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Design of Mini Turbojet Engine Combustion Chamber Liner With 200N Static Thrust

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Abstract

Design of mini turbojet engine with 200N static thrust at an air mass flow of 0.55kg/s, requiring annular type combustion chamber with liner capability of dividing the air mass flow in the primary zone by 20%, secondary zone 30%, dilution zone 50%, and with 4%-10% pressure loss. In the primary zone, it is necessary to have a recirculation zone that will become a stable combustion place. Liner geometry is obtained by analytical and empirical calculations, that is validated by numerical simulations at cold flow steady conditions. Analytical and empirical calculations resulting in the primary, secondary, and dilution zone respectively: the hole diameter: 2.153mm, 2.503mm, 5.005mm; number of holes: 44, 52, 44 holes; the distance of hole from inlet liner: 28.5mm, 47.5mm, 113.6 mm; air mass flow rates: 19.4%, 29.6%, 50%, and the pressure loss of the combustion chamber is 4%. The numerical simulation is performed by using the turbulent k-e model (extended wall) and has a difference resulted with analytical and empirical calculations on mass flow in the primary, secondary, and dilution zone: 3.44%, 9.09%, 8.88%, and the pressure drop is 10.86%. The recirculation zone that is fulfil injector placement criteria formed in the primary zone at the longitudinal cross-section position (q) from 32.72° to 360° with 32.73° in increment, with horizontal (H) and vertical (V) distance from inner liner wall are varies from 34 to 40 mm for H, and from 35 to 43 mm for V with outer recirculation tangential velocity variation from 43 to 60 m/s.

Keywords: *Mini turbojet, liner design, recirculation zone, air mass flow, pressure loss*

Nomenclature

T_1	=	Inlet compressor static temperature, K
T_2	=	Outlet compressor static temperature, K
T_{01}	=	Total inlet compressor temperature, K
T_{02}	=	Total outlet compressor temperature, K
P_2	=	Combustion inlet static pressure, Pa
P_3	=	Combustion outlet static pressure, Pa
P_{02}	=	Combustion inlet total pressure, Pa
P_{03}	=	Combustion outlet total pressure, Pa
γ	=	Gamma
W	=	Work, Watt
C_p	=	Constant pressure specific heat
C_c	=	Compressor speed
R	=	Gas constant
πcc	=	Efficiency combustion chamber, %

ΔP	=	Pressure loss, Pa
v	=	Outer recirculation tangential velocity (m/s)
A_{ref}	=	Reference area, m^2
U_{ref}	=	Reference speed, m/s
M_{ref}	=	Reference number Mach
q_{ref}	=	Reference dynamic pressure, Pa
$\dot{m}$	=	Mass flow, kg/s
$D_{f,L}$	=	Diameter flame liner, m
D_{out}	=	Diameter outer liner, m
d	=	Recirculation diameter (mm)
$A_{ann-out}$	=	Annulus Outer, m^2
A_{ann-in}	=	Annulus inner, m^2
A_{shaft}	=	Shaft area, m^2
L_L	=	Liner length, m
L_{pz}	=	Liner primary zone length, m
L_{sz}	=	Liner secondary zone length, m
L_{dz}	=	Liner dilution zone length, m
$\dot{m}_{pz}$	=	Mass flow primary zone, kg/s
$\dot{m}_{sz}$	=	Mass flow secondary zone, kg/s
$\dot{m}_{dz}$	=	Mass flow dilution zone, kg/s
K	=	pressure drop coefficient
ΔP_L	=	Pressure loss liner, Pa
q_{an}	=	Annulus dynamic pressure, Pa
C_D	=	Discharge coefficient
d_h	=	Hole diameter, m
n	=	Total hole
U_j	=	Jet speed, m/s
Pz	=	Primary zone
Sz	=	Secondary zone
Dz	=	Dilution zone
I_L	=	Inner length, m
H	=	Hight, m
Z	=	Length, m

1. Introduction

Mini turbojet engine is a type of internal combustion engine on a small scale that must have a special design (A.Hupfer. et. al, 2012,). It has a basic configuration which is consist of: intake, compressor, combustion chamber, turbine, and exhaust nozzle. Combustion chamber on mini turbojet has components that consist of casing and liner, where the formation of heat energy and high pressure occurs. This energy can be utilized by the turbine to rotate the compressor and generate thrust. Mini turbojet performance can be seen from the relationship between the value of thrust and the speed of the work area. The higher speed at the same ambient air condition, and at constant SFC, resulting smaller thrust value. This decreasing value in thrust happened because of the value of the fuel/air ratio is smaller, resulting in smaller fuel energy extracted by the turbine, which also causes the engine rotational speed to decrease (H. Cohen et all., 2001).

(Benini. et. al, 2007) use mini turbojet engine with diameter 22,8 cm, 200N in thrust, and 60.000 rpm engine rotation speed for research. In this present mini turbojet engine design, the objective of the design is to have a combustion chamber liner for 200N the same thrust value, but with a lower rotation speed and a smaller engine diameter compared to the previous mini turbojet engines research. Because of smaller dimensions of the combustor, the residence time of the fuel-air-mixture in the combustor chamber is very short (Fuchs, et.al, 2018). Furthermore, smaller combustion chamber for the same compressor pressure ratio has a higher air velocity across the liner. Thus, the liner hole size and its position in every combustion chamber zone must be determined to divided the airflow with suitable proportion and for the right placement of fuel injector to get optimum fast fuel/air mixture in the combustion process.

The selection of lower rotational speed is to get a lighter turbine workload. However, by decreasing engine rotational speed, the pressure ratio in the compressor will be decrease, thus requiring additional mass flow in the air. The addition of a larger air mass flow certainly provides an advantage in the form of increasing the working area of speed at the same thrust. An annular combustion chamber is choosing for this engine because of it has the advantages than the other types of combustion chamber in minimum cross-sectional area, minimum weight, and has a minimum pressure loss (A.H. Lefebvre, 1983).

To get optimum combustion in the chamber, a liner should be divided airflow by 20% in the primary zone, 30% in the secondary zone, and 50% in the dilution zone (Figure 1-1) (H. Cohen et all., 2001). Furthermore, in the primary zone, a recirculation/stabilization zone must be formed to perform a stable mixture of fuel and air (Figure 1-2) (Boyce, 2011).

