Design of Combustion Chamber for Micro Gas Turbine Based on Turbocharger

Part I: Chamber Preliminary Geometry

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Abstract

Automotive turbochargers resemble gas turbines, both consist of a centrifugal compressor and a turbine. However, the former are not equipped with a combustion chamber and consequently are significantly cheaper. Therefore, equipping turbochargers with well-designed

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combustion chambers offers a great opportunity to develop low-cost micro-gas turbine engines. This paper presents a basic and simple theoretical methodology for designing a small tubular combustion chamber to be incorporated into automotive turbochargers. The combustion chamber was designed according to the characteristics of the compressor and the turbine as well as the thermodynamic processes involved. The size and geometry of the chamber have been predicted and summarized for fabrication. Further check for the axial and radial temperature profiles as well as liner wall temperatures would have to be refined experimentally in future work.

1. Introduction

The combustion chamber (CC) is the most essential part of gas turbine engines (GTE). The main task of the CC is to burn large quantities of fuel, supplied through the fuel spray nozzles, with extensive volumes of compressed air, supplied by the compressor. As a result, high-temperature gases are produced and then expanded through the turbine section to generate power [1]. This task must be done with minimum loss in pressure and maximum heat release from the burned fuel which takes place in limited space. To obtain the required high power output, a comparatively small and compact combustion chamber must release heat at exceptionally high rates [11]. Furthermore, the CC should provide high combustion efficiency, reliable and smooth ignition, wide combustion stability limits, low-pressure loss, size and shape compatibility, low cost and durability and other requirements according to its applications [2]. Also, the CC had to be designed so that the combustion process continuously sustains itself and the temperature distribution is sufficiently below the maximum working temperature of the turbine. These requirements have made the design and construction of the CC in GTE extremely difficult. A solution to these difficulties requires a good understanding of the physical and chemical processes taking place inside it.

The CC of the GTE seems to be a mechanically simple device; however, this appearance is misleading because of the close interdependence of the various phases of its design. For instance, the holes and louvers arrangement, the fuel injection characteristics, the degree of uniformity of the air supply, and the location of the igniter mutually affect one another. Also, the CC involves complex three-dimensional flows, heat transfer, mass transfer, radiation, droplet evaporation, and chemical kinetics [7].

Before the arrival of computer and simulation software, the design of early CC was predominantly dependent on experimental work and needed a long time of cut-and-try development [7]. Moreover, during the last six decades, GTE technology has undergone substantial development, and its design and conceptualization are extensively undertaken based on empirical co-relations [5]. At present, the high cost of rig testing and the increased availability of complex CFD simulations have minimized the use of these experimental methods [6].

In recent years, small or micro GTE has become attractive as a propulsive power unit for small aircraft, power generation, and research applications where large GTE is not easily available. Despite being very expensive to manufacture, modern micro GTE matches the large engines in function and sophistication with the advantages of small and compact size, light-weight, low fuel consumption, low emitted emissions, and work with different types of fuel. These benefits make micro GTE desirable in many practical and educational applications. In engineering education, it can be used to familiarize the students with the operations, thermodynamics processes, parameters, and efficiencies calculations involved in such engines.

As mentioned above, the appearance of computational fluid dynamics (CFD) has made computer assistant programs an essential tool for GTE combustor design [2]. Several studies have utilized CFD simulations for designing and optimization of GTE combustion chamber systems [8, 9, and 10]. As a result, modern GTE combustors have been utilized to achieve high combustion and thermal efficiencies, power output, and emission reduction. Furthermore, modern new jet engines have achieved a pressure ratio of more than 22, a compressor outlet temperature of about 600°K, and a turbine inlet temperature of about 2000°K [11]. In spite of these improvements, the use of GTE is still restricted with respect to its potential due to the high cost and complexity of the design requirements.

For these reasons, several attempts have been made to develop micro GTE by adapting automotive turbochargers via incorporating a combustion chamber and lubrication as well as fuel system accessories. In this work, a small combustion chamber was designed using a simple methodology and available theories and concepts from the recent literature to develop a suitable combustion chamber according to the characteristics of the automotive turbochargers. The design procedure was divided into two parts. The first part is about the theory, primary assumptions, and the basic chamber geometry calculation including the shape, size, and its location in the turbocharger. The second part will be conducted in future work and dedicated to using CFD ANSYS-FLUENT Software for optimum tuning of the chamber geometry for smooth and stable combustion under limited turbine rooter temperature and good combustion efficiency.

