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Flame-Holding Configurations for Kerosene Combustion in a Mach 1.8 Airflow

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The goal of this study was to determine the stability of the flame in a recirculation region formed in a wall cavity with ignition provided by hydrogen injected in the base of the cavity and injection of kerosene upstream in the boundary layer formed along the wall leading to the cavity. The experimental conditions, i.e., Mach 1.8 and air stagnation temperatures to 1000 K, correspond to the beginning of the hypersonic flight regime also referred to as cold start conditions. The hydrogen and the preinjected kerosene flow rates were modulated during the tests and temperature probes placed in the cavity indicated their effect on the local equivalence ratio. Preinjection of kerosene reduced the local equivalence ratio at low air stagnation temperature by increasing the entrainment of fresh air into the recirculation region. At high temperatures the additional fuel brought by the presence of kerosene had a detrimental effect on the stability of the flame in the cavity.

Nomenclature

A = area, m^2
H = step height, 10 mm
$\bar{J}$ = momentum ratio
p = pressure, Pa
Q = mass flow, kg/s
Re = Reynolds number
r = density ratio
T = temperature, K
t_i = induction time, s
u = velocity ratio
α = wedge angle, deg
δ = shear-layer growth, rad, or, boundary-layer thickness, mm
ρ = density, g/cm^3
ϕ = equivalence ratio

Subscripts
h = hydrogen
ke = kerosene
0 = air stagnation conditions

Introduction

CLEAR technological, economical, and operational advantages exist when liquid hydrocarbon fuels, such as kerosene, are used in comparison with hydrogen-based systems for the development of small hypersonic vehicles. However, the flow features in a supersonic ramjet combustor, primarily the short residence time of a fuel–air mixture, which is $<10^{-3}$ s, along with the multistage physical–chemical mechanism of liquid hydrocarbon fuel burning, increase the difficulties of ignition and flame stabilization. If the selected fuel is amenable to operate at supercritical conditions, a significant decrease in the time required for the liquid fuel breakup and vaporization can be achieved. Further, if chemical decomposition accompanies these transformations, the potential formation of hydrogen or other active radicals will result in increased reactivity of the mixture and a reduction in the combustion length.

A simple evaluation of vaporized kerosene ignition time t_i shows that under typical conditions in a supersonic ramjet combustor, i.e, pressure p = 50–100 kPa and temperature T = 600–1000 K, t_i = 5–10 ms and, therefore, the traditional methods of simple fuel injection for the hydrocarbon-based flames in supersonic flows are not effective. This has been confirmed by experimental data in which the flame stability criterion for methane has been one order of magnitude lower than the corresponding value for hydrogen.[1] In the case of the liquid fuel injection, the vaporization and mixing processes, along with the chemical conversions via endothermic reactions and the formation of the active radicals, are additional processes compared with the hydrogen-based system. The addition of active components such as hydrogen or ClF_3, SiH_4 compounds, etc.[2–4] to the fuel, as promoters, results in a decrease in reaction induction time. This method is effective for the initiation of the combustion process but not for its stabilization during the flight as the proportion of added components may be up to 25%, thus increasing the volume and the complexity of vehicle.[5] Additionally, these promoters may lead to a decrease in the specific impulse. There is a need, therefore, to achieve conditions under which, following ignition, stabilization by a pilot flame with a very small rate of active components (1–2%) or self-stabilization by precombustion shock train or heat choking can be established.

Recently, considerable attention has been given to the problem of improving the reactivity of hydrocarbon fuels or products of their physical–chemical transformations. Overheating kerosene to 700–800 K permitted its use as a liquid in injectors and provided the necessary penetration to reduce the required mixing length through the increase in spray injector pressure differential.[6] However, increased injection pressure had a negative impact on dispersion and mixing of the fuel jet. Injection of the liquid in the plume formed behind a pylon increased the degree of mixing with reduced jet/air dynamic pressure. The results of these investigations have been presented in detail by

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Vinogradrov and Prudnikov[7] and include the geometric plume performance with injection of a liquid kerosene behind a thin, swept pylon installed on the wall of the duct. The data indicated that it is possible to use this method for liquid injection along with the traditional methods employed to enhance mixing.[3,8,9.]

