Analytical Study of Gas Turbine Combustor

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Abstract: The primary purpose of this study is to discuss the main requirements of gas turbine combustors in industrial engines. The principal geometric and aerodynamic features that are common to most types of gas turbine combustors are briefly reviewed. Reference is made to most of the key issues involved in combustor design and development. In this project, analytical formulae described by various researchers are studied and also their parametric study on the design of combustor is discussed in this report. The various combustor components such as diffuser, swirler, combustor liner, combustor casing and different zones are systematically designed and c-programming is provided for quick access of the design parameters. Manual calculations are somewhat tedious, so in order to save time and money this attempt is made. A technical discussion on combustor design procedure by using C programming is provided.

Index terms: Combustor, Reference Area, Diffuser, Swirler, Liner, Liner holes.

I. INTRODUCTION

A combustor is a part of a gas turbine engine where combustion takes place. It is also known as a burner, combustion chamber or flame holder. In a gas turbine engine, the combustor is fed with high pressure air by the compression system i.e. compressor. The combustor then heats this air at constant pressure. After heating, air passes from the combustor to the turbine.

The engines used a single chamber known as a can type combustor. Today three main configurations exist: can, annular and cannular.

II. COMBUSTOR TERMINOLOGY

The case is the outer shell of the combustor. The casing serves as a pressure vessel that must withstand the difference between the high pressures inside the combustor and the lower pressure outside. Diffuser is provided to slow the high speed, highly compressed air from the compressor to a velocity optimal for the combustor. The liner contains the combustion process and introduces the various air flow into the combustion zone The swirler are the part of the combustor that the primary air flows through as it enters the combustion zone.

Their role is to generate turbulence in the flow to rapidly mix the air with fuel. The function of primary zone is to sustain flame & to rovide optimum temperature. Gas diluted with air through intermediate holes. This air induces further turbulence and supplies more oxygen to complete the burning of soot formed during primary combustion. Gas is further diluted by air admission through the dilution holes to reduce temperature to that level which is acceptable to the turbine blades.
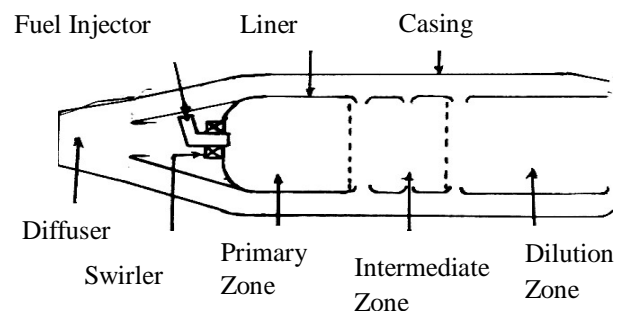

Figure.1: Combustor components

In axial-flow compressors, the stage pressure rise is very dependent on the axial flow velocity. To achieve the design pressure ratio in the minimum number of stages, a high axial velocity is essential, in many gas turbine engines, compressor outlet velocities may reach 150 m/s or higher. It is impractical to attempt to burn fuels in air flowing at such high velocities. Here the fundamental pressure loss would be excessive. Thus, before combustion can proceed, the air velocity must be greatly reduced, usually to about one-fifth of the compressor outlet velocity. This reduction in velocity is accomplished by fitting a diffuser between the compressor outlet and the combustor inlet.

a. Diffuser Geometry:

The geometry of straight-walled diffusers may be defined in terms of three geometric parameters, as shown in Figure 2.

1. Area ratio(AR)
2. Characteristic length to inlet dimension ratio(L/R1)

3. Divergence angle(θ)

These are related to each other by relation

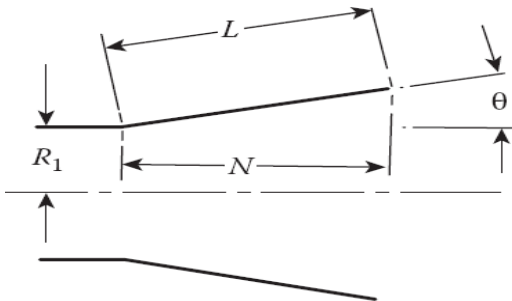$$AR = 1 + 2\frac{L}{R1}\sin\theta + (\frac{L}{R1}\sin\theta)^2 \ldots(1.1)$$

Figure2: Diffuser Geometry

1.Area ratio(AR): Function is to achieve prescribed reduction in velocity.

$$AR=A2/A1$$

Continuity eq^n ; $A2\times V2 = A1\times V1$

$$A2/A1=V1/V2$$

i.e. there is inverse variation in area ratio & velocity ratio. For max. AR there is more velocity reduction in diffuser i.e. high pressure recovery.

