Chand et al. 2021. *Int. J. Vehicle Structures & Systems*, 13(1), 125-128
ISSN: 0975-3060 (Print), 0975-3540 (Online)
doi: 10.4273/ijvss.13.1.24

**International Journal of**
**Vehicle Structures & Systems**
Available online at www.maftree.org/eja

# Study of Adiabatic Flame Temperature of a Jet Combustor using a Non-Circular Inlet

**D. Singh Chand[a], S. Parveen[b] and P. Singh[c]**

*Dept. of Aerospace Engg., Chandigarh University, Gharuan, Punjab, India*
*[a]Corresponding Author, Email: sdsinghchand25@gmail.com*
*[b]Email: Sabiha.aero@cumail.in*
*[c]Email: prabhatsinghrbl@gmail.com*

## ABSTRACT:

*An experimental investigation on heat transfer at various zones of the combustion chamber has been carried out using a non-circular inlet at the flame tube. With an aim to improve the turbulent level in flow, the non-circular section used here is an elliptical one. In addition to this, two rectangular tabs are placed at major axis of the ellipse to achieve an efficient mixing of fuel and air. Fuel used for combustion is kerosene while LPG gas is used for pre ignition. Fuel is fed to the chamber by gravity system and it has been atomized by two fish tank pumps. Ignition of the fuel is done by spark plug with a separate setup. The setup comprises of growler and CDI coil which are powered electrically. During the experiment, combustion has been initiated by allowing the air from blower to the chamber. The fuel is sprayed into the flame tube through fuel injector placed at a specified distance. After the proper mixing of fuel and air, the mixture is ignited by spark plug setup. Fuel tank has been calibrated for mass flow rate. The experiment has been carried out for different intervals of time and the heat transferred from the flame tube wall and chamber wall are measured using an infrared gun (ray gun) by pointing laser on the wall. The temperatures at different zones are measured. It is seen that the overall heat transfer at secondary zone is minimum when compared with the other zones for the same period of time. This indicates that if the fuel injector is placed before the secondary zone, then a maximum flame temperature can be obtained. This leads to an improvement in efficiency of the combustion chamber.*

## KEYWORDS:

*Non-circular section; Rectangular tab; Turbulence level; Fuel injector location; Combustion*

## CITATION:

D.S. Chand, S. Parveen and P. Singh. 2021. Study of Adiabatic Flame Temperature of a Jet Combustor using a Non-Circular Inlet, *Int. J. Vehicle Structures & Systems*, 13(1), 125-128. doi:10.4273/ijvss.13.1.24.

## 1. Introduction

For a combustion process that takes place adiabatically with no shaft work, the temperature of the products is referred to as the adiabatic flame temperature (FT). This is the maximum temperature that can be achieved for given reactants. Heat transfer, incomplete combustion and dissociation result in lower temperature. The maximum adiabatic FT for a given fuel and oxidizer combination occurs with a stoichiometric mixture (correct proportions such that all fuel and all oxidizer are fully consumed). The amount of excess air can be tailored as part of the design to control the adiabatic FT [1]. The stability of a flame is characterized by the ability to burn steadily at a fixed position without blowing out. Aircraft engines have strict stability requirements and therefore have only incorporated variable geometry with conventional combustor design to avoid any unacceptable flame blowout over a wide range of combustion air/fuel ratios [2].

Stoichiometric reaction is a unique reaction in which all the reactants are consumed. This means that the amount of oxidants present in the reaction is just enough to completely burn the fuel. Fig. 1 shows the adiabatic FT stoichiometric reaction. Assuming that air consists of 21% oxygen and 79% nitrogen by volume, the equation for a stoichiometric reaction of an air-methane mixture on a mole basis is given as follows [3],

$$CH_4 + 2(O_2 + 3.76N_2) \Rightarrow CO_2 + 2H_2O + 7.52N_2 \quad (1)$$

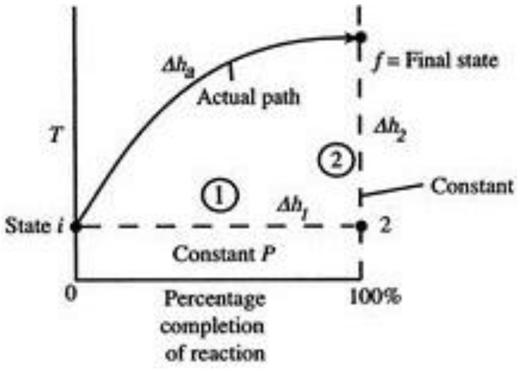

**Fig. 1: Schematic of adiabatic FT stoichiometric reaction**

The fuel/oxidant ratio is one of the most important parameters for combustion analysis and is normally reported in terms of a non-dimensional variable called equivalence ratio Φ. This is the actual fuel/oxidant ratio normalized by stoichiometric fuel/oxidant ratio as,

