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Flame Stabilization Characteristics of Strut Divided into Two Parts in Supersonic Airflow

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Flame stabilization experiments were conducted in a supersonic airflow of Mach number 1.5, using a strut divided streamwise into two parts. Hydrogen gas was injected into the interval between the two parts of the strut. The flame stabilization was definitely affected by whether the combustion region could be established in this space, and the flame stabilization characteristics changed drastically according to the distance between the two parts of the strut. A shadowgraph and schlieren photographs showed that no shock waves or expansion waves existed in the intervening space, and that waves did not directly control the flame-stabilization mechanism that was altered by the distance between two parts. In order to explain the present characteristic flame-stabilization from the standpoint of the competition between mass transfer and reaction, the velocity fields were measured by laser Doppler velocimeter, and the residence times in the intervening space were estimated. Through these observations and measurements, the flame-stabilization mechanism was clarified and the usefulness of this type of strut was demonstrated.

Introduction

PLANS to develop a space-plane and hypersonic transportation system are arousing the interest of many combustion engineers and researchers in ramjet and scramjet engines.[1,2] Fundamental experiments, as well as theoretical and numerical studies, have thus been carried out on mixing, ignition, and combustion in supersonic reactive flow. Combustion research workers are especially interested in flame stabilization in supersonic flow because this phenomenon is very drastic and theoretical considerations promise to be attractive.

It is very difficult to anchor an ignition point or a starting point of combustion reaction in supersonic flow. When fuel is injected from the wall of a ramjet or scramjet engine or from the struts, a subsonic flow region is needed to stabilize the combustion region. However, widening of a subsonic flow region necessarily entails an increase of pressure loss. Therefore, even if the well-known technique of utilizing the recirculation zone formed behind a bluff body is employed to ensure flame stabilization, a significant increase in pressure loss cannot be avoided. A breakthrough in reducing drag to a minimum has been made by incorporating a wall recess in the combustor, and experimental[3,4] and theoretical[5] studies have yielded favorable results. It is very exciting to hear that wall recesses have recently been successfully employed and flight-tested in some portions of the scramjet engine combustor by the Central Institute of Aviation Motors in Moscow.

Another difficulty is to ensure flameholding under any flow conditions of fuel and air, because the air intake condition greatly varies with speed, attack angle, or turning angle of the hypersonic vehicle. Therefore, in order to maintain thrust at a certain level, one more controllable factor, in addition to the amount of fuel, is necessary. One technique is to vary the portion of fuel that is injected into the two different modes, i.e., parallel to the flow and perpendicular to the flow.[6,7] The utilization of injector geometry variation should also prove to be useful in improving the total combustion performance.[8]

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In this study a strut model was devised and tested in supersonic airflow in an attempt to validate the possibility of the ideal strut, i.e., as mentioned above, ensuring flameholding under any flow condition, minimizing the pressure loss, and not complicating the structure. The strut with a backward-facing step reported in the literature is divided streamwise into two parts at the step, and the distance between the two parts can be changed. Fuel hydrogen is injected into the intervening space between two struts. In this study, we investigated the extent to which the flame is established by changing the total temperature and the amount of fuel, and observed the combustion region by optical devices. Then the flame-stabilization mechanism of the present strut is discussed.

Experimental Method

The two-dimensional strut model used and its setup are schematically shown in Fig. 1. A direct flame photograph is shown in Fig. 2. In the general type of strut, triangular prisms A and B in Fig. 1 are united, and fuel is injected behind the backward-facing step formed between strut A with the height of 15 mm, and strut B with a height of 10 mm. The distance L between struts A and B, both with a depth of 260 mm, is changeable in the present strut, and fuel is injected behind strut A. The total length of the present strut is 75 mm plus L, but the pressure loss is not increased much since the strut is divided streamwise into two parts. In spite of a small increase of pressure loss, a relatively large subsonic space can be obtained, and by controlling the interval between the struts, flame stabilization can be secured, even when the fuel or the supersonic main airflow velocity has been changed.

The outlet diameter of the supersonic nozzle used was 135 mm, and the Mach number of airflow was maintained at 1.5 in this experiment. The total temperature of the supersonic airflow was varied from 330 to 770 K, so that the static temperature at the nozzle exit was nearly equal to room temperature. Hydrogen gas was used as a fuel, its flow rate being 60–400 l/min. The fuel was injected at room temperature from a slit with a height of 1.2 mm and a depth of 40 mm, provided behind strut A. The total temperature of the airflow and the hydrogen flow rate were comparatively low, and therefore, the present experiments correspond to the crucial case for flame stabilization. In a sense, flame stabilization characteristics drastically appear and can be readily observed.