2. Non dimensional length (L/R1): In combination with the area ratio the length defines the overall pressure gradient which is the principal factor in boundary-layer

development. Usually, either the wall length, L, is used as a characteristic length. It is expressed in non dimensional form by dividing by a representative inlet dimension.

3. Divergence angle(θ) : In long diffusers of low θ, the pressure loss is high. With an increase in θ, both diffuser length and friction losses are reduced, but stall losses become more significant.

b. Swirler Design:

The primary-zone airflow pattern is of prime importance to flame stability. Many different types of airflow patterns are employed, but one feature common to all is the creation of a toroidal flow reversal that recirculates a portion of the hot combustion products to mix with the incoming air and fuel. These vortices are continually refreshed by air admitted through holes pierced in the liner walls, supplemented in most cases by air flowing through swirlers and by air employed in atomization.

One of the most effective ways of inducing flow recirculation in the primary zone is to fit a swirler in the dome around the fuel injector. Vortex breakdown is a well-known phenomenon in swirling flows; it causes recirculation in the core region when the amount of rotation imparted to the flow is high. This type of recirculation provides better mixing than is normally obtained by other

means, such as bluff bodies, because swirl components produce strong shear regions, high turbulence, and rapid mixing rates. These characteristics of swirling flows have long been recognized and have been used in many practical combustion devices to control the stability and intensity of combustion and the size and shape of the flame region.
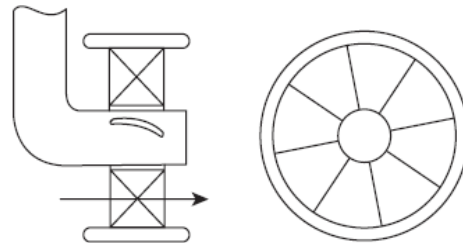

Figure 3: Axial swirler

The conventional notation for axial swirlers is indicated in Fig 3.2. This figure shows a flat-vaned swirler whose vane angle is constant and equal to θ_v. With curved-vane swirlers, the inlet blade angle is zero and the outlet angle is θ_v.

An important design requirement is that the swirler should pass the desired airflow rate for a given pressure drop ΔPsw, which is usually assumed to be equal to the liner pressure drop, ΔP_L. We have ,

$$m_{sw} = \left\{ \frac{2\rho_3\Delta P_{sw}}{K_{sw}\left[\frac{\sec\theta}{A_{sw}}\right]^2 - \frac{1}{A_L{}^2}} \right\}^{0.5} \ldots \qquad (1.2)$$

$$A_{sw} = \sqrt{\frac{(\sec\theta)^2}{\left(\frac{2\rho_3\Delta P_{sw}}{m_{sw}{}^2 K_{sw}} + \frac{1}{A_L{}^2}\right)}} \ldots \ldots \qquad (1.3)$$

$$S_N = \frac{2}{3}\frac{(D_{sw} - D_{hub})^3}{(D_{sw} - D_{hub})^2}\tan\theta_v \ldots \qquad (1.4)$$

Thus, for a simple axial swirler, the minimum vane angle required to obtain strong recirculation (SN > 0.6) for a typical swirler having Dhub/Dsw = 0.5 is calculated from Equation 1.4 as 38°.

c. Combustor Liner

Combustor casing is provided with a liner. The combustor liner contains the combustion process and introduces the various airflows into the combustion zone. To establish air flow pattern within the liner, there is need to determine the number, size, shape and deposition of liner holes. Necessary for easy light-up, efficient and stable combustion, adequate wall cooling and delivery of hot gases with a suitable temperature profile.

