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Experimental Studies on Self-Ignition of Hydrogen/Air Supersonic Combustion

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Self-ignition tests of a model scramjet combustor were conducted by using parallel sonic injection of gaseous hydrogen from the base of a blade-like strut into a supersonic airstream. The vitiated air was produced by burning H_2, O_2, and air to a stagnation temperature of 1000–2100 K and a stagnation pressure of 0.8–1.6 MPa. The effects of different parameters on the self-ignition limits were analyzed. In addition, the effects of the combustor's different wall configurations on self-ignition limits were specifically studied. It was found that the wall configurations of the combustor had a significant effect on self-ignition limits, which might have variations of 420–840 K deg in stagnation temperature; however, the local static temperature in the recirculation zones for different wall configurations remained the same at approximately 1100 K. It was found that self-ignition could initiate at the exit of the combustor and this can be considered as a weak self-ignition characteristic.

I. Introduction

IN recent years, the research and development of supersonic combustion ramjets (scramjet) has promoted the study of combustion in supersonic flows. Self-ignition of hydrogen/air supersonic combustion is one of the basic problems that needs to be resolved in the research and development of such engines.

Hydrogen fuel ignition in supersonic combustion testing was investigated by many researchers in the 1960s and 1970s. The self-ignition in a scramjet can be expected to occur at flight Mach numbers above 5 or 6 as a result of suitable flow conditions in the combustor. The major factors affecting self-ignition were found to be the static temperature, static pressure, fuel–air mixture, and residence time. In addition, the flameholder is necessary because the static temperature is too low and the residence time is too short in the mainstream of the combustor. The flameholder can provide an area where the static temperature is higher and the residence time is longer; thus, the ignition is more likely to be initiated and burning can be sustained. The jet interference of transverse fuel injection, the recirculation zone behind rearward-facing steps, and the base of instream fuel injection struts were generally applied to the flameholding. Based on a large amount of experimental results and data, Huber et al.[1] developed simple semiempirical models for self-ignition regions with a first-order effect, which gave a baseline for estimation of self-ignition in simple geometry. In addition, McClinton[2] conducted parameter studies of self-ignition characteristics of transverse injection for a hydrogen/air scramjet. His experimental data were compared with the semiempirical self-ignition limit model. However, at that time, the temperature in the recirculation zone, which was one of the dominating parameters of self-ignition, was specified considering the boundary-layer thickness, wall temperature, and temperature recovery factor, because there was no suitable measuring method available 20 years ago.

Recently, Whitehurst et al.[3] conducted parametric and time-resolved studies of self-ignition and flameholding in a clean-air supersonic combustor. They found that the ignition was likely to initiate far downstream and then propagate upstream with the speed of a detonation wave. However, the stagnation temperature of airstream in their experiments was 1250 K, which was relatively low, nevertheless, their experiments showed that self-ignition might initiate further downstream, not adjacent to the flameholder. Huh and Driscoll[4] in their studies of shock waves on supersonic hydrogen/air flames found that shock waves greatly enhanced the flame stability. The reason was believed to be the adverse pressure gradient caused by the shock that could enlarge the subsonic recirculation zone behind the flameholder. Kumar et al.[5] carried out studies of self-ignition characteristics with transverse injection of hydrogen into a vitiated airstream. The temperature in recirculation zone was not specified. The temperature recovery factor was utilized and determined experimentally. Kumar et al.'s[5] experimental results were in accordance with Huber's semiempirical model.[1] Tomioka et al.[6] studied the self-ignition in a model scramjet in high flight Mach number 6–8, using pilot fuel injection upstream of a rearward-facing step. Oxygen injected through the auxiliary injectors was used to improve the fuel-rich condition within the recess. In addition, a strut was mounted on the combustor wall to promote the autoignition. Guerra et al.[7] used precombustion of a fuel-rich mixture of hydrogen and oxygen to promote self-ignition. Their study confirmed the effect of the OH radical on the autoignition. In general, it has been recognized that hydrogen fuel ignition in supersonic combustion testing is frequently facility dependent.