To intensify the process of liquid fuel mixing and to increase the fuel residence time in the engine duct, it is useful to implement preinjection of part of the fuel in the isolator duct before the combustor or in the inlet and/or forebody of vehicle. The successful application of fuel preinjection has been demonstrated in studies of external burning with the aim of providing control forces acting on a vehicle or decreasing the forebody or afterbody drag. If high-energy/high-density fuels, for example, as suspensions in a base hydrocarbon, are envisioned, in particular for small vehicles, such fuel preinjection will be a principal means of providing rapid ignition and flame holding.

In the case of preinjection in the inlet, fuel jets may be used to control the shock system and the deceleration of the incoming airflow. This method has the potential to decrease the mixing length by at least a factor of 1.5–2, for the typical ramjet with the design Mach number around 6. Furthermore, this method of the injection may be accompanied by simultaneous thermal decomposition of the fuel and mixing enhancement through other means such as the mixing of gas with liquid or shock/spray interaction in the inlet flowfield.[10,11] The injector configuration has a strong effect on the supersonic inlet starting as the fuel injected upstream of the inlet entrance modifies the flow past the inlet's compression surface. The breakup of the fuel droplets, their mixing with the freestream flow, and evaporation may lead to degradation or an improvement of the inlet starting and operational changes, depending on the liquid fuel atomization process and flight conditions. To control these changes the liquid fuel may be supplied from a thin pylon with a low wave drag or in a wake behind it. Combining the fuel supply from pylons and in their wake may provide control of the shock system in the inlet. In addition, the inlet shock system, similar to the case of the gaseous fuel mixing,[10] may intensify the process of the droplet breakup (a secondary breakup mechanism) and their mixing upstream of the combustor intake.

Several practical issues arise for a preinjection of liquid fuel in the engine duct: 1) Mixing efficiency, flow deceleration and inlet performance; and 2) the effect of fuel preinjection on combustion using liquid hydrocarbon as a flame-holding source with ignition provided, for example, by a transient hydrogen flame.

A successful example of kerosene preinjection was the experiments on an axisymmetric scramjet model at $M = 6$ and $T_0 = 1500$ K under freejet conditions in the test facility at the CIAM Scientific Research Center (Turaevo), during which the ignition, piloting, and flame-holding characteristics in a scramjet combustor operating on kerosene with hydrogen as a pilot have been investigated.[12,13] In these experiments hydrogen-based flames in cavities have been used to provide an ignition and flame-holding mechanism for a kerosene flame based on liquid preinjection from the leading edge of the engine spike. Combined operation of the cavities with hydrogen equivalence ratios ranging from 0.24 to 0.64 maintained the kerosene combustion throughout the experiment duration. Hydrogen flow-rate modulation by sequential operation of the cavities' flow affected the amount of heat release in the model's duct, inducing upstream interaction and the deceleration of the flow to subsonic when the overall engine equivalence ratio had been increased to large values. Elimination of the hydrogen pilot flames in the cavities resulted in an extinction of the kerosene flame.

It is of interest to evaluate the abilities of cavities to provide flame-holding capabilities when the gaseous flame is removed. The experiments described next determined that these cavities are regions with rich mixtures, which receive only a small amount of fresh oxidant through the shear layer formed at their separation from the oncoming airflow. The morphology of the boundary layer in terms of preinjected liquid concentration, thickness, and temperature, play a significant role in the flame stability and structure of the recirculation region. The experiments covered the air stagnation temperature range between 300 and 1000 K, and probes inserted in the cavity measured the temperatures during the modulation of hydrogen flow rate with and without the preinjection of kerosene upstream of the supersonic nozzle. Two types of cavities, in addition to a generic rearward-facing step have been used, as described next.

