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Hot Test Studies in a Spark Ignited Vortex Combustion Chamber

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Hot tests are performed in a vortex combustion chamber using gaseous oxygen and gaseous hydrogen as the propellants by varying their mixture ratios, and nozzle throat diameter. The combustion is initiated in the combustion chamber using spark ignition. The oxidiser is injected tangentially at the aft end of the combustion chamber thus generating a bi-directional co-spinning vortex. Cold flow tests with real propellants are carried to estimate the pressure developed in the combustor. The temperature at the skin surface of vortex combustor is estimated from experiments. Test results indicate that the surface temperature is not above 305 K thus indicating the fact that combustion is confined to the inner core. The chamber pressure is found to be increasing with the increase of injection pressure. The reduction in throat diameter resulted in the increase in the chamber pressure.

1. Introduction

Combustion inside the rocket engine is associated with release of large quantity of heat and thus imposing a thermal load on the chamber surface resulting in a failure, fatigue in rocket engine and its components. A cooling method termed as vortex combustion cold-wall chamber (VCCW), which is characterized by co-spinning vortices in opposite directions inside the combustion chamber was introduced by Chiaverini et al., (2002). The tangentially injected oxidizer from the bottom end of the combustion chamber spirals to the top along the walls. On reaching the top the outer vortex reverses its direction and forms the bidirectional inner vortex. The fuel is introduced axially at the top end of the combustion chamber where it gets thoroughly mixed and is entrained with the oxidizer. The influence of oxidiser swirl injector number was studied by Zerrouki et al., (2012). The studies showed that the engine specific impulse was improved on increasing the number of injectors. The flow behaviour of VCCW using PIV techniques was done by Dechnana et al., (2012). The studies revealed that the injection velocity is the key parameter which gives both vortex strength and effective mixing of the propellants. The tangential velocity is found to increase with injection velocity. Also, the increase in the aspect ratio tends to decrease the tangential velocity. The influence of vortex chamber geometries like diameter ratio and aspect ratio on pressure drop and core size was studied by Vatistas et al., (2005). He found that the increase in Re increase the tangential velocity thus resulting in strong vortex. Increase in aspect ratio leads to the damping of tangential velocity. 3D simulation adopting RNG-kε model and non-premixed combustion model to study the influence of hydrogen injector ring diameter and oxidiser to fuel mass ratio on specific impulse of the combustion chamber was done by Yu et al., (2016). It was found that increase in the hydrogen injector ring diameter stabilises the flame. Further, the increase in oxidiser to fuel ratio reduces the area of high temperature zone at the top of the chamber. Increase in the hydrogen fuel injection ring diameter improved the specific impulse and the maximum value of 94.2% was obtained for the oxidizer to fuel ratio which was nearly stoichiometric. Majdalani et al., (2016) carried out the characterisation of a miniature vortex combustion cold wall combustion chamber with gaseous oxygen and hydrogen as the propellants. The simulation was three-dimensional, pressure based, finite volume unstructured solver which reduced the computation time and achieved faster convergence. Maicke et al., (2016) conducted numerical studies to investigate the effect of varying the injection conditions on the velocity structure in a vortex combustor. The

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parameters such as injector velocity, number of injectors, the injector diameter was found to have a direct impact on the mass flow rate of the propellant and hence on the swirl velocity. (Dai et al., 2016) carried out the comparative studies on the characterisation and the temperature of GH_2/GO_2 and GH_4/GO_2 flames in a laboratory scale rocket combustor. The results showed the theoretical temperature of 3200 K for a chamber pressure of 3 bar in both cases.

The flow phenomenon inside the vortex combustion chamber is found to be quite complex from literature, primarily due to the bi-directional forced and free vortices. Curcuruto et al., (2017) carried out detailed studies on the safety requirements and capabilities associated with high risk industries and reactors. The part of the rocket combustor which is most heat affected will be the nozzle throat. Guelailia et al., (2018) carried out analysis of thermal protection to the rocket nozzle by film cooling method. Major works carried out related to this topic are analytical due to the complexities in the design and fabrication of thrust chambers. The experimental works carried using the lab scale models with real propellants are in scarce. This lacuna is targeted in this paper and thus cold and hot flow studies on a lab scale model of a vortex thrust chamber are performed. The present study is carried out in two phases.