The objective of this study is to determine the self-ignition characteristics of hydrogen parallel injected into a Mach number 2.5 supersonic vitiated airstream using a blade-like strut injector in our newly established supersonic combustion facility. Because the nonintrusive laser diagnostics on supersonic combustion flowfield are well developed, the static temperature in the combustor, especially the temperature in the recirculation zones, can be measured directly by coherent anti-Stokes Raman spectroscopy (CARS). Therefore, a comparison be-

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tween the recovery temperature evaluated by Huber's model and the value measured by CARS can be carried out.

Four types of wall configurations were tested that were initially designed for different optical access requirements. They actually played the roles of rearward-facing step, forward-facing step, and their combination. It was the wall configurations that caused the dramatic variance of self-ignition limits, which was somewhat beyond our estimation.

II. Experimental Design

The test facility was described in Ref. 8. The high-temperature test air is produced by the combustion of hydrogen, oxygen, and air in a heater. The vitiated air contains oxygen in a volume fraction equal to that of normal air. The heater can provide vitiated air with a temperature of 2100 K, a pressure of 2.0 MPa, and a flow rate of 1.5 kg/s, so that the free flight of Mach number 7 and 25 km altitude can be simulated.

The stagnation temperature is a critical factor in the self-ignition process. Two methods were used to measure the stagnation temperature. In the case of temperatures below 2000 K, *B*-type thermocouples were used to measure the stagnation temperature directly. The thermocouple data corrections, as a result of heat radiation, conduction, and inertia, were conducted by using a method in which the coefficients of the correction terms were carefully determined by experiments. When temperatures were higher than 2000 K, no proper thermocouples were available, an indirect method was used in which the stagnation temperature was calculated from the stagnation pressure data, the flow rates of gases, and the throat area of the main nozzle. This method was verified by the thermocouple data below 2000 K. The temperature data difference between two methods was within ±100 K, which means the uncertainty in temperature is ±5% for temperatures higher than 2000 K.

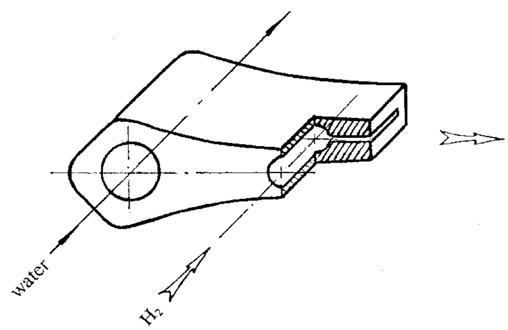

Fig. 1 Schematic of blade-like strut hydrogen injector.

To study the hydrogen parallel injected into the supersonic airstream and to avoid unnecessary shock waves introduced by a strut, the hydrogen injector and the air nozzle were designed in an integrated modular structure. Figure 1 shows the structure of a typical blade-like strut. The upper and lower contour walls of the strut and the combustor wall form two half-parts of a nozzle, which produces the Mach number 2.5 two-dimensional supersonic airflow. The blade-like strut that has a narrow slot of 0.95 × 20 mm in the center of the strut base for the hydrogen injection is mounted in the center of the entrance of the combustor.

The strut is sandwiched mechanically between the air heater and the combustor, so that it is easy to change struts having different hydrogen injectors. The leading part of the strut, which is located in the stagnation temperature zone, is water cooled to avoid being burned out. Two *K*-type thermocouples were buried in the strut base to monitor the base wall temperature.

As shown in Fig. 2, the supersonic combustion chamber is a rectangular duct that has an entrance cross section of 30 × 30 mm. The duct is composed of three sections. The side walls that are parallel to the two-dimensional nozzle have boundary-layer correction angles of 0.5, 1.5, and 3 deg for three sections. Ten pressure ports were arranged along the centerline of each side wall. Motorola MPX2200 0–0.3 MPa pressure transducers were used to monitor the static pressure on the side walls.