Experimental Setup

The experiments were carried out in a two-dimensional, direct-connect wind tunnel with a rearward-facing step as a main flame-holding mechanism. The facility has been described in detail elsewhere.[14] The test hardware consists of a hydrogen-based vitiated heater that is capable of heating the air to a maximum stagnation temperature of 1200 K. The air is directed via a bellmouth to a two-dimensional converging–diverging nozzle that ends at a rectangular test section with an entrance of 2.54 × 2.54 cm. The converging–diverging nozzle is interchangeable and the facility provides six fixed nozzles with the same cross-sectional exit area that give a Mach number variation of 1.6–3.6 at the test-section entrance. All of the experiments described here were performed with the Mach 1.8 nozzle. The test section is made of copper and operates in a heat-sink mode. The combustion section is designed to diverge at $7H$ downstream of the step with a half-angle of 3 deg to delay the onset of thermal choking. The test section is equipped with quartz windows on the three sides that do not include the injectors to permit visual access to the flowfield. Wall temperatures and pressures are measured using 15 pressure ports and five thermocouples.

Three different step configurations were evaluated in this study (Fig. 1). The first configuration featured a rectangular rearward-facing step shown in Fig. 1a. Hydrogen was injected at sonic velocity from the base of the step via three 1-mm-

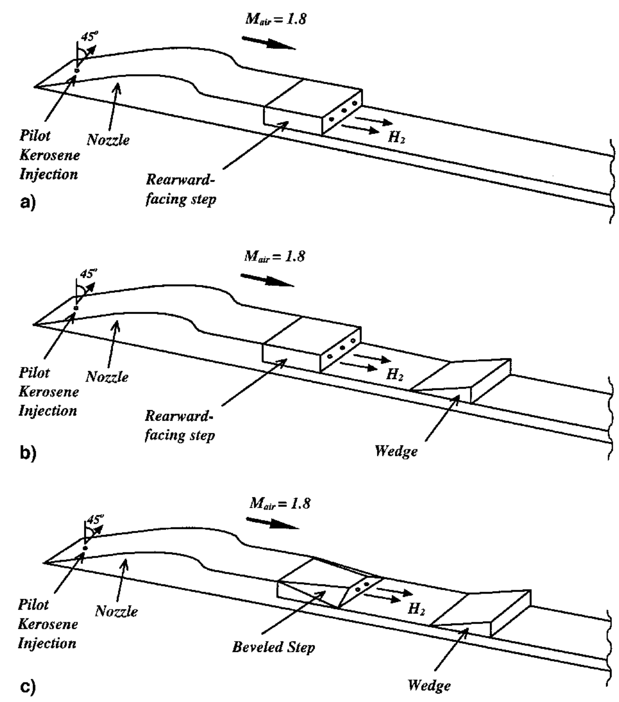

Fig. 1 Experimental configurations: a) two-dimensional rearward-facing step with base injection, b) two-dimensional step with base injection and 30-deg wedge (cavity), and c) beveled step with base injection and 30-deg wedge.

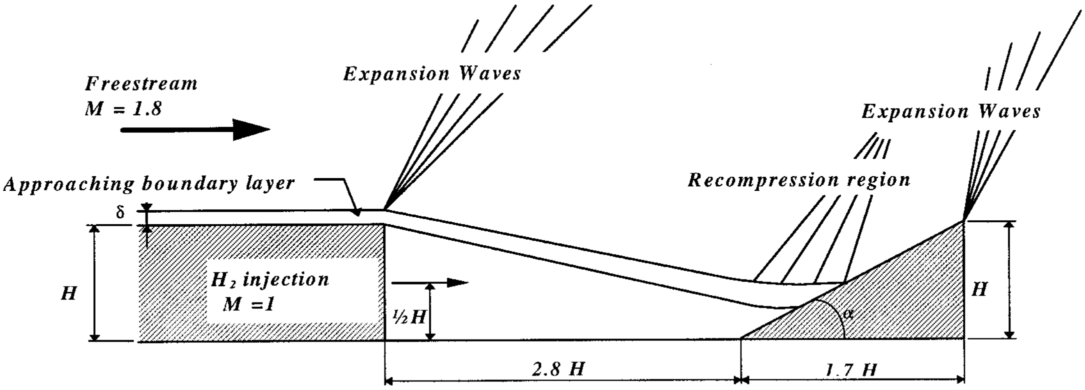

Fig. 2 Schematic diagram of the flow in the cavity region with hydrogen injection in the base and detachable rearward-facing wedge.

