the fuel temperature (T_f) and pressure (P_f) measured just upstream the nozzle. The control of fuel temperature at 750±20K benefits the accuracy of mass flowrate, because the mass flowrate is not very sensitive to the temperature in this range. Considering the measurement accuracies of throat area, fuel pressure, and fuel temperature, the overall uncertainty associated with the measured fuel mass flow rate was within 5%.

C. Criterion of Flame Stabilization

During each experiment, the pilot hydrogen was turned on at 3.5 s and turned off at 5.0 s. Supercritical kerosene was turned on at 4.0 s and turned off at 8.5 s. Fig. 3 shows the typical time histories of the pilot hydrogen pressure and the static combustion pressure at the location of x = 700 mm for three cases of stable combustion, blowout, and marginal state. This location lies at the rear part of the cavity, thus the static pressure at this location can reflect the combustion in the cavity. As shown in Fig. 3, stable combustion is established if the combustion pressure maintains at least 3.5 s after pilot hydrogen is turned off; flame blowout occurs immediately once the pilot hydrogen shut down; Marginal state is the case that the stable combustion stops at an intermediate moment.

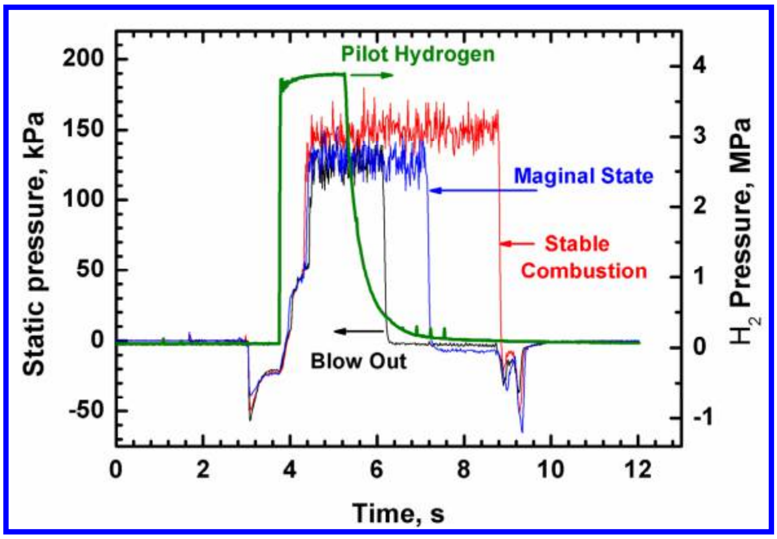

Fig. 3 Histories of pilot hydrogen pressure and static combustion pressure at a location of x = 700 mm for the cases of stable combustion, blowout, and marginal state.

III. Results and Discussions

A. Effect of Air Stagnation Temperature

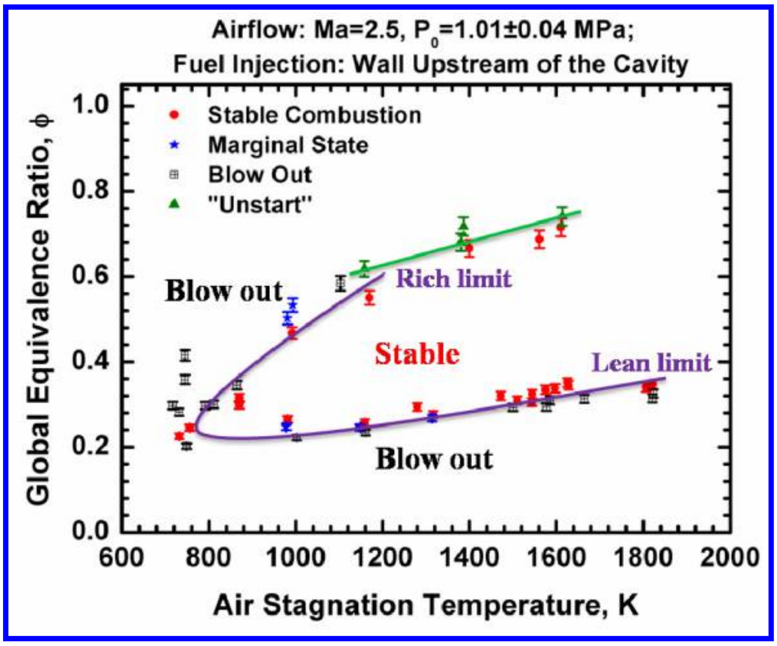

Fig. 4 Combustion stabilization modes of supercritical kerosene injected from the wall upstream of the cavity in Mach 2.5 airflows at different air stagnation temperatures.

