DESIGN OF A GAS TURBINE COMBUSTOR UNDER AERODYNAMIC CONSIDERATIONS

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ABSTRACT

A theoretical design of a tubular type gas turbine combustor design was carried out in this paper in aerodynamic design point of view. Aerodynamic design processes plays a vital role in the design and performance of gas turbine combustion systems. With good aerodynamic design and good matching fuel-injection system, a trouble free combustor design may be arrived. By considering the inlet parameters such as pressure, temperature, density and air mass flow rate of a combustor, a design process was carried out. Design process involves the geometric dimensional calculations of various geometries in a combustor like casing cross-sectional area and its length, linear cross-sectional area and its length, swirler design calculations, etc. Thermodynamically, ideal constant pressure process takes place inside a combustor.

Nomenclature:

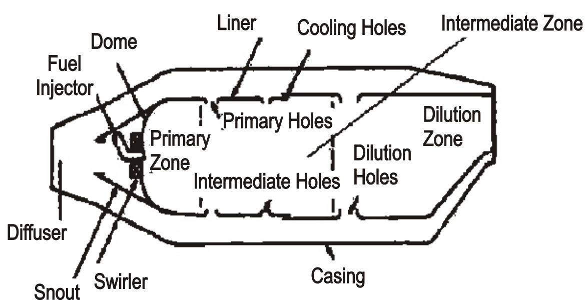
P	total pressure, Pa
q	dynamic pressure, Pa
R	gas constant, 286.9 J/Kg K
T	total temperature, K
m	air mass flow rate
A	area, m^2
ρ	density, Kg/m^3
C_D	discharge coefficient
U	velocity, m/sec
θ	swirler vane angle or initial jet angle
S_N	swirler number
Y	jet penetration, m
α	hole bleed ratio
Δ	difference
D_{hub}	swirler hub diameter, m
D_{sw}	swirler diameter, m
D_L	liner diameter, m
D_{ref}	casing diameter, m
d	diameter, m
L	length, m
n	number of holes
n_v	number of vanes
t_v	thickness of vanes
J	momentum flux ratio
M	mach number
γ	specific heat ratios

Subscripts:

3	combustor inlet plane
4	combustor outlet plane
h	hole value
j	jet value
g	gas value
ref	reference value
sw	swirler value
max	maximum value
DZ	dilution zone

I. INTRODUCTION

The primary purpose is to highlight the design requirements of gas turbine combustors (tubular type) and to describe its role in performance. The principal geometric and aerodynamic features in most types of gas turbine combustors are briefly reviewed. Combustor is a direct-fired air heater in which fuel is burned almost stoichiometrically with one-third or less of the compressor discharge air. There are three features in all gas turbine combustors (i) primary zone, (ii) intermediate zone and (iii) dilution zone. The main design requirements of gas turbine combustor are complete combustion (proper mixing of oxidizer and fuel), self-sustaining flame, uniform exit temperature profile, small physical size and weight, wide range of applications and minimizing pollutant emissions. Fig 1 below shows the typical cross section of a combustor.



Typical Combustor Cross Section (Lefebvre, A.H., 1983)

Fig. 1. Conventional gas turbine combustor

II. DESIGN CALCULATIONS

Combustor Casing Area Calculations

From Ref [1], for a tubular combustor, the pressure loss factor $\Delta P_{3-4}/q_{ref}$ and overall pressure loss, $\Delta P_{3-4}/P_3 = 0.07$ which is quoted as percentage was considered. By assuming the suitable inlet conditions of a combustor, a combustor casing area can be evaluated from the formula (1).

$$\frac{\Delta P_{3-4}}{P_3} = \frac{\Delta P_{3-4}}{q_{ref}} \left(\frac{R}{2}\right) \left\{ \frac{m_3 T_3^{0.5}}{A_{ref} P_3^2} \right\} \qquad ...[1]$$

A. *Combustor Liner Area Calculations*

It is advantageous to have liner cross-sectional area as large as possible which results in lower velocities and longer resident times, so that smooth ignition, good flame stability and combustion efficiency were achieved. For any given casing area, if the liner area is increased, the annulus area gets decreased which results in reducing the static pressure drop across the liner holes and raise in the annulus velocity. A high static pressure drop ensures an air jet enters the liner holes to have turbulence intensity for proper mixing with the combustion products.

