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Study of Scramjet Combustor for Fuel/Air Mixing and Flame Stability

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ABSTRACT

Supersonic combustion technology owns an important position in the research of air-breathing hypersonic vehicle. In order to make higher combustion efficiency within milliseconds, fuel/supersonic-flow mixing must be enhanced, especially liquid hydrocarbon fuel, which has to go through the processes of droplet breakup, atomization and evaporation before ignition. As one of the most effective structures of flame stabilizer, cavity has gained more and more attention during scramjet combustor research, especially the tandem dual-cavity, which has a remarkable advantage in promoting fuel/air mixing and flame stability.

Mixing, Ignition and flame holding in a scramjet combustor, among the three critical components of the scramjet engine, the combustor presents the most formidable problems. The complex phenomenon of supersonic combustion involves turbulent mixing, shock interaction and heat release in supersonic flow.

In order to accomplish this task, it requires a clear understanding of fuel injection processes and thorough knowledge of the processes governing supersonic mixing and combustion as well as the factors, which affects the losses within the combustor. The designer shall keep in mind the following goals namely,

i) Good and rapid fuel air mixing
ii) Minimization of total pressure loss
iii) High combustion efficiency

KEYWORDS: Scramjet Combustor, Dual cavity combustor, Ramp cavity based combustor, Flame stability, Flow fields with combustion and without combustion.

INTRODUCTION

Although the research of scramjet ground-test and flow field diagnosis has gotten several breakthroughs in recent years[5], the capture of flow field details still relies on numerical methods, which can provide insight into the interaction of swirling flow, fuel evaporation, mixing, and turbulent combustion. The purpose of this paper is to evaluate the accuracy of physical models, meanwhile, to find the impact of the fuel-jet velocity on supersonic combustion. First, a test case was carried out without and with combustion to validation the physical and numerical model used in this work. After that, the supersonic combustion flow field characteristics of the dual-cavity scramjet combustor were analyzed in details, especially the flow pattern inside the cavity, for three different velocities of fuel-jet.

Nomenclature

P_t total pressure
T_t total temperature
P static pressure
T static temperature
Y mass fraction
Φ the fuel/ air equivalence ratio

1. Combustion Field in Dual-cavity Scramjet Combustor:

Fig.1 is a schematic view of a tandem dual-cavity scramjet combustor model designed by Institute of Mechanics of Chinese Academy of Sciences (CAS)[8]. The inlet air total temperature was 1800K, the total pressure was 1.1Mpa, the static pressure was 84kpa, the flow rate was 1340g/s, the inflow Mach number was 2.33, and the air components mole fraction rate was N2:O2:H2O 56.8:19.2:24.0. And the back pressure was 100kpa, the environmental temperature was 286K. In the experiment, two types of fuel were provided, pilot H2 and liquid kerosene. The upper and under wall both own 5 jet holes of pilot H2, as well as the kerosene jet holes. The diameter of pilot H2 jet holes was 1.0mm, and that of kerosene jet holes was 1.2mm. And H2/air equivalence ratio was 0.09. The total temperature, total pressure, flow rate and equivalence ratio of the supercritical kerosene were 750K, 4.3MPa, 66g/s and 0.72, respectively.

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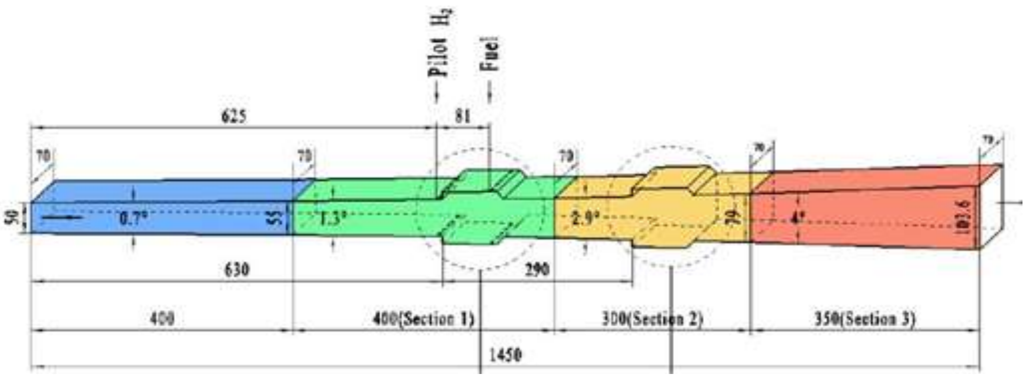