Figure 4 shows the combustion stabilization modes of supercritical kerosene injected from the wall upstream of the cavity in terms of the fuel equivalence ratios and stagnation temperatures of inlet airflows. Symbols in the figure denote experimental data, while lines are fitted boundary of stable combustion. Experiments were carried out at stagnation temperatures of 1000-1800 K, air mass flow rates of 1100-2000 g/s, mass flow rates of supercritical kerosene ranged from 25 to 60 g/s and the corresponding equivalence ratio of 0.2-0.8. It is noted that the global equivalence ratio in the figure is defined using the total fuel and overall inlet air. The error bar for the global equivalence ratio is ±3% on the base of consideration that the uncertainty associated with the measured fuel mass flow rate was within 5% and the uncertainty associated with the air mass flow rate was within 1%. Air stagnation pressures were mainly 1.02±0.04 MPa.

The outline of the stable zone in figure 4 is different with the one of the premixed flame, whose lean and rich limits are almost symmetrical with inflection point at equivalence ratio around 1.0. The figure shows that the rich-fuel blowout limit is sensitively proportional to the stagnation temperature of the freestream but the lean-fuel blowout limit is less. The global equivalence ratio range for the stable combustion is wider at high temperatures than that at low temperatures. The inflection point between the lean and rich limits is around 750K and Φ=0.24. The correlation proposed by Driscoll *et al.* for the blowout limit of diffusion flame cannot explain the phenomena in this work, because the fuel in this work is injected from the wall upstream of the cavity and at least mixes with the air stream before it is entrained into the shear layer, thus it is expected that the condition in this work is somewhat close to ideal premixed model.

The reason for the difference between the experimental result and ideal premixed model will be qualitatively analyzed as follows. Firstly, since recent study [8] demonstrated that the cavity generally make the flame stabilize in the shear layer at the condition of fuel injected upstream of the cavity, the local equivalence ratio in the shear layer should be more precise for the description of the blowout limit. However, the local equivalence ratio cannot be acquired in the current experiment. For simplicity, the global equivalence ratio is used in the work. The global equivalence ratio and the local one can be associated by the mixing upstream of the shear layer. Thus the injection depth of fuel in the combustion area should be one key parameter, which is unfortunately not fully clear now. Secondly, the high temperature unreacted reactant into the shear layer from the recirculation zone of the cavity also influences the local equivalence ratio in the shear layer. Thirdly, the high stretch rate in the shear layer should influence the flame speed, eventually affecting the blowout limit. These items should be considered for developing a model to explain the current experimental data in future.

It is interesting to find that “unstart” state occurs inside the stable combustion zone, such as the equivalence ratio of 0.741 at 1613 K in the figure. The “unstart” state in this work is defined that an increase in the pressure at the combustor entrance caused by combustion, lowing Mach number of the inlet airflow. The “unstart” narrows the stable combustion zone.

B. Effect of Fuel Injection Location

Compared with fuel injected from the wall upstream of the cavity, another fuel injection location at the rear bottom of the cavity floor shown at the bottom of Fig. 1 was used to study the effect of fuel injection location on the blowout limits of supercritical kerosene in the same Mach 2.5 airflow.