2. Experimental methodology

For the present investigation, the combustion chamber is designed to generate a thrust of around 56 N. The combustion chamber is designed for a maximum chamber pressure of 8 bar. The propellant mixture ratio is varied in the range of 1 to 3. The chamber walls are designed considering the hoop stress giving factor of safety of 5 at ground test conditions. The chamber is designed for an aspect ratio (*L/D*) of one, with diameter (*D*) and height (*L*) values of 50.8 mm, and is made of high-grade steel, SS304, having the wall thickness of 8 mm. The combustion chamber and its accessories are fabricated at Vikram Sarabhai Space Centre of Indian Space Research Organisation (ISRO) at Trivandrum.

Table 1: Configuration of vortex combustion chamber

Sl. No.	Description	Dimensions
1	Chamber diameter	50.8 mm
2	Chamber length	50.8 mm
3	Throat diameter	19.05 mm
4	Throat length	2.54 mm
5	Contraction ratio	7.1 mm
6	Nozzle exit diameter	26.93 mm
7	Area ratio	2.0
8	Nozzle length	13.33 mm
9	Convergence diameter	25.4 mm
10	Number of oxidizer swirl injectors	Four
11	Diameter of each swirl injector	2.8 mm
12	Axial fuel injector diameter	1.5(3Nos)

Table 2: Instrumentation details

Measuring Parameters	Transducer	Range	Accuracy (%)	Make
Upstream pressure of Propellants	21NA Strain Gauge	0-100 bar	±0.5	ISRO
Chamber Pressure	21NA Strain Gauge	0-20 bar	±0.5	ISRO
Mass flow meter for oxidiser	Coriolis Type	0-0.05 kg/s	±0.1	Micromotion
Mass flow meter for hydrogen		0-0.1 kg/s		
Temperature	K-type thermocouple (response time = 100 ms)	-200-1200^{o}C	1^{o}C	ISRO
	C-type thermocouple (response time = 100 ms)	0 - 2500^{o}C	1^{o}C	ISRO

Table 1 shows the configurations of combustion chamber. The fuel selected is gaseous hydrogen and oxidiser is gaseous oxygen. The section view of the entire thrust chamber including the location of pressure and temperature measurement tapings are shown in Figure 1. The photograph of the fabricated parts is shown in Figure 2. The fuel injection is done axially through the three ports of 1.5mm diameter each, spaced equally at 120^{o}, provided at the centre of the top plate. The pressure measurement ports are provided at the top plate and also on the chamber surface wall near the oxidiser injection. The instrumentations that are used for the experimentation are detailed in Table 2. The combustion products are exhausted through the convergent divergent nozzle having a throat diameter of 19.05 mm. To withstand high thrust force and temperature generated during the expansion in nozzle, the inner contour of nozzle is made of Carbon-Carbon material and bonded with the inner surface of the thrust chamber. The influence of throat diameter in chamber pressure development is also analysed using a nozzle with throat diameter of 12.75mm.
All the experiments are carried at propulsion research lab of Vikram Sarabai Space Centre at Indian Space Research Organization. Initially, cold flow tests are carried in the thrust chamber with different oxidizer to fuel mixture ratio of 1.57 and 1.93, and pressure inside the combustor is recorded. This is followed by the hot test experiments considering combustion, where the pressure developed inside the chamber is recorded. Four different hot tests are carried out with mixture ratios of 1.8 and 2.3. To study the effect of throat diameter on the chamber pressure, hot test is conducted at throat diameters of 19.05 and 12.75mm. The maximum chamber pressure is limited to below 8 bar as per the design conditions. The ignition is initiated using the spark plug mechanism immediately after the injection of propellants.