According to Ref [2], the ratio of liner area to reference area ranges from 0.6 to 0.72 for conventional combustors. By using this relation, liner area can be calculated. From these areas, their respective diameters can be calculated i.e., diameters of the casing and the liner. By keeping all inlet parameters constant, except variation in mass flow of air leads to increase in casing and liner areas as shown in graph below.

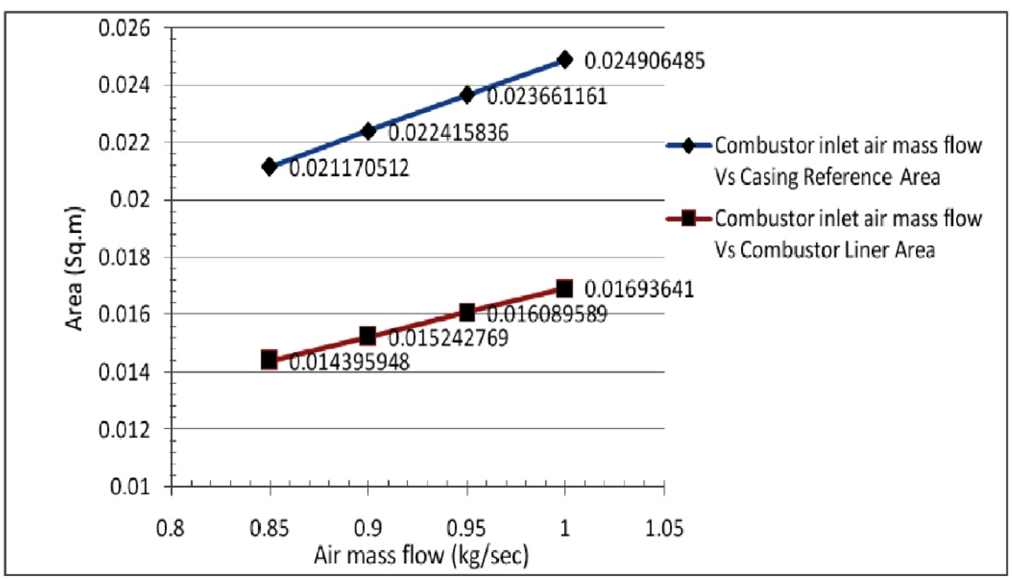


Fig. 2. Variation of combustor casing area and liner area with air mass flow rate.

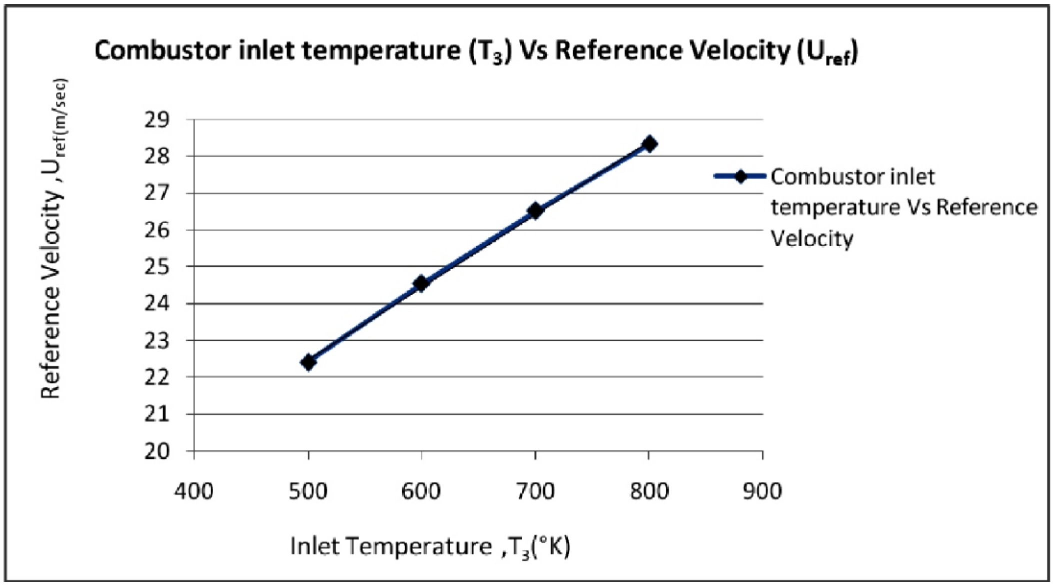


Fig. 3. Variation of combustor inlet temperature with reference velocity.