Owing to the requirements of optical access, four types of wall configurations were designed on the parallel side walls that were perpendicular to the two-dimensional nozzle. In the first configuration, the duct walls are flat and smooth, on which along the centerline there are small holes opened for observation of the ignition. In the second configuration, each side wall has four slots, which are used as optical access of laser diagnostics originally. After filling in stoppers, the side walls are still uneven and have concavities 10 mm in depth, 10 mm

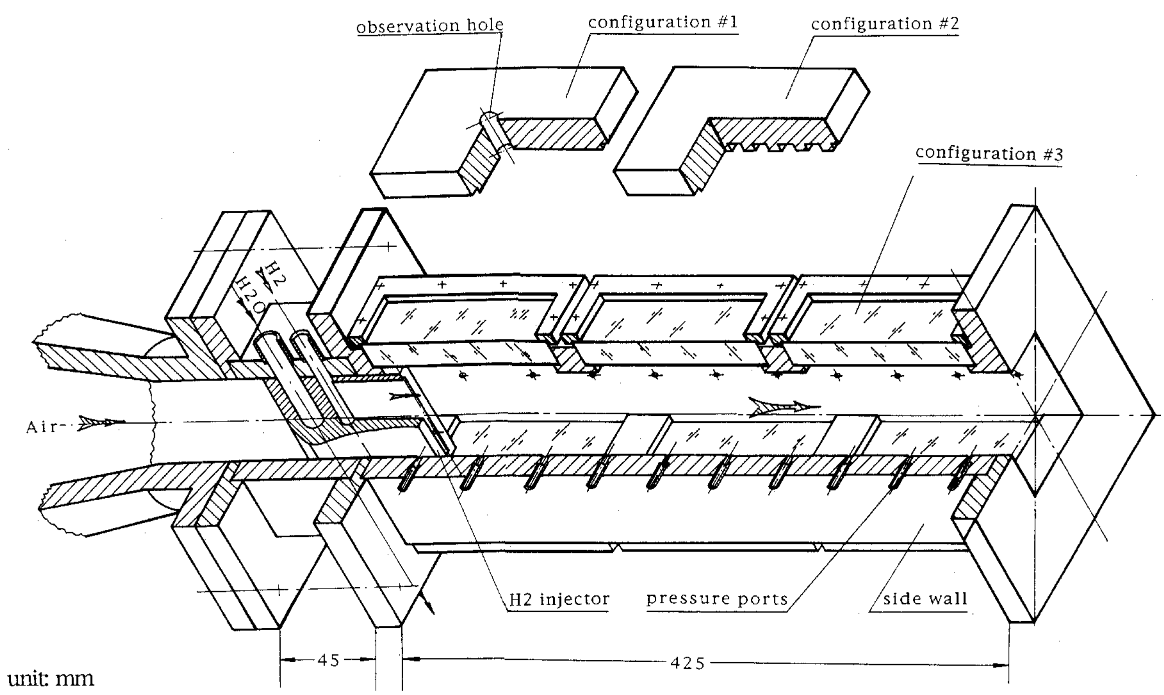

Fig. 2 Schematic of the combustor configurations.

in width, and 10 mm in space. In configurations no. 3 and no. 4, each side wall has a rectangular hollow space of 100 × 30 mm, which is used to prevent the fused silicon window from being damaged. The depth of the hollow space is of 5 and 50 mm, respectively.

A nonintrusive laser diagnostic system CARS was developed to measure the static temperature in the combustor.[9]

A personal computer-controlled gas flow system was established to perform experiments with an accuracy and reliability within a few seconds. The computer also served as data acquisition and processing for pressure and temperature. The critical elements of the gas system are sonic throat nozzles, in which the flow rates of gases are determined by the plenum pressure of the nozzles under the fixed diameters of the throat nozzles. The plenum pressure was provided by using gasdynamic regulators through driving nitrogen. The pressure signals were sent to a personal computer. The standby gases (air, H_2, O_2, and N_2) with proper flow rates are released through gasdynamic valves driven by electromagnetic valves that are programmed by the computer. When the experiment is completed, all of the acquired temperature and pressure data are stored and displayed on the screen or printed out in the form of data tables or data profiles.