Table 3: Measurement ports and location as shown in Figure 1

No.of ports	Measuring port	Measuring parameter	Location
1	P_{inj-O2}	Oxygen injection pressure	*x/L*=0.9, *r/R*=1
2	P_{C1}	Chamber pressure at bottom surface	*x/L*=0.8, *r/R*=1
3	P_{C2}	Chamber pressure at top surface	*x/L*=0, *r/R*=0.9
4	T_{C1}	Temperature inside the combustor at bottom surface	*x/L*=0.8, *r/R*=1
5	T_{C2}	Temperature inside the combustor at top surface	*x/L*=0, *r/R*=0.9
6	ST	Skin temperature at the Top plate	*x/L*=0, *r/R*=0.9

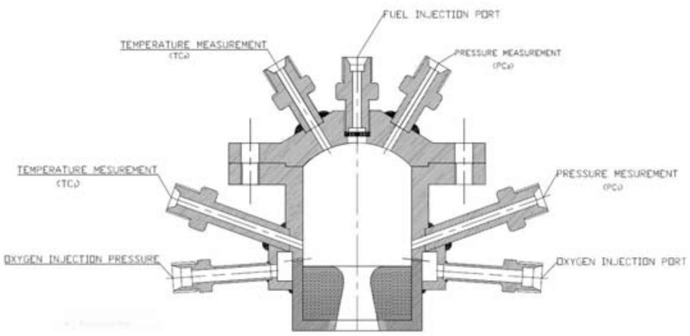

Figure 1: Sectional drawing of vortex combustion chamber showing various measurement locations.

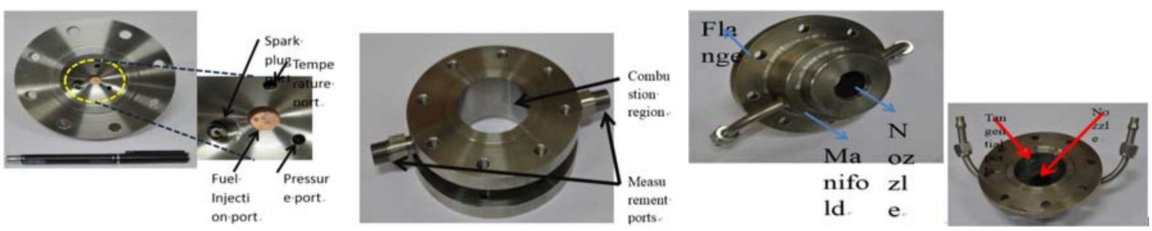

Figure 2: Photograph of the (a): top-plate.(b) combustor body (c) bottom portion and oxidiser manifold

Table 3 and Figure 1 indicate the measurement locations of pressure and temperature tapings. The pressure measurement ports, P_{C1} is located at the bottom end of the chamber at *x/L*=0.8 and *r/R*=1, and P_{C2} is located at the top end of the chamber at *x/L*=0 and *r/R*=0.9. These two locations are chosen to understand the pressure variations due to vortex reversals. In addition, further instrumentation could not be facilitated in the considered chamber due to the space restrictions. The experimentation is fully automated using the electronic controllers. The injection pressure of the propellants in to the chamber is regulated using the non-venting type spring loaded pressure regulator controlled by the electro-pneumatic valves, and they are measured using the strain gauge type pressure transducers. The sequential *on-off* switching of injectors is done using the solenoid valves using the Programmable Logical Controller circuit. The flow rate of propellants is measured using the Coriolis type mass flow meter. Figure 3(a) shows the schematic of VCCW for the present study. The oxidizer is injected at *x/L*=0.9 as shown in Figure 3(a).