Fig.1. 3D configuration of the Combustor test Rig

1.1) Flow flied without fuel jet

The pressure isolines without fuel jet and flow streamlines in the first cavity were depicted in Fig.2. The shockwaves interaction can be seen clearly from Fig.2 (a). Although boundary layer was separated in the cavity, there was no separation shock in the upstream of the cavity. The reattachment shock wave, induced by the shear layer against the backward wall of the cavity, caused a high pressure region and then the flow began to expand. Because the distance of two cavities were long enough, the flow field figures in second cavity were similar as the first one.

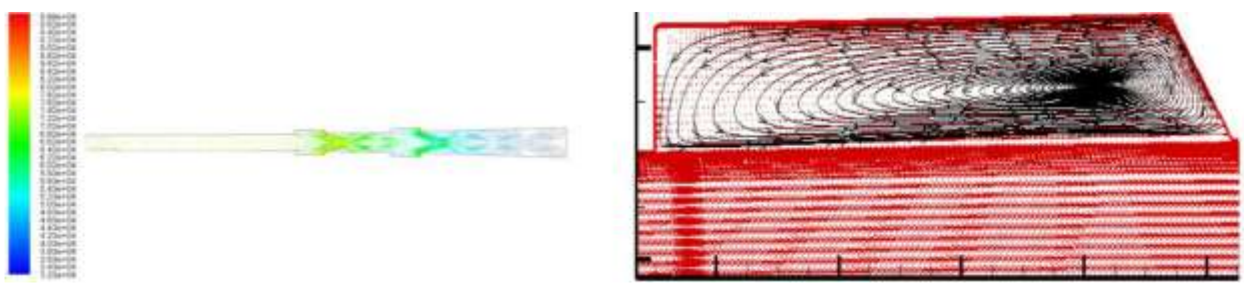


Fig.2 (a) The pressure isolines (b) Flow streamlines in the first cavity

1.2) Flow field with combustion

As shown in Fig.3, two vortexes with different sizes rotating in the same direction were formed, since the interaction of the swirl-flow and the fuel-jet in the first cavity. The rotating direction of the larger vortex was opposite to the fuel-jet, which could enhance the mixing and atomization, meanwhile provided a stable low speed region and brought kerosene back into depths of the cavity to establish stable combustion, which could be seen in high temperature regions in Fig.4, and prevented most of kerosene from flushing by the high speed main air. The smaller vortex has a same direction as the fuel-jet, thus it couldn’t provide stable combustion, as shown in Fig.4 it is corresponding to the low temperature region. However, its existence protected the upstream cavity back wall from heat in a certain extent. Additionally, unburned fuel was blew away to the second cavity for a further combustion as soon as it meets main stream, which is helpful to improve combustion efficiency and to shorten the combustor length.

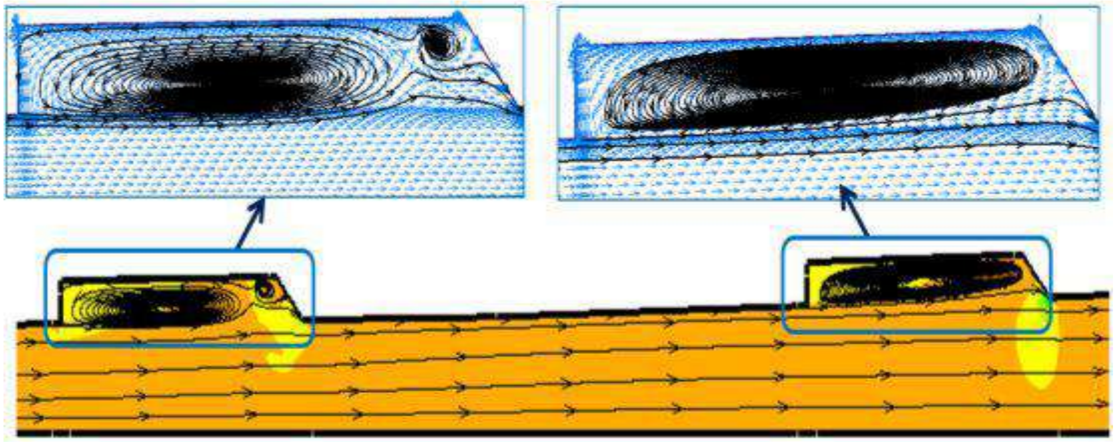
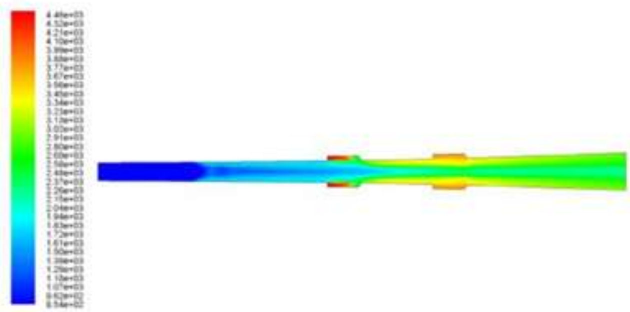