B. Flow parameter Calculations

Flow parameters, which decides the Aerodynamic performance of different combustor designs. According to Ref [3], inside the combustor, the pressure and temperature everywhere are assumed to stagnation values for which $M < 3$. From the known values of P_3 and T_3, the density ρ_3 can be calculated from the ideal gas equation (2)

$$P_3 = \rho_3 R T_3 \quad ...[2]$$

According to Ref [1], the following reference quantities $U_{ref}, M_{ref}, q_{ref}$ can be evaluated.

$$U_{ref} = \frac{m_3}{\rho_3 A_{ref}} \quad ...[3]$$

The reference velocity, which is the mean velocity across the plane of cross sectional area of the casing in the absence of a liner, remains same for variations in parameters like P_3, ρ_3 and m_3 except T_3.

$$q_{ref} = \frac{1}{2} \rho_3 U_{ref}^2 \quad ...[4]$$

$$M_{ref} = \frac{U_{ref}}{(\gamma RT)^{0.5}} \quad ...[5]$$

C. Casing and Liner Length Calculations

From Ref [4],

L/D ratio values for Liner	–	3 to 6
L/D ratio values for Casing	–	2 to 4

By choosing suitable L/D ratio values, liner and casing lengths were calculated by substituting the corresponding casing and liner diameters. Length of Liner = Length of Primary Zone + Length of Dilution Zone.

D. Dilution Zone Design

The Dilution Zone Design variables are the number and size of the air admission holes and the zone length. If there is adequate penetration of the dilution air jets, a satisfactory temperature profile at the combustor outlet can be ensured. Thus, optimum number and size of the dilution holes must be determined.

From Ref [1], According to Cranfield Design Method, for tubular combustors, L_{DZ} the length of the dilution zone should be around 1.5 times the liner diameter.

$$L_{DZ} = 1.5\, D_L \quad ...\ [6]$$

$$\Delta P_L = 3 \text{ to } 4\% \text{ of } P_3 \quad ...\ [7]$$

$$U_j = (2\, \Delta P_L / \rho_3)^{0.5} \quad ...\ [8]$$

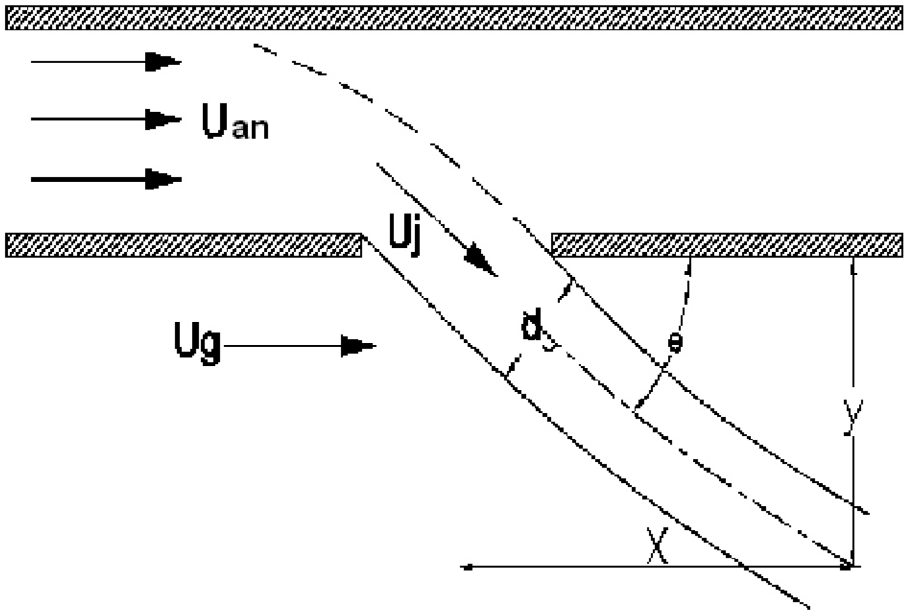


Fig. 4. shows jet penetration through liner hole

From the above relations, the pressure drop across the liner and velocity of the jet can be determined.