If liner wall contains a row of n holes, each of which has an effective diameter dj , then the total mass flow rate m_j of air through these holes is given by

$$m_j = \frac{\pi}{4}n\,d_j{}^2\,\rho_3 U_j \ldots\ldots\ldots \qquad (1.5)$$

Now

$$U_j = \left(\frac{2\Delta P_L}{\rho_3}\right)^{0.5} \quad \text{.....................} \quad (1.6)$$

Hence,

$$m_j = \frac{\pi}{4} n\, d_j^2\, (2\rho_3 \Delta P_L)^{0.5} \quad \text{.........}(1.7)$$

Add,

$$n\, d_j^2 = \frac{15.25\, m_j}{\left(P_3 \frac{\Delta P_L}{T_3}\right)^{0.5}} \quad \text{...............}(1.8)$$

$$d_h = \frac{d_j}{C_D^{\,0.5}} \quad \text{..................} \quad (1.9)$$

III. ALGORITHMS

T_3, P_3, T_5, P_5, $T_5^{'}$, A/F, C_v, T_{effi}, C_{pg}, R, e, f, , B, P_4, A, C_d, h, t_n, K_{sw} these are floating type global variables.

a. Algorithm to Calculate Mass Flow Rates and Reference Area

This algorithm is used to calculate mass flow of fuel, mass flow rate of air and reference area of combustor.

Pdef, ma3, ma, mf, mg, mpz, $T_5^{'}$, T_5, W, W_t, Pr, a, b, s, J, L_l, c, qref, arf, ar, A_{ref}, U_{ref}, R_o, A_l, D_l, L_{dz}, L_{iz}, L_{pz}, PF, m_{pzm}, m_{pzh}, m_{dz}, m_{iz}, d_{hpz}, d_{jpz}, x, g, i, j, m_{sw} are the various float type variables.

START
Read (Pressure ratio Pr)

$$T_5 \leftarrow \frac{T_4}{Pr^{(\gamma-1)/\gamma}}$$

$$T_5^{'} \leftarrow T_4 \times T_{effi} \times (T_4 - T_5)$$

Write (Turbine exit temperature, T_5, $T_5^{'}$)
Read (Total work output in kW, W)

$$W_t = 2 \times W$$

$$mf \leftarrow \frac{W_t \times 10^3}{[(afr+1) \times C_{pg} \times (T_4 - T_5^{'})]}$$

$$m_a \leftarrow m_f \times afr$$

$$m_{pz} \leftarrow \frac{m_a}{0.5}$$

$$m_{a3} \leftarrow \frac{m_{pz}}{0.25}$$

$$b \leftarrow \frac{R}{2}$$

$$c \leftarrow \left(\frac{m_{a3} \times \sqrt{T_3}}{P_3}\right)^2$$

Write(Work required to run the turbine ,W_t)
Write(Mass flow rates, m_f,m_a,m_{a3})

$$A_{ref} \leftarrow \sqrt{(b \times e \times f \times c)}$$

$$R_o \leftarrow \frac{P_3}{R \times T_3}$$

$$U_{ref} \leftarrow \frac{m_{a3}}{R_o \times A_{ref}}$$

Write(Reference area, A_{ref})

Write(Reference velocity, U_{ref})
Read(Area ratio, ar)

$$A_l \leftarrow ar \times A_{ref} \qquad (3.12)$$

$$D_l \leftarrow \sqrt{\frac{A_l}{(pi/4)}}$$

$$L_{pz} \leftarrow 1.5 \times D_l \qquad (3.14)$$

$$L_{iz} \leftarrow 0.5 \times D_l$$

$$P_{def} \leftarrow P_3 - P_4$$

$$P_d \leftarrow P_{def} \times 10^{-5}$$

$$\Delta P_L = \beta \times P_{def}$$

$$dpl \leftarrow \Delta P_L \times 10^{-5}$$

$$J \leftarrow e \times f \times \frac{\Delta P_L}{P_3}$$

$$Ji \leftarrow J \times 10^{-5}$$

Write(Liner area, A_l)
Write(Liner diameter, D_l)
Write(The liner lengths are L_{dz}, L_{iz})
Write(The value of pressure differences, P_d, dpl)
Write(The value of pressure drop, Ji)
Read(The value of pattern factor, PF)

$$s \leftarrow \ln\left(\frac{1}{1-PF}\right)$$

$$L_l \leftarrow D_l \times \frac{1}{A \times J \times s}$$

$$L_{pz} \leftarrow L_l - (L_{dz} + L_{iz})$$

Write(The liner lengths are, L_l, L_{pz})
HALT
functionTwo:

b. Algorithm to Calculate Number of Holes on Liner

This algorithm is used to calculate diameter of liner holes and number of liner holes.

roundnpz, roundniz, roundndz are the various intiger variables.