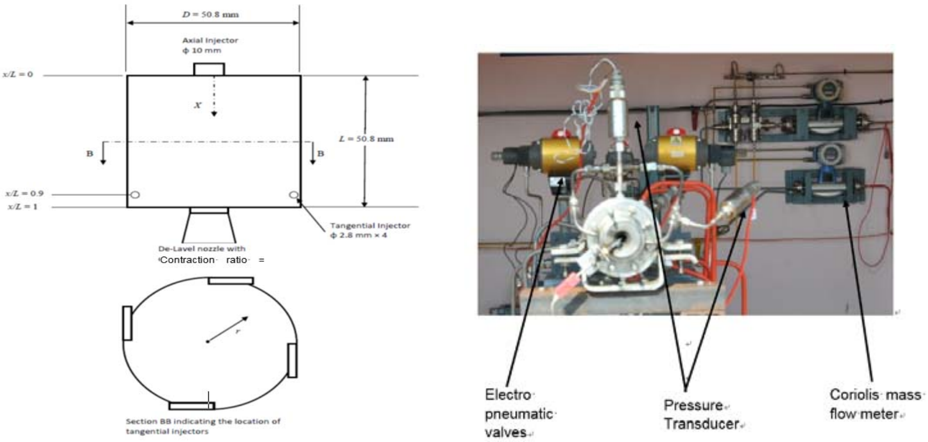

Figure 3: (a) Schematic of the vortex combustion chamber used in the present study.(b) Vortex combustion chamber mounted on the test rig.

Safety is ensured before conducting the hot test. Initially, cold flow trial tests are done with real fluids to check the valve functioning and to leakage in the flow lines. The fuel lines are purged with gaseous helium prior to the admission of gaseous hydrogen. Choked orifices are used in the fluid lines to suppress any downstream disturbance from the combustor to the upstream. The sequence of operation is also checked and finally the spark plug is tested after venting the fuel pipe line. A manual abort switch is also provided to terminate the sequence at any time in between the run-in case of malfunctioning of any of the sub-systems of the test set-up. Figure 3(b) shows the vortex combustion chamber with the measuring instruments mounted on the test rig.

3. Results and discussion

3.1 Cold flow analysis

Table 4: Cold flow test results in the vortex combustion chamber

Propellants	Injection pressure (bar)	Mass flow rate (g/s)	Mixture ratio	Chamber pressure (bar)			
				Before H_2 injection		After H_2 injection	
				P_{C1}	P_{C2}	P_{C1}	P_{C2}
O_2	5.7	28	1.93	1.8	1.2	1.3	0.95
H_2	35	14.5					
O_2	5	26	1.57	1.6	1	1.1	0.9
H_2	33	16.5					

The experimental results of cold tests carried at an oxidizer to fuel mixture ratios of 1.57 and 1.93 and the corresponding pressure of the propellants and their mass flow rates are presented in Table 4. In both mixture ratios, maximum pressure measured inside the chamber is not more than 1.8 bar, despite the fact that the inlet injection pressure of oxygen and hydrogen are 5 and 33 bar, respectively. In the range of mixture ratios considered, the chamber pressure (P_{C1}) before the hydrogen injection is found to be in the range of 1.6 - 1.8 bar. However, after the injection of hydrogen, the chamber pressure, P_{C1}, reduced to 1.1 - 1.3 bar. Similar trend is observed for chamber pressure P_{C2}. This reduction in pressure upon hydrogen injection may be due to the expansion of the inner core due to the diffusion of hydrogen when injected axially. The variation of pressure of P_{C1} is observed to be higher before and after the hydrogen injection (around 0.5 bar) when compared to the variation of chamber pressure P_{C2}. This is due to the fact that the chamber pressure P_{C1} is measured near the tangential injection port where the bi-directional rotating vortices are expected to influence the pressure.