Fig. 3. The structure of vortexes in cavities(with combustion)



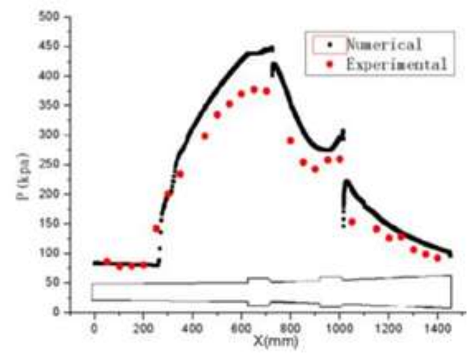


Fig. 4.The contours of the temperature Fig.5. The pressure distribution of bottom wall

Additionally, the accuracy of the discrete phase simulation was proved to be satisfactory as shown in Fig.5 with the wall pressure distribution comparison between the present numerical and the experiment results in.

2) Development of the ramp cavity based Scramjet Combustor:

2.1) Ramp injectors

One of the strategies to solve the aforesaid problems of mixing is generation of axial vortices. Axial vortices possess a better far field mixing characteristics. Also they are being propagated to a considerable distance, even with the suppressing characteristics of the supersonic core flow. Ramp injectors are considered to be a key feature to generate axial vortices. Figure 6 & depicts some of the characteristics of Ramp injectors flow field. The following are the characteristics of the ramp injectors.

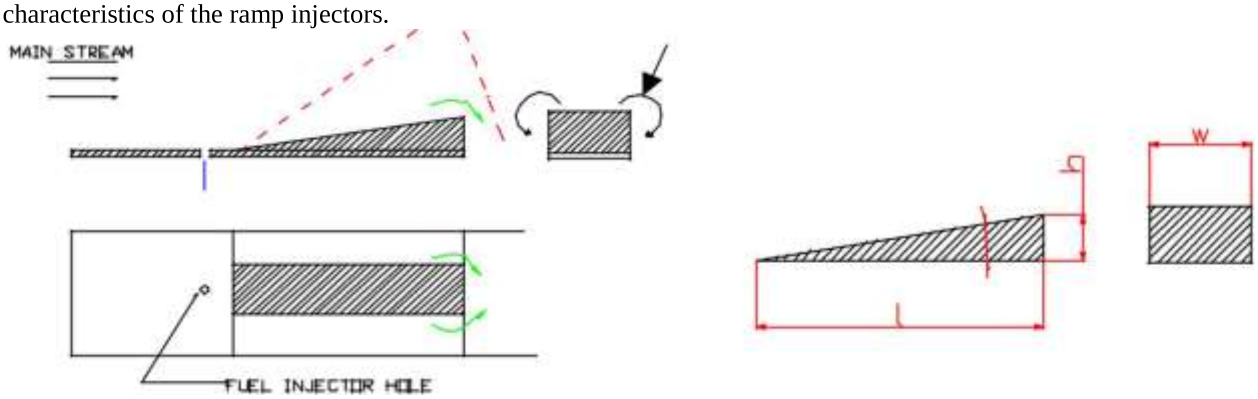


Fig.6: The Ramp injector flow field and its geometry

1)The spillage vortices contra rotating vortices generated by compression
2) Pre-compression by the Ramp face produces favorable region for injection.

3) Stagnation region near the leading edge of the Ramp injector improves ignition.
4) The strength of the spillage vortices increase with increase of core flow mach no, thus retaining the performance at higher operating conditions.

