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Design and Analysis of Annular Combustion Chamber for a Micro Turbojet Engine

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Abstract**—**The design of high performance combustion chambers for turbojet engines is considered as one of the most challenges that face gas turbine designers, since the design approach depends on empirical correlations of data derived from the previous design experiences. The objective of this paper is to design a combustion chamber that suits the requirements of a micro-turbojet engine with 400 N output thrust and operates with kerosene as fuel. In this paper, only preliminary calculations related to the annular type of combustion chamber are explained in details. These calculations will cover the evaluation of reference quantities, calculation of required dimensions, calculation of air distribution and pressure drop, estimation of number and diameters for air admission holes, as well as aerodynamic considerations. The design process is then accompanied by analytical procedure using commercial CFD ANALYSIS tool; ANSYS 16 CFX software. After conducting CFD analysis, the design process will be then iterated in order to gain satisfactory results. It should be noted that the design of the fuel preparation and installation systems is beyond the scope of this work, and it will be discussed separately in another work.

Keywords**—**Annular combustion chamber, micro-turbojet engine, CFD ANALYSIS, pressure drop.

NOMENCLATURE

Symbols and Abbreviations

A_{case}	Case cross sectional area
A_{ref}	Reference area
A_L	Liner cross sectional area
A_{shaft}	Shaft cross sectional area
a_s	Sonic speed, m/s
$\dot{m}_a$	Mass Flow Rate of air
$\dot{m}_j$	Mass flow rate of jet air
$\Delta P_{3\text{-}4}$	Total Pressure Drop across the combustor
ΔP_L	Liner pressure drop, Pascal
$\dot{m}_f$	Mass flow rate of fuel
$\dot{m}_g$	Mass flow rate of combustion products
PF	Pattern Factor
α	Equivalence ratio
q	Dynamic head, Pascal
U	Velocity
U_{ref}	Reference Velocity
U_j	Velocity of the jet flow
T	Temperature
T_3	Total inlet temperature
T_4	Turbine inlet temperature
P_3	Total inlet pressure
L	Length
d	Diameter
d_h	Hole diameter
d_j	Jet diameter
Y_{max}	Maximum jet depth
ρ	Density
ρ_3	Inlet total density of the air
ρ_g	Total density of the gas
ρ_j	Total density of the jet flow
M	Mach number
H_L	Height of the flame tube
J	Momentum flux ratio
K	Hole pressure drop coefficient
n	Number of air admission holes
C_D	Discharge coefficient
$\propto$	Ratio of the jet mass flow of air to the annulus mass flow
R	Universal gas constant
γ	Specific heat ratio

Subscript

in	Inlet value
out	Outlet value
L	Liner
Ann	Annulus value
pz	Primary zone
sz	Secondary zone
dz	Dilution zone
ax	Axial flow
comp	Compressor
j	Jet
ref	Reference value

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I. INTRODUCTION

THE combustion chamber or combustor is one of the most important components in a conventional gas turbine engine, through which the combustion process takes place, it is always positioned in between the compressor and turbine assemblies. It is believed that annular type of combustors is the most widely used in today aero-engines among the other types, these types being tubular and tubo-annular. Annular combustor type is designed in such a way that an annular liner is mounted concentrically inside an annular casing. There are many features of using this type of combustors, and these may include more stable combustion, relatively shorter size, lower pressure drop, and less surface area. Moreover, the use of this type of combustors tends to obtain very uniform temperatures at the exit cross sectional area. This paper presents only preliminary design of an annular combustion chamber that suits the requirements of a micro-turbojet engine with 400 N output thrust. It has to be noted that the design approach of a turbojet combustion chamber depends on extensive use of an experience database and empirical correlations along with extensive testing program [1]. High performance combustors can be designed considering wide range of requirements such as high combustion efficiency, low fuel consumption, low pressure loss, high durability and reliability, optimum size and shape, as well as low emissions of smoke and gaseous pollutant species. These technical and environmental issues have made the design of combustion chambers very sophisticated, and made the use of the empirically based approaches alone to become insufficient. However, when such design approaches are supported with CFD analysis, the design tool for combustion systems becomes more efficient. Priyant [4] has discussed a design methodology using the same approach for designing an annular combustion chamber suits the requirements of a low bypass turbofan engines to be used in jet trainer aircrafts. The design process was also enhanced by CFD analysis using ANSYS 14.5 software. Bronwyn [2] has considered first principles and design methods of the Northern Research and Engineering Corporation (NREC) series to redesign a combustor liner for a 200-N mini gas turbine engine. Some parts of the NREC processes have been modified during the design process due to the impractical results or different requirements for the small engine compared to a typical gas turbine. A small and weak recirculation zone has resulted from CFD simulations of this combustor.

