Supersonic Combustion of Hydrogen in a Vitiated Airstream Using Transverse Injection

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Theme

IN this paper, an investigation of the two-dimensional supersonic jet interaction flowfield with and without chemical heat release is presented, and the spontaneous ignition limits of the bulk flame produced far downstream are determined. Highly underexpanded hydrogen and nitrogen jets are injected from a converging slot nozzle perpendicular to the supersonic vitiated airstream, at various airstream and injectant conditions. The parameters varied during the experiments include the airstream stagnation temperature and oxygen concentration, and the injection pressure. The temperature profiles and the Schlieren photographs of the resulting flowfield with chemical heat release are compared with those of nonreacting case. From these results, the ignition mechanism of supersonic diffusion flame and the extent to which chemical heat release changes the jet interaction flowfield are discussed.

Contents

The experiments were carried out in the Mach 1.81 supersonic combustion wind tunnel at atmospheric pressure. This tunnel was designed to use the city gas-air combustion gas (vitiated air) as the test medium. The stagnation temperature of the vitiated airstream is variable from about 1000 K to 1700 K by variation of the equivalence ratio. The oxygen concentration is also variable from about 9% to 16% by adding oxygen to the airstream. The exit cross section of the tunnel nozzle is 45.00 mm × 34.42 mm. Nominal Reynolds number for the equivalence ratio of 0.5 is 9.286×10^6 per meter. The flat plate model spans the 45-mm wide test section and its length is 200 mm. In the flat plate model a slot nozzle, which has a span of 35.0 mm and width of 0.1 mm, is flush mounted.

In case of hydrogen injection, with increase of the stagnation temperature of the vitiated airstream (T_0), keeping the injection pressure (p_{0j}) constant, a bulk flame appears far downstream of the test section. The static temperatures of the airstream above which the ignition of the bulk flame occurred are shown in Fig. 1, where T_s and p_f are the static temperature and the static pressure in the undisturbed supersonic airstream, respectively. In this series of experiments, the oxygen concentration of the airstream (X_{0_2}) was held constant at about 10%. The ignition temperature is found to depend on p_{0j}/p_f, and it decreases with increasing p_{0j}/p_f. This pressure dependency compares favorably with the result obtained by Bier et al. using a circular injector.[1]

Although the bulk flame is formed far downstream of the test section, the ignition in the flowfield near the slot nozzle is not always observed. Figure 2a shows an instantaneous Schlieren photograph of the nonreacting flowfield near the slot nozzle. In this example, hydrogen was injected at $p_{0j}/p_f = 26.5$ into the airstream of $T_0 = 1520$ K. If the boundary layer on the flat plate is fully turbulent, an oblique shock is produced by the boundary-layer separation which generates a separated region upstream of the jet and the oblique shock crosses the strong bow shock produced by the interaction of the supersonic airstream and the jet.[2] This photograph shows these prominent features of the turbulent boundary layer. For nitrogen injection, the interaction flowfield is found to be exactly similar to that for hydrogen injection.

With increasing X_{0_2} and keeping T_0 constant at about 1540 K, spontaneous ignition takes place in the upstream separated region. When the amount of oxygen to be added is increased

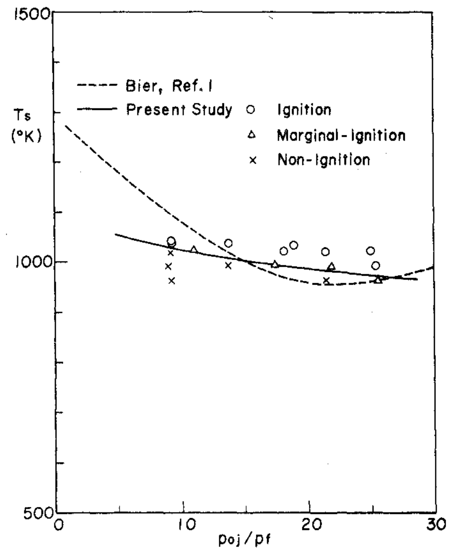

Fig. 1 Ignition temperature.