3.2 Hot test analysis

In hot tests cases, four trials are conducted by varying the oxidizer tangential injection pressure. The tangential injection pressure of the oxidizer was increased progressively to analyze its influence on the chamber pressure and the temperature. The test results are tabulated in Table 5. In all the cases, fuel is injected axially at 41 bar and a mass flow rate of 11.5 g/s. In the first test, the oxidizer is injected at 1.8 bar at a mass flow rate of 21 to 27 g/s. The temperature T_{C2} measured is 610K momentarily at the time of ignition and reduced to 300K over a period of 5 seconds. This is due to the initiation of combustion at the initial stage. The chamber pressure developed during the test and was found to be almost same at P_{C1} and P_{C2} .In second test case, the oxidizer is injected at 2.8 bar at a mass flow rate of 27 g/s. The temperature T_{C2} measured is 500K which is lower than that of the previous case in test #1. This reduction in temperature is due to the increase in the oxygen flow rate. The temperature reached 500 K momentarily at the time of ignition and later reduced to 310K. The skin temperature of the vortex combustion chamber measured to be 305K. In third test case, the oxidizer injection pressure is increased to 5.5 bar. The maximum chamber pressure is measured to be 2 bar. The temperature, T_{C2} significantly reduced to 350 K at the instant of ignition and the skin temperature was measured to be 305 K. It can be inferred that the increase in the tangential injection pressure of the oxidizer has increased the vortex strength inside the combustion chamber and hence sufficiently provided the cooling to the combustion chamber wall. The fourth hot test alone is carried using the nozzle throat diameter of 12.75mm to compare the chamber pressure and temperature rise in the combustion chamber compared to the standard throat diameter nozzle of 19.05 mm (Table 1). The chamber pressures (P_{C1} and P_{C2}) were measured to be higher when throat was reduced to 12.75 mm. Figure 4 (a&b) shows the temperatures and the chamber pressure developed in the chamber for 12.75 mm throat nozzle. The injection pressure of oxygen is 8.5 bar and that of hydrogen was 41 bar. The test was conducted at the same mixture ratio of 2.3. It is noted that the skin/surface temperature of the combustion chamber did not increase beyond 300 K in all cases.Thus, it can be corroborated as a feat achieved using the VCCW mechanism in vortex combustion chamber that could retain the wall temperature to around 300 K even though the internal combustion temperature is around 3000 K Dai J et al. (2016).

Table 5: Hot test results

Test no.	Nozzle Throat Diameter (mm)	Mixture ratio	Injection pressure (bar)		Chamber pressure (bar)		Flow rate (g/s)		Chamber Temperature (K)		Skin Temperature at top plate (K)
			H_2	O_2	P_{C1}	P_{C2}	H_2	O_2	T_{C2}	T_{C1}	ST
1	19.05	1.8	41	1.8	0.8	0.75	11.5	21	610	305	305
2	19.05	2.3	41	2.8	1	0.9	11.5	27	500	305	305
3	19.05	2.3	41	5.5	2	1.4	11.5	27	350	305	305
4	12.75	2.3	41	8.5	7.5	6.5	11.5	27	350	305	300

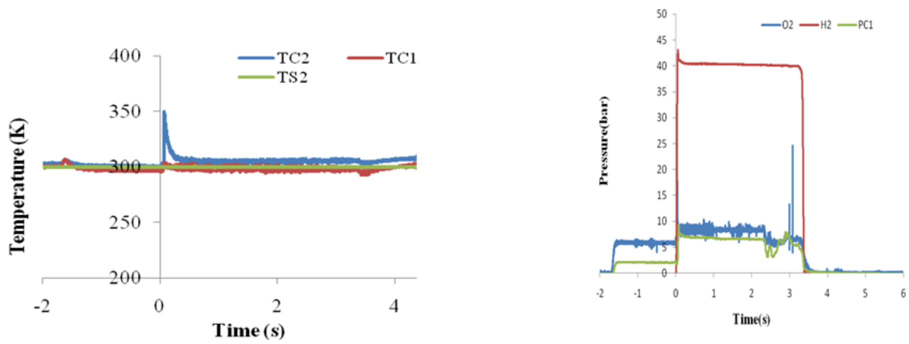

Figure 4: Variation of (a) temperature and (b) chamber pressure in a vortex combustion chamber in hot test#4 for oxidizer injection pressure of 8.5 bar.

4. Conclusion

A lab scale model of vortex combustion thrust chamber is fabricated for carrying cold and hot tests experiments. In case of experiments carried in cold test, the maximum chamber pressure developed inside the combustor is around 1.8 bar and 1.6 bar for the oxidizer to fuel ratio of 1.93 and 1.57, respectively. In case of hot test, the chamber pressure was found to be increasing with the tangential injection pressure of the oxidiser. The temperature measured at the top plate of the combustor (T_{C2}) was found to be decreasing with the increase in oxidizer injection pressure. The temperature measurements at the surface of the combustor in all test conditions indicated the maximum value of around 305 K, thus corroborating the fact that the vortex flow-based combustion chamber substantially reduces the wall temperature despite the combustion temperature almost being at 3000 K.

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