II. DESIGN PROCEDURE

The design procedure has been shown in Fig. 1. Moreover, the equations utilized in the design procedure have been presented which are sufficient for the reader to understand the design methodology idea.

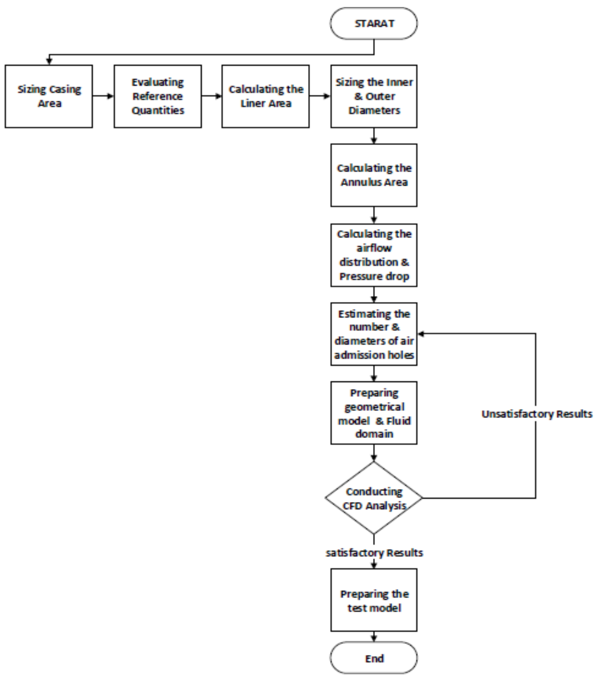

Fig. 1 Design procedure flowchart

A. Initial Design Parameters

The design procedure has been carried out based on the initial design parameters which are mostly the compressor exit and turbine inlet constraints. Table I illustrates the initial parameters used for the design procedure.

TABLE I
INITIAL DESIGN PARAMETERS

Symbol	Quantity	Value
$\dot{m}a$	Mass flow rate of air	0.83 kg/s
T_3	Inlet Total Temperature magnetic induction	460 K
P_3	Inlet Total Pressure	4 bar
$\dot{m}f$	Mass flow rate of fuel	0.01355 kg/s
ΔP	Total Pressure loss	0.05
T_4	Turbine Inlet Temperature	1173 K
M_{comp}	Compressor outlet Mach number	0.395
ρ	Compressor outlet total density	3.03 kg/m^3
d_{case}	Engine casing diameter	0.150 m

B. Sizing and Calculations of Reference Parameters

1. Sizing of Casing Diameter

The chamber casing should have the same diameter of the engine casing. Once the casing diameter is determined, most of the other combustion chamber dimensions together with the calculations of most of the reference parameters such as the reference velocity, reference Mach number and overall pressure drop can be easily determined.