3) Cavity Based Injection

Generation of acoustic oscillations is also considered to be a better candidate to achieve better mixing. Unsteady shear layers generate acoustic oscillations. Wall mounted cavities generates these oscillations to aid the mixing enhancement. The Cavity parameters in figure 7. Cavities are characterized by their L/D ratio. There are three regimes of cavity behavior, categorized by the shear layer separation and its reattachment. For cavities of L/d less than 1, the shear layer reattaches way past the trailing edge of the cavity it generates transverse oscillations. These cavities are called as 'Open Cavities'. This type of oscillations aid in penetration of fuel For L/D more than 2, the separated shear layer attaches to the bottom wall of the cavity, it generates longitudinal oscillations, which aid in flame holding characteristics. The third type of cavities is square and transition cavities, where L/D is one or close to one. They exhibit a very low level of oscillations.

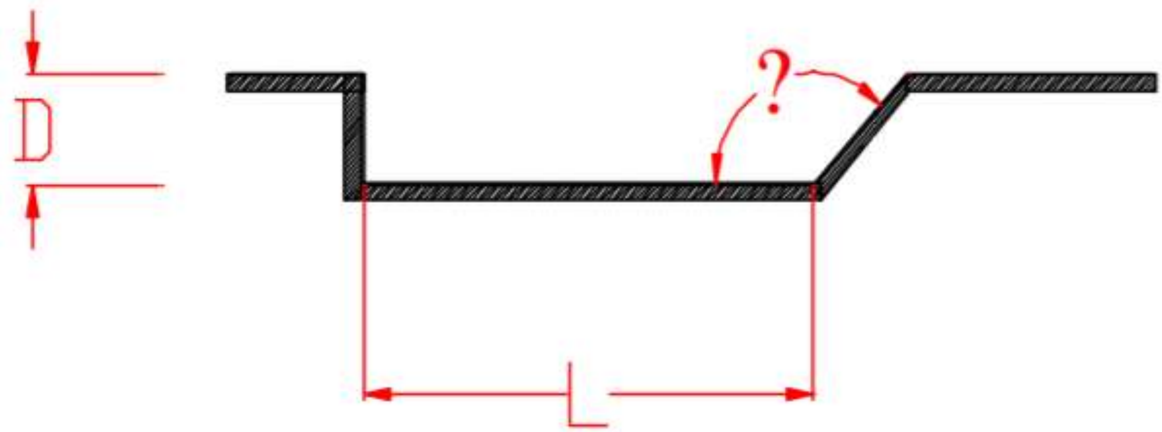


Fig.7. Cavity parameter

3.1) Combination of ramp and Cavity injector

The overall performance of ramp and cavity injectors can be improved by combining them properly. The combination of cavities and ramps generate a three dimensional flow field and turbulence for better mixing and combustion. Ramps will enhance the fuel penetration in to the core and cavities will enhance the flame holding characteristics. The ramp generated axial vortices can be utilized to scoop out the hot gases generated at cavities to improve the combustion efficiency. Thus Ramp and Cavity combination shows promising characteristics for better scramjet combustor performance.

3.2) Test objectives

1. To study the flow field characteristics of Ramp-cavity based Scramjet combustor.
2. Demonstration of ignition and sustained supersonic combustion with Kerosene fuel in the two dimensional supersonic combustor with Ramp-cavity injection.

The following table 1 shows the design criterion.

Sr No	Parameter	Criterion
	Ramp Injector	
1	Length	Evaporation length of droplets
2	Wedge angle	Compression and shock strength
3	Ramp base width (w)	Area blockage by ramp
4	Ramp Spacing (w1)	Minimum the blockage area-distribution
	Cavity Injector	
1	Length	Ramp Base height
2	Cavity depth (D)	L/D ratio needed
3	Trailing edge angle	Shock strength at the Trailing Edege

3.3) Combustor Test Facility

The setup consists of a Hydrogen burner as an on-line gas generator, anaxi-symmetric convergent-divergent nozzle for accelerating the test gas to the desired supersonic condition and a circular to rectangular transition duct. The supersonic combustor has two parts; one constant area section with backward facing step in which the ramps and cavities are located and the second one is diverging area combustor Kerosene fuel was injected transversely upstream of the ramps through five orifices of 0.4 mm diameter through the top and the bottom walls of the combustor. Kerosene was also injected through five 0.4 mm orifices parallel to the flow through the ramp base. Pilot Hydrogen was injected to ensure the ignition and sustained combustion of kerosene fuel. The fuel injection scheme was shown in fig. (8). Wall pressures along the axial length of the Hydrogen burner, convergent- divergent nozzle, transition duct and supersonic combustor were measured with strain gage type pressure transducers. The burner stagnation temperature and the wall temperatures were measured with Tungsten-Rhenium thermocouples. Skin temperatures were also recorded during the test.

