

PERFORMANCE EVALUATION AND FLAME STABILIZATION OF STAGNATION POINT REVERSE FLOW COMBUSTOR

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Abstract

The conventional gas turbine engines use straight flow combustors. The reverse-flow layout effectively uses the air flow to cool down the combustor liner and the transition piece as a counter flow heat exchanging process. The absorbed heat by the air is returned back to the system. The reverse flow configuration causes the flow to stagnate and hot products to reverse and leave the combustor.

One of the major challenges facing designers of low NO_x emission combustion systems is flame stability, as the weaker combustion process is more vulnerable to small perturbations in combustor operating conditions. Since further reduction of NO_x will likely require even leaner mixtures, schemes for lean stability extension must be considered. Stability can be dependent on the balance between flow and flame propagation velocities. In combustors where combustion is limited by reaction rates, however practical combustors do not operate in either limit. To stabilize a flame in the desired region of interest, various stabilization methodologies are adopted that either enhance the flame propagation speeds or create zones with low velocities where a flame can be sustained for inspection of premixed flame stability in Stagnation Point Reverse Flow combustor model, using Computational Fluid dynamics(CFD). The CFD analysis yielded the results which go with actual experimental results.

Keywords: combustor, stagnation, flame stability, reverse flow, Computational Fluid Dynamics (CFD) etc..

1. INTRODUCTION

Combustion and its control are essential to our existence on this planet. Today the world uses around 70% of energy which is produced from combustion process. A quick glance around our local environment shows the importance of combustion in daily life, such as electricity we use, combustion in Automobiles, Boilers, Refineries etc. Different types of combustion are possible using different types of fuel. Most commonly used fuels are coal, natural gas, petroleum, etc. Currently combustion has become an important part of the Aircraft industry. The performance parameters of an Aircraft highly depends on the process of combustion taking place inside the combustion chamber which in turn depends on the stable burning and mixing of the fuel air mixture and its further propagation in a gas turbine engine. The above mentioned are some of the benefits of the combustion process, on the other hand combustion also has some downsides like environmental pollution. The major pollutants produced by combustion are unburned and partially burned hydrocarbons, Nitrogen Oxides (NO and NO₂), Carbon Monoxide (CO), Sulfur Oxides (SO₂ and SO₃), particulate matter in various forms. The contamination of air may lead to specific health hazards, smog's, acid rain, global warming, ozone depletion etc. One of the major challenges faced by the aviation industry in current scenario is low NO_x emissions which are due to the emission of Chloro -Flouro -Hydrocarbons. The Stagnation Point Reverse Flow (SPRF) combustion operates stably with ultra-low NO_x emissions in both premixed and

non-premixed modes of operation over a wide range of combustor operating conditions.

2. COMBUSTION CHAMBER

The essential component of the modern gas turbine engine where in the air and fuel are mixed in a proper proportion and ignited is known as a combustor. The combustion chamber has the difficult task of burning large quantities of fuel, supplied through the fuel spray nozzles with extensive volumes of air supplied by the compressor and releasing the heat in such a manner that the air is expanded and accelerated to give a smooth stream of uniformly heated gas at all conditions required by the turbine. This task must be accomplished with the minimum loss in pressure and with the maximum heat release for the limited space available. Combustion chambers must be designed to ensure stable combustion of the fuel injected and optimum fuel utilization within the limited space available and over a large range of air/fuel ratios. The combustion chamber design depends on the application and requirements in each case. Efficient combustion has become increasingly important because of the rapid rise in commercial aircraft traffic and the consequent increase in atmospheric pollution, which is seen by the general public as exhaust smoke.

2.1 Reverse Flow Combustor

Reverse Flow Combustor is a combustion chamber in which the flow leaves the combustion chamber in the opposite

direction to the conventional combustion chamber. It reduces the length of the engine and makes the transportation much easier. Reverse-flow annular combustion chambers are used mainly in engines whose last compressor stage is a centrifugal-flow type compressor. Reduced length will allow single shaft sitting on two bearings instead of three. This will reduce the vibration and maintenance problems. The reverse-flow process also allow warmer air to serve as the dilution air to control the NO_x formation instead of using other energy to preheat the dilution air or use cold air which could quench the flame and produce CO .

2.2 Stagnation Point Reverse Flow Combustor (SPRF)

The performance of dry, low NO_x gas turbines, which employ lean premixed (or partially premixed) combustors, is often limited by static and dynamic combustor stability, power density limitations and expensive premixing hardware. To overcome these issues, a novel design, referred to as the Stagnation Point Reverse Flow (SPRF) combustor has been recently developed. The combustor in which the velocity of the air-fuel mixture goes to zero is called stagnation point reverse flow combustor. Unlike other combustors wherein air enters and leaves from opposite ends in this it leaves from the same end opposite to close end of the combustor. This type of engine is best suited for low NO_x emission, which is presently one of the challenges faced by the aircraft industry.