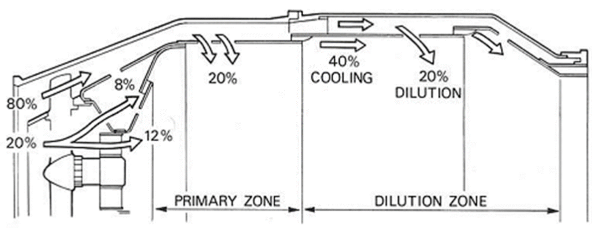

Figure 1-1: Liner airflow distribution (H. Cohen et all., 2001)

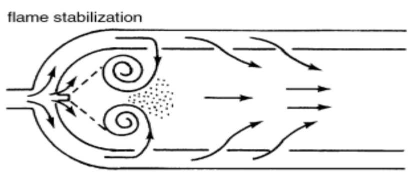

Figure 1-2: Combustion stabilisation area (Boyce, 2011)

This recirculation zone is not only being able to mix fuel and air, but also can caused a pressure drop in the combustion chamber. The wider recirculation zone, the easier fuel and air mixed, but it will cause a pressure drop in the liner that causes a pressure drop in the combustion chamber (A.H. Lefebvre, 1983). Generally, design of combustion chamber liner is to obtain air distribution over the entire combustion chamber zone and establishing recirculation zone for fuel injector position placement is performed by using analytical/ empirical calculation method, numerical simulations and then validated by experiment.

2. Methodology

The design of mini turbojet engine is obtained by determining the DRO and thermodynamic calculations for each component. The design of annular combustion chamber is using the Lefebvre analytical calculation rules by considering the formation of a recirculation/ stabilisation zone and the combustion process in the liner.

2.1. Related Works

Preliminary design to obtain the annular combustion chamber dimensions: primary zone, secondary zone, and dilution zone was carried out by using method of TDP (The theoretical design point), CDP (Minor compromise in efficiencies) and CAT-d (Current engine casing diameter) without including the combustion process (cold flow). The comparison of those three methods used, the result was CAT-d method is the best with a low amount of pressure loss than other methods (Mayers, 2015).

To determine the distribution of air in the annular combustion chamber liner, analytical calculation was used on the liner diameter, liner length, hole diameter, and flow distribution in the primary, secondary, and dilution zones by including the combustion process. After that, obtained design results are numerically simulated to validate the calculation. The result obtained from the numerical simulation was the optimal gas exit temperature of the combustion with minimum pressure loss. The combustion that seen in numerical simulations show that it is shorter than other combustion in its class which gives it an advantage in the size of space constraints (Mark et all., 2016).

The design of the liner in the annular combustion chamber by including the combustion process is carried out by determining the fuel and air ratio in advance. The next step is to determine the fuel injector area, the size of the primary zone, the size of the secondary zone and the dilution zone by calculating the distribution of the mass flow of air entering each zone and the temperature of the liner. Then, determine the velocity on the liner, the number and diameter of the holes using the jet penetration calculation was obtained [8]. Comparison of the results of analytical and numerical calculations shows the temperature of the gas exiting the combustion chamber is in optimal conditions, at different liner lengths (Enache et all., 2017).

The preliminary design of the annular type of mini turbojet combustion chamber which has a thrust of 400 N by including the combustion process is carried out by determining the size of the casing diameter, reference area, liner area, air distribution and the number of holes in each zone in the liner using Lefebvre analytical calculations, which are validated by using numerical simulation. The numerical simulation results show that the average outlet temperature distribution has a difference of 0.25%. Then, the average outlet velocity is in the range of 216 m/s, which is sufficient to achieve the targeted thrust (Mohammed, 2019).

The design of the annular combustion chamber on a mini turbojet that has a thrust of 1200N by including the combustion process carried out using the Lefebvre method. The calculation begins by determining the design specifications, type of combustion chamber, type of diffuser, size of the diffuser, reference value, pressure drop by paying attention to combustion, liner size, airflow distribution and diameter of the hole in the liner. The results of the analysis show that there is the largest error value between analytical and numerical calculations on the distribution of airflow on the on-design in the primary zone of 28.14%. Furthermore, the outlet velocity between numerical and analytical simulations in the off-design case 2 has the largest error of 12% (C.A. Putra, 2020).

The annular combustion chamber optimisation can be determined by liner geometry using the kriging experimental method which is including the combustion process that will interpolate the sample results. For sensitivity analysis, the spearman correlation method is used to calculate efficiency, pattern factor, pressure loss, temperature inlet turbine and average correlation. The optimum point for each parameter was determined using MOGA (Multiple Objective Genetic Algorithm). The result was showing that the kriging method is the best method for obtaining parameter values (Habibi et all., 2019).

2.2. Problem Definition

The distribution of air in each liner zone is needed to get optimum combustion according to the temperature required by the turbine. The optimum combustion is achieved by the dividing air mass flow in each zone namely, primary, secondary, dilution zone and formation of a recirculation zone in the primary zone. To form a recirculation, it is necessary to design a liner which includes the length for each zone, inner diameter, outer diameter, and holes in each zone as shown in Figure 2-1. However, with the formation of recirculation zone, a pressure drop will occur in the combustion chamber. Therefore, this study aims to create a liner which can dividing air mass flow in each zone, form recirculation zone that creates stable combustion and minimizes pressure drop in the combustion chamber.

