47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit
31 July - 03 August 2011, San Diego, California

AIAA 2011-6108

Measurements of the Blowout Limits of Supercritical Aviation Kerosene in a Supersonic Combustor

Jing Wang[1], Xuejun Fan[2], Taichang Zhang[3], Gang Yu[4], and Jianguo Li [5]
Institute of Mechanics, Chinese Academy of Science, Beijing 100080, P. R. China

Combustion and flame stability of supercritical kerosene were studied experimentally in a supersonic model combustor at various air and fuel conditions. The lean and rich blowout limits of supercritical kerosene injected from the bottom of a cavity flameholder were examined in Mach 2.5 airflow. It was found that the rich blowout limit was very sensitive to the stagnation temperature of the airflow while the lean limit was only slightly affected. Damkohler number was used to correlate the two limits. On the other hand, the lean blowout limits of supercritical kerosene injected upstream the cavity were investigated and compared at three different Mach numbers of 2.0, 2.5 and 3.0.

I. Introduction

THE combustion process in scramjet combustor includes fuel and air mixing, ignition, flame propagation and stabilization and so on. Among them, maitaining a stable flame in the combustor is crucial for the successful design of a practical scramjet. In high-speed flow the mechanism of combustion stability is very complicated due to the strong interaction between chemical reactions and turbulent flow. To fully understand the mechanism, it is necessary to clarify the flow structure in flame holder, the mass exchange law between recirculation zone and mainstream, the mode of flame stabilization, and the limits of stable combustion. [1]

The key parameters controlling the flame stabilization are the characteristic times of the flow field and the chemical reactions. Through a systematic theoretical analysis, Ozawa[1] proposed that the lean and rich limits of the premixed flame could be correlated using a single non-dimensionalized parameter, i.e. the Damkohler number, which is the ratio of flow time to chemical reaction time. The flow time is inverse proportional to the characteristic length scale of the flame holder divided by the characteristic velocity. The characteristic time of chemical reaction depends on the fuel equivalence ratio, temperature and pressure of the premixed reactants. Based on these studies, Marrison et al[2] further developed a theoretical model that can be used to design the structure of the flame holder. This model treats the flame zone as a Well-stirred reactor (WSR), and the blowout limits of WSR are then calculated using simplified reaction mechanism. The application of Marrison's model was limited because the effects of fuel injection location and the process of fuel-air mixing have been neglected. For the case of non-premixed reactants, no single curve exists as that in the premixed cases. Recently Driscoll and Rasmussen et al[3-6] have carried out a series of theoretical and experimental studies on the lean blowout limits of cavity-stabilized flames for hydrogen, ethylene, methane and acetylene in a supersonic combustor. They showed that the stability limits were largely affected by the fuel injection location and thus the WSR model is not realistic for non-premixed flames.[6]

The primary goal of the present work is to obtain qualitative data on the rich/lean blowout limits of a cavity flame with injection of supercritical aviation kerosene in a supersonic combustor with well-defined experimental conditions. Another goal is to develop the correlations of the blowout limits to the flow and fuel conditions.

---

[1] Assitant professor, National Key Laboratory of High Temperature Gas Dynamics, wangjing@imech.ac.cn.
[2] Professor, National Key Laboratory of High Temperature Gas Dynamics, fanx@imech.ac.cn, member AIAA.
[3] Assitant professor, National Key Laboratory of High Temperature Gas Dynamics.
[4] Professor, National Key Laboratory of High Temperature Gas Dynamics, member AIAA.
[5] Professor, National Key Laboratory of High Temperature Gas Dynamics.

II. Experimental Specifications

A. Test Facility

The experiments were conducted in a Mach 2.5 direct–connect test facility, 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 with H_2, O_2 and air, was used to supply heated airflow with stagnation temperature of 800-2200 K and stagnation pressures of 0.7-1.3 MPa. The stagnation pressure and temperature of the vitiated air were measured using a CYB-10S pressure transducer and a Type-B thermocouple, respectively. Different convergent-divergent nozzles were used to accelerate the flow to Mach 2.0, 2.5 or 3.0.