m_{a3}, m_a, D_l, delpl, m_{cl}, m_{pzm}, m_{sw}, m_{pzh}, m_{dz}, m_{iz}, d_{hpz}, d_{jpz}, g, n_{pz}, n_{iz}, d_{jiz}, d_{hiz}, d_{hdz}, d_{jdz}, n_{dz} are the various float variables.
START

$$m_{cl} \leftarrow m_{a3} \times 0.75$$

$$m_{pzm} \leftarrow m_a$$

$$m_{pzh} \leftarrow m_{pzm}$$

$$m_{dz} \leftarrow m_{a3} \times 0.3$$

$$m_{iz} \leftarrow m_{a3} \times 0.15$$

Write (The mass flow rates are, m_{cl}, m_{pzm}, m_{pzh}, m_{dz}, m_{iz})

$$d_{hpz} \leftarrow 0.1 \times D_l$$

$$d_{jpz} \leftarrow d_{hpz} \times \sqrt{Cd}$$

$$g \leftarrow \sqrt{P_3 \times (delpl/T_3)}$$

$$n_{pz} \leftarrow \frac{15.25 \times m_{pzh}}{d_{jpz}^{\,2} \times g}$$

roundnpz $\leftarrow$ round(n_{pz})

$$n_{iz} \leftarrow n_{pz}/2$$

roundniz $\leftarrow$ round(n_{iz})

$$d_{jiz} \leftarrow \sqrt{\frac{15.25 \times m_{iz}}{n_{iz} \times g}}$$

$$d_{hiz} \leftarrow \frac{d_{jiz}}{\sqrt{Cd}}$$

$$d_{hdz} \leftarrow 0.15 \times D_l$$

$$d_{jdz} \leftarrow d_{hdz} \times \sqrt{Cd}$$

$$n_{dz} \leftarrow \frac{15.25 \times m_{dz}}{d_{jdz}{}^2 \times g}$$

roundndz $\leftarrow$ round(n_{dz})
Write(The hole diameters, d_{jpz}, d_{jiz}, d_{jdz})
Write(The number of holes, n_{pz}, n_{iz}, n_{dz})
HALT

c.   Algorithm to round of the number of hole value.
START
tempRound is an integer value.
calculatedDiffrence is a float value.
int tempRound $\leftarrow$ (int)n_{pz}
calculatedDiffrence $\leftarrow n_{pz} -$ tempRound
if(calculatedDiffrence>=0.5)
return tempRound+1
else
return
tempRound
HALT
Function Three

d.   Algorithm to Calculate Swirler Diamentions
This algorithm is used to calculate swirl number, swirler area and swirler diameter.
R_o, m_a, A_l, Delpsw, delpsw, i, u, S_n, j, A_{sw}, n_v, m, o, q, D_{sw}, x_vane, x these are some float type variables.
START
Delpsw $\leftarrow P_3 \times 0.03$
delpsw $\leftarrow$ Delpsw $\times 10^{-5}$
Write(The pressure difference across the swirler, delpsw)
Read(The value of vane angle, x_vane)
i $\leftarrow \tan(0.0174 \times$ x_vane$)$

$$S_n = \frac{2}{3} \frac{\left(1 - \frac{D_{hub}}{D_{sw}}\right)^3}{\left(1 - \frac{D_{hub}}{D_{sw}}\right)^2} \tan(\theta v)$$

$$j \leftarrow \frac{2 \times R_o \times \text{Delpsw}}{K_{sw} \times m_a{}^2}$$

$$A_{sw} = \sqrt{\frac{1 + \tan^2(\theta v)}{\frac{2 \times R_o \times \Delta P_{sw}}{K_{sw} \times m_a{}^2} + \frac{1}{A_l{}^2}}}$$

Write(Swirl number, Sn)
Write(The swirler area, Asw)
Read (The number of vanes, nv)

$m \leftarrow -(0.5 \times n_v \times t_n \times (1 - h))$
$o \leftarrow (pi/4) \times (1 - h^2)$
$q \leftarrow m^2 - (4 \times o \times (-A_{sw}))$

$$D_{sw} \leftarrow \frac{-m + \sqrt{q}}{2 \times o}$$

Write(The swirler diameter, D_{sw})
HALT
Function Four

e.   Algorithm to Calculate Diffuser Dimensions
This algorithm is used to calculate diffuser inlet area, diameter, radius and diffuser length.
A_l, A_2, v_1, v_2, AR, R_o, m_a, A_1, D_1, R_1, deffusion_angle, L, M, y, A_{ref}, $A_2=A_{ref}$, deffusion_angle=y these are some float variables.
START
Read(The diffuser inlet velocity, v_1)
Read(Diffuser exit velocity, v_2)