The test duration was 20 s at longest, but 5–10 s was sufficient to observe and photograph the flame stabilization. In

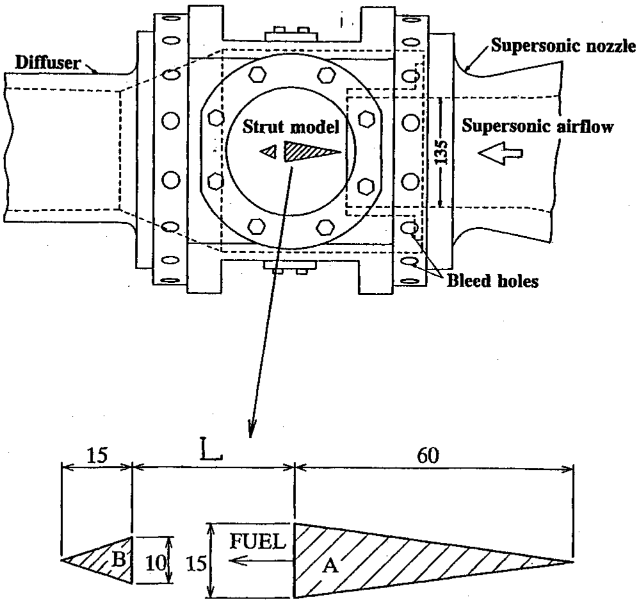

Fig. 1 Experimental apparatus and strut model.

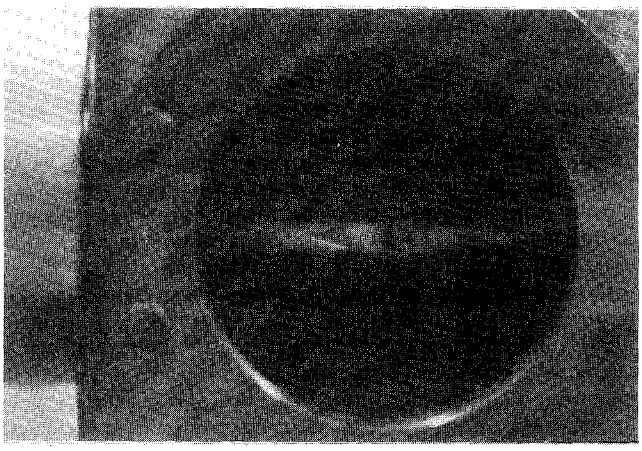

Fig. 2 Direct flame photograph.

order to observe the combustion zone optically, two triangular holes with the same shape as the cross section of struts A and B shown in Fig. 1 were made in two Pyrex® glasses with a thickness of 10 mm, and two struts were thrust into these two glasses that were situated on both sides of the test section with a depth of 240 mm. For each distance between two struts, at least one set of glasses was prepared.

The pressure inside the test section was a bit below atmospheric pressure, enabling the test section in air from the 16 holes (diam 19 mm) made along the circumference near the supersonic nozzle exit that cooled the two glasses and canceled the expansion waves formed around the nozzle exit.

After Mach number 1.5 flow was established, the igniter set just above the intervening space between the two struts activated and hydrogen gas was injected. A spark-type igniter was used with a power of 16 J. As soon as the flame was established, the igniter was retracted immediately and optical measurements were carried out.

Flameholding Tests

The regions in which flameholding is possible were obtained by changing the total temperature of airflow, the hydrogen flow rate, and the interval L between the two struts. The results are shown in Figs. 3–8. When the interval between the two struts was less than 10 mm, flameholding was impossible at any hydrogen flow rate. Although a flammable region clearly appeared when L = 20 mm (Fig. 3), the extent of the hydrogen flow rate was limited for flameholding. If L was 25 mm (Fig. 4), the flammable region widened, but flameholding at L = 30 mm became uncertain and unstable, as shown in Fig. 5.

By making the intervening space wider than about 40 mm, the combustion region was re-established, although the region deviated to the higher hydrogen flow rate as seen in Fig. 6. When we widened the interval even more, the flammable region extended to a lower rate of hydrogen flow, as shown

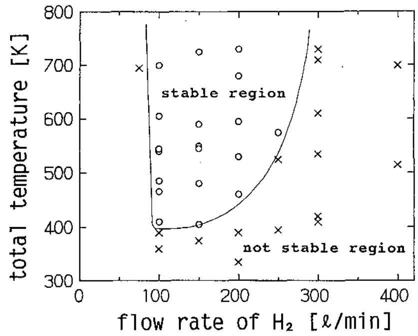

Fig. 3 Flame stabilization regions (L = 20 mm).