The model combustor is shown in Fig. 1. It had a total length of 1450 mm and consisted 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 was 70 mm in height and 51 mm in width. In Fig. 1, the “0” indicated at the beginning of the constant area section represents the origin for all the static pressure distributions to be presented and discussed later.

A pairs of integrated fuel injector/flame holder cavity modules in tandem were installed on both sides of the combustor, each of with a depth of 12 mm in height and a degree of 50 aft ramp angle and an overall aspect ratio of 7. There was two orifices of 4.0 mm in diameter for kerosene injections, one at the cavity floor and the other at 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 used 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 measurements was approximately 3%.

The entire test facility was mounted upright on a platform and can be translated laterally and vertically. It usually takes approximately 2.5 seconds to establish a steady supersonic airflow and a typical run lasts 7 seconds or so.

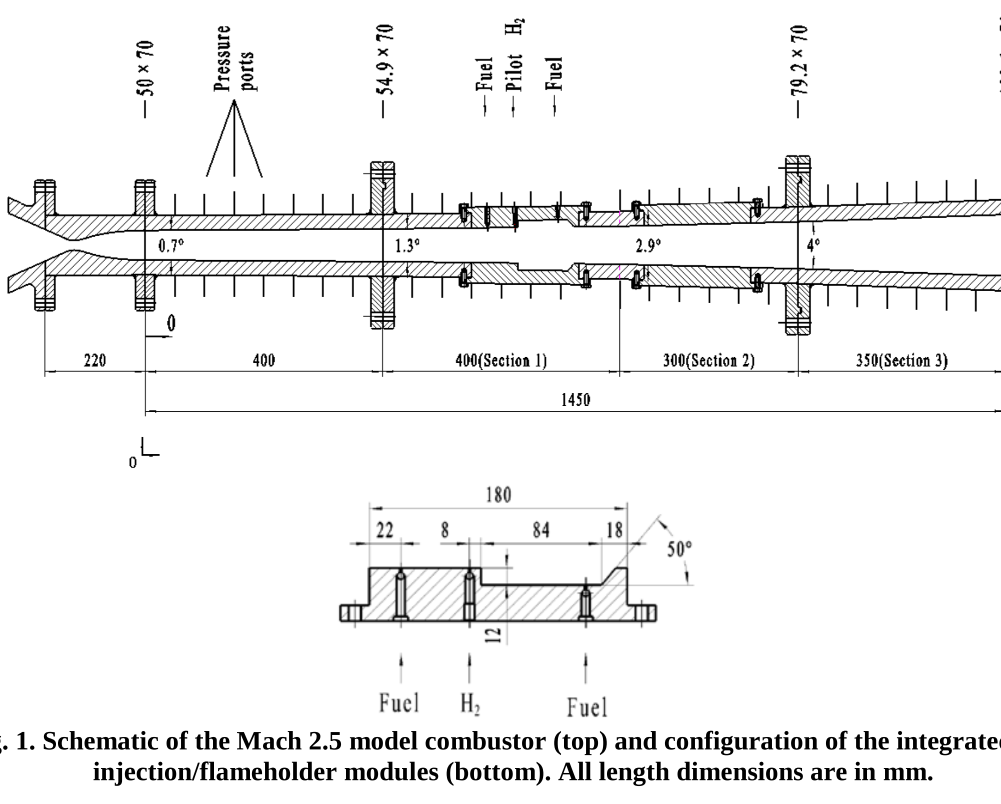

Fig. 1. Schematic of the Mach 2.5 model combustor (top) and configuration of the integrated fuel injection/flameholder modules (bottom). All length dimensions are in mm.

B. Kerosene Delivery and Heating System

Supercritical kerosene at temperature of 750±20 K was prepared under varying pressures using a two-stage kerosene heating and delivery system. A schematic of this system is show n in Fig 2. The first stage heater was a storage type that can heat kerosene of 0.8 kg up to 570 K with negligible coking deposits and the second-stage heater was a continuous type, which was capable of rapidly heating kerosene to 750 K within a few seconds.

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. 3, 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 achieve the feedback control of the heating system. Stable fuel temperature and pressure at the exit of the heating system were accomplished and maintained during each experiment.