$$\emptyset = \frac{(Fuel/Oxidant)actual}{(Fuel/Oxidant)stoichiometric} \quad (2)$$

The value of $\emptyset = 1.0$ is defined as stoichiometric condition. Conditions where there is an excess of oxidant present in the mixture are “lean”, $\Phi < 1.0$. Similarly, mixtures with an excess of fuel are “rich”, $\Phi > 1.0$. Eqn. (2) is valid when the ratio is calculated on both mass and mole basis, provided that the actual and stoichiometric ratios are calculated consistently [4].

## 2. Flame temperature

FT is determined by the energy balance between reactants and the products at equilibrium. If the reaction zone is spatially very thin in comparison to the rest of the domain of interest, then it is a common practice to denote the maximum temperature in reaction zone to be FT. If the combustion process takes place adiabatically, and with no work or changes in kinetic or potential energy, then FT is referred to as adiabatic FT. This is the maximum temperature that can be achieved for the given reactants because any heat transfer from the reaction zone and any incomplete combustion would tend to lower the temperature of the products. Experimental measurements of adiabatic FT are very difficult and in most cases a calculated value is more reliable than the experimental measurements. For most hydrocarbons, the maximum adiabatic FT occurs at slightly above stoichiometric conditions ($\Phi = 1.05$). However, there are exceptions to norm such as $C_2H_2$. FT refers to stoichiometric mixtures, except those marked by Oates et al [5]. Flames can be classified in many ways. Based upon how the fuel and oxidizers reach in the reaction front, there are non-premixed flames, partially and fully premixed flames.

The nature of reaction zone is used to categorize the flames to stirred reactors or plug flow reactors. The flow characteristics of incoming reactants divide the flame types into turbulent and laminar flames. There are a number of such flame classifications and a discussion of all of them is beyond the scope of this paper. Only the relevant categories are defined and discussed. In non-premixed flames, the fuel and oxidizer are present on either side of the reaction zone. They are brought to the reaction zone in an un-mixed state due to diffusion of reactants in and out of the products reaction zone. In such flames, the reaction zone is established at a location where the total enthalpy of the reactants present must balance the total enthalpy of the products generated plus any energy losses. Thus for non-premixed flames, the reaction ideally takes place at stoichiometric conditions thereby producing maximum possible FT for a given combination of reactant species [6]. In fully premixed flames, the fuel and the oxidizer are thoroughly mixed prior to reaching the reaction zone, also known as the flame front. For these flames, the position of the reaction zone is not defined by diffusion of reactants but by balancing the local convective velocity of reactants with the rate of consumption of the reactants which is popularly known as flame speed.

Based on stabilizing method, fully premixed flames can be burned at equivalence ratios other than 1. Thus lower FTs can be easily achieved. In partially premixed flames, the fuel is injected into the oxidizer flow just upstream of the flame. Under such conditions, there is not enough time for the fuel and oxidizer to mix thoroughly so the concentration gradients across the flow are generated in the reactant stream which then enters the flame front. These flames are neither purely non-premixed, nor are fully premixed, hence they are termed as partially premixed. Such flames are characterized by their degree of un-mixed, which is a measure of how much the radial concentration profiles of the flow deviate from a fully premixed case [6]. The presence of turbulence has an extremely important influence on the combustion. The rate of flame propagation is greatly enhanced by the turbulence.

The important parameters influencing turbulent flame propagation are the fluctuating component of gas velocity and turbulence length scale. Turbulence also causes increased burning rates in diffusion flames. The increased fuel-air mixing is due to forced mixing of small fuel-lean or fuel-rich elements of gas by turbulent forces. These small elements of gas are called eddies. The analytical adjustment called eddy diffusivity, accounts for the enhanced mixing at the reaction front. This approach is taken as a convenience and is based on empirical correlations rather than fundamental principles [4]. Fig. 2 shows the turbine combustion system. During fuel-air mix in the reaction zone, the individual turbulent eddies can have widely differing values of fuel-air ratio and temperature. Because the reaction rates are very sensitive to these variables, the turbulence characteristics can strongly influence the rates and end products of the combustion process [7].