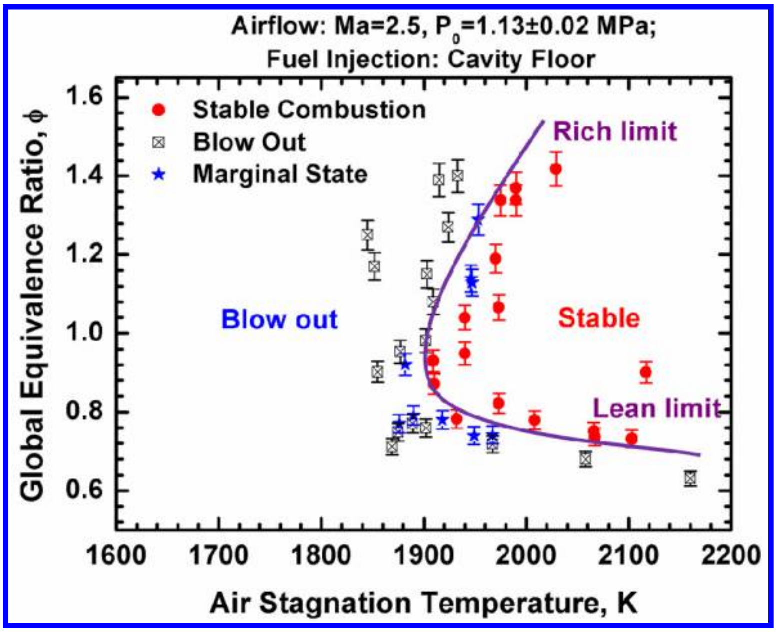

Fig. 5 Combustion stabilization modes of supercritical kerosene injected from the cavity floor in Mach 2.5 airflows. Symbols are experimental results and the line is the fitted or extrapolated boundary in all figures below.

Figure 5 shows blowout limits of supercritical kerosene injected from the cavity floor in terms of the fuel equivalence ratios and freestream stagnation temperatures. Experiments in the figure were conducted at stagnation temperatures of 1800-2200 K, stagnation pressures of 1.13±0.02 MPa, and air mass flow rates of 1200-1500 g/s. The fuel mass flow rate ranged from 65 g/s to 140 g/s, and the corresponding equivalence ratio was over the range of 0.6-1.5. It is seen from the figure that both much higher stagnation temperature and equivalence ratio were required to maintain the stable combustion in the condition of fuel injection from the rear bottom of the cavity, compared with the result in the condition of fuel injection from the wall upstream of the cavity. The major reason for the high equivalence ratio should be that in the case of fuel injection from the rear bottom of the cavity most of the fuels were directly injected into the mainstream and mixes with the downstream air of the cavity, while only few fuels were taken into the cavity by the air entrained from the shear layer up the cavity. The major reason for the high air stagnation temperature should be that the residence time of reactant in the flameholder, especially the shear layer, is shorter than the case with fuel injection from the wall upstream of the cavity. It can be concluded that use the wall injection upstream of the cavity is more suitable for stabilizing flame.

Figure 5 also shows that the rich-fuel blowout limit is sensitively proportional to the freestream stagnation temperature and the lean-fuel blowout limit is inversely proportional. The trend of lean-fuel blowout limit is different in two cases with different fuel injection locations. The reason is that the global equivalence ratio, not local equivalence ratio in the cavity, is used. Although it is hard to clearly deduce the local equivalence ratio from the global equivalence ratio, it should be necessary for explanation of the different trend.

The “unstart” state doesn’t occur even at such high equivalence ratio as 1.6 in the case of fuel injection from the bottom of the cavity, which indicates that this injection location allows much more amount of fuel. The major reason should be that the front step effectively restrains the upstream propagation of pressure.

C. Effect of Airflow Mach Number

Blowout limits of supercritical kerosene injected from the wall upstream of the cavity were investigated and compared at two different Mach numbers of 2.5 and 3.0. The experimental data are plotted in Figs. 4 and 6, respectively.