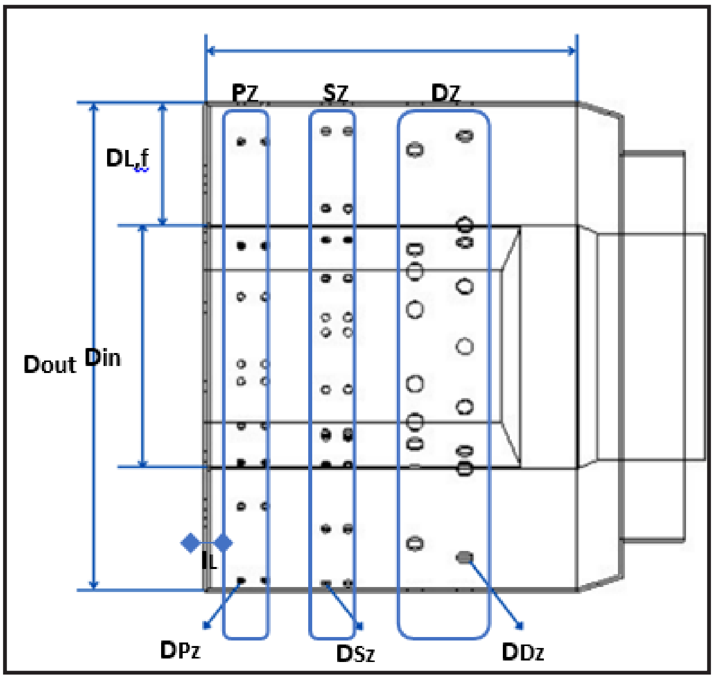

Figure 2-1: Geometry of combustion chamber liner

2.3. Design Methodology

The design method that used in this mini turbojet combustion chamber with a 200N thrust is using a Lefebvre rule to obtain the geometry, distribution airflow in each liner zone, formation recirculation zone, and pressure drop that is useful in the combustion process. However, the validation by numerical simulation is only limited to the cold flow process where there is no combustion process. The using of design method can be seen in Figure 2-2:

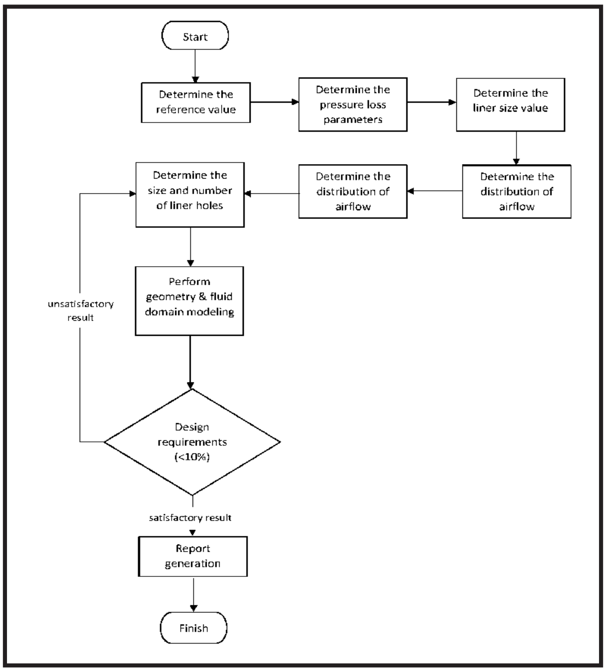

Figure 2-2: Design Methodology Flow diagram

2.3.1 Initial Design Parameters

To do the liner design, it is necessary to have the initial value contained in the output design compressor that have been done and the value desired by the turbine. In the Table 2-1, the design parameter values are the initial value for analytical calculations on the combustion chamber liner.

Table 2-1: Initial design parameters

Symbol	Name	Value
$\dot{m}_a$	Air mass flow	0,55 kg/s
T_{03}	Total of compressor temperature inlet	390,514 K
P_{03}	Total of pressure compressor outlet	243180 Pa
$\dot{m}_f$	Fuel mass flow	0,0134 kg/s
T_{04}	Total of turbine temperature inlet	997,51 K
P_{04}	Total of pressure turbine inlet	233452 Pa
ρ_{03}	Total density compressor outlet	1,6 kg/m^3

2.3.2 Reference Value

Determination of reference value is the main step to obtain the size of combustion chamber. The reference values are including area, speed, Mach number, and dynamic reference pressure. The reference area is the maximum casing without a liner, to find the reference area you can use equation (2-1). After getting reference area, it is needed speed reference that can be calculated with mass flow, density, and reference area, the relationship can be seen through equation (2-2). To get the reference Mach number, it takes the value of air propagation speed and the reference speed that has been obtained. The reference Mach number calculation is obtained through equation (2-3). The dynamic pressure calculation is obtained by knowing the compressor density value and the reference speed. The relationship between these values can be formulated through equation (2-4).

$$A_{ref} = \left(\frac{R}{2} \left(\frac{\dot{m}\sqrt{T_{02}}}{P_{02}} \right)^2 \frac{\Delta P_{02-03}/q_{ref}}{\Delta P_{02-03}/P_{02}} \right)^{0,5} \quad (2\text{-}1)$$

$$U_{ref} = \frac{\dot{m}}{\rho_2 x A_{ref}} \quad (2\text{-}2)$$

$$\mathrm{M_{ref}} = \frac{\mathrm{U_{ref}}}{\mathrm{as}} \quad (2\text{-}3)$$

$$\mathrm{q_{ref}} = \frac{\rho_3 \mathrm{U^2}_{\mathrm{ref}}}{2} \quad (2\text{-}4)$$

2.3.3 The value of pressure loss parameter

In the design combustion chamber process, there are two sources of pressure loss, diffuser and liner. For the design of combustion chamber without diffuser, the pressure loss only comes from the liner, so the pressure loss can be expressed through equation (2-5) below:

$$\frac{P_{t3-4}}{P_{t3}} = \frac{\mathrm{P}_{3-4}}{\mathrm{P}_3} \quad (2\text{-}5)$$

Next, liner pressure loss can be achieved using this equation (2-6) below:

$$\frac{\Delta P_{t_l}}{q_{ref}} \quad (2\text{-}6)$$

2.3.4 Liner size

Liner is where the combustion occurs in the combustion chamber. To get the size of the liner geometry, it must be determined in advance the ratio of the cross-sectional area of the liner to the cross-sectional area of the casing using equation (2-7), and to get the area liner, it can be calculated using equation (2-8).

$$K_{opt} = 1 - \left(\frac{(1 - m_{sn})^2 - \lambda}{\frac{\Delta P_{3-4}}{q_{ref}} - \lambda r^2} \right)^{1/3} \quad (2\text{-}7)$$

$$A_L = K_{opt} A_{ref} \quad (2\text{-}8)$$

Furthermore, inner liner must have the size that matches the turbine disc which aims to be able to carry out optimum combustion through nozzle guide vanes. To determine the height of the flame tube, it can be determined through the ratio of the outer diameter to the inner diameter of the liner which can be obtained from equation (2-9).

$$D_{f,L} = \frac{D_{out} - D_{in}}{2} \quad (2\text{-}9)$$

Annulus area can be divided into two, inner annulus and outer annulus. Outer annulus is a difference between reference area and cross-sectional area liner, to get annulus outer area it can be calculated by using equation (2-10).