2. Evaluation of Reference Quantities

Evaluation of reference quantities plays crucial role in chamber design to facilitate the analysis of the combustor flow characteristics. These quantities include the reference area, reference velocity reference Mach number and reference dynamic head.

i. Evaluation of Reference area

The reference area can be calculated using the following formulae

$$A_{ref} = [\frac{R}{2} [\frac{\dot{m}\sqrt{T}}{P3}]^2 \frac{\Delta P3-4}{qref} [\frac{\Delta P3-4}{P3}]^{-1}]^{0.5} \quad (1)$$

However in this case, the reference area can be obtained by subtracting the shaft casing area from the outer casing area.

$$A_{ref} = A_{case} - A_{shaft} \quad (2)$$

$$A_{ref} = 0.0164 \text{ m}^2$$

ii. Evaluation of Reference Flow Velocity

The reference flow velocity can be calculated using continuity equation:

$$U_{ref} = \frac{\dot{m}a}{\rho a \times Aref} \quad (3)$$

$$U_{ref} = 16.7 \text{ m/s}$$

iii. Evaluation of Reference Mach Number

The reference Mach number can be calculated using the following equation:

$$M_{ref}=\frac{Uref}{as} \quad (4)$$

where:

$$as=\sqrt{\gamma \times R \times t3}$$

thus:

$$M_{ref}=0.0393$$

iv. Evaluation of Reference Dynamic Head

$$q_{ref}=\frac{pin \times Uref}{2} \quad (5)$$

$$q_{ref}=391.329 \text{ Pa}$$

3. Calculation of Liner Area

Empirical calculations gained from the previous design experiences show that the ratio of liner cross sectional area to the reference area is approximately 0.666 [3].

$$\frac{AL}{Aref} \approx 0.666$$
$$A_L = 0.109 \text{ m}^2$$
$$D_{out}= 0.132 \text{ m}$$

4. Sizing Inner Liner

The inner liner has to be sized in such a way it can be match with the turbine disk, to allow combustion products passing smoothly through the nozzle guide vanes (NGV).

Thus the inner liner diameter has the same value of the turbine disk.

$$D_{in}=0.061 \text{ m}$$

Furthermore, the height of the flame tube is defined as the difference between the outer diameter and the inner diameter of the liner can be obtained using the following equation:

$$H_L=\frac{D\,out - Din}{2} \quad (6)$$
$$H_L = 0.0357 \text{ m}$$

5. Calculation of Annulus Area

The annulus area can be divided into two sections which are outer annulus area and inner annulus area, the outer annulus area is the difference between the reference area and the liner cross sectional area, it can be calculated using the following equation:

$$A_{ann\text{-}out}=A_{ref}- A_L \quad (6)$$
$$A_{ann\text{-}out} = 0.00373 \text{ m}^2$$

The inner annulus area is the difference between the inner liner cross sectional area and the shaft wall cross sectional area.

$$A_{ann\text{-}in}= A_{L\text{-}in} - A_{shaft} \quad (8)$$
$$A_{ann\text{-}in} = 0.00174 \text{ m}^2$$

6. Length of the Liner

In this approach, the length of every zone is calculated separately, and the sum will be the liner total length.

The length of the primary zone can be calculated using the following equation:

$$L_{pz}=\frac{2}{3} D_L \quad (7)$$
$$L_{pz} = 0.071 \text{ m}$$

The length of the secondary zone can be calculated using the following equation:

$$L_{sz}=\frac{1}{2} DL \quad (8)$$
$$Lsz=0.018 \text{ m}$$

The length of the dilution zone can be calculated using the following equation:

$$L_{dz} = D_L \times (3.83\text{-}11.83PF+13.4PF2) \quad (9)$$

Considering the value of 0.25 for the PF, typical values always lie in the range between 0.25-0.4 [5].

$$L_{dz}=0.061 \text{ m}$$

$$L_L = L_{pz} + L_{sz}+ L_{dz} \quad (10)$$
$$L_L = 0.103 \text{ m}$$

C. Calculation of the Airflow Distribution and Pressure Drop

Calculation of the required airflow rate by each zone is of prime importance for combustor design, since the number, location and size of the holes for a specific zone will be then calculated once the required airflow rate is determined.