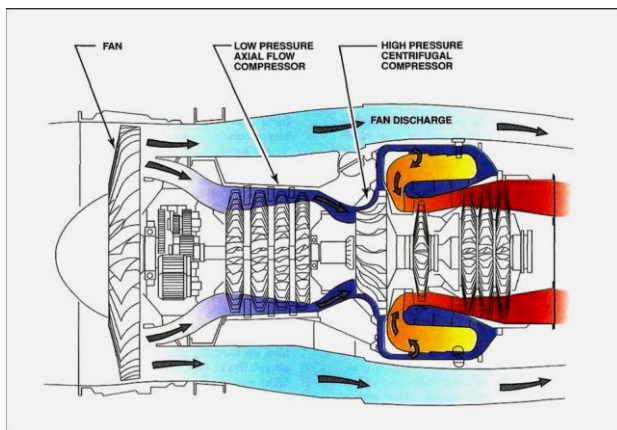


Fig.1 Stagnation Point Reverse Flow Combustor

The design of the SPRF combustor allows mixing of reactants with hot combustion products and radicals within the combustor, prior to combustion. Thus, no external premixing of fuel and air is required. This combustor is able to operate stably at very lean fuel-air mixtures and with low NO_x emissions even when the fuel and air are not premixed before entering the combustor, making it an exciting option for ground power and aircraft gas turbines. Fuel-air mixing measurements in case of non-premixed operation indicate that the fuel is shielded from hot products until it is fully mixed with air, providing nearly premixed performance without the safety issues associated with premixing.

3. TWO DIMENSIONAL MODEL OF THE SPRF COMBUSTOR WITH DIMENSIONS PARTS

Table 1. Dimensions of the SPRF Combustor

Parts of Model	Dimensions(in mm)
Air inlet Diameter	20
Fuel inlet Diameter	10
Length of Air inlet	15
Length of fuel inlet	10
Diameter of Combustion chamber	40.5
Length of combustion chamber	142.5
Outlet diameter	27

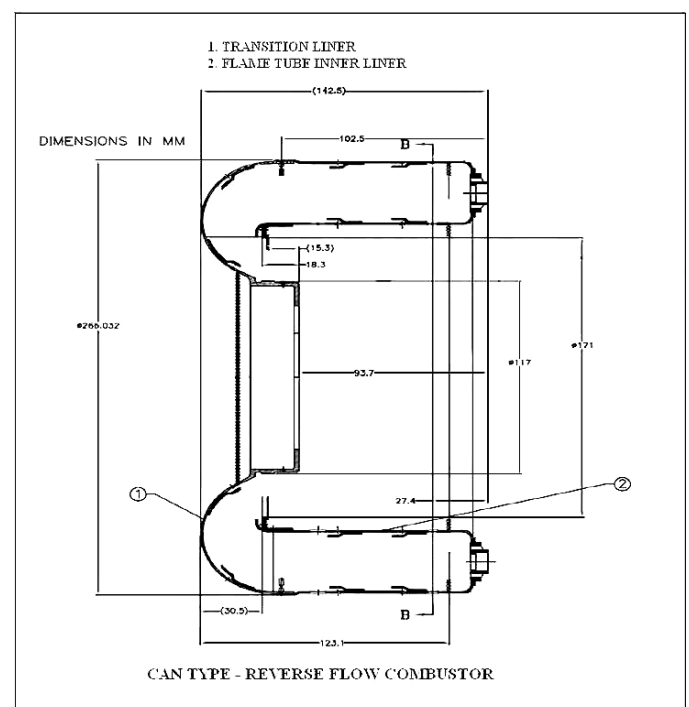


Fig.1.1 Stagnation Point Reverse Flow Combustor Model

To simplify our analysis, the reverse flow combustor is assumed with out any air secondary air intels. The primary air inlet is of diameter 20 mm. To have a better performance and stability, the premixed air fuel mixture is considered. The fuel inlet is of 10 mm diameter. The length of air inlet is 15 mm and the length of fuel inlet is 10 mm. The difference of 5 mm length is the region where fuel and and air mixing starts. The diameter of the combustion chamber is 40.5 mm and its length is 142.5 mm. The outlet diameter is of 27 mm.

4. BOUNDARY CONDITION AND ANALYSIS RESULTS

Flow analysis in the Stagnation Point Reverse flow Combustor was carried out using the analysis software ANSYS-FLUENT. Below given Table presents a list of the different boundary conditions, namely the type of velocity and thermal boundary conditions applied along each boundary region.

Table 2. Boundary Conditions (Parameters)

Boundary region	Type of boundary condition	Thermal condition type
Air inlet	Prescribed velocity	Fixed temperature
Fuel inlet	Prescribed velocity	Fixed temperature
Axis of symmetry	Axis Zero	heat flux
Quartz wall	Law of the wall	Combined convection and conduction
Exhaust	Zero velocity gradient	Zero temperature gradient
Air inlet wall	Law of the wall	Zero heat flux
Fuel inlet wall	Law of the wall	Zero heat flux

The regions named "Air inlet wall" and "Fuel inlet wall" refer to the inlet duct walls for both reactant streams and the zero flux condition neglects any heat transfer between the two streams. A run was made increasing the inlet fuel temperature, but only marginal differences in the results were found. Hence, it was concluded that it is a good approximation to neglect heat transfer between the two streams. The Stagnation Point Reverse flow Combustor is analyzed for different boundary conditions.