2. Combustor Configuration

As shown in Figure 1. The basic components of a combustor are: (1) the diffuser, used in combustors to decrease the high air velocity from the compressor to a velocity more suitable to sustain the combustion process. (2) The combustor's liner has two main functions; to contain the combustion process, and to regulate the air into different airflows. Since the liner is made to contain the combustion process, it should be designed and built to withstand extended high-temperature cycles and it should be cooled using part of the airflow. (3) The fuel injector is responsible for introducing fuel to the primary combustion zone. (4) The igniter that starts the combustion process which usually is an electrical spark igniter.

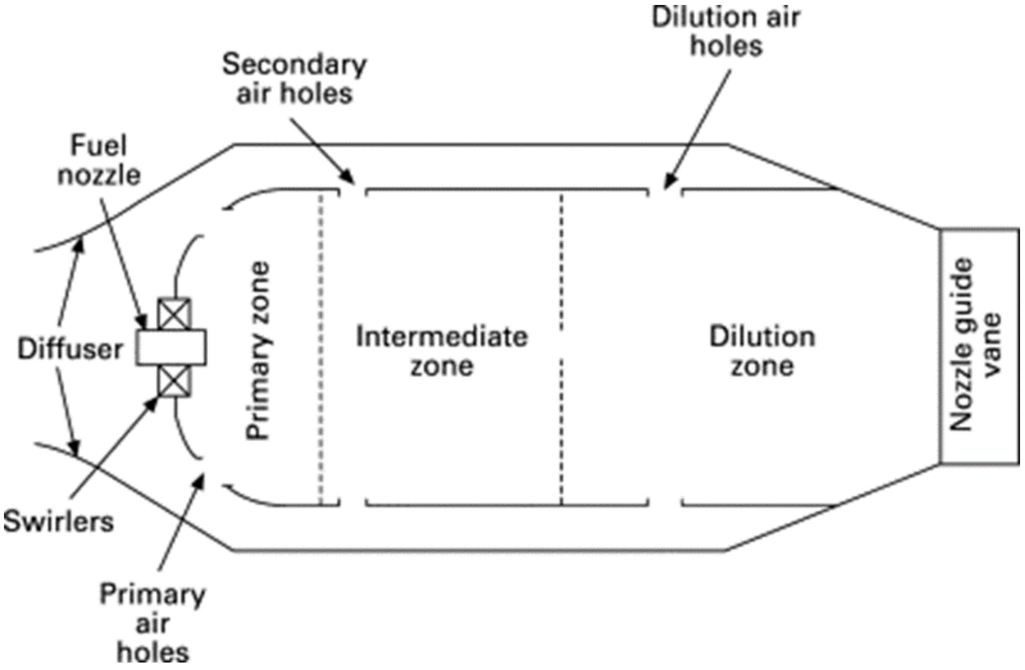

Figure 1. Gas Turbine Combustion Chamber Components

3. Combustion Process

In the beginning, the air leaving the compressor at high pressure and velocity must be defused to a few m/s at the entrance of the combustor liner. Very little air, around 10%, enters the combustion liner and is mixed with the injected fuel from a fuel injector. The rest of the air from the compressor goes through the space between the liner and the combustor casing to be used for cooling the combustor walls and then will be mixed with produced hot gases to keep it at the turbine working temperature. The combustion process in gas turbine combustors is diffusion-type combustion. Even though there are many designs and different shapes of combustors, in all gas turbine combustion chambers the combustion processes take place in three zones: (1) Primary zone, (2) Secondary or intermediate zone (Burning zone), and (3) A dilution zone, as shown in Figure 1. The total air entering the combustor is divided so that the flow is distributed among these three zones and the space between the liner and casing.