1. Calculation of Primary Zone Total Airflow Rate

The total airflow needed for the primary zone can be calculated using the following formulae:

$$\dot{m}_{pz}=14.77\times\propto pz \times m_f \quad (11)$$

$\propto_{pz}$ =0.9. Therefore; 14.77 "stoichiometric ratio"

$$\dot{m}_{pz} = 0.180 \text{ kg/s}$$

It is assumed that 60% out of the total airflow of the primary zone enters the liner axially through the frontal area, and the rest of the total airflow enters the liner through the annulus. Thus:

$$\dot{m}_{ax\text{-}pz} = 0.072 \text{ kg/s}$$
$$\dot{m}_{ann\text{-}pz} =0.1087 \text{ kg/s}$$

It should be noted here that 50% out of the annulus primary zone airflow enters the combustion zone through the outer annulus, and the rest of the airflow enters through the inner liner.

2. Calculation of Secondary Zone Total Airflow Rate

$$\dot{m}_{sz}=14.77\times\propto sz\times\dot{m}_{sz} \quad (14)$$

Therefore; $\propto_{sz} = 1.7$

$$\dot{m}_{sz} = 0.34 \text{ kg/s}$$

And the jet mass flow rate of air for secondary zone can be calculated by subtracting the primary zone airflow from the total mass flow of air required for secondary zone.

$$\dot{m}_{jsz} = \dot{m}_{sz} - \dot{m}_{pz} \quad (15)$$

$$\dot{m}_{jzs} = 0.232 \text{ kg/s}$$

It should be noted here that 50% out of the total jet mass flow of air required for the secondary zone enters the combustion zone through the outer annulus, and the rest of the airflow enters through the inner liner.

3. Calculation of Dilution Zone Total Airflow Rate

$$\dot{m}_{dz} = \dot{m}_{p} - (\dot{m}_{pz} + \dot{m}_{jsz}) \quad (12)$$

$$\dot{m}_{dz} = 0.49 \text{ kg/s}$$

It should be noted here that 70% out of the dilution zone airflow enters the liner through the outer annulus, and the rest of the airflow enters through the inner liner.

TABLE II
AIRFLOW DISTRIBUTION AMONG DIFFERENT COMBUSTOR

			Percentage of the mass flow rate of air
Primary zone	Outer liner	Axial Flow	40% out of the total $\dot{m}$pz
		1st row	30% out of the total $\dot{m}$ann-pz
		2nd row	20% out of the total $\dot{m}$ann-pz
	Inner Liner	1st row	30% out of the total $\dot{m}$ann-pz
		2nd row	20% out of the total $\dot{m}$ann-pz
Secondary zone	Outer Liner	1st row	30% out of the total $\dot{m}$jsz
		2nd row	20% out of the total $\dot{m}$jsz
	Inner liner	1st row	30% out of the total $\dot{m}$jsz
		2nd row	20% out of the total $\dot{m}$jsz
Dilution zone	Outer liner		70% out of the total $\dot{m}$dz
	Inner liner		70% out of the total $\dot{m}$dz

D. Liner Air Admission Holes

The need of the liner air admission holes is to provide enough air for every zone.

1. Air Admission Holes for Primary and Secondary Zones

The number and diameter of the air admission holes for both primary and secondary zones can be estimated using the following equations:

$$K = 1 + \frac{\Delta PL}{qan} \quad (13)$$

$$C_D = \frac{a1 \times (K-1)}{\sqrt{4 \times K^2 - K(2-\propto)^2}} \quad (18)$$

$$d_h = \frac{dj}{\sqrt{CD}} \quad (14)$$

$$n \times dj = \frac{15.25 \times mj}{\sqrt{Pin \times \frac{\Delta PL}{Tin}}} \quad (15)$$

The diameter of the jet (d_j) can be estimated on the basis of a specified value for the maximum penetration depth, since all the other terms are readily calculated. In order to achieve the best performance results, typical maximum penetration (Y_{max}) for small annular combustion chambers which is in the range of 0.14-0.25 of the liner flame tube height (HL) is encountered, and for estimating the diameter and number of holes for both primary and secondary zones the value of 0.2HL and 0.15HL has been considered respectively. The following empirical equations have been used in order to estimate the diameter of the jet:

$$\frac{Ymax}{dj} = 1.25 \times \sqrt{J} \left[\frac{\dot{m}g}{\dot{m}g + \dot{m}a}\right] \quad (21)$$

$$J = \frac{\rho j \times Uj}{\rho g \times Ug} \quad (22)$$

$$U_j = \sqrt{\frac{2 \times \Delta PL}{\rho in}} \quad (23)$$

Taking into consideration that the liner pressure drop has been guessed for every row of different combustion zones, considering the jet mass flow of air entering every row, and the value of 0.6 has been maintained for the discharge coefficient.