Boundary conditions are applied initially by using water as a fuel so that the flow pattern is viewed and further analyzed using Jet-A as fuel, and flow parameters are plotted accordingly. Stagnation Point Reverse flow Combustor thermal parameters are analyzed for Temperatures 1300 K and 1500 K in 2-D and for 1300 K in 3-D.

The Boundary Conditions of Fuel for 2-D model of the combustor are tabulated below

Table 3. Inlet Boundary Conditions (Values)

Inlet Conditions	Value
Inlet Pressure (JET A)	18 bar
Inlet Temperature (JET A)	300 K
Inlet Air Pressure	3.5 bar
Inlet Air Temperature	433 K

The Outlet conditions for the same combustor are tabulated below:

Table 4. Outlet Boundary Conditions (Values)

Outlet Condition	Value
Outlet Pressure	3 bar
Outlet Temperature	1300 K and 1500 K

By taking the results for 2-Dimensional Stagnation Point Reverse Flow Combustor as a reference, analysis for 3-Dimensional model was performed, only for the best result obtained (1300 K). Boundary conditions assigned for 3-Dimensional Stagnation Point Reverse Flow Combustor are Analogous to that of the Boundary Conditions assigned to the 2-Dimensional model of the combustor.

Table 5. Three Dimensional Boundary Conditions (Values) for uncontrolled Flow

Velocity	Temperature
90 m/s	1300 K
120 m/s	1300 K
160 m/s	1300 K

After the results for 3-Dimensional model were recorded analysis for uncontrolled flow was taken into account for further detailed understanding. Uncontrolled flow is the flow in which only inlet conditions are mentioned and the flow is observed, that is it helps us understand how the flow actually flows inside the combustion chamber. This analysis was performed for the three velocities as mentioned in above table 5.

5. RESULTS AND DISCUSSION

Stagnation Point Reverse Flow (SPRF) combustion chamber will undergo changes in different parameters like temperature, pressure, velocity, under different boundary conditions mentioned. The results were calculated for 2D model, for different boundary condition and the best preferable condition obtained were used for simulating 3D model. Then an uncontrolled flow analysis was performed on 3D model to know how actually the flow will propagate inside the stagnation point reverse flow combustor.

5.1 Two Dimensional SPRF Combustor Analysis Results

5.1.1 Jet A is used as Fuel at TET of 1300 K

Pressure Variation

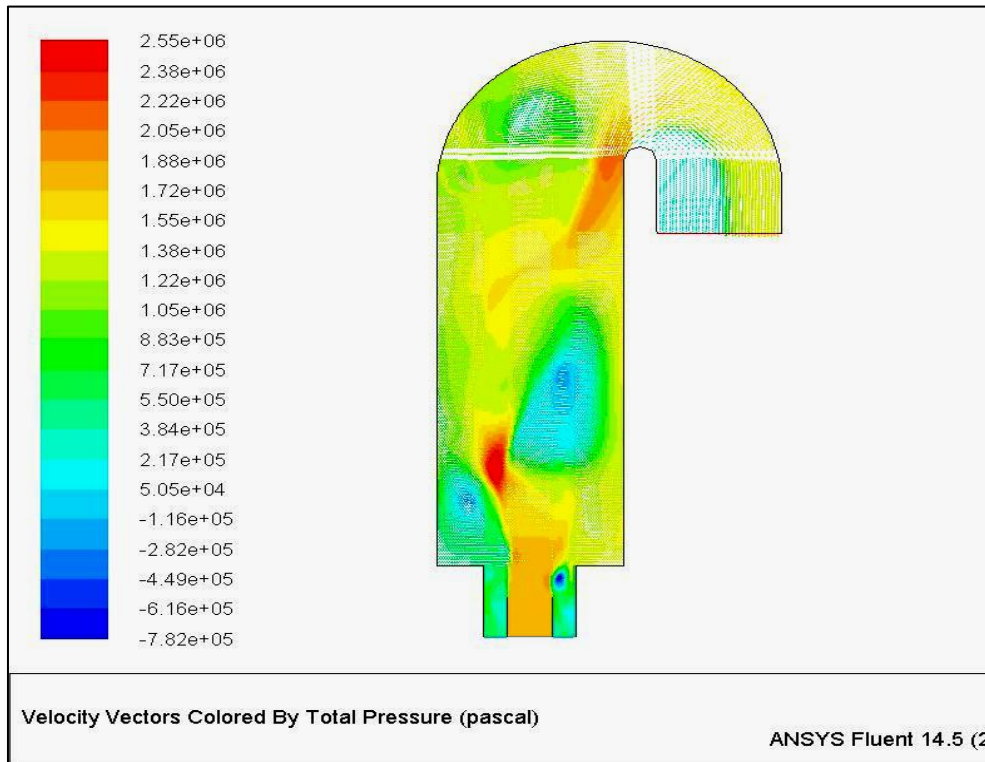


Fig. 2 Velocity Vector colored by Total Pressure for Jet-A as Fuel at TET of 1300 K