$$AR \leftarrow \frac{v_1}{v_2}$$

$$A_1 \leftarrow A_2 \times \frac{v_2}{v_1}$$

$$D_1 \leftarrow \frac{A_1}{pi/4}$$

$$R_1 \leftarrow \frac{D_1}{2}$$

Write(The value of area ratio, AR)
Write(The diffuser inlet area, A_1)
Write(The diffuser inlet diameter, D_1)
Write(The diffuser inlet radius, R_1)
Read(The diffusion angle in degree, y)
$M \leftarrow \sin(0.0174 \times y)$

$$L \leftarrow \frac{-1 + \sqrt{AR}}{M/R_1}$$

Write(Length of diffuser, L)
HALT
Function Five

f.   Algorithm to Calculate Fuel Injector Parameters
This algorithm is used to calculate coefficient of discharge, flow number and orifice diameter.

Delpf, Cd_inj, D_o, R_f, t, FN, angle, x_spr, ld, Z, m_f these are some float variables.
START
Read(The value of length to diameter ratio, ld)
Read(The fuel density, R_f)
Read(The fuel pressure difference, Delpf)
$Cd_{inj} \leftarrow 0.827 - 0.0085 \times$ ld

$$Z \leftarrow \sqrt{R_f \times \text{Delpf} \times 10^5}$$

$$FN \leftarrow \frac{m_f}{Z}$$

$$D_o \leftarrow \sqrt{\frac{m_f}{1.11 \times Cd\_inj \times Z}}$$

Write(The coefficient of discharge, Cd_inj)
Write(The flow number, FN)
Write(The orifice diameter, D_o)
Read(The value of spray cone angle, x_spr)

$$t \leftarrow \frac{0.00805 \times \sqrt{R_f} \times FN}{D_o \times \cos(x\_spr \times 0.0174)}$$

Write(The film thickness, t)
HALT.

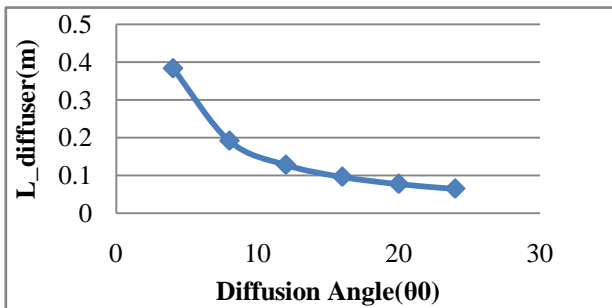## IV. RESULTS

1. Effect of diffusion angle on diffuser length:

Figure 4: Effect of diffusion angle(θ) on diffuser length(L_diff)

As the diffusion angle increases the length of diffuser get reduce, which is beneficial in order to reduce the weight of engine. Again large diffuser deflection is required for large recirculation area and to reduce the pressure losses.

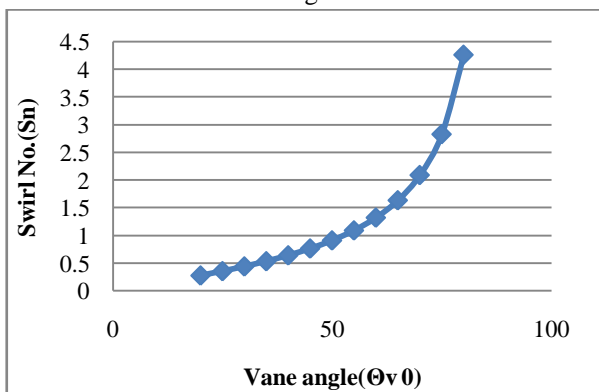2. Effect of various vane angle on swirl number:

Figure 5: Effect of various vane angle(θ_v) on swirl number(Sn).

As the swirl angle increases the swirl number also increases. For strong recirculation the swirl number should be greater than the value .0.6(Sn>0.6), for that proper swirl angle selection is important, after calculations it is clear that the swirl angle should be greater than 35^0 to get Sn>0.6
.