From Ref [5], the maximum penetration of round air jets into a tubular liner is given by

$$Y_{max} = 1.25\, d_j\, J^{0.5}\, m_g/(m_g + m_j) \quad \text{... [9]}$$

For tubular combustors, Y_{max} = 0.33 D_L. Assuming suitable C_D and d_h values, d_j can be determined from the below relation

$$d_h = \frac{d_j}{C_D^{0.5}} \quad \text{... [10]}$$

$$C_D = \frac{1.25\,(K-1)}{[4\,K^2 - K\,(2-\alpha)^2]^{0.5}} \quad \text{... [11]}$$

for plain circular, oval and rectangular holes

$$C_D = \frac{1.65\,(K-1)}{[4\,K^2 - K\,(2-\alpha)^2]^{0.5}} \quad \text{... [12]}$$

for plunged holes Then, the total mass flow rate of air through these holes is given by

$$m_j = \frac{\pi}{4} n d_j^2\, \rho_3\, U_j \quad \text{... [13]}$$

From Ref [6, 7 and 8], the following expression can be used for calculating the optimum number of dilution holes for best mixing:

$$n_{opt} = \pi \frac{(2J)^{0.5}}{C} \quad \text{... [14]}$$

Where C is an experimentally-derived constant.

E. Swirler Design

The airflow pattern in primary-zone is of prime importance for flame stability. Toroidal flow reversal, which entrains and recirculates a portion of the hot combustion products to mix with the incoming air and fuel. A swirler can be fitted in the dome around the fuel injector, causes swirling flows (flow recirculation) to produce strong shear regions. A swirl flow controls the stability and intensity of combustion and the size and shape of the flame region. From Ref [9], for axial swirler, air flow rate m_{sw} is given by,

$$m_{sw} = \frac{\{2\rho_3\, \Delta P_{sw}\}^{0.5}}{\left\{K_{sw}\left[\left(\frac{\sec\theta}{A_{sw}}\right)^2 - \frac{1}{A_L^2}\right]\right\}^{0.5}} \quad \text{... [15]}$$

Frontal area of the swirler is given by

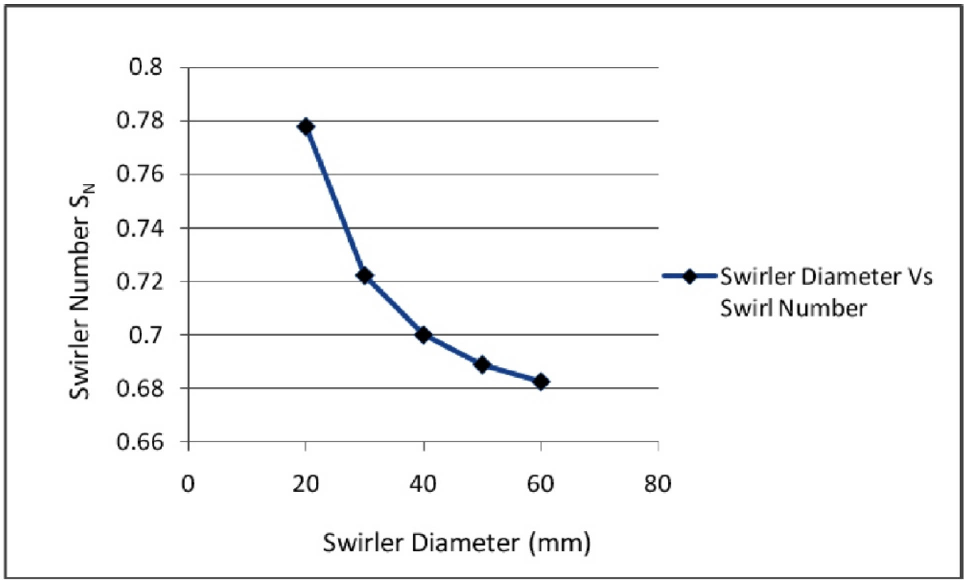


Fig. 5. shows variation of swirl number with swirler diameter.