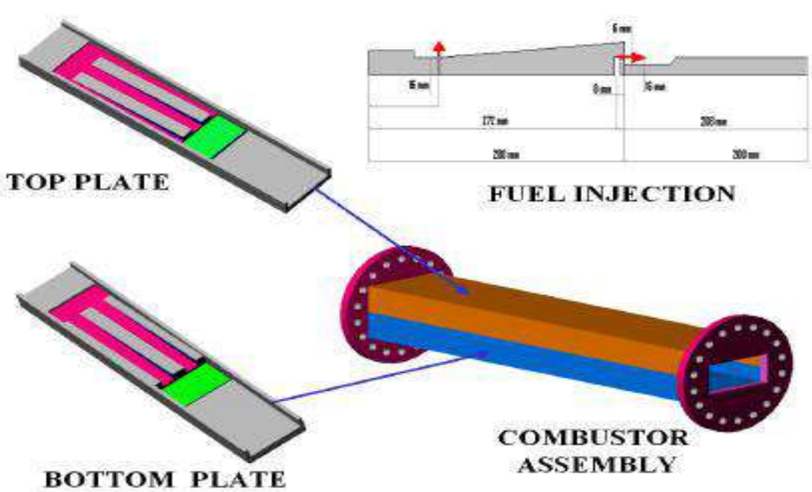


Fig 8: Ramp Cavity Based Scramjet Combustor

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3.4) Test conditions

Flight Mach No. : 6.0
Flight altitude : 32 km
Combustor entry Mach No. : 2.4
Burner stagnation temp. : 1500 K
Fuel equivalence ratio : 0.4
Test gas flow rate : 0.85kg/sec
Kerosene mass flow rate : 26 gm/sec
Kerosene injector pressure : 16.6 bar

3.5) Results and Discussion

The following tables give details of the achieved flow conditions.

Table 2

S.N	Parameter	Theoretical	Actual
1	Burner Stagnation pressure	14.0 Bar	12.23 Bar
2	Burner Stagnation temperature	1500.0 K	1343.0 K

The following table depicts the mass flow rates during the experiments.

Table 3

S.N	Parameter	Hot reacting flow	
		Expected	Actual
1	Air (Kg/s)	0.750	0.625
2	Hydrogen (Kg/s)	0.014	0.012
3	Oxygen (Kg/s)	0.180	0.181
4	Fuel (gm/s)	24.0	26.00
5	Pilot Hydrogen flow (g/s)	2.00	1.9
6	Equivalence Ratio – combustor (kerosene)	0.40	0.467
7	Equivalence Ratio – combustor (Hydrogen)	0.1	0.1

The figure 9 shows the static pressure and the wall flushed temperature distribution along the combustor, for various instants of the test sequence. There is a marked pressure and temperature rise between the ‘without fuel injection” case to the “Kerosene injection case”. Also the maximum pressure and temperature occurred during the injection of both hydrogen and kerosene.