Temperature Variation

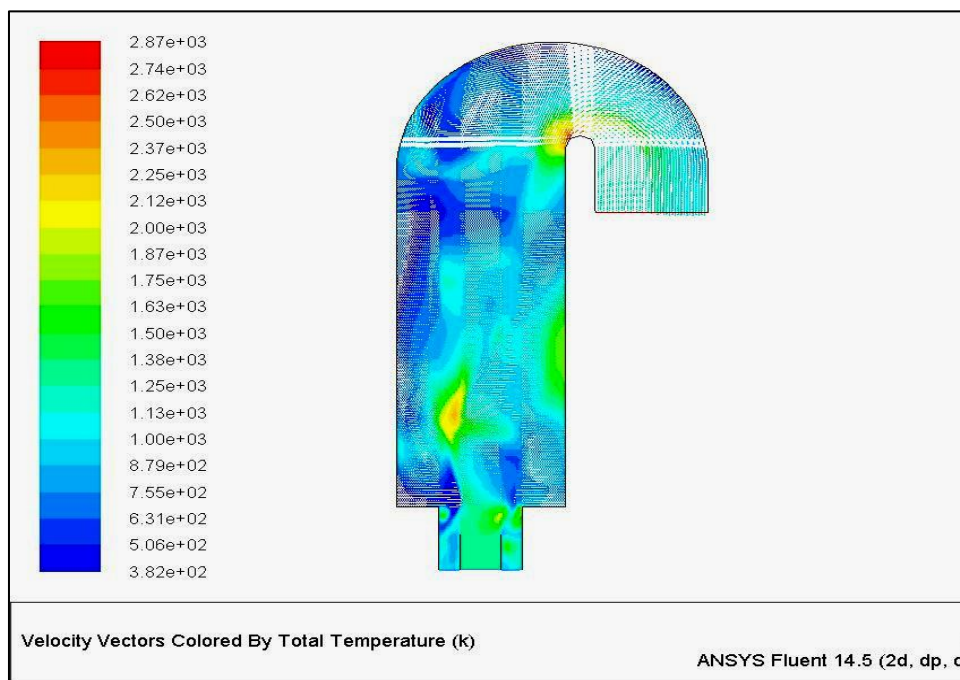


Fig. 3 Velocity Vector colored by Total Temperature for Jet-A as Fuel at TET of 1300 K

Flow analysis was carried out using Jet-A as fuel. The above fig 2. Shows the variation of pressure for 1300 K Turbine Entry Temperature (TET). It can be observed that there is very low pressure loss and the maximum pressure achieved is also low. So, it can be said that there is no much change in pressure observed in the SPRF for 1300 K TET. Now coming to the temperature, here also variation observed is less and hence stable operation takes place. Local peaks are less in this case when compared to 1500 K. Burning process taking place inside the combustor can be noted by the increase in temperature till certain portion. In this case the outlet temperature is given and hence it is called restricted flow. The variation of temperature for 1300 K is shown in Fig 3. The velocity variation for 1300 K is show in plot of velocity variation (Fig 4). It can be observed that the velocity near the inlet area is high; this is due to the ignition process taking place inside the combustor. As the flow propagates velocity decreases and will reach zero at the curled part of the combustor and therefore it is called stagnation point reverse flow combustor.