$$A_{ann-out} = A_{ref} - A_L \quad (2\text{-}10)$$

To calculate the length of the liner, each zone is calculated separately, and the sum each zone will be the total length of liner. The length of primary zone can be determined by the equation (2-11). Meanwhile, to determine the length of secondary and dilution zone, it can be obtained from the equation (2-12) and (2-13), with PF value can be considered in the range 0,25 – 0,4.

$$L_{pz} = \frac{2}{3} \sim \frac{3}{4} D_L \qquad (2\text{-}11)$$

$$L_{sz} = \frac{1}{2} D_L \qquad (2\text{-}12)$$

$$L_{dz} = D_L \times (3{,}83 - 11{,}83PF + 13{,}4PF2) \qquad (2\text{-}13)$$

2.3.5 Distribution of Airflow

Calculation of airflow in each zone is needed for the design of the combustion chamber, because when the airflow rate in each zone is known, so it can determine the total, location, and hole size in each zone. For the total airflow rate in the primary zone can be calculated through equation (2-14)

$$\dot{m}_{pz} = 14{,}77 \times \propto_{pz} \times m_f \qquad (2\text{-}14)$$

This zone is a process of fuel and air mixture for combustion. Total airflow rate in secondary zone can be calculated through equation (2-15)

$$\dot{m}_{sz} = 14{,}77 \times \propto_{sz} \times m_{sz} \qquad (2\text{-}15)$$

The value of $\propto_{sz}$ is 1.7 in airflow secondary zone, 50% of the total mass flow of the required air jet enters the combustion zone through the outer annulus and the rest enters inner liner.

The total airflow rate in the dilution zone can be calculated by equation (2-16)

$$\dot{m}_{dz} = \dot{m} - (\dot{m}_{pz} + \dot{m}_{jsz}) \qquad (2\text{-}16)$$

2.3.6 Liner Hole Size and Number

To determine the number and diameter of holes that enter through the primary zone and secondary zone can be calculated through equation (2-17), (2-18).

$$n \times d_j = \frac{15{,}25\, \dot{m}_j}{\sqrt{P_{in} \times \frac{\Delta P_L}{T_{in}}}} \qquad (2\text{-}17)$$

$$U_j = \sqrt{\frac{2 \times \Delta P_L}{\rho_{in}}} \qquad (2\text{-}18)$$

2.3.7 Distance of each hole and between zones

Each zone has two rows of holes with the same diameter and number of holes, except for the dilution zone which has a different number of holes. In each zone, the distance between the holes is placed in the middle of the length of the liner, taking into account the two holes of each zone. For holes between zones, the liner length of each zone is reduced by the length of each zone used by the hole.

2.3.8 Numerical Simulation

Numerical simulation of airflow in this combustion chamber design is a validation of the mass flow and pressure distribution of the liner design using analytical/empirical methods without combustion process (cold flow). In addition, this cold flow simulation is carried out to see the formation of a recirculation zone in the primary zone which is where air and fuel mix. By knowing the location of the recirculation zone, it can determine the position of the igniter and fuel injector for optimum combustion.

Flow simulation in the combustion chamber is a flow dynamic modelling to see the characteristics of airflow in the combustion chamber. This flow modelling is expressed in the modified Navier-Stokes by including turbulent flow model. To solve this equation, numerical method is used with one of discretization methods, namely the finite volume method. For this reason, the volume of airflow in the combustion chamber must be discretized which is expressed in the form of a grid/mesh. In addition, boundary conditions are needed in order to obtain a flow solution in the combustion chamber. The result of meshing on the combustion chamber liner can be seen in Figure 2-3. Meshing in the combustion chamber used a hexa-hederal type with a total of 9.615 million number of cells according to the mesh independence study on the one axial and two outer liner primary zone hole at YZ plane (Figure 2-4). Furthermore, the boundary conditions of the inlet and outlet in the combustion chamber can be seen in Figure 2-5.