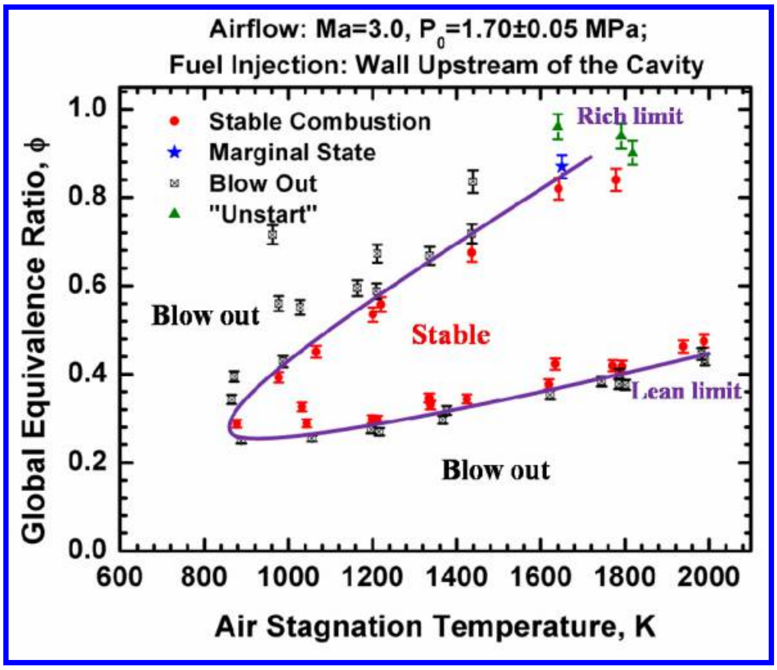

Fig. 6 Combustion stabilization modes of supercritical kerosene injected from upstream wall of the cavity in Mach 3.0 airflows.

Figure 6 shows the combustion stabilization modes of supercritical kerosene in terms of the fuel equivalence ratios and stagnation temperatures of inlet Mach 3.0 airflows. Experiments were carried out at stagnation temperatures of 900-2000 K. Stagnation pressures were mainly 1.72±0.03 MPa. Fig. 6 shows that the stable combustion can be maintained at low stagnation temperatures and low equivalence ratios. The profile is similar to the result in Mach 2.5 airflows shown in Fig. 4. However, there are some differences. First, the trend of lean-fuel blowout limit branch proportional to the stagnation temperature is much more obvious in the Mach 3.0 airflow. Second, the lowest 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. Third, it is easier to cause “unstart” in the Mach 2.5 airflow than in the Mach 3.0 airflow. For example, “unstart” occurs inside the rich-fuel limit in the Mach 2.5 airflow at stagnation temperatures of around 1600 K, but does not in the Mach 3.0 airflow.

D. Effect of Airflow Stagnation Pressure

Effect of inlet airflow stagnation pressure on the lean-fuel blowout limit was examined at three different conditions, respectively. The results are plotted in Figs. 7-9. The supercritical kerosene was injected from the wall upstream of the cavity.

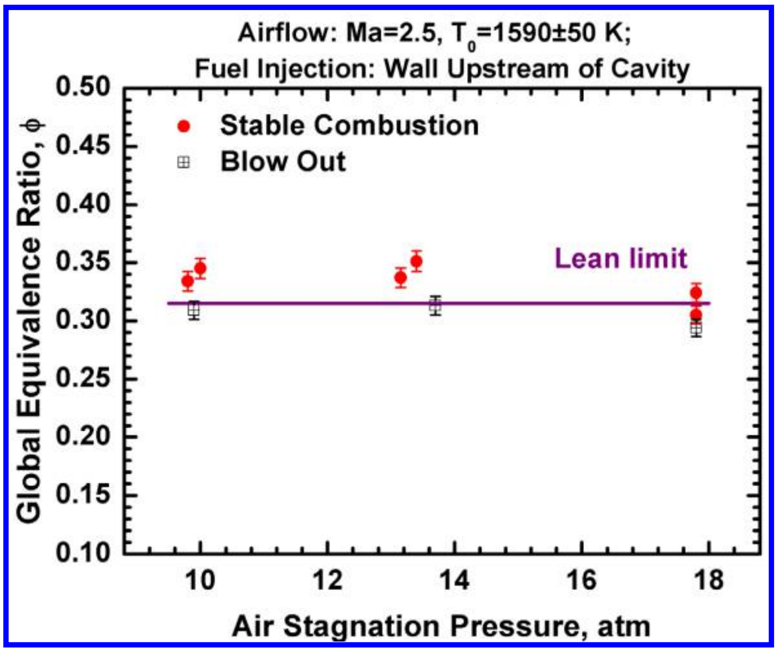

Fig. 7 Lean-fuel blowout limits of supercritical kerosene in Mach 2.5 airflows at stagnation temperatures of 1590±50 K and in a stagnation pressure range of 10-18 atm.

Figure 7 shows the lean-fuel blowout limit at a stagnation pressure range of 1.0-1.8 MPa and stagnation temperatures of 1590±50 K in Mach 2.5 airflows. The boundary is always at the equivalence ratio of 0.315±0.02 over such large stagnation pressure range. Except 3% error bar, the slight uncertainty should come from the difference of the air stagnation temperature. Fig. 8 shows the lean-fuel blowout limit at a stagnation pressure range of 1.1-2.4 MPa and stagnation temperatures of 1370±50 K in Mach 3.0 airflows. The boundary is always at the equivalence ratio of 0.32±0.01. Fig. 9 shows the lean-fuel blowout limit at a stagnation pressure range of 1.6-3.0 MPa and stagnation temperatures of 1780±40 K in Mach

3.0 airflows. The boundary is always at the equivalence ratio of 0.40±0.025. It is 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 can be negligible.