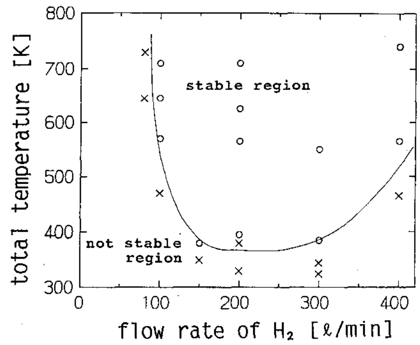

Fig. 4 Flame stabilization regions (L = 25 mm).

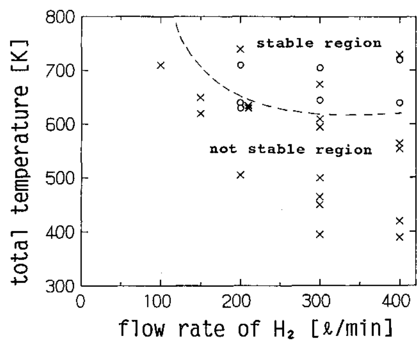

Fig. 5 Flame stabilization regions (L = 30 mm).

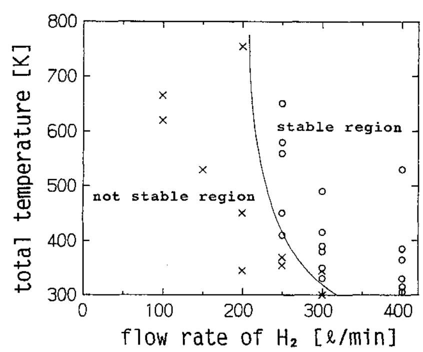

Fig. 6 Flame stabilization regions (L = 40 mm).

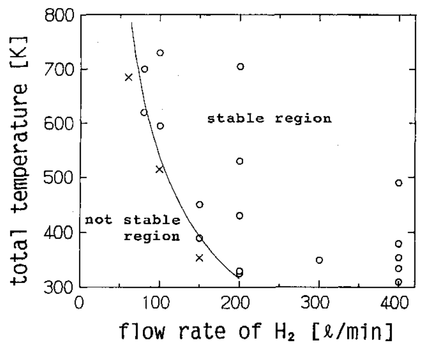

Fig. 7 Flame stabilization regions (L = 50 mm).

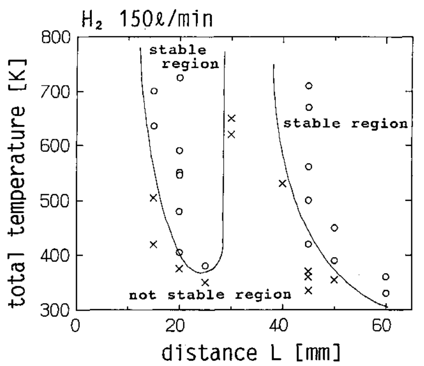

Fig. 8 Variation of the flame stabilization region with the interval L.

in Fig. 7. Without strut B, meaning $L = \infty$, however, no combustion region was found. Whenever flame was established behind strut B as seen in Fig. 2, flame also existed between the two struts, i.e., flameholding was impossible unless a flame existed in the interval.

Figure 8 shows the data rearranged in a map of the total temperature vs the intervening space, with the hydrogen flow rate being kept constant (150 l/min). The combustion region was divided into two parts as predicted from the tendencies shown in Figs. 3–7; around L = 30 to 40 mm flameholding was impossible at the present total temperature of airflow.

In the following chapters, the very characteristic phenomena shown in Fig. 8 are investigated and elucidated.

Optical Measurements

The shadowgraph and the schlieren photographs were taken to determine whether or not the density field was significantly dependent on L, and whether it affected the flameholding characteristics. Figure 9 shows a shadowgraph in the case of L = 20 mm. From right to left, we can see the attached shock wave, the expansion wave at the rear end of strut A, and the shear layer lying almost horizontally between the supersonic airflow outside the interval and the subsonic hydrogen flow inside the interval.

The location of these waves and the shear layer was not affected by L, and no wave incident upon the intervening space was observed. This observation did not depend on the existence of a flame, except for a slight effect of gas expansion behind strut B in the case of combustion. Schlieren photographs also described exactly the same phenomena.