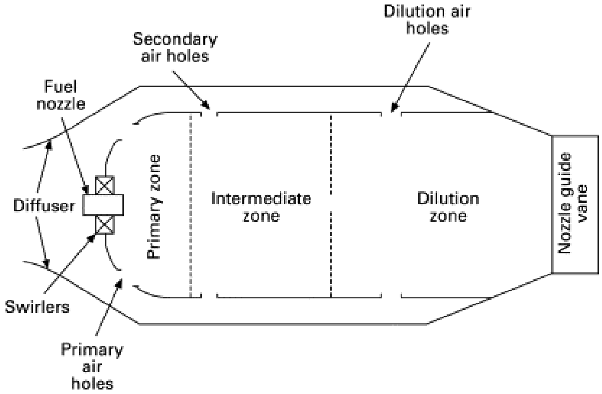

**Fig. 2: Simplified representation of a turbine combustion system**

## 3. Design of combustor inlet

The innovation adopted is the non-circular inlet of flame tube tabs. The design of flame tube is made elliptical with which two tabs are attached on major axis. The elliptical geometry produces turbulence by which fuel and air must move slowly enough for the flame to propagate upstream and ignites the fresh mixture. This helps in stabilizing the flame by providing a continual source of ignition to the incoming fuel. It also serves as a zone of intense mixing within the combustor [3]. Fig. 3 shows the combustor inlet. The outer casing inlet as shown in Fig. 4 is a circular section and it is designed in CATIA according to the calculations. There are many constraints with which the combustor design is achieved. The dimension is decided on the size of compressor and turbine. The combustor has to accept the compressor exit conditions and it should cater to the required turbine inlet conditions for maximized turbine performance. Combustor inlet area reference is assumed to be 0.000923 $m^2$.

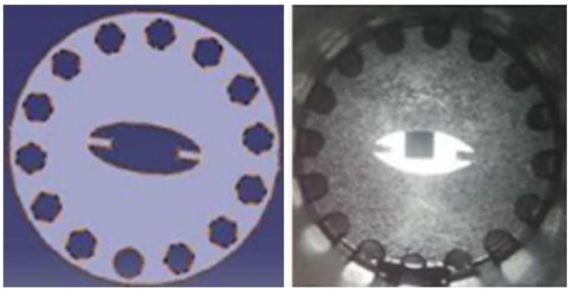

**Fig. 3: Combustor inlet**

**Fig. 4: Outer casing**

Effective control of air distribution is vital to attainment of the complete and stable combustion, correct burner exit temperature profile and acceptable liner temperature for long life. Since the stoichiometric ratio is approximately 50:1, the essential feature is that the air should be introduced in stages. About 30% of air in primary zone is provided for rapid combustion. Around 30% of total air is then introduced in secondary zone to complete the combustion. Finally, in dilution zone the remaining air is mixed with the products of combustion and it is cooled down to the temperature required at the inlet of the turbine [5]. Fig. 5 clearly shows the geometric specification of an inlet. Fig. 6 shows the flame tube used in the experiment. Inlet air allowance is 30% of air mass flow rate. The inlet area based on the calculation is found to be 0.00082$m^2$. One of the (major) axis of ellipse is assumed and other specifications of ellipse area is acquired. The fuel/air ratio on a mass flow basis is used in the actual constituents of air. We would get about 0.0667 a value of 0.5% difference [7].