III. Experiments

A typical experiment running time is 7 s. The major gases (air, O_2, and H_2) are released 1 s after the pilot air, and hydrogen is ignited by a spark. It takes 0.8 s to achieve the required temperature and pressure in the combustor. Figure 3 gives the static pressure distribution on the combustor wall with time as a parameter. In addition, it shows that the supersonic flowfield reached a steady state within 2 s. At that time, hydrogen was injected at sonic speed into $M = 2.5$ supersonic airflow. As the mixture was ignited and combustion was sustained, the static pressure in the combustor increased immediately; the pressure distribution was stable while the flame was stabilized.

As a monitor of ignition process, a Panasonic M9000 video camera was used to observe and record the ignition process. This imaging system provided 25 frames of images per second. The video records show that the flowfield inside the combustor is dark before hydrogen jet ignited. When the self-ignition and flame stabilization condition was achieved, the bright flame was observed through the view windows and diamond-shaped flame appeared at the exit of the combustor.

IV. Results and Discussion

The self-ignition tests were conducted with four types of combustor configurations. Each configuration was tested with

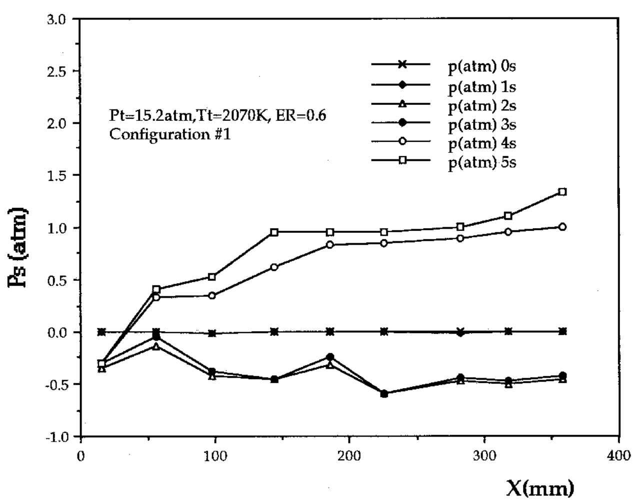

Fig. 3 Static pressure distribution in combustor for combustor wall configuration no. 1.

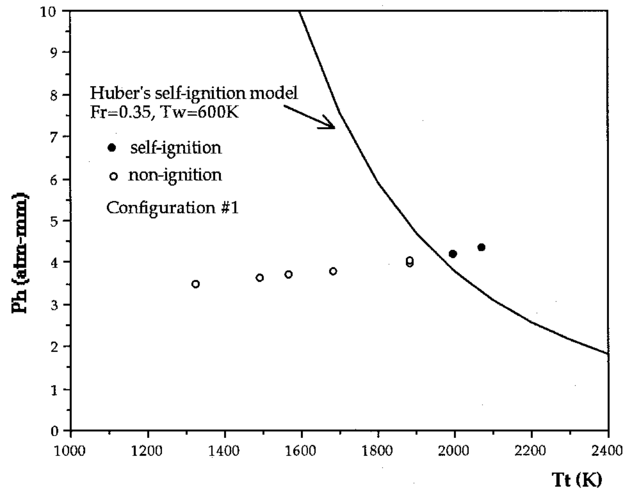

Fig. 4 Self-ignition data in combustor wall configuration no. 1. The uncertainty in T_t = 6 3% for $T_t \leq 2000$ K, 6 5% for $T_t > 2000$ K and the uncertainty in Ph = 6 1%.

a series of runs, in which the stagnation temperature varied between 1000–2100 K; the stagnation pressure varied in 0.8–1.6 MPa, and the equivalence ratio of 0.6 was maintained.