3. Effect of turbine work output on fuel mass flow rate distribution for different pressure ratios.
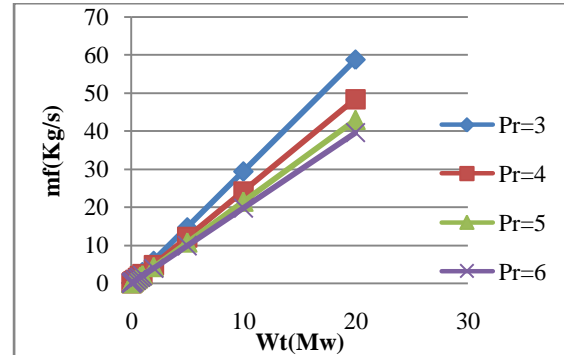

Figure 6: Fuel mass flow rate(mf) Vs turbine work output(Wt) for different pressure ratios.

As we increase the pressure ratio, the fuel consumption for different powers also increases

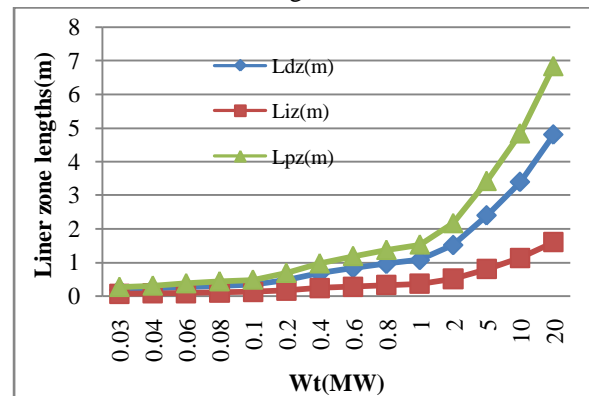4. Combustor Liner Length and Holes Distribution:

Figure 7: Liner Length (L) distribution Vs Turbine Power(W_t)

Length of liner for primary zone is larger than other two, as primary combustion takes place in this zone and air requirement is more for combustion. Length of dilution zone is next shorter where cooling of hot gases takes place to make them sustainable by turbine blades and next is intermediate zone where combustion incomplete combustion product takes place.
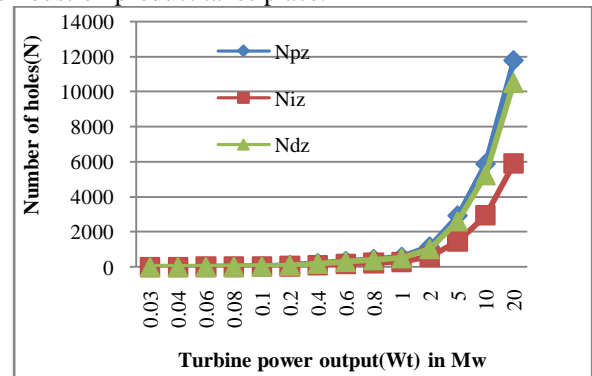
Figure 8: Number of holes(N) distribution Vs turbine power output(Wt) at pressure ratio=3.

For good cooling effect we need to increase the number of holes on the dilution zone, it is possible by reducing the diameter of dilution holes, because temperature at the combustor exit should required to be less so that turbine blades are able to sustain.
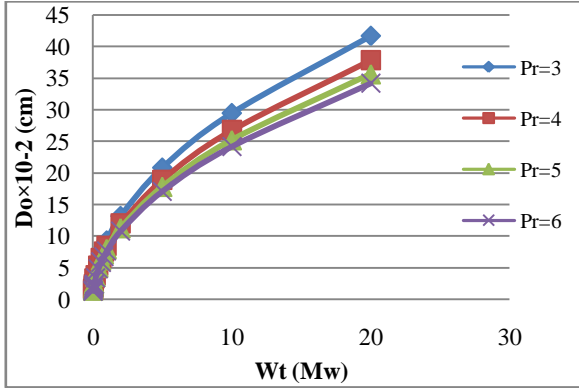
5. Fuel Injector Parameters

Figure 9 : Orifice diameter(D_o) Vs turbine power output(Wt) for various pressure ratios.

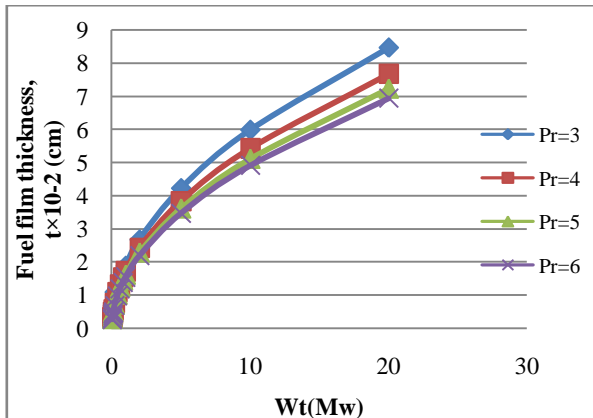The nozzle diameter reduces with increase in pressure ratio.