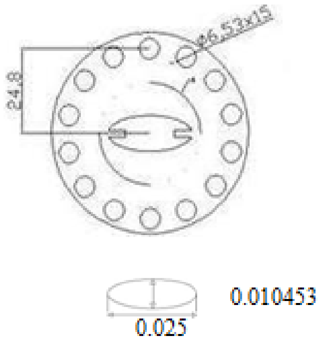

**Fig. 5: Inlet geometry specifications**

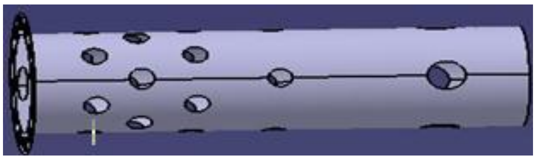

**Fig. 6: Flame tube**

## 4. Results and discussions

The velocity inside the combustor was contoured to verify whether a strong turbulent flow exists. The computational results as shown in Fig. 7 show that it is enough to force the flow to stick to the outer walls. The fuel injector location was determined using Fig. 8, which has been installed 10cm following the combustor inlet where the velocity began to drop. The flame was generated using LPG and the temperature differences were calculated for 2 min and 5 min time intervals and are presented in Table 1. The heat transfer inside the combustion chamber (i.e.) between the casing and the flame tube has been calculated. Convection is usually the dominant form of heat transfer in liquids and gases [1].

**Table 1: Results at 2 min and 5 min intervals**

| Zone | Flame tube (°C) | | Outer surface (°C) | |
|---|---|---|---|---|
| Interval | 2 min | 5 min | 2 min | 5 min |
| Primary zone | 284.2 | 382.1 | 49.4 | 60.5 |
| Secondary zone | 347.4 | 394.4 | 50.9 | 63.8 |
| Tertiary zone | 241.3 | 363.6 | 53.2 | 66.2 |

The rate of convective heat transfer is given by,

$$Q = h\ A\ dT \tag{3}$$

Where, h = convective heat transfer co-efficient (for mild steel, it is 7.9W/$m^2$K), A = cross sectional area, dT = temperature difference. The temperature has been determined at primary, secondary and tertiary regions. The distance from the flame tube inlet for the primary, secondary and tertiary zone is 0.1m, 0.09m and 0.11m respectively. To area is calculated using,

$$A = 2\pi Rh + 2\pi rh + 2(\pi R^2 - \pi r^2) \tag{3}$$

Where, r = inner radius of the hollow cylinder, R = outer radius of the hollow cylinder, h = height of the hollow cylinder. The calculated area of primary, secondary and tertiary zone is 0.03655 $m^2$, 0.032965 $m^2$ and 0.040133 $m^2$ respectively. Table 2 and Table 3 depict the temperature difference and convective heat transfer co-efficient at time interval of 2 min and 5 min during experimental work. It is clear that most of the temperature rise is occurring in the secondary zone which in turn shows the effectiveness of non-circular inlet of combustion chamber.

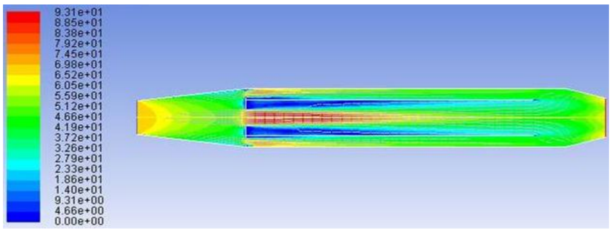

**Fig. 7: Velocity contour**

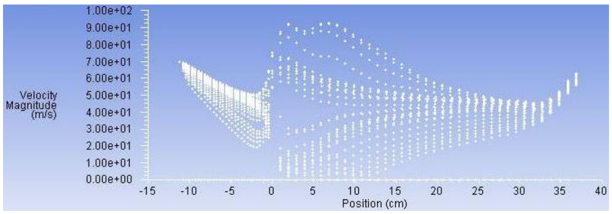

**Fig. 8: Velocity vs. Position**

**Fig. 9: Experimental combustor in operation**

**Table 2: FT at 2 min and 5 min intervals**

| Zone | Temperature (K) | |
|---|---|---|
| Interval | 2 min | 5 min |
| Primary zone | 507.8 | 594.6 |
| Secondary zone | 569.5 | 603.6 |
| Tertiary zone | 461.1 | 570.4 |

**Table 3: Convective heat transfer at 2 min and 5 min intervals**

| Zone | Heat transfer (W) | |
|---|---|---|
| Interval | 2 min | 5 min |
| Primary zone | 146.6247 | 171.687 |
| Secondary zone | 148.311 | 157.192 |
| Tertiary zone | 146.192 | 180.85 |

## 5. Conclusion

From the experimental results presented in this paper, it is concluded that overall heat transfer at secondary zone is minimum when compared with the other zones for the same period of time. This indicates that if the fuel injector is placed before the secondary zone, then a maximum FT can be obtained which leads to an improvement in efficiency of the combustion chamber.

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