diam orifices equally spaced in the transverse direction with the step height of the rearward-facing step, H = 10 mm. Figure 1b shows the formation of a cavity by adding a wedge at 2.8H downstream of the step. Figure 1c shows the third configuration that features a rearward-facing, beveled-edge step, i.e., a ramp, with either a 15- or 30-deg wedge. The purpose of the beveled-edge step is to facilitate the penetration of the kerosene–air mixture in the cavity. The beveled-edge step has the same step height, 10 mm, as the rectangular step. For this configuration, hydrogen is injected from the base of the step at a height of 1/2H via two 1-mm-diam orifices equally spaced in the transverse direction. The effective cavity volume is reduced in this configuration. In all configurations a discharge electrode positioned at the base of each step provided the ignition source for the hydrogen flow. Kerosene was injected in the subsonic portion of the nozzle at 15 deg relative to the local surface.

Figure 2 represents a schematic of the rearward-facing step with mass injection through the base of the step into the recirculation region. A cavity was formed by a removable rearward-facing wedge placed between 2.8 and 4.5H downstream of the step. The wedge angle α was either 15 or 30 deg in these experiments. The supersonic flow expands through a series of expansion waves at the corner of the step. The turbulent boundary layer separates and forms a free shear layer that undergoes recompression toward the end of the cavity. In the recompression region the flow turns upward because of the presence of the wedge. The size of the recirculation region depends on the amount of mass addition and heat released in this region. At the edge of the rearward-facing wedge the flow expands once again with realignment in the wake of the afterbody.

Kerosene was injected into the boundary layer in the subsonic portion of the nozzle at an axial location that corresponds to an area ratio A/A^* of 3.17, as shown in Fig. 1. The purpose of this injector was to seed a small amount of kerosene into the boundary layer approaching the step with the goal of obtaining a combustible mixture capable of maintaining the cavity flame once the hydrogen flow was removed. The injector hole for the pilot fuel had an orifice diameter of 1 mm and the injection was at 15 deg relative to the local surface.

Three temperature probes located at axial locations of 1.2, 1.8, and 2.3H upstream of the step provided the temperature measurements inside the cavity. All of the temperature probes were located at a height of 1/2H in the lateral direction.

Table 1 Experimental conditions[a]

Two-dimensional step		
Wedge angle, deg	ϕ_{H_2}	Q_{PK}, cc/min
	T_O = 300 K	
0	0.02	60
0	0.03–0.01	0
0	0.01	20
30	0.01	40
30	0.03–0.01	0
30	0.03–0.01	40
	T_O = 1000 K	
0	0.06	60
30	0.03	70
30	0.05–0.02	0
30	0.05	160
—	—	—
—	—	—

[a]Two-dimensional step and cavity formed by two-dimensional step/30-deg wedge.

Table 2 Experimental conditions[a]

Beveled step (ramp)		
Wedge angle, deg	ϕ_{H_2}	Q_{PK}, cc/min
	T_O = 300 K	
15	0.02–0.01	120
15	0.02–0.01	40
15	0.02–0.01	80
30	0.03–0.01	0
—	—	—
	T_O = 1000 K	
15	0.04	60
30	0.05	55
30	0.05	30–100
30	0.04	40–60
30	0.05–0.02	0

[a]Beveled-step (ramp) and cavity formed by ramp + 30-deg wedge or ramp + 15-deg wedge.

Results

Flame-Holding Evaluations

In all experiments at T_O = 1000 K, after steady flow conditions were established, the hydrogen pilot was ignited and kerosene was injected at the various flow rates. At lower temperatures ignition of hydrogen was initiated during the wind-tunnel startup, then the pressure was raised to establish nominal experimental conditions followed by kerosene injection upstream of the supersonic nozzle.

Tables 1 and 2 indicate the experimental conditions in terms of the geometric configuration, air stagnation temperature T_O, hydrogen equivalence ratio based on the total air massflow ϕ_{H_2}, and kerosene flow rates Q_{PK}. These flow rates are shown for comparison only because the recirculation region contained rich mixtures that received only small amounts of fresh air with a significant local variation in the equivalence ratio from case to case. Where a range is indicated, the flow rate has been throttled throughout the experiment and extinction occurred at the highest value. As shown in a following section, only a part of the injected kerosene remained in the boundary layer. The remainder penetrated into the main flow and had only a minor effect on the processes of interest in the recirculation region. Because these experiments attempted to determine the conditions under which the preinjected kerosene would flame-hold without the presence of the hydrogen flame, two procedures have been used. 1) throttling of the hydrogen once the kerosene was injected at constant flow rate and ignited, and 2) modulating the kerosene flow rate while maintaining the hydrogen flow rate constant to determine a limiting value beyond which additional kerosene leads to the flame extinction.