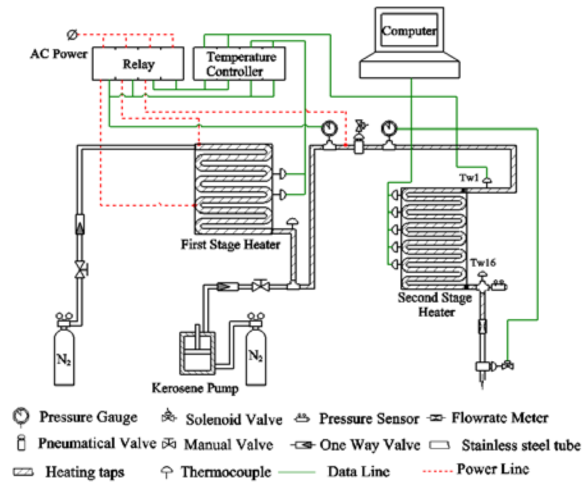

Fig. 2 Schematic of kerosene delivery and heating system.

The 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 sonic nozzle was chosen according to different mass flow of the supercritical kerosene in the experiment. It was installed in parallel at the exit of the second-stage heater, as shown in Fig. 2. The mass flow rate of each sonic nozzle was determined based on the fuel temperature and pressure measured just upstream the nozzles. 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. Classification of the 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. Figures 3 shows the typical time histories of pilot hydrogen pressure and static combustion pressure at location of x = 700 mm for the cases of stable combustion, blowout, and marginal combustion. Stable combustion was established if the combustion pressure maintained at least 3.5 s after pilot hydrogen turned off; Flame blowout occurred when the combustion stopped immediately after the pilot hydrogen shutdown. All the other cases are called marginal state when the combustion stopped at an intermediate moment as shown in Figure 3.

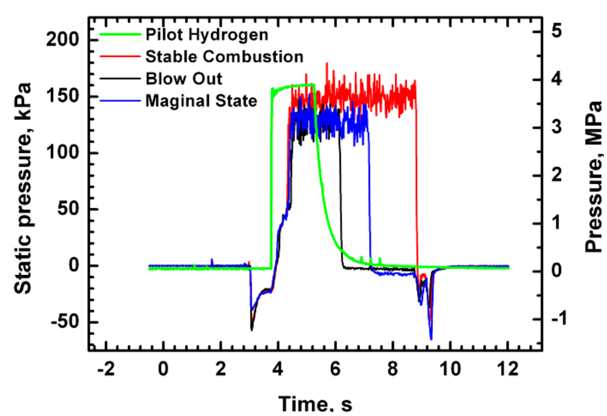

Fig. 3 The histories of pilot hydrogen pressure and static combustion pressure at location of x = 700 mm for the cases of stable combustion, blowout, and marginal combustion.

D. Calculation of Damkohler Number

It is known that the most important non-dimensional scaling parameter in the theory of flame stability is the Damkohler number. This number is dependent on the flow time and the reaction time. For the case of premixed systems, there are many previous studies that report values of Damkohler number, such as those of Ozawa[1], Zukowski and Marble[8] and so on. For example, the result of Ozawa for premix kerosene-air combustion in an afterburner showed that the stable region was surrounded by a rich limit and by a lean limit. Ozawa defined the premixed time scale (τ_{PREMIX}) to be a function of pressure and inlet temperature of the premixed reactants. For the case of nonpremixed reactants, there is no single curve reported that is similar to that of Ozawa until the recent correlation and the analysis presented by Driscoll and Rasmussen.[3] They considered a cavity-stabilized nonpremixed flame in supersonic heated air flow. And they defined the Damkohler number used to correlate the blowout data to be

$$D_a = \frac{H/U_{00}}{\left(\frac{\alpha_0}{S_{L0}^2}\right)\left(\frac{1atm}{P}\right)^n\left(\frac{300K}{T}\right)^m} \quad (1)$$

where H is the cavity height, U_{00} is the free stream velocity, P and T is the free stream static pressure and temperature, the exponential n and m are to be 1 respectively. α_0 is the thermal diffusivity and S_{L0} is the stoichiometric laminar burning velocity, both are evaluated at 300 K and 1 atm. However, the values of .α_0 and S_{L0} of supercritical kerosene can not be determined accurately in our experiments, instead n-decane are chosen as the single species surrogate of kerosene.