Photography suggests that the present flameholding characteristics are not related to the structural specificity such as wave interactions in the intervening space, and it is suggested that the phenomena may be caused by the competitive function of the mass transfer and the chemical reaction, which explains the flameholding of recirculation[9] behind a bluff-body and wall recess.[3,4] Therefore, the velocity field was examined by laser Doppler velocimeter (LDV), and then the average residence time was calculated.

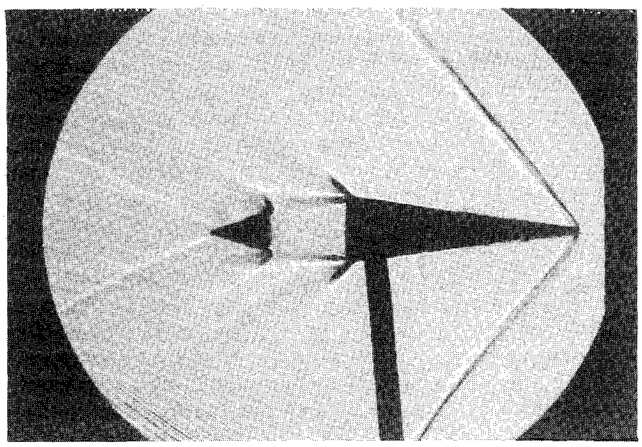

Fig. 9 Shadowgraph around the strut without flame (L = 20 mm).

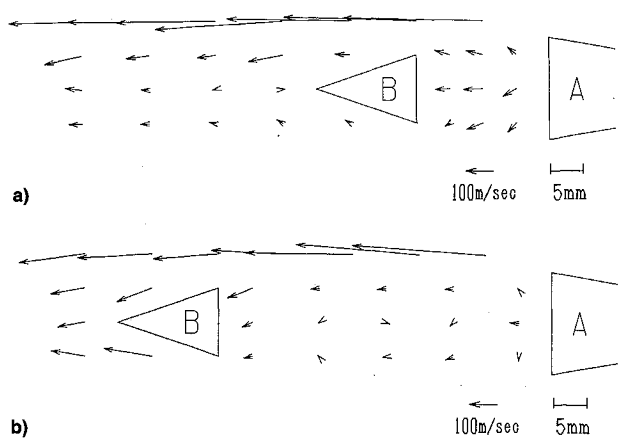

Fig. 10 Velocity field measured by LDV.

The LDV system using an argon ion laser with 2 colors/4 beams as a light source provides a two-dimensional velocity field. An optical fiber probe driven by a stepping motor was set on a stage movable in the three directions. The operation of this system was controlled by a personal computer, and therefore, the velocity of several or more points could be measured for one experiment of 10-s duration. Titanium dioxide powders were employed as scattering particles. Since the intervals between the two struts in which the flameholding is possible are limited as shown in Fig. 8, velocity measurement was made without flame.

Figure 10 shows the velocity vectors around the two struts for short and long intervals (L = 20, 50 mm). The vectors in the interval in the case of L = 20 mm mostly indicate the hydrogen velocity injected from a slit behind strut A with a velocity of about 70 m/s. Compared with this region, velocities in the region behind strut B seem to be very low. However, velocities are not instantaneous values, but the time-averaged values, so that turbulent flow with high intensity is predicted, making a strong momentum exchange between the main supersonic airflow and the subsonic fuel flow.

In contrast with the short interval, rather slow velocities were detected in the interval when L = 50 mm. It is suggested that very intense momentum exchange was conducted in the interval in this case, and therefore the trace of hydrogen injection velocity of about 70 m/s disappeared just after fuel injection. Since the velocities must have all directions, the direction of the time-averaged vectors is not fixed. Therefore, the intervening space is considered to almost be a stirred-reactor.

Whether the combustion region can be sustained in the intervening space determines the total flameholding of the present strut system. In order to obtain the characteristic

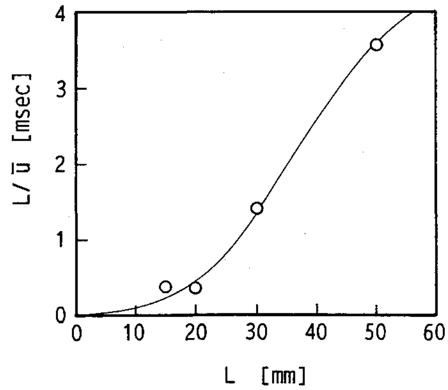

Fig. 11 Variation of the flow residence time in the interval.