In all experiments at T_0 = 1000 K, with all configurations, the pilot flame extinguished for hydrogen $\phi_{H_2} < 0.05$. With the 30-deg wedge and $\phi_{H_2} = 0.05$, the kerosene flow rate could be increased to large values, e.g., Q_{PK} = 100 cc/min for the ramp and 160 cc/min for the step before the flame extinguished. The flow rates correspond to equivalence ratios of 0.08 and 0.13, respectively, based on the total air mass flow rate through the test section. This increase in flame stability is attributed to the formation of a larger recirculation region with a hydrogen mass addition that received comparatively large quantities of fresh air. The last two experiments with the ramp at 1000 K show the kerosene flow rate range for which the flame in the recirculation region was maintained at different ϕ_{H_2}. The small difference in hydrogen equivalence ratio may be misleading because, locally, in the recirculation region the variation of the equivalence ratio was substantially larger. Reduction in the hydrogen flow rate resulted in the flame extinction at all kerosene flow rates indicated in Table 2 for both step and ramp configurations. For experiments at low T_0, the recirculation region resisted the injection of kerosene and subsequent throttling of hydrogen.

Note that in Tables 1 and 2 at low T_0, even for configurations that do not create a cavity, i.e., wedge angle α = 0 deg or form only a small cavity α = 15 deg, the hydrogen flame resisted the kerosene injection. The flame was maintained even as the hydrogen flow rate was throttled to very low values and it extinguished only when $P_h - P_{\text{local}}$ dropped below 1 psi (6890 Pa). This behavior was noticed for all kerosene flow rates up to 120 cc/min, which corresponded to an equivalence ratio based on total airflow of 0.05.

It was estimated that the increased stability of the flame at low T_0 was a result of a less rich mixture in the cavity and, subsequently, thermocouples were inserted at different locations in the cavity to identify the effects of 1) air stagnation temperature, 2) hydrogen flow rate and, 3) preinjected kerosene flow rate.

It should be noted that the measured temperatures were affected by the size of the recirculation region and by the temperature gradients that changed with the amount of heat release in this area. These measurements are presented next for stagnation temperatures of 300 and 1000 K.

Low-Temperature Case, T_0 = 300–600 K

Figure 3 shows the temperature distribution in the cavity formed by the two-dimensional, rectangular step with a 30-deg wedge as the hydrogen flow rate was reduced during the experiment. Kerosene was not injected in this case. From the temperature levels measured at 1.2, 1.8, and 2.3H downstream of the step, it can be seen that the cavity was a region of rich-burning gases with the temperature increasing as the hydrogen flow rate was reduced. The time origin is arbitrary in this and the following diagrams. The hydrogen pressure, which was proportional with the flow rate until the injectors became unchoked, is shown in Fig. 3 along with the local pressure. As heat addition was added, the recirculation region was modified and the thermal gradients in the cavity were displaced. The colder regions always remained closer to the hydrogen injectors, indicating a richer mixture in that region throughout the hydrogen throttling sequence. These measurements were taken on the centerline of the jet and it is likely that a more complex thermal gradient map exists because of the formation of several recirculation cells within the cavity, with higher temperatures farther out in a crossflow direction. Similarly, other thermal gradients are likely to exist in the region bound by the hydrogen jet and the cavity wall. The amounts of hydrogen were reduced to very low levels, indicated in Fig. 3 by the difference between hydrogen stagnation pressure and the local pressure the flame extinguished, at approximately 82 s. The probe placed at 2.3H reached very high temperatures around the 70-s mark and was physically destroyed beyond the 80-s mark.