Figure 10: Fuel film thickness(t) Vs turbine power output(Wt) for various pressure ratios.

The decrease in fuel film thickness takes place as an increment in the pressure as well as turbine power output is done.
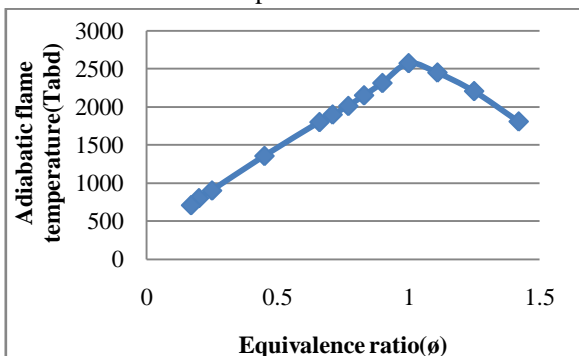
6. Adiabatic Flame Temperature

Figure 11 : Adiabatic flame temperature(Tabd) Vs equivalence ratio($\emptyset$).

At equivalent ratio is one($\emptyset$=1), i.e. stoichometric composition, the adiabatic flame temperature reaches the peak temperature e.g. 2573K for Kerosene fuel. As the equivalence ratio increases, the adiabatic flame temperature also get increase upto stoichometric composition after that the temperature get reduces.

IV. CONCLUSION

As the manual calculations are very tedious and time consuming job. It should get overcome with the help of computer simulations for design of combustor. It is advantageous as in this practice no need to perform the experiment again and again user get the required parameters affecting combustor design by just providing required output from the gas turbine in the c program. It is also beneficial to select design giving better performance due to ease in comparison between two or more design.

REFERENCES

1. Lefebvre A.H.(1965), *"Progress And Problems In Gas-turbine Combustion" ,* Tenth Symposium (International) on Combustion, pp.1129-1137.
2. Gupta A.K.(1997), *"Gas Turbine Combustion : Prospects And Challenges"*,Energy Convers, Vol. 38, No. 10-13,pp.1311-1318 .
3. Gupta, A. K., Lilley, D. G., and Syred, N. (1984), "*Swirl Flows"*, Abacus Press, Tunbridge Wells, UK.
4. Sovran, G., and Klomp, E. D.(1967), *"Experimentally Determined Optimum Geometries for Rectilinear Diffusers with Rectangular, Conical or Annular Cross Section,"*in G. Sovran, ed., Fluid Mechanics of Internal Flow, Elsevier, Amsterdam, pp. 270–319.
5. Channwala S. A. & Kulshreshtha D.B. (2006),"*Numerical Simulation to study the effect of divergence angle on performance of inlet diffuser section of gas turbine chamber*", Tenth International Congress of Fluid Dynamics ,December 16-19, Stella Di Mare Sea Club Hotel, Ain Soukhna, Red Sea, Egypt, ICFD10-EG-30I3.

Books:
1. Lefebvre, A. H. & Ballal, D. R.,2010. *Gas Turbine Combustion Alternative Fuels and Emissions.* 3rd ed. CRC Press is an imprint of the Taylor & Francis Group,.
2. Samanta, D.,2006. *Classic Data Structure.* New Delhi, 7th printing 2006. Prentice Hall of India Private Limited.
3. Rajaraman, V., 1994. *Computer Programming in C.* New Delhi, 2nd Edition, Prentice Hall of India Private Limited.
4. Ganesan, V.,2000. *Computer Simulation Of Compression-Ignition Engine Processes.* Hyderabad, First published 2000, Universities Press(India) Limited.
5. Cohen, H., Rogers, G.F.C. & Saravanamuttoo, H.I.H.,1987. *Gas Turbine Theory.* 3rd Edition, Longman scientific and Technical , New York, 40-200. .
6. Mathur, M. L., Sharma, R. P., 1976. *Internal Combustion Engine.* 1st Edition, 23rd Reprint 2012, Dhanpat Rai Publications (p) LTD, 894-923.