Once the jet diameter is defined, the total number of the air admission holes can be then obtained from the continuity equation as follows:

$$m_j = \frac{\pi}{4} \times n \times dj^2 \times \rho_{in} \times U_j \quad (16)$$

Once the jet diameter is defined, the real diameter of the hole can be easily found using (19).

The discharge coefficient of the hole can be calculated using (18) taking the value 1.25 for $a1$ that is set for surface holes.

2. Air Admission Holes for Dilution Zone

The number and diameter of the air admission holes for dilution holes can be estimated using Fig. 2. From Fig. 2, for the given value of $\frac{\dot{m}J}{\dot{m}g} = 0.203$

$$\text{The value of } \frac{(2 \times DL + Dj)^2}{n \times dj \times DL} \approx 4$$

Therefore, the number of holes can be calculated using the following equation:

$$n = \frac{(2 \times DL + Dj)^2}{4 \times dj \times DL} \quad (17)$$

III. GEOMETRICAL MODEL

The geometry of the liner has been modeled using CATIA software release 21.

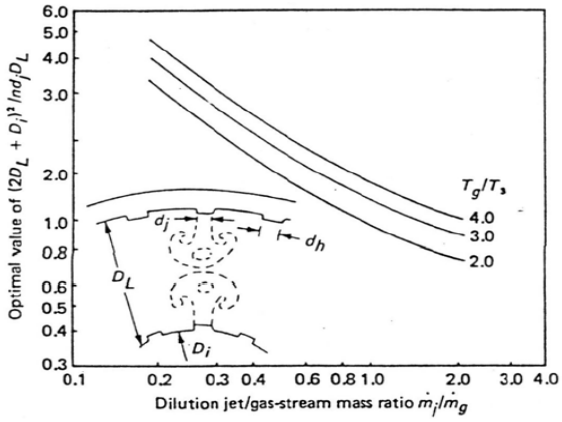

Fig. 2 Dilution zone design chart [1]

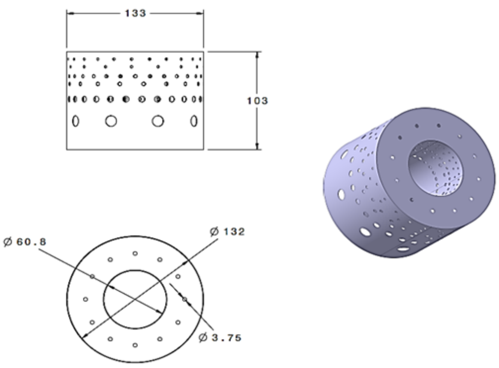

Fig. 3 Geometrical model of the combustor liner

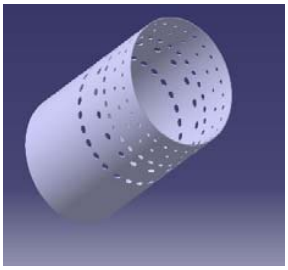

Fig. 4 Inner liner geometrical model

IV. Generation of the Fluid Domain

The fluid domain of the combustor has been generated using CATIA software. Fig. 10 illustrates the fluid domain of the designed combustor.