Figure 4 shows a comparison between the temperature with and without preinjection of kerosene for a generic-step configuration without a wedge, which resulted in a smaller recirculation region than the cavity. The temperature is plotted vs the hydrogen-equivalence ratio based on total air mass flow. Figure 4 shows that the temperatures were higher in the case of kerosene injection, which is most likely because of an increase in the fresh air supply in the recirculation region brought by a more rapid growth of the shear layer formed at the recirculation region boundary. This accelerated growth may be caused by the presence of the liquid in the boundary layer. Figure 5

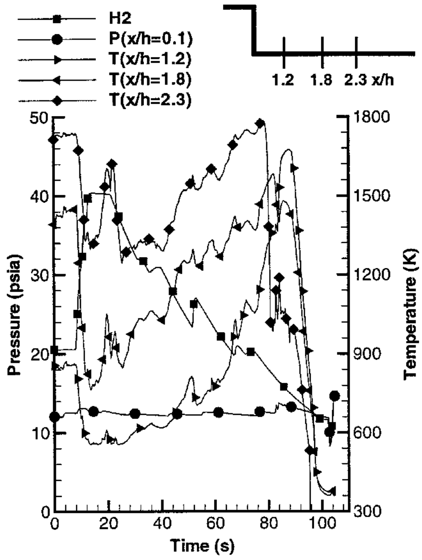

Fig. 3 Cavity temperature distribution at T_0 = 300 K and hydrogen throttling in the absence of kerosene preinjection.

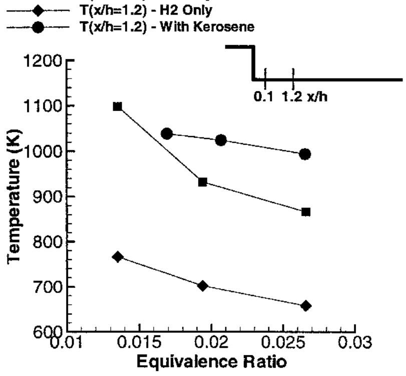

Fig. 4 Comparison of recirculation region temperatures with and without preinjection of kerosene in the boundary layer at T_0 = 300 K and ER_{ke} = 0.07 cc/min.

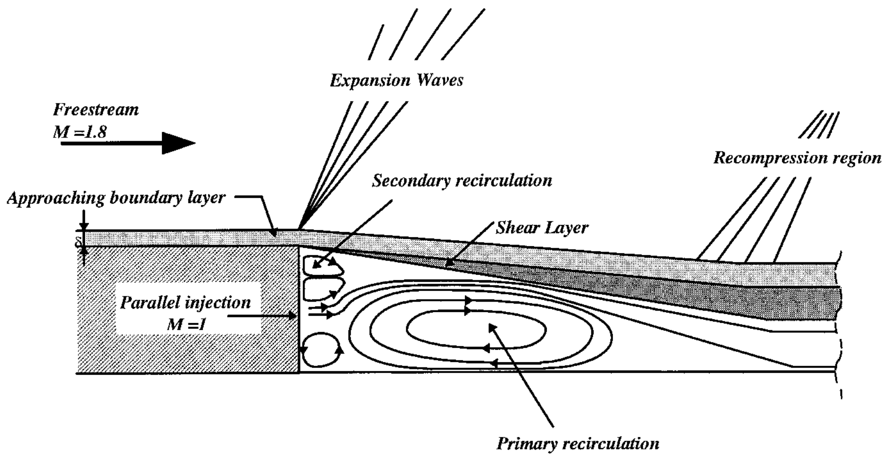

Fig. 5 Recirculation region pattern with base injection indicating the shear layer between the oncoming boundary layer and the recirculating gases behind the step.

shows a schematic of the growth of the shear layer at a simple, two-dimensional recirculation region. Although it can be assumed in a first approximation that the flow pattern in the cavity is two-dimensional, the presence of the sidewalls produce additional recirculations,[15] resulting in complex three-dimensional streamlines. Because the shear layer grows by depending on the two streams' density ratio through the following equation[16]:

$$\delta \sim \frac{(1 - u)(1 + \sqrt{r})}{1 + u\sqrt{r}} \tag{1}$$

the increase in density as a result of the seeding of liquid in the gaseous boundary layer results in a faster growth of the shear layer. It is estimated that this faster growth results in an increase in the amount of fresh air brought in the rich recirculation region in the cavity, resulting in higher measured temperatures.