III. Results and Discussion

A. Fuel Injected from the Cavity Floor

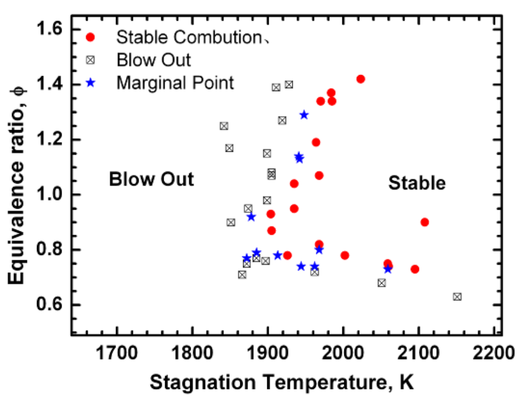

Fig. 4 The combustion stabilization modes in terms of the fuel equivalence ratios and stagnation temperature of air flow(Mach=2.5).

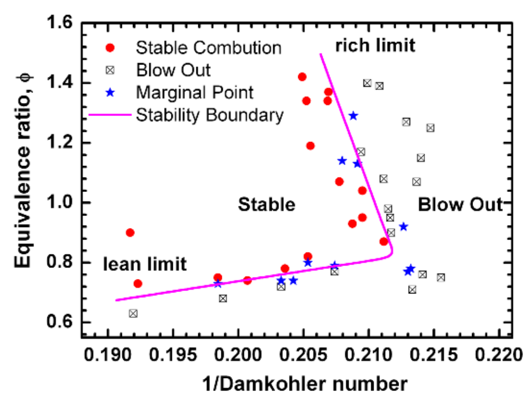

Fig. 5 The lean and rich blowout limits in terms of the fuel-air equivalence ratios and the inverse Damkohler number.

Figure 4 plotted combustion stabilization modes in terms of the fuel equivalence ratio and stagation temperature of air flow. All experiments in Fig. 4 were conducted in the Mach 2.5 combustor at stagnation temperatures of 1800-2160 K, stagnation pressures of 1.12-1.15 MPa, and air mass flowrates of 1200-1500 g/s. The kerosene was injected at the supercritical conditions of 750±20 K and 3.5-5.5 MPa. The fuel mass flowrate ranged from 65 g/s to 140 g/s, and the corresponding equivalence ratio was 0.6-1.5. The rich and lean blowout limits could be clearly identified from Fig. 4 and the stable combustion region was shown to be expanded with the increased stagnation temperature.

Fig. 5 shows the correlation of lean and rich blowout limits in terms of the fuel equivalence ratios and the inverse Damkohler number for supercritical kerosene injected from the cavity floor. Damkohler number is defined by Eqn. 1 and overall fuel-air equivalence ratio (Φ) is defined as the mass flow rate of fuel divided by the mass flow rate of air steam, divided by the stoichiometric fuel-air ratio. The overall profile of the blowout limit curve in Fig. 5 is similar to that of a premixed flame in Ozawa's theory[1], except that the lean and rich blowout limits are much more symmetric in the case of premixed flame. For this cavity floor fuel injection, the best linear fit to the rich and lean blowout data in Fig. 5 are

$$\Phi = 26.05 - 119.05\ Da \quad (2)$$

$$\Phi = -0.62 + 6.81\ Da \quad (3)$$

Eqn. (2) and (3) indicate that increasing the Damkohler number, such as, by increasing the cavity height H or increasing the burning velocity S_{L0}, will stabilize the flame. Increasing the static pressure or the air steam temperature also leads to improved cavity-flame stability.