Velocity Variation

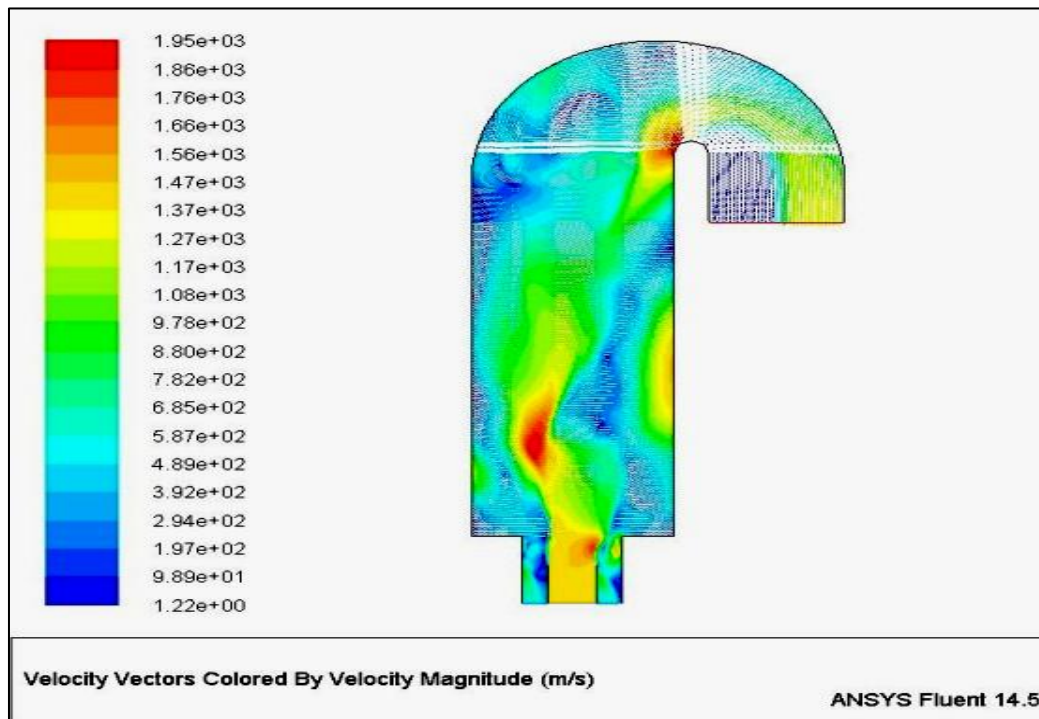


Fig. 4 Velocity Vector colored by Velocity Magnitude for Jet-A as Fuel at TET of 1300 K

5.1.2 Jet-A is used as fuel and Turbine Entry Temperature (TET) is 1500 K

After obtaining results for 1300 K TET, analysis was performed for 1500 K Turbine Entry Temperature (TET). The plots of variation in pressure, temperature, and velocity were obtained. Same as that of 1300 K low pressure loss was noted. Even the maximum pressure achieved is also same for both the cases. The local temperature in 1500 K is higher than compared to 1300 K, and moreover for the second case local peaks obtained are very high as compared to the first case, which is not a good sign for a good combustor design. So, from this it can be said that combustor will operate well for low TET's. The variation in velocity inside the combustion chamber for 1500 K TET follows the same distribution pattern. That is velocity is high at the initial stages and then reaches zero. For this case pre-ignition is observed. That is the air and fuel will burn before entering the combustion chamber. Condition used for this case is Lean pre-mixed combustor.