At the location of kerosene injection the boundary layer is only beginning to form. Based on the dependence of jet penetration in a transverse flow[17] on the transverse momentum ratio of the injectant liquid to the freestream

$$\bar{J}_{\text{ke}} = \frac{Q_{\text{ke}}^2/(A^2\rho_{\text{ke}})}{J_0} \tag{2}$$

and a boundary-layer growth of as $1/\sqrt{Re}$, it was estimated that the amount of kerosene that remains in the boundary layer is about 52% of the total injected corresponding to a boundary-layer equivalence ratio of 0.5 at 300 K for the case shown in Fig. 4. It is estimated that this lean boundary layer provided additional fresh air in the recirculation region. Tomioka et al.[18] noticed a similar shear-layer growth caused by heat release, although the parameters responsible for shear-layer growth, i.e., velocity ratio and density ratio, remained practically unchanged. Furthermore, as more heat is released in the recirculation region, the size of the recirculation region is increased and the relative angle between the oncoming boundary layer and the recirculating flow becomes more favorable for mixing. At $T_0 = 1000$ K the same kerosene flow rate results in a boundary-layer equivalence ratio of 0.64, clearly with less oxidant available.

High-Stagnation-Temperature Case, T_0 = 1000 K

Figure 6 shows the temperature distribution in a cavity formed by the two-dimensional step and the 30-deg wedge as the hydrogen flow rate was reduced. Kerosene was not injected in this case. The temperatures are lower in the cavity by 50–100 K at each location in comparison with the T_0 = 300-K

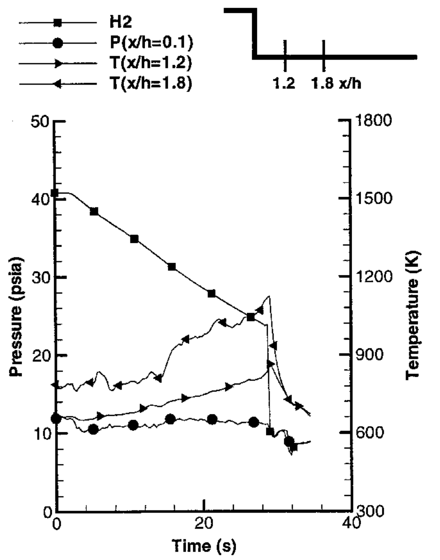

Fig. 6 Cavity temperature distribution without kerosene preinjection at T_0 = 1000 K.

case, despite the increased air stagnation temperature. This is most likely because of the formation of a richer recirculation region. At approximately 20 s mark, the flame was extinguished by the facility operator.

As kerosene was injected, the additional fuel brought in the recirculation region caused the flame extinction. At 1000 K the boundary layer was richer than in the 300 K case; hence, less fresh oxidant is entrained in this region. When the hydrogen flow rates were increased, the size of the recirculation region grew and the flame was stable for increased kerosene flow rates, as indicated in Table 2.

Summary

An evaluation of the effects of preinjection of kerosene, stagnation temperature, and modulation of a hydrogen pilot flame on several cavities indicated the following:

1) The cavities are regions of rich mixtures in which the flame stability is strongly affected by the air stagnation temperature via changes in the local equivalence ratio.

2) The geometries investigated in this study, i.e., ramp vs two-dimensional step and cavity vs rearward-facing step had a small effect on the flame stability in the recirculation region.

3) High air stagnation temperature resulted in rich mixtures in the cavity and the addition of preinjected kerosene resulted in flame extinction, except in the case when large hydrogen flow rates were present. In this case the enlargement of the

recirculation region led to the entrainment of additional quantities of fresh air contributing to the flame stability.

4) At low T_0 the flame held, even when large kerosene flow rates were injected. The proportion of kerosene seeded in the boundary layer is not expected to grow proportionally with the total amount injected; therefore variation of the preinjected kerosene had only a small effect.

5) With kerosene preinjection at low T_0, an increase in temperature was noted in the cavity, most likely as a result of an increase of the shear-layer growth at the boundary between the recirculation region and the oncoming boundary layer, which brought additional fresh air in the recirculation region.

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