B. Fuel Injected upstream the Cavity

Further experiments were conducted to examine the effect of free stream Mach number on the blowout limits. The fuel injection location was moved from the floor to upstream of the cavity. Figure 6 plotted the lean blowout limits in terms of the fuel equivalence ratios and stagnation temperature of air flow at three different Mach number of 2.0, 2.5 and 3.0. The rich blowout limit could not be obtained because a rich fuel injection upstream the cavity will cause the boundary layer separation moving upstream into the facility nozzle due to excessive heat release.[7]

The Mach 2.0 experiments in Fig. 6 were performed at stagnation temperatures of 800-2000 K, static pressures of 0.91-0.93 MPa, air mass flowrates of 1200-1900 g/s, the fuel mass flowrates ranged from 20 g/s to 35 g/s at the supercritical conditions of 750±20 K, 3.5-5.5 MPa, and the corresponding equivalence ratio was 0.2-0.3. For the cases of the Mach 2.5, experiments were carried out at stagnation temperatures of 800-2000 K, static pressures of 0.77-0.79 MPa, air mass flowrates of 1350-1800 g/s, the mass flowrates of supercritical kerosene ranged from 30 g/s to 40 g/s and the corresponding equivalence ratio was 0.2-0.4. As to the Mach 3.0 combustor, experiments were carried out at stagnation temperatures of 800-2000 K, static pressures of 0.54-0.56 MPa, air mass flowrates of 1350-1850 g/s, the fuel mass flowrate ranged from 35 g/s to 50 g/s and the corresponding equivalence ratio was 0.2-0.5.

Obviously, at the same Mach number 2.5, the lean blowout limit is expanded widely with fuel injection upstream the cavity in Fig. 6 compared to that with fuel injection from the cavity floor in Fig. 4, which demonstrates that the injection location has large effects on flame stabilization.

It is noticed that at the blowout limit in Fig. 6 the fuel equivalence ratio increases with the increased stagnation temperature which is opposite to the tendency in Fig. 4. This is probably due to the fact that the definition of the overall fuel equivalence ratio in this work could not represent the actual local values. It is necessary to develop a model to relate these two equivalence ratios.

It can also be seen that the slope of lean blowout limit in Fig.6 increases with the entrance Mach number of the combustor, which indicates the combustion at the same fuel equivalence ratio becomes less stable at higher Mach number.This phenomena could be related to fuel-air mixing processes but definitely need further studies.

If a single parameter such as Damkohler number could be used to correlate the data for different Mach number in Fig. 6, it is suggested that the exponentials of P and T in eqn. (1) should be adjusted to values other than one, which were found to be 0.5 and 0.3 respectively for fuel injected from upstream the cavity, as seen in eqn. (4). The lean blowout limits at three different Mach number of 2.0, 2.5 and 3.0 were shown in Fig. 7.

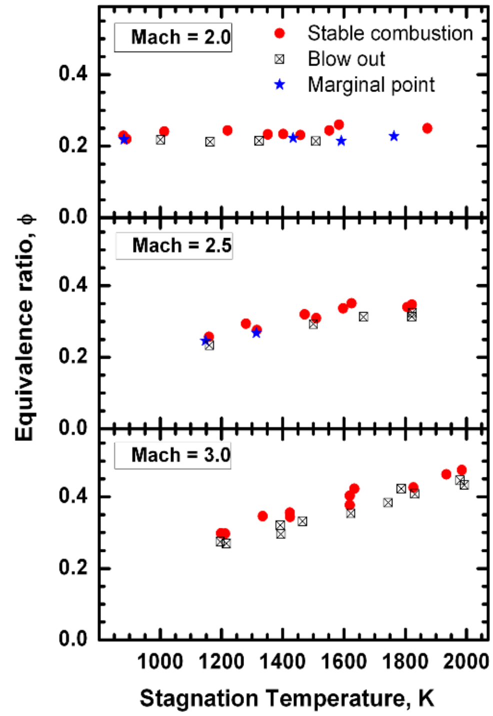

Fig. 6 The correction of the fuel equivalence ratios and stagnation temperature of air flow with different Mach number 2.0, 2.5 and 3.0 under the three conditions: stable combustion, blow out and marginal state.