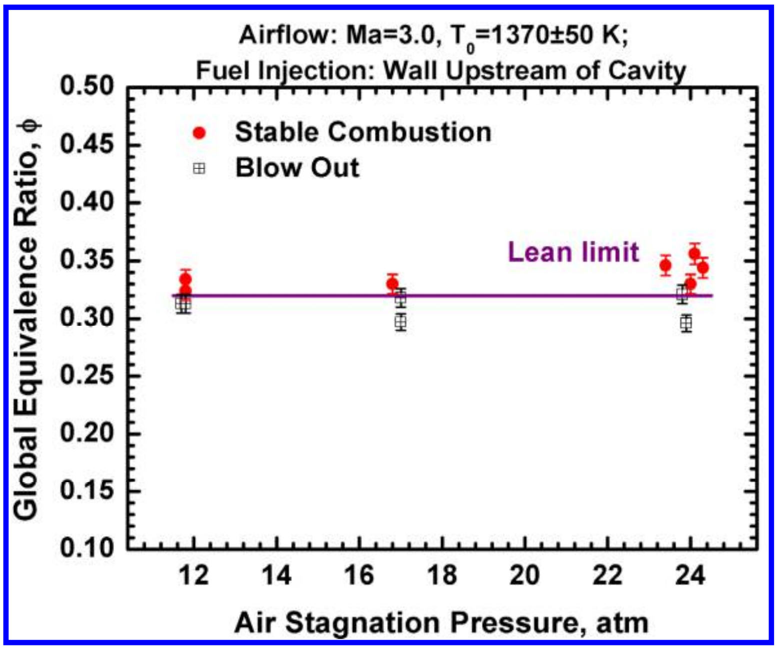

Fig. 8 Lean-fuel blowout limits of supercritical kerosene in Mach 3.0 airflows at stagnation temperatures of 1370±50 K and in a stagnation pressure range of 11-24 atm.

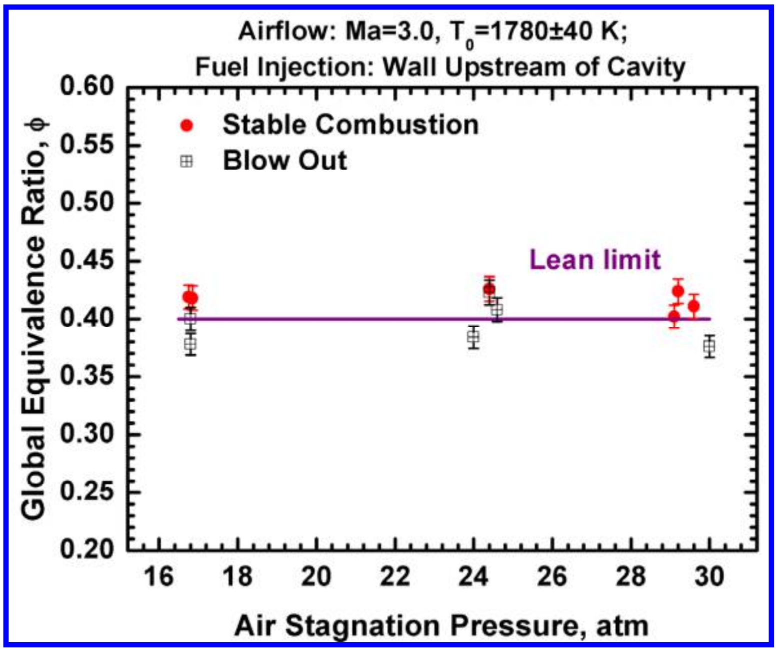

Fig. 9 Lean-fuel blowout limits of supercritical kerosene in Mach 3.0 airflows at stagnation temperatures of 1780±40 K and in a stagnation pressure range of 16-30 atm.