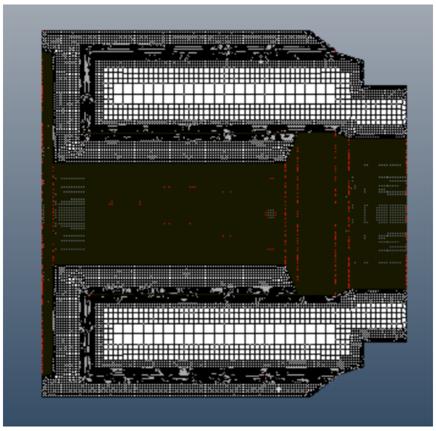

Figure 2-3: Combustion chamber mesh

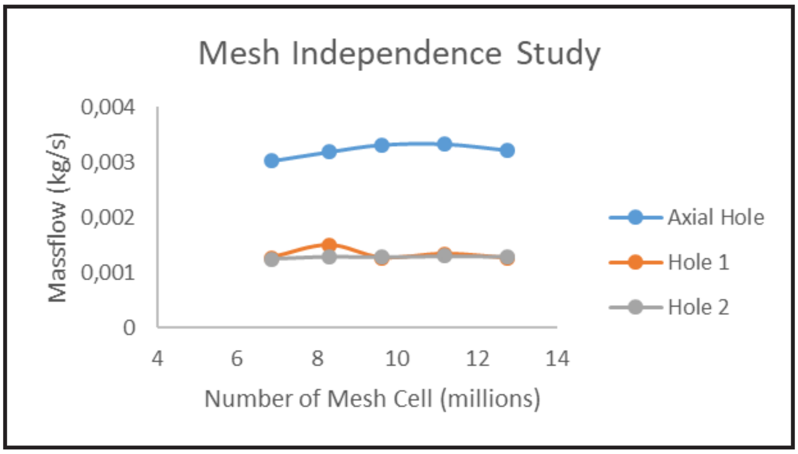

Figure 2-4: Mesh Independence Study

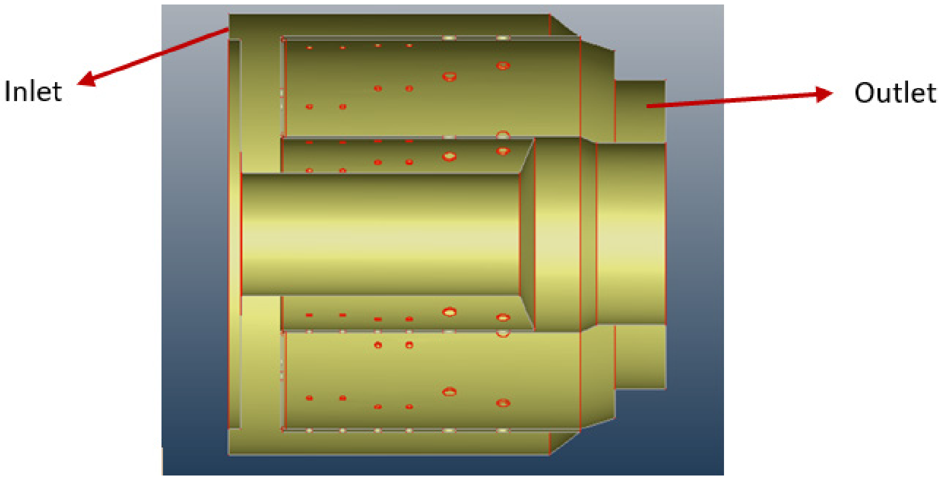

Figure 2-5: Numerical simulation boundary condition

Numerical simulation of airflow in this combustion chamber used a turbulent model. (Fuchs. et.al, 2018) used k omega SST-Menter for combustion process simulation of very small jet engine with annular type combustion chamber. This result then compared to the experiment result and for whole temperature level is quite similar, but the maximum local temperature in the simulation is clearly higher. The local temperature maximum from the experiment and simulation at the radial positions are close to each other. However, the chosen simple approach without detailed information about the fuel atomization, film formation and vaporization inside the sticks does not deliver reasonable results in local temperature distribution. (A. C Mangra, 2020) obtaining optimal configurations for micro gas turbines with numerical simulation by using k-e with scalable wall function. The experimental procedure then will begin and the numerical results will be compared with the experimental ones. (Gieras. M, 2013) conducted a numerical simulation of aerodynamic “cold” flow inside a GTD-350 turbine engine combustor by using k-e with scalable wall function. This numerical simulation resulting data the percentage of mass flow of air through the holes and slots in the combustor can be used to determine the boundary and initial conditions for the calculation of spraying, mixing and combustion processes of fuel in the chamber. Furthermore, the mass airflow is distributed very unequally to the inlet holes positioned around the swirler, and to obtain a smaller loss of pressure it is necessary to optimize the geometry of the whole combustor.

In this research, a turbulent model that is used to simulate the airflow is k-e (extended wall) turbulent model which is a model derived from Yang-Shih model. In this model, the equation is for obtaining the kinetic energy k and dissipation turbulent e in the first layer grid is not solved. Variable k and e are defined using a wall function that derives from direct numerical simulation (DNS). The k-e wall function model used is different from the standard model (Launder and Spalding, 1974). Furthermore, the turbulent time scale and viscosity are defined as the same as Yang-Shih model. By using wall function in k-e turbulent model, the boundary layer modeling of the airflow in the combustion chamber can be more accurate.

3. Result and Analysis

Table 3-1 shows the result of aerodynamic calculation of the designed combustion chamber in the form of the geometry length and diameter in combustion chamber. The length of geometry includes the length of liner, primary zone, secondary zone, and dilution zone. The obtained diameter is the combustion chamber diameter, and airflow diameter between casing and liner.

Table 3-1: Combustion chamber geometry calculation results

Symbol	Name	Value (mm)
L_L	Liner Length	113,64
L_{PZ}	Primary zone length	28,5
L_{SZ}	Secondary zone length	19
L_{DZ}	Dilution zone length	66,1
$D_{L,f}$	Diameter flame liner	38
D_{out}	Diameter outer liner	147

The holes total number and dimension value in each liner zone are shown in Table 3-2. Holes are placed on the inside and outside in each zone. For primary zone, there is a hole for axial flow that is lie at the front of combustion chamber liner entry. In primary zone, there are axial and radial flow from front, outer liner, and inner liner holes. The front of combustion chamber liner entry zone (axial) has 14 holes with a 3.38 mm diameter, for outer and inner primary zone, there are 44 holes with 2.153 mm diameter. In secondary zone, there are inner and outer section and two rows with 52 holes with 2.503 mm diameter. In dilution zone, there are inner and outer section with 44 holes with 5.005 mm diameter.

Table 3-2: Result of liner hole dimension calculation

Zone	Section	Row	Number of holes	Hole diameter (mm)
Primary	-	Axial flow	14	3,38
	Outer Liner	1	11	2,153
		2	11	2,153
	Inner Liner	1	11	2,153
		2	11	2,153
Secondary	*Outer Liner*	1	13	2,503
		2	13	2,503
	Inner Liner	1	13	2,503
		2	13	2,503
Dilution	*Outer Liner*	1	10	5,005
		2	12	5,005
	Inner Liner	1	10	5,005
		2	12	5,005

Comparation of analytical calculated mass flow and numerical simulation is shown in Table 3-3. There is a difference about 3.44% in total mass flow primary zone, 7.61% in the axial mass flow primary zone, and 2.39% in the primary zone-annular. At the secondary zone mass flow, there is a difference of 9.09% on total mass flow, and in the dilution zone the difference values is 8.88%.

Table 3-3: Analytical and numerical comparison on mass flow

Symbol	**Name**	**Analytic (kg/s)**	**CFD (kg/s)**	**Error (%)**
$\dot{m}_{pz}$	Mass flow primary zone	0,108006	0,111722	3,44
$\dot{m}_{pz,ax}$	Mass flow primary zone - axial	0,021601	0,023247	7,61
$\dot{m}_{pz,ann}$	Mass flow primary zone - annular	0,086405	0,088475	2,39

Symbol	Name	Analytic (kg/s)	CFD (kg/s) θ	Error (%)
$\dot{m}_{sz}$	Mass flow secondary zone	0,163209	0,148358	9,09
$\dot{m}_{dz}$	Mass flow dilution zone	0,278786	0,303551	8,88

Comparison of analytical and numerical calculations on pressure and temperature in the combustion chamber without combustion, can be seen in the Table 3-4. The differences at total and static inlet temperatures are 0,0308% and 0,0851%. At the total and static inlet pressures, there is a difference about 0.104% and 0.454%. Furthermore, the difference at total and static output temperatures are 0.763% and 4.55%, and at total and static output pressure are 10.86% and 11,85%. The results of the difference between analytical and numerical on pressures and temperatures at the inlet and outlet combustion chamber are small and satisfy the design requirement.