$$A_{sw} = \frac{\pi}{4}\left(D_{sw}^2 - D_{hub}^2\right) - 0.5\, n_v\, t_v \left(D_{sw} - D_{hub}\right) \quad [16]$$

From Ref [10], Swirl Number S_N can be calculated which decides whether flow recirculation occurs or not and is given by,

$$S_N = \frac{2}{3} \frac{\left\{1 - \left(\frac{D_{hub}}{D_{sw}}\right)^3\right\}}{\left\{1 - \left(\frac{D_{hub}}{D_{sw}}\right)^2\right\}} \tan\theta \quad \ldots [17]$$

If $S_N < 0.4$, the flow is weak and no recirculation

$S_N > 0.6$, the flow is strong and recirculation occurs

From the above graph, for a constant hub diameter, Dhub and increase in swirler diameter, Dsw causes decrease in swirl number, S_N.

From Ref [11], the size of the recirculation zone is increased by

1. An increase in vane angle
2. An increase in the number of vanes
3. A decrease in vane aspect ratio
4. Changing from flat to curved vanes

III. MODELING OF TUBULAR TYPE COMBUSTOR

By following the above mentioned design calculations, a full scale model was developed in 3D modeling software package.

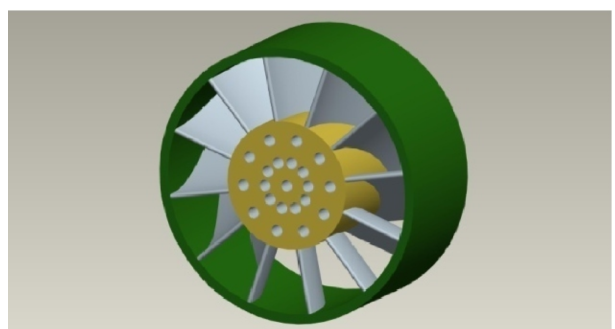


Fig. 6. Swirler Design with fuel inlet

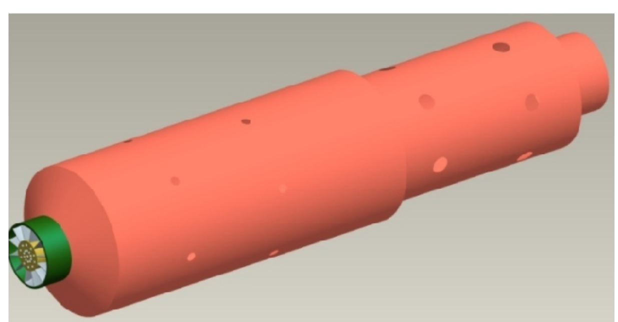


Fig. 7. Combustor design without casing

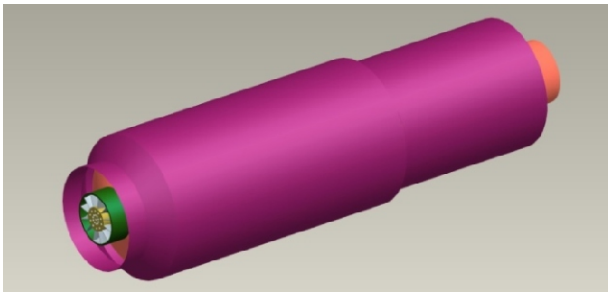


Fig. 8. Combustor design with casing

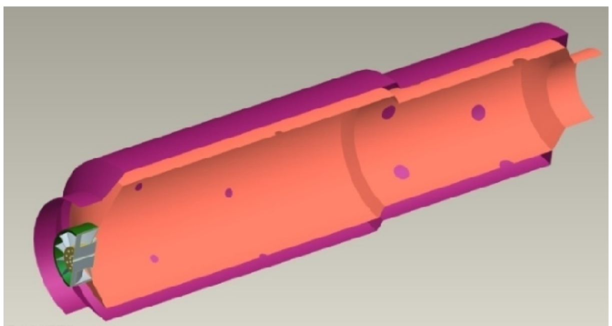


Fig. 9. Sectional view of a combustor

IV. CONCLUSION

This paper clearly explains how various design parameters are arrived from the references to achieve good aerodynamic design of gas turbine combustor (tubular type). Further, this design can be evaluated by using any CFD tools in combustion modeling.

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