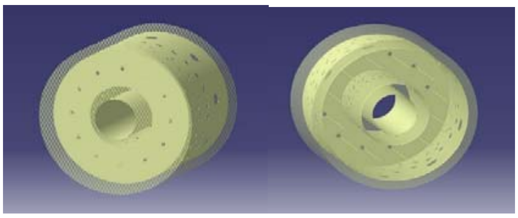

Fig. 5 Fluid domain of the combustor

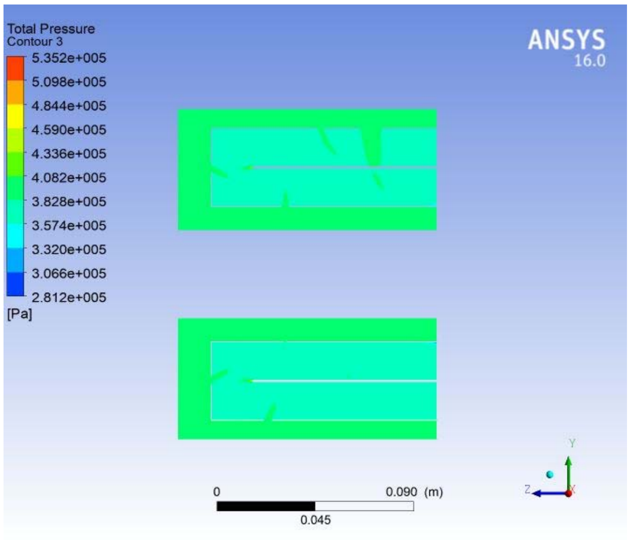

Fig. 6 Total pressure contour

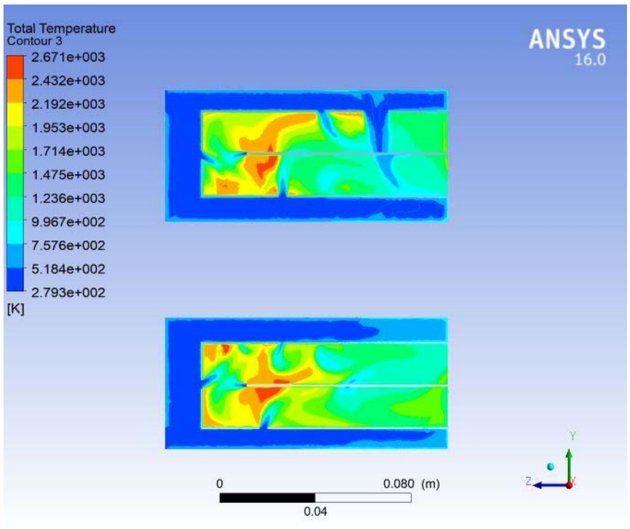

Fig. 7 Total temperature contour

TABLE III
NUMBER AND DIAMETER OF AIR ADMISSION HOLES

			Number of admission holes	Diameter of admission hole (mm)
Primary zone	Outer liner	Axial Flow	12	3.75
		1st row	24	2.5
		2nd row	16	2.5
	Inner Liner	1st row	31	1.8
		2nd row	21	1.9
Secondary zone	Outer Liner	1st row	29	3.5
		2nd row	18	3.8
	Inner liner	1st row	32	2.8
		2nd row	18	3.6
Dilution zone	Outer liner	1st row	27	5.9
		2nd row	9	11.2
	Inner liner	1st row	28	3.76
		2nd row	0	0