In configuration no. 1, because the combustor wall was flat and smooth, there is not a low speed recirculation zone as a flame holder except the blade-like strut base which is 8.4 mm in width and 30 mm in length as shown in Fig. 1. Experiments show that the dominate parameter of self-ignition limits is the stagnation temperature of the airstream. The self-ignition and self-sustain burning do not occur until the stagnation temperature increases to above 2000 K while the Mach number of the airstream is 2.5. The corresponding static temperature has to be 1030 K and the static pressure has to be 80 kPa. The experimental data are plotted on Fig. 4, where each data point represents one run and identifies whether or not self-ignition occurred. For comparison to Huber's model, the pressure-length scale product and stagnation temperature are chosen as correlation parameters. In Huber's model the correlation for base recirculation zone is given by[1]

$$Ph = \frac{8 \times 10^{-9} c^{9600/T_r} U}{80 \times (P_B/P)} \tag{1}$$

where h is the strut base half-height in millimeters, P_B is the pressure in the base recirculation zone in standard atmosphere, and P and U are the static pressure and velocity of the air main stream, respectively. T_r is recovery temperature in the base recirculation zone and is given by

$$T_r = F_r(T_t - T_w) + T_w \tag{2}$$

where F_r is temperature recovery factor and T_w is wall temperature. Solving Eqs. (1) and (2) will generate a family of pressure scale parameter vs temperature as a function of F_r. It is the curve of recovery factor F_r being 0.35 that passes through the self-ignition limits data zone and the self-ignition data falling to the right of the curve. The corresponding T_r is 1090 K for T_t = 2000 K and T_w = 600 K, which are measured by thermocouples. On the other hand, the temperature in the recirculation zone is measured at 1100 ± 30 K by CARS. Therefore, the two critical parameters 1) the temperature in the recirculation zone and 2) the temperature recovered factor have matched each other by using both direct and indirect measurements. This result shows that the self-ignition data are in accordance with Huber's semiempirical model.

It has been observed that when the correlation parameters approach the self-ignition limits, the self-ignition may occur first outside of the combustor, then the burning zone may either

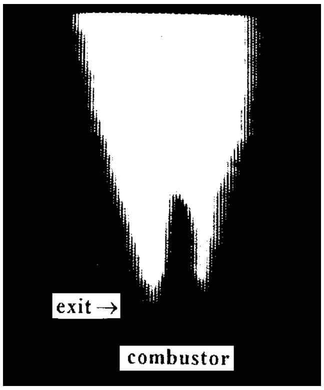

Fig. 5 Flame photograph outside the combustor exit before ignition inside.

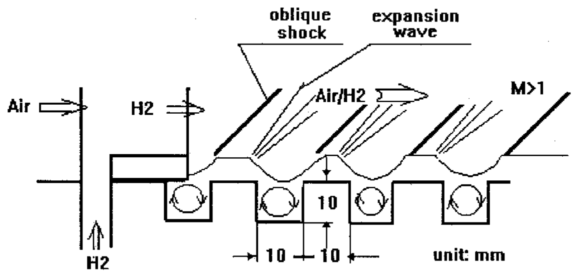

Fig. 6 Schematic of wave system in combustor wall configuration no. 2.