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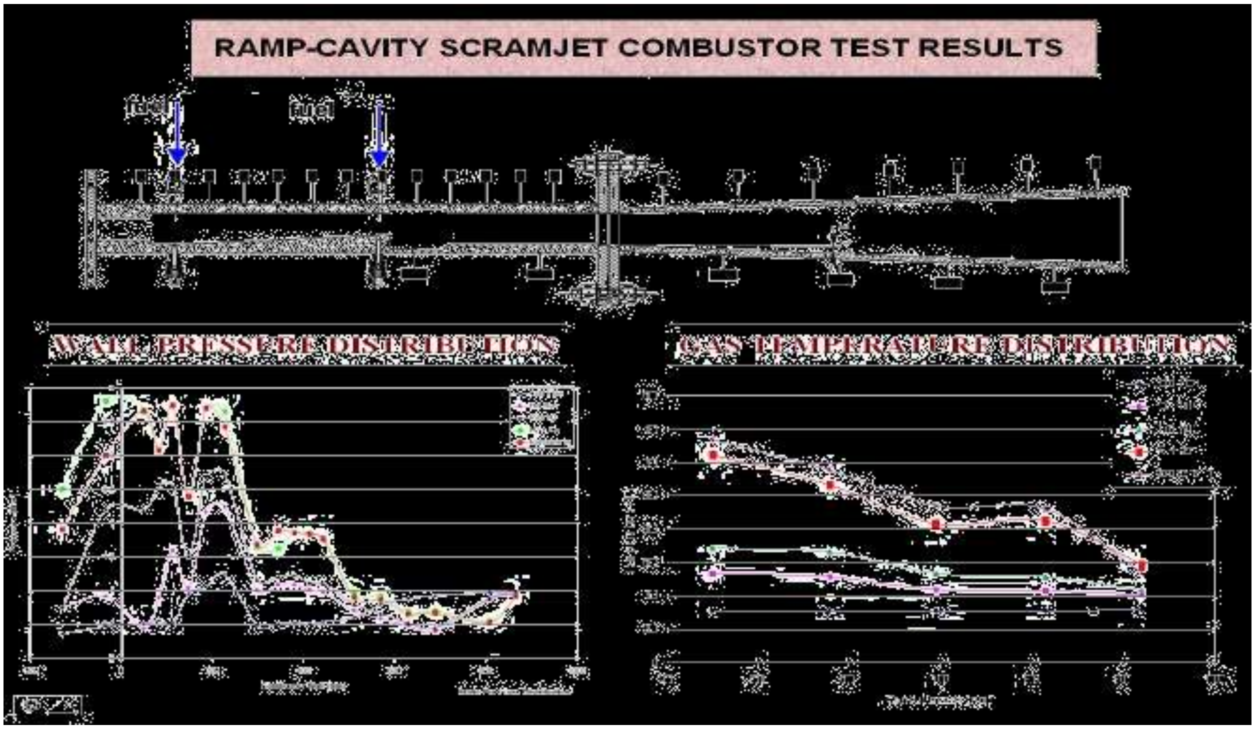

4) Development of Barbotage Injection System:

Effervescent atomization is a phenomenon in which gas has to be introduced into the liquid with a very low velocity, leading to turbulent two-phase flow that can improve penetration and vaporization of the fuel jet spray. The difference in the densities of liquid and the gas, the interaction between the two phases are helping in breaking the liquid to smaller droplets and reducing the flow dimensions for the liquid which helps in injecting the liquid fuel as very fine droplets. Barbotage injection with liquid Kerosene and Hydrogen/Air has a definite advantage in terms of breakup of droplets for better mixing with the supersonic air stream and combustion enhancement. Also using hydrogen as the barbotaging gas creates favorable conditions for the kerosene combustion also. The basic configuration of the barbotage injection unit is shown in the Fig 10. The kerosene is injected through a central tube into a mixing zone, to which the Hydrogen flows through the annular gap around the kerosene tube. In the mixing zone, gas bubbles into the liquid. Then the two-phase flow is injected into scramjet combustor through the injection orifices.