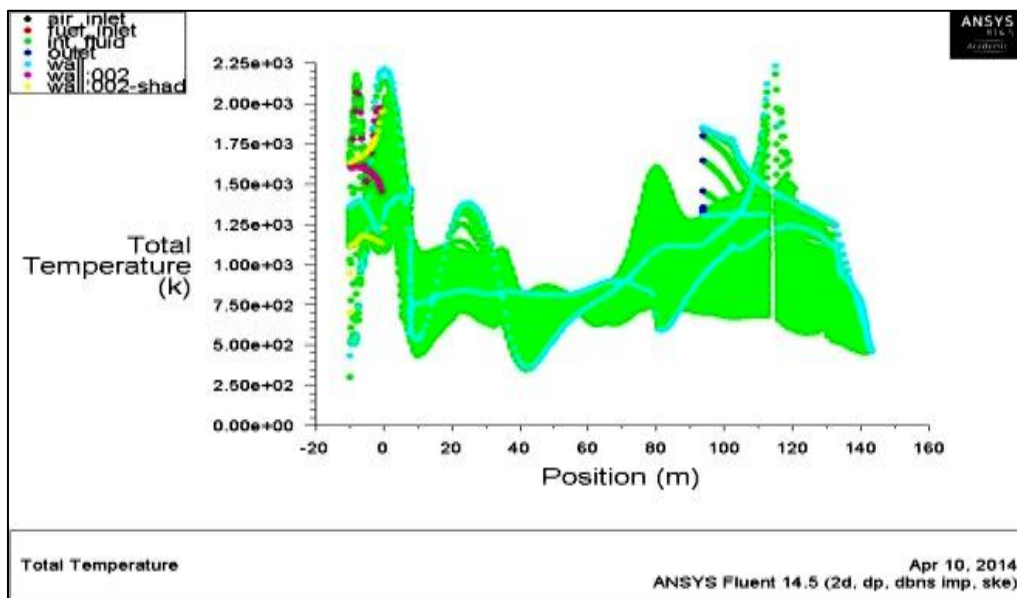


Fig. 5 Temperature variation along Y-axis for 1300 K TET

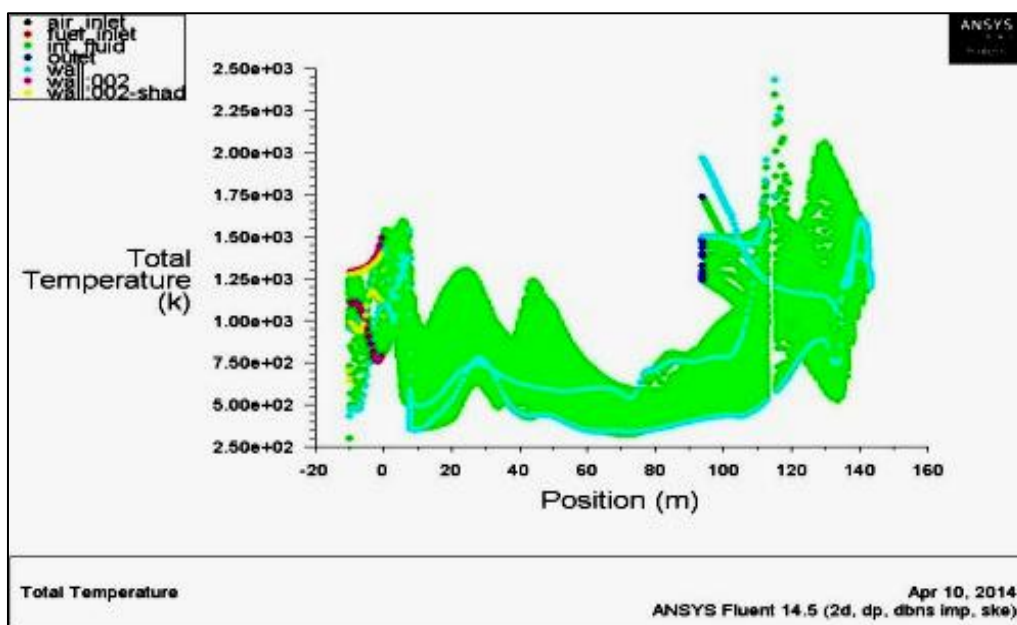


Fig. 6 Temperature Variation along Y-axis for 1500 K TET

Above fig 6. gives only the temperature variation throughout the combustion chamber along Y-axis. From this graph the value of temperature at each point can be obtained or peak temperature, mean temperature etc., These values can be used for evaluating the pattern factor and the profile factor of the combustor. The quality of combustor exit temperature distribution is generally expressed in terms of two non-dimensional parameters viz. Pattern Factor. Profile Factor can be defined a simple measure of the temperature profile at the exit of a combustor and is usually defined as the maximum fractional temperature deviation from the combustor average exit temperature. Pattern Factor is used to express the radial temperature distribution factor.

$$\text{Profile Factor} = \frac{\{T_{mr} - T_4\}}{\{T_4 - T_3\}}$$

$$\text{Pattern Factor} = \frac{\{T_{max} - T_4\}}{\{T_4 - T_3\}}$$

Where,

T_{max} is the maximum recorded temperature,

T_3 is the inlet air temperature,

T_4 is the mean exit temperature, and

T_{mr} is the maximum circumferential mean temperature

Table 6. Profile and Pattern Factor for 1300 K

Parameter	Experimental value	Analytical value	Percentage Deviation
Profile Factor	0.45	0.416	7.55
Pattern factor	2.22	2.011	9.4

The above table 6 shows the comparison of the results with the experimental with the help of two non-dimension numbers Profile Factor and Pattern Factor.

5.2 Three Dimensional SPRF Combustor Analysis

Result

Property variation in a Stagnation Point Reverse Flow (SPRF) combustor for 1300 K Turbine Entry Temperature (TET) for 3D model was analyzed. The method used for this analysis was Large Eddy Simulation (LES), using which the flame stability and propagation was computed and plotted. It

was observed that the pressure loss inside the combustor was found to be less than 5%. The temperature increases gradually and reaches its peak Temperatures and uniformly decreases as the gas propagates out to the Turbine. Temperature is restricted from 1300 K to 1500 K due to material limitations which may account for the damage of the material used for fabrication. In this analysis the combustor was tested only for 1300 K and was found functioning efficiently with stabilized flame propagation. The stability of the flame depends on the length and cone angle of the flame. Velocity increases as the ignition takes place in the combustor, the peak local velocity of around 169 m/s is achieved inside the combustion chamber which gradually decreases at the exit. Velocity will reach zero at the stagnation point and again increases as it reaches the entry of the turbine.

5.2.1 Variation of Different Parameters in Combustor by Varying Inlet Velocities

This analysis was carried out without assigning any outlet boundary conditions so that the exact velocity variation across the combustor can be known, and it was observed that there was increase in pressure loss and temperature was also found to be decreasing as the fluid reaches the Turbine Entry Temperature (TET).

The contours of the velocity magnitude and its variation across the combustor at the velocity of 90 m/s. Flame was found to be less stable and the velocity reaches to zero at the stagnation point and then uniformly increases to the average value as it reaches the outlet of the combustion chamber.