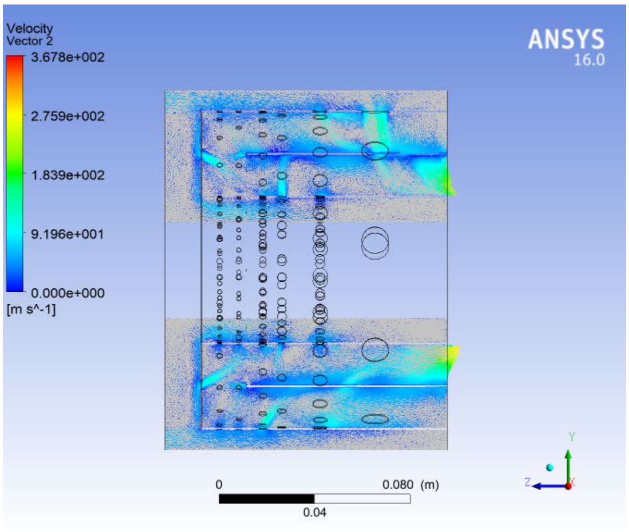

Fig. 8 Velocity vector

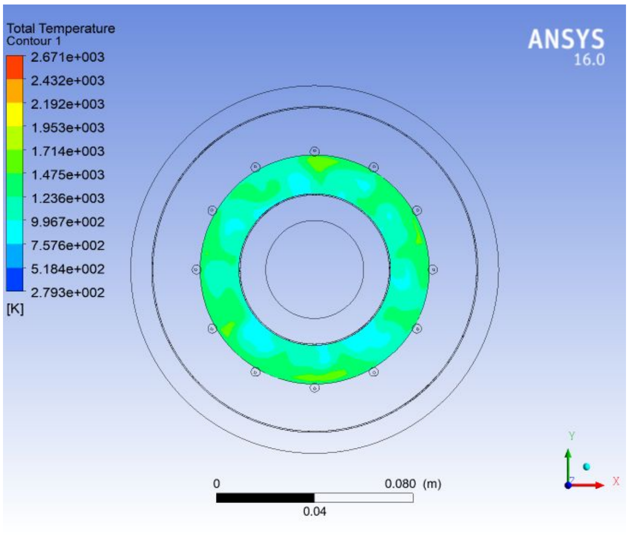

Fig. 9 Total temperature contour- exit flow

V. CFD Analysis

CFD analysis has been achieved using ANSYS 16 CFX.

VI. Results and Discussion

The preliminary design of an annular type of combustion chamber that suits the requirements of a micro-turbojet engine with 400 N output thrust has been discussed in this paper.

CFD analysis shows that the temperature distribution at the outlet section is relatively uniform, and the average turbine inlet temperature is in the range of 1180 K which is close to the desired value. Furthermore, the average outlet velocity of the combustion products is in the range of 216 m/s, which is sufficient to achieve the targeted thrust. In addition; the pressure loss is in the range of the designed limit. Moreover; it is observed that the flame has extended beyond the limit of the combustion zone; this will inevitably lead to raise the outlet temperature.

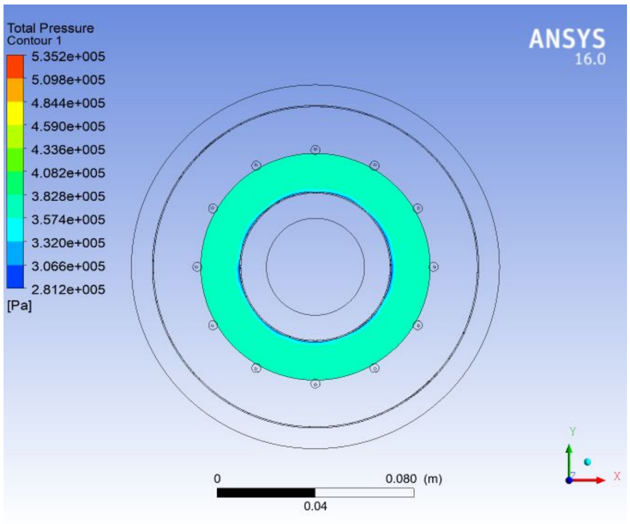

Fig. 10 Total pressure contour- exit flow

Average Turbine Intlet Temperature	1.187e+03 [K]
Max Turbine Inlet Temperaure	1.626e+03 [K]
Max Flame Temperature	2.527e+03 [K]
Outlet Total Pressure	3.716e+05 [Pa]
Average Outlet Velocity	2.163e+02 [m s...
Max Outlet Velocity	3.678e+02 [m s...
Outlet Mass Flow Rate of Air	-8.436e-01 [kg s...

Fig. 11 Screenshot – outlet parameters

Experimental test is recommended in order to ensure that the performance quality of the designed chamber is high enough to gain the targeted thrust. If the experimental test results in a smooth burning and a stable combustion, the designed model will be considered for manufacturing and installation; otherwise the design process must be iterated.

VII. Conclusion

The design calculations have been achieved based on empirical correlations of data derived from previous design experiences which is suitable for preliminary phase. For future work, the design process must be iterated and the model must be modified and tested until high performance is gained.

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