The main combustion process takes place in the primary and secondary zones. At the end of the intermediate burning zone, all fuel should be burnt, so that the function of the dilution zone is just to mix the hot gas with the dilution air. The combustor performance is measured by its efficiency, the pressure decrease encountered in the combustor, and the evenness of the outlet temperature profile. Also, the pressure loss in a combustor is a major problem, since it affects both fuel consumption and power output [7]. A pressure loss occurs in a combustor because of diffusion, friction, and momentum [7]. To avoid the thermal loading effect, the profile factor, which is the ratio between the maximum exit temperature and the average exit temperature, should be carefully considered due to its responsibility for the turbine's health.

4. Combustor Design

During this study, many design methods for combustion chambers have been reviewed and investigated [7, 8, 12, 13, 14, 16, and 17]. According to physical, aerodynamics, constrictions, and scaling effects, the idea behind the design of the combustor should be based upon the following concepts. Relative to the engine size, combustor geometry is extremely essential, since a slight shape change could lead to an increased combustion stay-time or residence time [7]. Furthermore, the fuel-air mixture should be lean to make the turbine inlet temperature within an acceptable range.

The designing method of CC for GTE offered by Lefebvre [12, 13, and 16] has been used by many searchers to provide the main dimensions of the combustor according to a given set of input data. This method is powerful to compute the reference parameters, based on the requirements of mass flow, temperature, and reference area used. These quantities are used for analysis and comparison with other arrangements of CC and are typically associated with flow characteristics, such as velocity, Mach number, and dynamic pressure. The CC sections or zones were defined based on the mass distribution and combustion processes rule. Also, the dimensions of the diffuser, the primary, secondary, and dilution zones, can be determined according to the characteristics of the flow. For this type of engine, the CC must be designed for minimum possible pressure loss due to low-pressure ratios associated with the cycle. In the present work, the CC design procedure was applied to design a simple tubular combustion chamber capable to be used for a small gas turbine engine based on an automotive turbocharger. In this design, all the focus has been given to achieving satisfactory operation that the flame must be selfsustaining and combustion must be stable over a range of fuel-air ratios to avoid high exit temperature during transient operation.

5. Combustion Chamber Geometry

5.1 Reference Area

The dimensions of a combustor might be determined either by aerodynamics or by chemical rate control [7]. Generally, when the combustor is sized for a specific pressure loss, it will be sufficient to accommodate the chemical process too [13]. According to Lefebvre [4, 16, and 13], the diameter of the combustion chamber can be calculated by:

$$A_{rf} = \frac{\pi D_{rf}^2}{4} \qquad (1)$$

Where A_{rf} is the reference area and it is defined as the maximum cross-sectional area (area of the outside diameter of the casing) and can be calculated by using the pressure losses approach as defined by Lefebvre [6].

$$A_{rf} = \left[K \left(\frac{\dot{m}_3 \sqrt{T_3}}{P_3} \right)^2 \left(\frac{\Delta P_{3-4}}{q_{rf}} \right) \left(\frac{\Delta P_{3-4}}{P_3} \right)^{-1} \right]^{0.5} \qquad (2)$$

The constant $K = Ra/2$ is the aerodynamics consideration constant and its value is 143.5 J/kgK [12]. Where $\dot{m}_3$ is the air mass flow rate at the combustor inlet, T_3 and P_3 are the total temperature and pressure at the combustor inlet, $\Delta p_{3-4}/q_{rf}$ is the ratio of pressure drop through the combustor, $\Delta P_{3-4}/P_3$ is the ratio of the overall pressure drop and the pressure drops in the diffuser and liner, and q_{rf} Is the reference pressure. Due to the fact that this project develops a tubular chamber, where pressure losses throughout the combustion chamber are around 6-8%, it was defined as an initial approximation that, the pressure loss in the flame tube is around 5% [13].

$$q_{rf} = \frac{1}{2}\rho_3 {V_{rf}}^2 \qquad (3)$$

ρ_3 Is the air density at the combustor inlet and V_{rf} is the reference velocity which can be calculated from:

$$V_{rf} = \frac{\dot{m}_3}{\rho_3 A_{rf}} \qquad (4)$$

Lefebvre [4] and Melconian & Moldak [12] suggested some typical values, for tubular combustors and they are listed in Table 1:

Table 1 Representative values of pressure-loss terms for Combustors [4, 12].