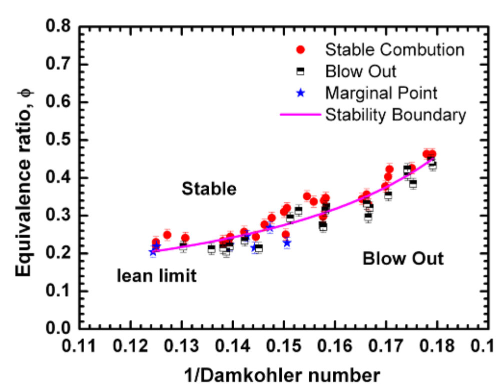

Fig. 7 The lean blowout limits in terms of the fuel-air equivalence ratios and the inverse Damkohler number at three different Mach number of 2.0, 2.5 and 3.0.

$$D_a = \frac{H/U_{00}}{\left(\frac{\alpha_0}{S_{L0}^2}\right)\left(\frac{1atm}{P}\right)^{0.5}\left(\frac{300K}{T}\right)^{0.3}} \tag{4}$$

IV. Conclusion

Combustion stabilization plays an important role in successful operation of supersonic combustion ramjet, and it is also a significant challenge due to the high velocity of air flow and complexity of chemical reaction involved. But the combustion stabilization mechanism is still not fully understood, predominantly due to the lack of experimental data of blowout limits of flames for various operating conditions. The current study focuses on blowout limits for flames stabilized with a cavity in a heated supersonic air stream. Fuel is injected directly into the combustor from two locations: the floor and the upstream of the cavity.

For the cavity floor fuel injection case, approximately 50 measured values from supercritical kerosene combustion are plotted using a global Damkohler number reported by Driscoll et al, which is used to obtain the correlation curves including a rich and a lean limit branch. For the fuel injection upstream the cavity, the results shows that the slope of lean blowout limit has an opposite sign to that with fuel injection from the cavity floor, and the slope increases with increased Mach number. Further studies is required to explore these phenomena.

Acknowledgments

Current research program at the Chinese Academy of Sciences was supported by the National Natural Science Foundation of China under Contractor No. 91016005, 10979067 and 10621202. The authors would like to acknowledge Mr. X. S. Wei, Prof. X. N. Lu, and Mr. Y. Li for their technical supports.

References

[1]Ozawa, R. I., "Survey of Basic Data on Flame Stabilization and Propagation for High Speed Combustion Systems," *U.S. Air Force AFAPL Technical Report* TR-70-81, 1970.

[2]Morrison, C. Q., Lyu, H. Y., and Edelman, R. B., "Fuel Senditivity Studies based on a Design System for High Speed Airbreathing Combustor", *ISABE* 99-7235 1999.

[3]Driscoll, J. F., and Rasmussen, C. C., "Correlation and Analysis of Blowout Limits of Flames in High-Speed Airflows, Journal of Propulsion and Power", *Journal of Propulsion and Power*, Vol.21, No.6, 2005, pp. 1035.

[4]Rasmussen, C. C., Driscoll, J. F., Hsu, K.-Y., Donbar, J. M., Gruber, M., and Carter, C. D., "Stability Limits of Cavity-Stabilized Flames in Supersonic Flows", *Proceeding of the Combustion Institute*, Vol.30, 2004, pp. 2825-2931.

[5]Rasmussen, C. C., Dhanuka, S., and Driscoll, J. F., "Visualization of Flameholding Mechanisms in a Supersonic Combustor Using PLIF", *Proceeding of the Combustion Institute*, Vol.31, 2007, pp. 2505-2512.

[6]Chadwick, C., Rasmussen, C. C., and Driscoll, J. F., "Blowout Limits of Flames in High-Speed Airflows:Critical Damkohler Number", *AIAA Paper* 2008-4571, *44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference &Exhibit*, July 2008, Hartford, CT.

[7]Fan, X. J., Yu, G., Li, J. G., Zhang, X. Y., and Sung, C. J., "Investigation of Vaporized Kerosene Injection and Combustion in a Supersonic Model Combustor", *Journal of Propulsion and Power*, Vol.22, No.1, 2006 January-Feburary, pp. 103-110.

[8]Zukoski, E. E., and Marble, F. E., "Experiments Concerning the Mechanism of Flame Blowoff from Bluff-Bodies", *Proceedings of the Gas Dynamics Symposium on Thermochemistry*, Northwestern U, Evanston, IL, 1956, pp. 205-225.