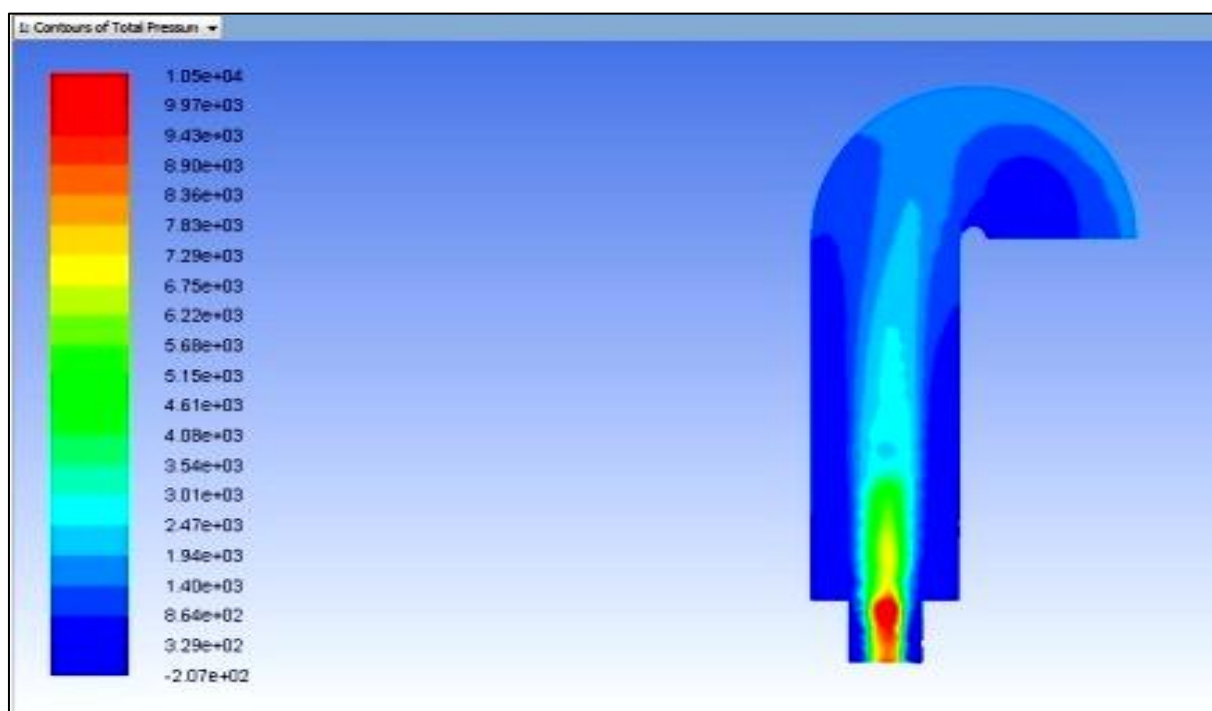


Fig. 7 Contours of Total Pressure

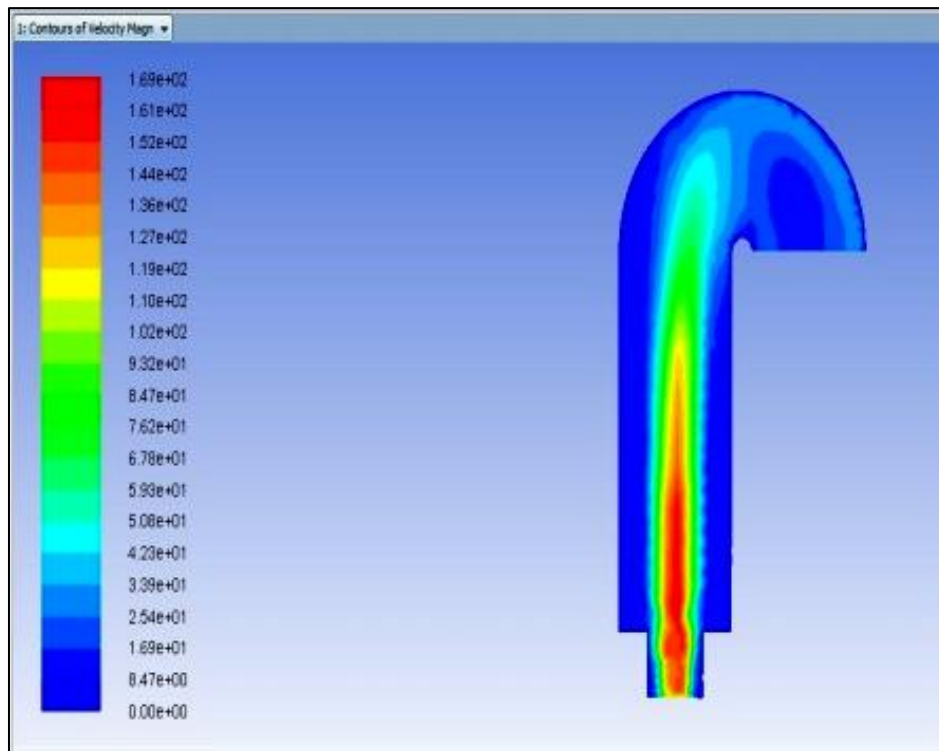


Fig. 8 Contours of Velocity Magnitude

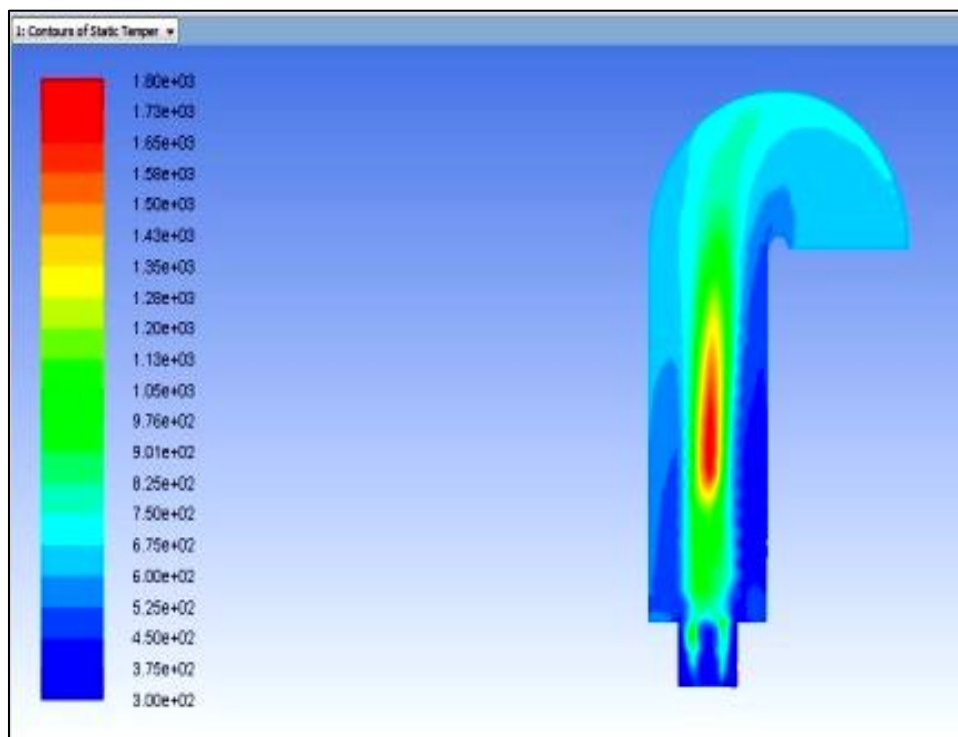


Fig. 9 Contours of Static Temperature

The above figures show the variation of the flow parameters when Large Eddy Simulation was carried out on the 3-D modeled combustor. This analysis was carried out only by assigning the inlet boundary conditions so that the flame stability is observed. It was inferred that at velocity 120 m/s the flame was stable with minimum decrement in pressure and temperature whereas for velocity 160 m/s flame was

found to be unstable and in this case pre-ignition is also seen at the inlet due to high velocities. The pressure loss was found to be more but the Temperature has increased and reaches its peak value of around 1570 K which is considered as very high temperature for the combustor operation in today's scenario.

6. CONCLUSION

Numerical simulations were performed using a commercial CFD code in an attempt to evaluate the performance, mixing and combustion characteristics of the SPRF combustor. In order to determine how the combustor is able to operate stably at very lean conditions and to produce low emissions even in premixed operation.

Jet-A as Fuel:

- For Jet-A as fuel and for 1300 K of Turbine Entry Temperature (TET) there is very low pressure loss and the maximum pressure achieved is also low. The Temperature variation is less and hence stable operation takes place. Efficient Burning takes place which results in increase in temperature till certain portion and again returns to normal temperatures and it is a restricted flow. It can be inferred that combustor will operate well for low TET's.
- Measurements of the velocity field, Temperature and Pressure in premixed modes show a low average velocity zone with high levels of turbulence in the upper half of the combustor. Based on the geometry of the combustor, this zone is expected to exist over a range of flow conditions (excepted for very low loadings where the flow is laminar and combustion occurs before reaching the stagnation zone). The flame is indeed anchored in this region of high turbulence intensity, and that this is where most of the heat release occurs. This results in an operation of the combustor even at high loadings and very lean equivalence ratios.