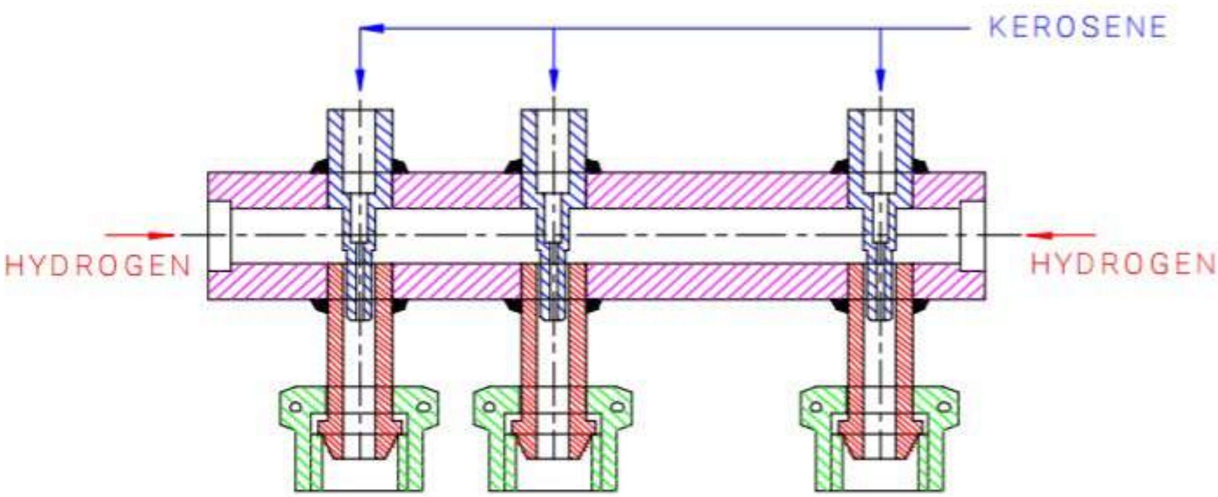

Fig 10: Barbotage system

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The flow visualization studies were carried out with the above system by allowing the jets to atmosphere. Plates 3 & 4 show the difference between the pure kerosene injection and that of barbotaging. It clearly indicates the breakup of droplet to very fine diameters and increased spread angle.

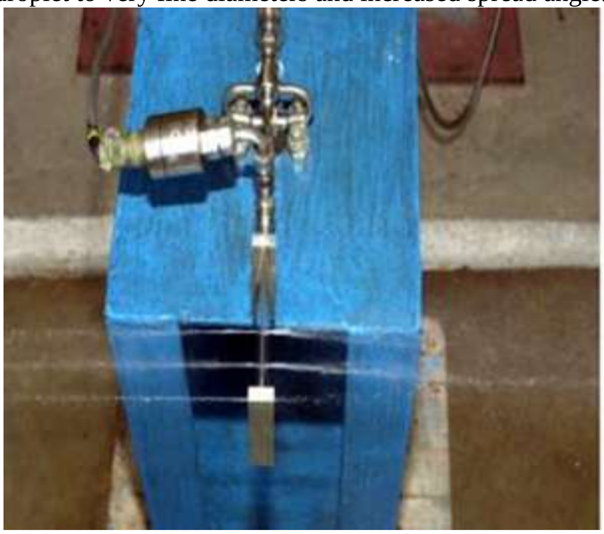

Plate 3: Kerosene Plate 4: Barbotage

Injection Injection

An experiment on Ramp-Cavity based combustor, with Barbotage injection system, was conducted. The following figure shows the Ramp-Cavity combustor with Barbotage injection system.