propagate into the combustor or stand outside. When the flame stands outside, the flame has a W shape as shown in Fig. 5. The central region at the combustor exit is a triangular dark unburned zone. The bottom of the burning zone is close to the wall side on the photograph. This result is somewhat similar to Ref. 4, which indicates that self-ignition may initiate far downstream. However, it is an unstable state, which means the basic stream parameters are in a critical situation but have not yet fully reached the self-ignition condition; it might be considered a weak self-ignition characteristic. The ignition may be caused by many factors from the wall, for example, compression waves, friction heating in boundary layers, adiabatic wall temperature, etc. From the static pressure data on the combustor wall (Fig. 3), before the whole duct is ignited, the static pressure is lower than 0.1 MPa and the supersonic flow will undergo overexpansion at the exit; however, after the duct is ignited the static pressure increases over 0.1 MPa immediately and the supersonic combustion flow will undergo underexpansion at the exit. When the static pressure inside the combustor is lower than the ambient back pressure, the unburned supersonic flow mixture will be compressed first at the exit; after compression, the mixture static temperature will increase. If the increasing temperature reaches the self-ignition condition, the mixture outside will be ignited. This might be used to partially explain the weak self-ignition and why the flame has a distinct triangular dark zone. The weak self-ignition is the precursor of strong self-ignition. When the stream parameters exceed the self-ignition limits, the hydrogen/air mixture will self-ignite inside the combustor from the base recirculation zone and combustion will be self-sustaining. In this situation, the static pressure in the combustor is higher than ambient back pressure. The supersonic combustion flow emerges from the duct and expands first, then undergoes a series of expansion and compression. Therefore, a series of bright diamond shaped zones can be observed.

In configuration no. 2, instead of the flat and smooth wall, there are slots on the combustor wall that would introduce expansion waves, oblique shock waves, and low-speed recirculation zones (Fig. 6). After the oblique shock waves, the static temperature and static pressure will increase and in the recirculation zone the mixture residence time will be longer, so that it could be expected that the stagnation temperature of self-ignition limit should be lower than that of configuration no. 1. These analyses have been confirmed by experiments. Figure 7 gives the experimental self-ignition data and shows that when the stagnation pressure is 1.3 MPa, the self-ignition limit is 1580 ± 50 K in stagnation temperature, which is 420 K lower than configuration no. 1.

Figure 8 shows experimental self-ignition data for configurations no. 3 and no. 4. It is found that, although their depths have 10 times difference, these two configurations have almost the same stagnation temperature of self-ignition limits that are lower than that of configuration no. 2. When the stagnation pressure is 1.3 MPa, the self-ignition limit is 1160 ± 35 K in stagnation temperature, which is 420 K lower than that for configuration no. 2 and is close to the self-ignition limit recovery temperature (1090 K) of the base recirculation zone in configuration no. 1. Figure 9 shows the side wall static pressure data for configuration no. 3. Compared with Fig. 3, it can be seen that before the supersonic speed mixture is ignited, the static pressure is already over 0.1 MPa and is much higher than that for the configuration no. 1. Figure 10 may be used to explain these results. In the wave pattern introduced by the space hollows, except the oblique shock waves and recirculation zones, there might be bow-shock waves and local normal shock waves in the vicinity of the forward-facing steps.

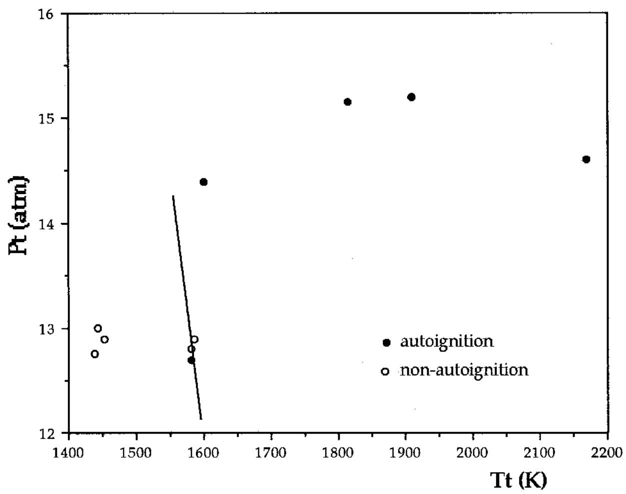

Fig. 7 Self-ignition data in combustor wall configuration no. 2. The uncertainty in T_t = 6 3% for $T_t \leq$ 2000 K, 6 5% for $T_t >$ 2000 K, and the uncertainty in P_t = 6 1%.