Table 3-4: Analytical and numerical comparison at pressure and temperature

Symbol	Name	Analytic (kg/s)	CFD (kg/s)	Difference (%)
T_{02}	The total temperature of the combustion chamber inlet	390,5143K	390,394K	0,0308
T_2	Combustion chamber inlet static temperature	388,77K	3389,101K	0,0851
T_{03}	Total temperature of combustion chamber outlet	390,51K	387,527K	0,763
T_3	Combustion chamber outlet static temperature	388,77K	371,057K	4,55
P_{02}	Combustion chamber inlet total pressure	243180P_aP_a	242926P_aP_a	0,104
P_2	Combustion chamber inlet static pressure	239032,8P_aP_a	240119P_aP_a	0,454
P_{03}	Combustion chamber outlet total pressure	233452,8P_aP_a	208085P_aP_a	10,86
P_3	Combustion chamber outlet static pressure	229305,6P_aP_a	202131,8P_a P_a	11,85

For the recirculation zone, the value of Z and H at each hole position in the primary zone has an average value 1,35 mm and 2,21 mm.

The result of analytic calculation is validated by CFD simulation. One of the results of the numerical simulation of airflow in the combustion chamber liner can be seen in Figure 3-2. The recirculation/stabilization zone is formed in the primary zone with its center position from liner inner wall can be define as a vertical (V) and horizontal (H) distance. This recirculation position from liner inner wall at various combustion chamber longitudinal cross- section can be seen at Figure 3- 1 to Figure 3-3 and Table 3-5 below :

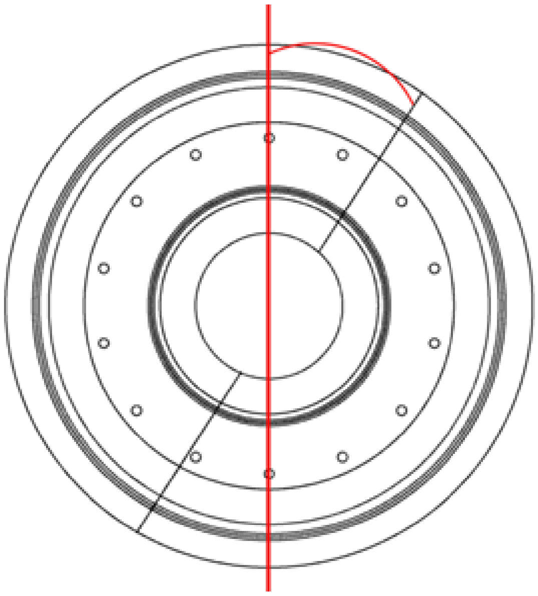

Figure 3-1: Longitudinal cross-section position angle

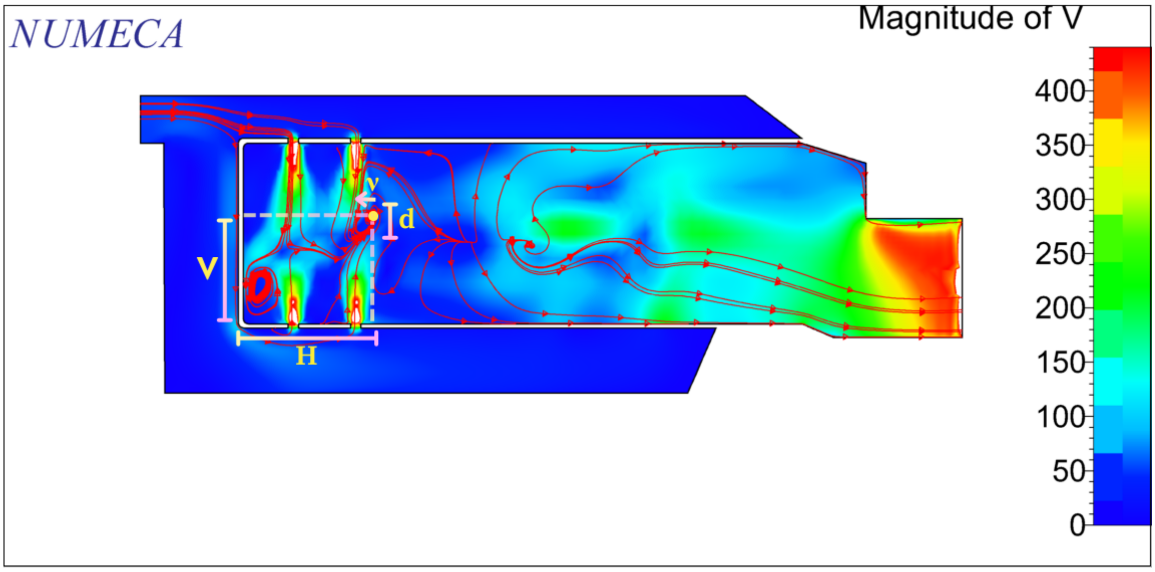

Figure 3-2: Airflow streamline and velocity contour on longitudinal combustion chamber cross-section