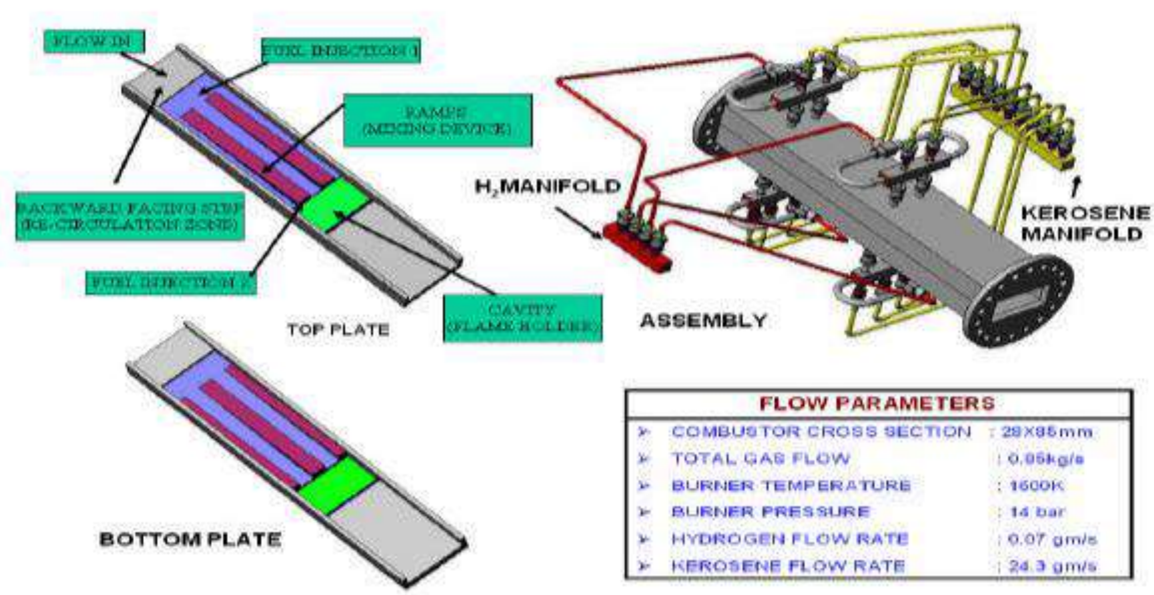

Fig 11: Ramp-Cavity with Barbotage system

4.1) Results and discussion

The following figure 12 shows the wall pressure distribution and the temperature distribution of the rampcavity test with Barbotage injection. The kerosene injection was 26g/s for "the kerosene injection only" (without barbotaging) case and 24.3gm/sec for the Barbotage injection case. Comparing to condition of injection of kerosene only, the Barbotage injection generated higher pressure and temperature rise, with comparable amount of fuel injected.

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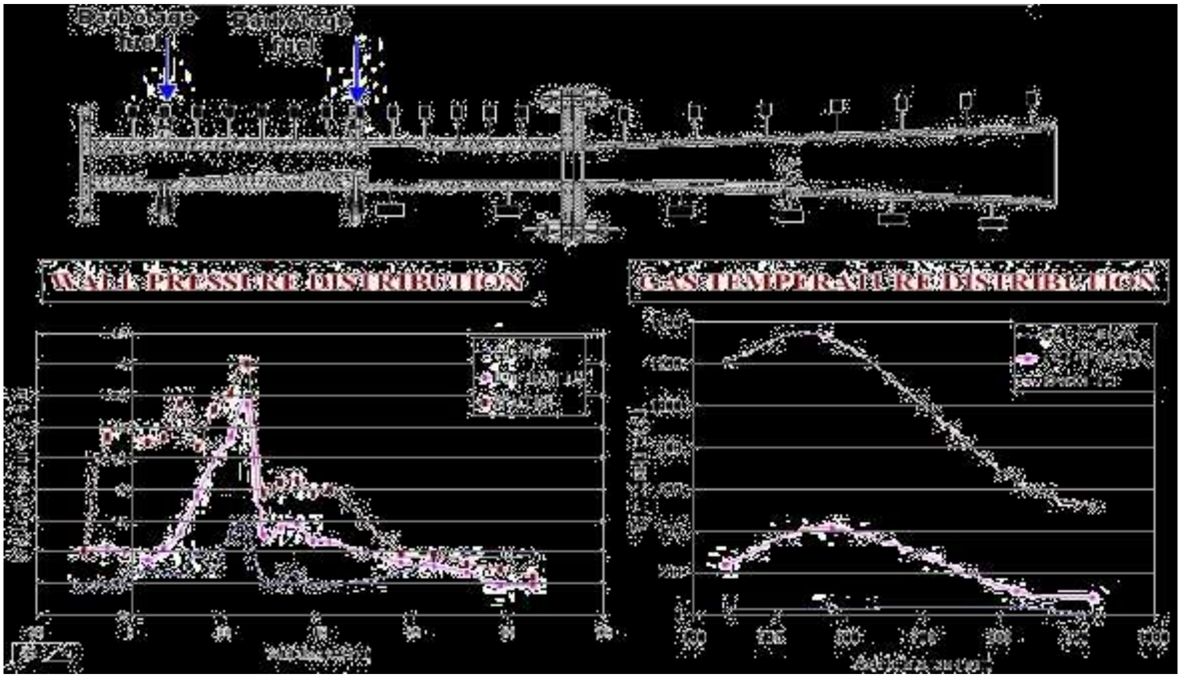

Fig 12: Pressure and Temperature distribution (Ramp-Cavity with Barbotage system

5) Conclusions:

From the above discussion, the following conclusions can be drawn:

- After the injection of kerosene, two vortexes with different sizes rotating in the same direction were formed since the interaction of the swirl-flow and the fuel-jet in the upstream cavity. The larger vortex provided a stable flame and the smaller one protected upstream cavity back wall from heat in a certain extent.
- Unburned fuel was blew away tothe downstream cavity for a further combustion as soon as it met main stream, which was helpful to improve combustion efficiency and to shorten the combustor length.
- The mass of kerosene involved into the cavity was determined by the jet-velocity, which then influenced the combustion efficiency.
- The Flame was anchored at the cavity inside the combustor.
- The Barbotaging of kerosene produced very fine droplets and higher cone angles of injection, duringthe injection to the atmosphere.
- Barbotaging ofkerosene with hydrogen produced higher-pressure and temperature rise with comparatively lesser amount of kerosene injection.

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