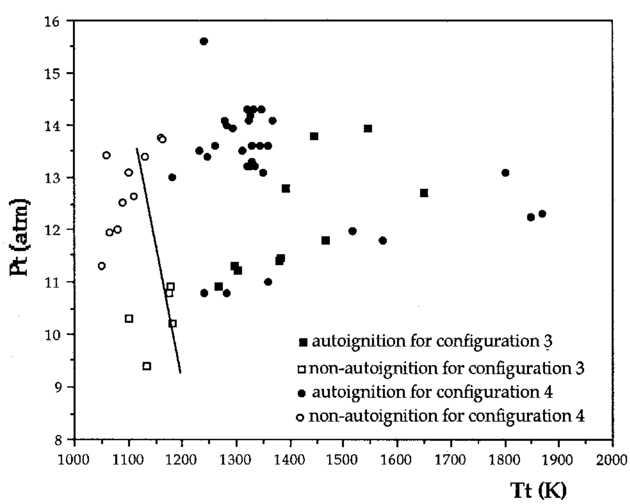

Fig. 8 Self-ignition data in combustor wall configurations no. 3 and no. 4. The uncertainty in T_t = 6 3% for $T_t \leq$ 2000 K, 6 5% for $T_t >$ 2000 K, and the uncertainty in P_t = 6 1%.

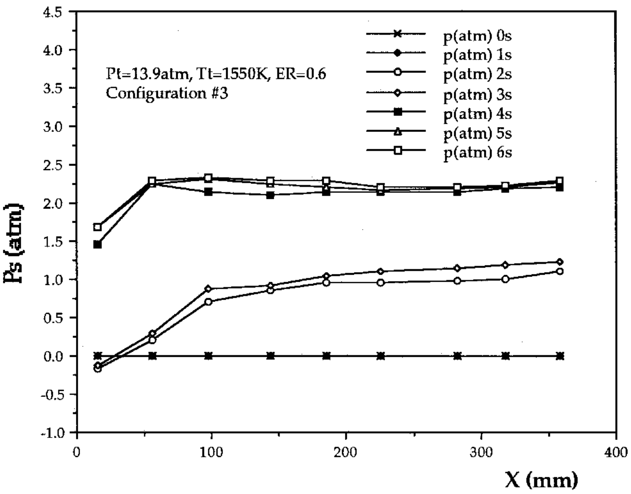

Fig. 9 Static pressure distribution in combustor for combustor wall configuration no. 3.

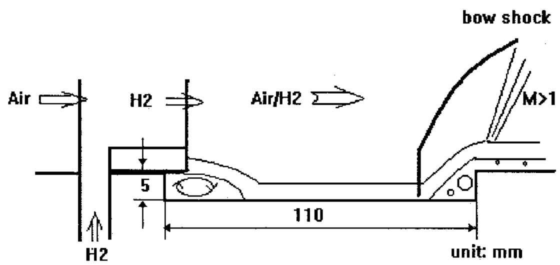

Fig. 10 Schematic of wave system in combustor wall configurations no. 3 and no. 4.

In the local stagnation zones the recovery temperature might be close to the stagnation temperature. This could be used to explain that in configurations no. 3 and no. 4, although their depths are different, their self-ignition limits are approximately the same and the stagnation temperature limits are much lower than that for wall configurations no. 1 and no. 2.

V. Conclusions

1) The self-ignition limits of hydrogen/air supersonic combustion are greatly dependent on the configuration of the combustor wall. They may have 420–840 K variation in stagnation temperature owing to the different combustor configurations.

2) The hydrogen/air self-ignition limit is around 1100 K in static temperature in local recirculation zones for all configurations, no matter how different their stagnation temperature is.

3) The consistency between the temperature in the recirculation zone measured directly by CARS and the recovery temperature evaluated by using Huber's model shows that our experimental results of self-ignition are in agreement with Huber's semiempirical model, and the latter gives a baseline for estimation of self-ignition in simple geometry.

4) The self-ignition may initiate at the exit of the combustor first, then the flame propagates inside the combustor, depending on the flow parameters and combustor configurations. This might be considered as a weak self-ignition characteristic.

Acknowledgment

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