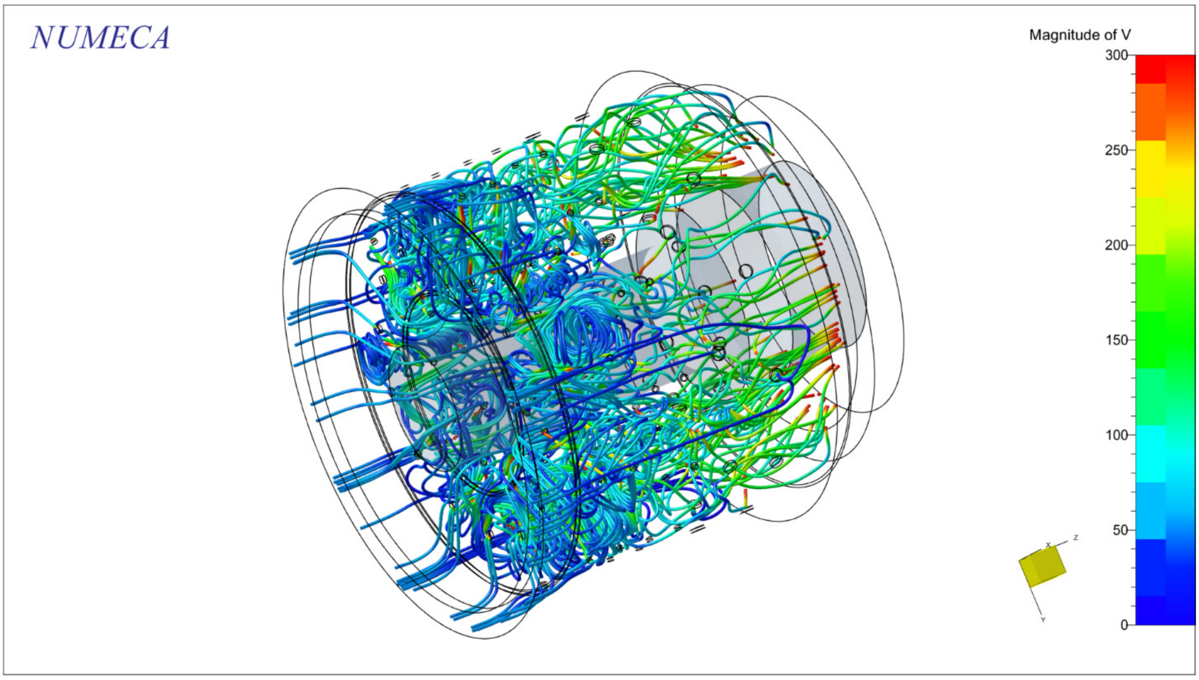

Figure 3-3: Airflow streamline in combustion chamber

Table 3-5: Recirculation Data at Various Combustion Chamber Longitudinal Cross- Section

θ (deg)	Recirculation 1				Recirculation 2				Recirculation 3				**Recirculation 4**			
	H (mm)	**V (mm)**	**d (mm)**	n (m/s)	**H (mm)**	**V (mm)**	**d (mm)**	n (m/s)	**H (mm)**	**V (mm)**	**d (mm)**	n (m/s)	**H (mm)**	**V (mm)**	**d (mm)**	n (m/s)
25.71	19.62	50.46	15	150	79.97	13.91	4	90	-	-	-	-	-	-	-	-
32.72	4.91	10.23	16	80.6	13.69	26.92	35	45	34.55	47.35	42	51.25	57.59	12.85	80	135
40	26.79	39.19	8.3	10.2	31.61	6.14	7	65	56.77	11.25	3	136	-	-	-	-
51.42	19.95	50.18	9	90	-	-	-	-	-	-	-	-	-	-	-	-
65.45	3.47	9.84	13	98	12.39	58.7	6	95	14.39	10.87	6	32.44	37.04	43.14	8	43.48
77.14	13.29	56.41	6	68	32.8	19.71	1.9	34	34.67	38.17	12	35	58.24	22.51	9	188
80	28.58	9.12	7	72.3	35.3	41.16	10	66.8	57.18	15.62	7	227	-	-	-	-
98.18	3.18	7.49	11	134.6	14.42	57.36	4	90	36.79	40.74	7	48.5	-	-	-	-
102.85	55.22	14.44	7	92	68.6	41.84	8	103	-	-	-	-	-	-	-	-
120	40.2	21.8	13	81.6	78.89	24.24	8	150	-	-	-	-	-	-	-	-
128.57	36.8	41.71	14	81.1	-	-	-	-	-	-	-	-	-	-	-	-
130.9	6.85	8.51	4	64.7	36.92	40.28	7	60	-	-	-	-	-	-	-	-
154.28	19.18	50.69	10	36.5	-	-	-	-	-	-	-	-	-	-	-	-
160	4	3.95	7	66.8	14.03	53.76	15	116	-	-	-	-	-	-	-	-
163.63	3.99	20.53	2	133	18.32	10.15	9	41	28.64	25.43	5	45.5	-	-	-	-
180	20.97	23.82	23	63.5	-	-	-	-	-	-	-	-	-	-	-	-
193.36	3.78	7.97	10	82.8	19.07	9.36	9	45	29.15	24.87	5	35	-	-	-	-
200	18.57	41.75	16	45	-	-	-	-	-	-	-	-	-	-	-	-
205.71	70.79	35.68	25	80.5	-	-	-	-	-	-	-	-	-	-	-	-
229.09	6.69	8.91	7	118.4	37.7	39.45	6.7	54.7	-	-	-	-	-	-	-	-
231.42	8.27	22.89	13	26	24.28	42.54	5	44.5	-	-	-	-	-	-	-	-
240	4.94	5.97	7	67	43.61	55.31	14	50	78.89	11.6	6	79	-	-	-	-

θ (deg)	Recirculation 1				Recirculation 2				Recirculation 3				**Recirculation 4**			
	H (mm)	**V (mm)**	**d (mm)**	n **(m/s)**	**H (mm)**	**V (mm)**	**d (mm)**	n **(m/s)**	**H (mm)**	**V (mm)**	**d (mm)**	n **(m/s)**	**H (mm)**	**V (mm)**	**d (mm)**	n **(m/s)**
257.14	68.56	42.47	13	77.7	-	-	-	-	-	-	-	-	-	-	-	-
261.81	3.15	6.62	10	87.23	8.23	14.86	2	65.03	35.7	39.95	10	53.8	56.62	15.57	4	96
280	36.57	40.51	83	85	50.85	11.52	11	100	-	-	-	-	-	-	-	-
282.85	34.78	38.48	11	70	59.36	23.21	10	65.3	-	-	-	-	-	-	-	-
294.54	4.08	9.89	16	83.1	36.87	43.53	13	60.4	56.72	11.92	12	56	-	-	-	-
308.57	7.18	23.73	18	11.2	44.56	30.17	4	75.2	-	-	-	-	-	-	-	-
320	55.58	19.64	8	63	59.82	16.08	10	199	64.88	39.9	6	49.8	-	-	-	-
327.27	5.31	9.87	14	149.17	15.45	19.78	3	101	36.24	47.02	9	55.1	57.93	11.44	9	140.8
334.28	67.38	47.96	25	90.5	-	-	-	-	-	-	-	-	-	-	-	-
360	3.38	8.82	9.8	88.4	41.2	35.16	4	30.9							-	-