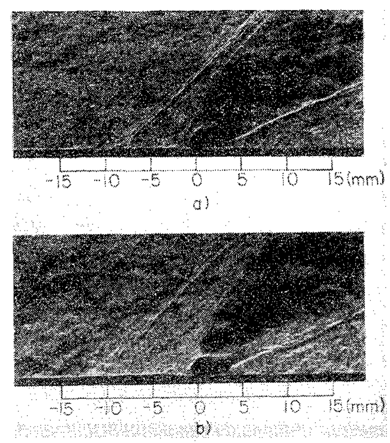

Fig. 2 Instantaneous Schlieren photographs of jet interaction flowfield: a) without chemical heat release; b) with chemical heat release.

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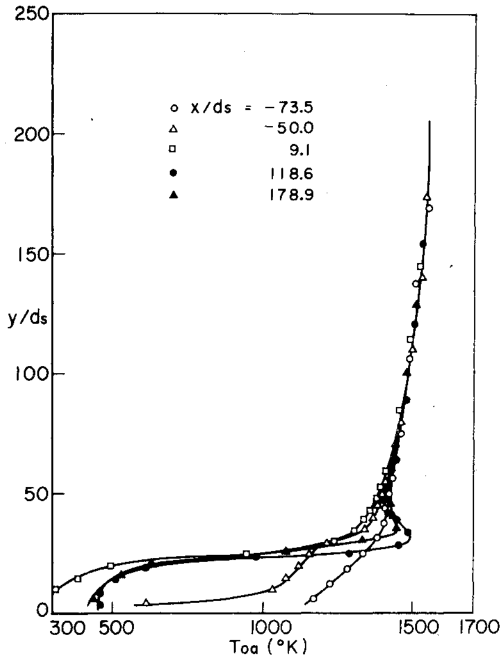

Fig. 3 Vertical temperature distributions of combustion flowfield.

to $X_{O_2} = 13.5\%$, ignition in the upstream separated region becomes stable and the luminosity increases. At the same time, after a small induction zone a weak turbulent diffusion flame appears immediately downstream of the hydrogen jet. Figure 2b shows an example of the instantaneous Schlieren photographs of the combustion flowfield near the jet. This photograph was taken at $T_0 = 1540$ K, $X_{O_2} = 13.4\%$ and $p_{0j}/p_f = 25.6$. Comparing this figure with Fig. 2a, several differences between the nonreacting and the reacting cases are evident. In particular, it is found that the separation distance increases significantly due to the chemical heat release in the upstream separated region. For $p_{0j}/p_f = 25.6$, the twenty-percent increase is observed. However, the chemical heat release changes neither the separation shock angle nor the bow shock angle. On the other hand, the reattachment shock which is produced downstream of the jet differs in shape significantly.

Figure 3 shows the vertical temperature distributions of the flowfield at almost the same conditions as those of Fig. 2b. In this figure, x and y represent coordinates parallel and normal to the flat plate, respectively (x is measured from the sonic nozzle), d_s sonic nozzle width, and T_{0a} stagnation temperature measured by the thermocouple. The temperature profile at $x/d_s = 73.5$ displays that, with approaching the plate surface, the temperature decreases gradually in the undisturbed supersonic airstream at a small gradient and rapidly in the upstream separated region. On the other hand, at $x/d_s = -50.0$, a temperature bulge appears in the region where the temperature decreases rapidly toward the plate surface. Since this bulge appears only in the downstream part of the separated region, the exothermic chemical reaction occurs in this restricted region. This fact supports the ignition model suggested by Thayer and Corlett.[3] At $x/d_s = 9.1$, this temperature bulge disappears and this location corresponds to the induction zone. Downstream of $x/d_s = 118.6$, a temperature peak is seen in the mixing layer between the supersonic airstream and the hydrogen flow. The peak value is about 1500 K and at most 130 K higher than the surroundings. It is evident that the peak locations correspond to those of the weak turbulent diffusion flame.

The temperature in the upstream separated region is not so high as that observed in the usual hydrogen air flame. This fact may be attributed to the rapid binary reactions which may occur in this region. The separated region is the source of the reactive species such as radicals and free atoms which are necessary for the main exothermic reactions. The separated turbulent boundary layer containing these reactive species passes over the jet and mixes with hydrogen gradually. It is found from comparison of temperature profiles with Schlieren photographs that the temperature peak appears downstream of the point where the reattachment shock crosses the mixing region of supersonic airstream and hydrogen, where the static temperature and pressure increase, and the velocity decreases. Therefore, it is concluded that the ignition of hydrogen injected transversely into the supersonic airstream occurs in the upstream separated region, and that the bulk flame produced far downstream of the test section is not essential to the supersonic combustion.

References

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