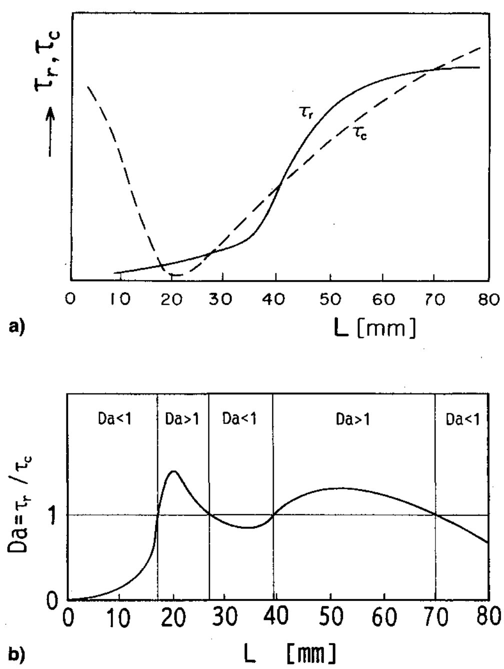

Fig. 12 Variation of a) residence time, predicted chemical reaction time and b) Damköhler number with the interval distance *L*.

residence time τ_r of the flow, the interval distance L divided by the mean value of the time-averaged velocities along the centerline of the struts was calculated as shown in Fig. 11, showing that the millisecond order of residence time increases with L.

Discussion

Flameholding of a strut divided into two parts showed a very characteristic tendency, as seen in Fig. 8. To explore the mechanism of this characteristic flameholding, optical measurements were carried out. Since no effect of wave interaction on flameholding in supersonic flow was found, the competitive function between τ_r and the chemical reaction time τ_c is discussed here.

Although the reaction time in the interval between the two struts is quite difficult to obtain experimentally, the prediction of its rough properties is possible. When the interval L is short, the gas mixture in the interval should be generally rich because the air entrainment is small, as found in Fig. 10a, which shows that the velocity vectors of hydrogen flows themselves do not yet cause intensive momentum exchange. The reaction time of this rich mixture, therefore, must be sufficiently large.

When L becomes large, the residence time must be large as well, because the gas mixture in the interval should be lean on the average since a strong momentum exchange occurs as shown in Fig. 10b. Therefore, a stoichiometric gas mixture is produced on an average between L = 20–50 mm, where the reaction time must be shortest. This tendency of τ_c is schematically shown in Fig. 12a, with τ_r obtained in Fig. 11.

In order to establish the combustion region, the residence time must be longer than the reaction time. This means that the Damköhler *Da* number is larger than unity. As shown in Fig. 12b, we can obtain two regions available for flameholding, consistent with experiments. The Damköhler number around L = 30 mm was close to unity, and in fact, flameholding was very uncertain, i.e., the flame was sometimes established and sometimes extinguished. Also, in case of very short intervals and very large intervals, flameholding was definitely impossible. Although Figs. 12a and 12b do not show an exact relationship, but rather a general view of the present phenomena on the basis of experimental observations, such an explanation of the present flameholding mechanism seems reasonable.

If the above-mentioned mechanism is correct, the chemical reaction time in Fig. 12a would move downward when airflow temperature becomes high, and therefore, the flameholding region would widen. If the Mach number of airflow is higher, the residence time would not change much because only more intensive turbulent mixing would occur, and therefore, the present strut system may be employed with higher Mach numbers.

Concluding Remarks

Experiments on a model of controllable strut, which can change a part of the structure in response to the airflow condition, were carried out in a supersonic airflow of Mach number 1.5. If the airflow temperature becomes higher, the stable flameholding region may widen and the present characteristics may disappear. However, since the total temperature of airflow in this experiment was not so high as predicted in an actual scramjet engine, the distinctive state of this flameholder appeared with very drastic variations in the intervening distance between the two struts. The flame stabilization mechanism was explored and discussed. The results can be summarized as follows:

1) When the intervening space between two struts was widened, flameholding was possible in two regions of the intervening space.

2) No shock or expansion wave interaction exists in the intervening space, and so it did not affect the present flameholding characteristics.

3) The velocity measurement by LDV indicated an intensive momentum exchange through the shear layer formed between supersonic airflow and subsonic fuel flow, and therefore, the intervening space can be approximately considered as a stirred-reactor.

4) The flame stabilization mechanism can be explained as being due to the competition of the mass transfer rate and the chemical reaction rate, i.e., due to the Damköhler number.

Further measurements in the near future of such factors as temperature and concentration profile in the intervening space are needed to support the above-mentioned explanation of the flameholding mechanism. The present strut system still has some demerits if it is applied to engines as it is. The present strut model and experiments showed one possibility of controllable strut, and a fundamental explanation of the flameholding mechanism was presented.

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