From Figure 3-3 and Table 3-5, the contour of combustion chamber air speed magnitude at inlet is 75 m/s, the annulus entry speed ranges from 50-70 m/s, the air inlet velocity in the liner hole is about 75-500 m/s and the exhaust air from the combustion chamber liner to the turbine has a speed around 200-300 m/s. At the primary zone, the recirculation is formed at most of cross-section position (q), except at q = 257.14°, 282.85°, 320° for recirculation formed only at secondary zone, q = 240° only at dilution zone, and no recirculation is formed at q = 160°. Furthermore, there is a recirculation formed at primary and secondary or primary and dilute zone for one cross-section position (q =32.72° Primary-Secondary, 65.45° Primary-Secondary, 77.14° Primary-Secondary, 120° Primary-Dilute, 154.28° Primary-Dilute, 231.42° Primary-Secondary, 280° Primary-Secondary, 294.54° Primary-Secondary, 308.57 Primary-Secondary). For injector placement, a forming recirculation position at primary zone must be far enough from liner inner wall, has low velocity and sufficient size for right mixture with fuel. Base on this requirement, there are cross-section positions q with near inner wall at 32.72°, 65.45°, 80°, 98.18°, 120°, 154.28°, 163.63°, 180°, 196.36°, 200°, 205.71°, 229.09°, 231.42°, 261.81°, 280°, 294.54°, 308.57°, 334.28°, 360°, and high outer recirculation tangential velocity at 25.71°, 40°, 51.42°, 77.14°, 80°, 102.85°, 128.57°, 180°, 280°. Hence, from that data, the possible suitable place for injector placement is at q = 32.72°, 65.45°, 98.18°, 130.9°, 163.63°, 196.36°, 229.09°, 261.81°, 294.54°, 327.27°, 360° where that place is the cutting plane crossing through the primary zone hole which is the opposite liner hole from the outer and inner liner hole forming a collision flow resulting a recirculation. The recirculation at that cross-section positions have H value varies from 34 to 40 mm, and V values varies from 35 to 43 mm with outer recirculation tangential velocity variation from 43 to 60 m/s.

At the secondary zone, continuation of combustion from the primary zone will happened when the mixture of fuel and air is not perfect. Thus, it will be mixed again in this zone and the recirculation flow should be exist in a cold flow. The position of recirculation in cold flow of this zone is explained at previous paragraph and the flow streamline is shown in Figure 3-3 which has an average velocity 60 m/s. Furthermore, the last zone is a dilution zone that aims to make uniform and cooler airflow from primary and secondary zone. Figure 3-3 shows the recirculation zone has been decreasing and airflow is towards the exhaust of the combustion chamber with an average velocity is 100 m/s.

4. Conclusion

The geometry of the combustion chamber liner is obtained by using analytical calculations with empirical data, namely by obtaining the length, diameter, and area of the liner. The bore diameter and air mass flow rate distribution on the liner have also been obtained. The difference between analytical and numerical simulation in mass flow rate at the primary zone is 3.44%, secondary zone is 9.09%, and dilution zone is 8.88%. The simulation results in the primary zone show that there is a recirculation zone at longitudinal cross-sectional section q from 32.72° to 360° with 32.73° in increment with H value variation is from 34 to 40 mm, V values variation is from 35 to 43 mm and outer recirculation tangential velocity variation from 43 to 60 m/s. the possible suitable place for injector placement. This recirculation zone can mix with the fuel which will form a continuous combustion. The results of analytical calculations from empirical data and numerical simulations are satisfying combustion chamber design requirements.

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Contributor ship Statement

RRS developed the simulation and prepared the manuscript; VW took the role of mentor and supervisor; RFNA processing numerical simulation data, and RSK plays the role of examiner

References

A. H. Lefebvre, Gas Turbine Combustion, Florida: CRC Press, 1983

A. Hupfer, W. Erhard and H.-P. Kau, Investigation of Combustor Concepts for Micro Gas Turbine Jet Engines, 23rd International Symposium on Transport Phenomena, Auckland NZ, 2012

A.C Mangra. “Design and Numerical Analysis of a Micro Gas Turbine Combustion Chamber”. Engineering, Technology & Applied Science Research (Vol.10, No.6, p. 6422-6426), 2020

Benini, E., Giacometti, S., “Design, manufacturing and operation of a small turbo-jet Engine for Research Purpose. Journal of Applied Energy” 84, Elsevier, 2007

Boyce, M. P. “*Gas turbine engineering handbook*”. Elsevier, 2011

C. A. Putra, “Design and Analysis of Annular Combustion Chamber for a Micro Turbojet Engine”. Final Report, Bandung Institute of Technology, 2020

Enache, M., Mangra, A., Carlanescu, R., & Florean, F. “The design of an annular combustion chamber”. In *Aerospace Europe CEAS 2017 Conference, Bucharest*. 2017.

F. Fuchs, V. Meidinger, N. Neuburger, T. Reiter, M. Zündel, A.Hupfer. “Challengesin designing very small jet engines - fuel distribution and atomization”. 16th International Symposiumon Transport Phenomena and Dynamics of Rotating Machinery, Apr 2016, Honolulu, United States.

Gierras, M. “Computational Study of an aerodynamic flow through a turbine engine combustor”. Archivum Combustionis (Vol.33, no.1). 2013.

Habibi, F. I., Hartono, F., & Prayogo, H. Optimization of an Annular Combustion Chamber for Micro Turbo Jet System. In *IOP Conference Series: Materials Science and Engineering* (Vol. 645, No. 1, p. 012009). IOP Publishing. 2019.

H. Savanamutto, C. Rogers and H. Cohen, Gas Turbine Theory, Harlow: Pearson education, 2001.

Mark, C. P., & Selwyn, A. Design and analysis of annular combustion chamber of a low bypass turbofan engine in a jet trainer aircraft. Propulsion and power research, 5(2), 97-107. 2016.

Meyers, B. C. The preliminary design of an annular combustor for a mini gas turbine. *ISABE 2015 (Awatef Hamed, Faculty Work and Research, College of Engineering and Applied Science)*. 2015.

Mohammed, R. S. E. Design and analysis of annular combustion chamber for a micro turbojet engine. *International Journal of Aerospace and Mechanical Engineering*, *13*(4), 282-287. 2019.

Numeca Fine/Open User Guide. Numeca. 2013