- Good agreement with analytical solution and experimental observations was obtained in terms of Pattern factor, Profile factor (Table 6) and Flame shape. From the results obtained, the reverse flow combustor can be employed in a small scale engines and also as Gas Turbine Starting Unit, as the increases in inlet air velocity causes pre- ignition, this sets the limit to inlet air velocity.
- In summary, the SPRF combustor creates a combination of a low velocity, high turbulence region and the stagnation point and internal product recirculation due to the reverse flow that creates a stable combustion process under a large range of combustor operating conditions.

FUTURE SCOPE OF WORK

- Detailed measurements of the mixing field have been performed in the SPRF combustor, but the fluid mechanic aspects, like turbulence generation, responsible for this mixing process have not been addressed here. Relative roles of the turbulence generated by various features like shear layer between the opposed streams, the stagnation zone and velocity fluctuations due to the unsteady heat release can be quantified by extending the velocity measurements to a wider range of configurations.

- Limiting assumptions should still be listed as base for further work. First, the assumption of adiabatic walls might be refined. In order to capture the possible complex stabilization at the swirled edges, more refined wall temperature modelling as well as a detailed chemical mechanism can be done.
- The equivalence ratio oscillation is one of the major sources of heat release fluctuations, and is one of the most important factors determining the characteristics of instabilities. Its effects on combustion dynamics need to be addressed in the future.

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