E. Effect of Combustor's Diverging Angle

Diverging angle of a combustor has a significant influence on the thermally chocking and ignition in the supersonic combustor. Thus it is concerned to investigate its influence on the blowout limit.

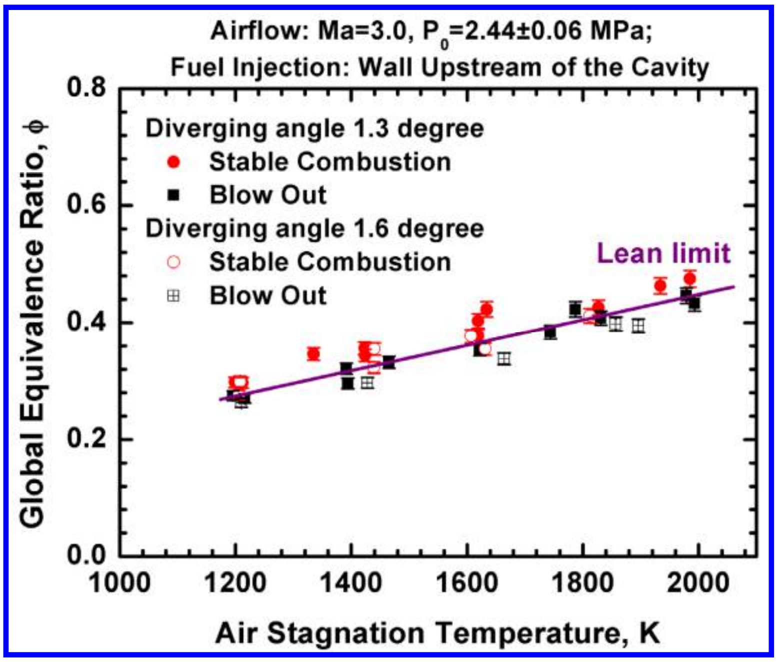

Fig. 10 Lean-fuel blowout limits of supercritical kerosene injected from the wall upstream of the cavity in a Mach 3.0 airflow with different combustor diverging angles.

Figure 10 shows the lean-fuel blowout limits of supercritical kerosene in Mach 3.0 airflows with different combustor diverging angles (section 1 in Fig. 1), such as 1.3º and 1.6º. Supercritical kerosene was injected from the wall upstream of the cavity. Experiments were carried out at stagnation temperatures of 1200-2000 K and stagnation pressures of 2.44±0.06 MPa. It is seen that the influence of diverging angle on the lean-fuel blowout limit can be negligible in the studied diverging angle range.

IV. Concluding Remarks

This work focused on experimentally studying blowout limits of supercritical kerosene cavity-stabilized flames in heated Mach 2.5-3.0 supersonic airstreams.

Effect of fuel injection location on the blowout limit was examined in the supersonic combustor. Results indicate that fuel injection from the wall upstream of the cavity is more suitable for stabilizing flame, and fuel injection from the rear bottom of the cavity allows much more amount of fuel.

Effects of airflow Mach number, airflow stagnation pressure and combustor's diverging angle on the blowout limit were further studied at the condition of the fuel injection from the wall upstream of the cavity. The blowout limits of supercritical kerosene combustion in different Mach airflows of 2.5 and 3.0 are plotted using a global equivalence ratio and the airflow stagnation temperature. The boundaries present a similar profile: the rich-fuel blowout limit is very sensitive to the freestream stagnation temperature but the lean-fuel blowout limit is slight sensitive or not. However, there are some differences. For the rich-fuel blowout limit, "unstart" can occur inside of the blowout limit in the lower Mach airflow, which would render a new boundary of stable combustion. For the lean-fuel blowout limit, the proportional dependence of equivalence ratios on the airflow stagnation temperature increases with Mach number increasing, which cannot be explained by using the correlation for the premixed flame and the correlation proposed by Driscoll *et al.* for the non-premixed flame. Further studies on local equivalence ratio in the zone of stabilizing flame are required to explore these phenomena. Moreover, results of different inlet airflow stagnation pressures indicate that the influence of stagnation pressure on the lean-fuel blowout limit of supercritical kerosene can be negligible. Finally, the lean-fuel blowout limits of supercritical kerosene in Mach 3.0 airflows with different combustor diverging angles show the influence of diverging angle on the blowout limits can be negligible in the diverging angle range of 1.3-1.6º.

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