Combustor	$\frac{\Delta P_{3-4}}{P_3}$	$\frac{\Delta P_{3-4}}{q_{rf}}$	$\frac{\dot{m}_3\sqrt{T_3}}{A_{rf}P_3}$
Multi-can	0.053	40	0.003
Can-annular	0.054	30	0.0035
Annular	0.06	20	0.0045

5.2Combustion Efficiency

Figure 2 lists the combustion efficiency as a function of θ as defined by Lefebvre [7]. Here, θ is defined in equation (5).

$$\theta = \frac{P_3^{1.75} A_{ref}\ D_{ref}^{0.75}\ exp^{\frac{T_3}{300}}}{\dot{m}_3} \qquad (5)$$

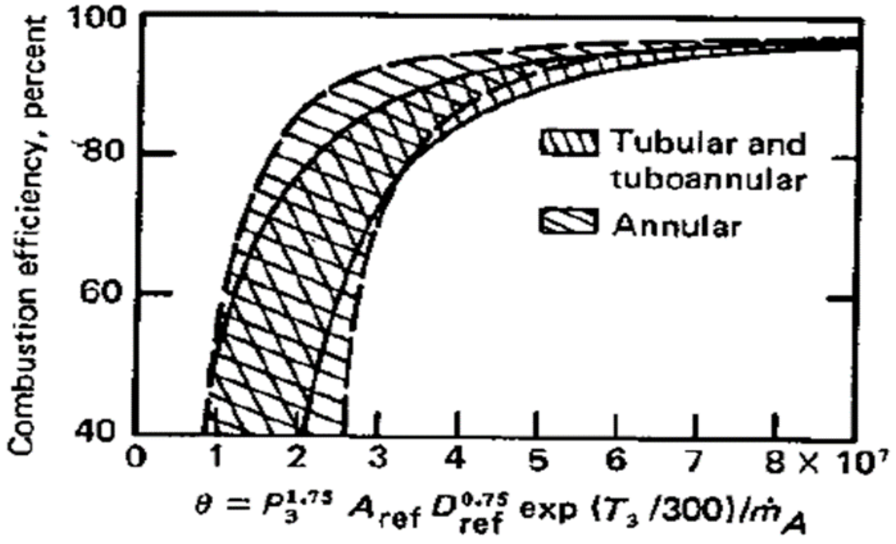

Figure 2. Relation between Combustion Efficiency and Theta Parameter [7]

By substituting the values from table 1. We get $\theta = 4.92 \times 10^7$ which is corresponding to combusting efficiency of more than 90%.

5.3 Combustion Liner Diameter

For tubular combustion chambers, the combustor liner area is calculated from the relation $A_l = 0.7A_{ref}$ [7, 12]. The liner diameter can then be calculated from $A_l = \pi D_l^2/4$.

5.4 Annulus area

The Annulus area A_{an} can be calculated from $A_{an} = A_{ref} - A_l$

6. Diffuser Design

The targeted design dimensions of the diffuser are shown in Figure 3. By assuming that 80 % of the air entering the combustion chamber is directed to the annulus area, the snout area can then be calculated from equation (6) [20].

Snout area is calculated by:

$$A_s = A_0 \frac{\dot{m}_{rz}}{\dot{m}_3} \frac{1}{C_{ds}} \qquad (6)$$

and A_0 is defined as:

$$A_0 = \frac{\dot{m}_3}{\dot{m}_{an}} A_{an} \qquad (7)$$

Where $\dot{m}_{rz}$ is the mass flow rate of air entering the flame tube and C_{ds} is the coefficient of discharge and is assumed to be 0.65. By assuming $\dot{m}_{rz}$= 20 % of $\dot{m}_3$ then A_s and D_s can easily be obtained.

The length of the diffuser is determined from $L_{df} = (r_0 - r_3)/tan\varphi$ and φ is evaluated from equation (8) [4].

$$\frac{\Delta P_{dif}}{P_3} = 1.75\, R_a \left[\frac{\dot{m}_3\sqrt{T_3}}{P_3}\right]^2 \frac{(tan\varphi)^{1.22}}{{A_3}^2} \left[1 - \frac{A_3}{A_0}\right]^2$$

(8)

$Ra = 287\ kj/kgk$, and by considering the typical pressure ratio $\Delta P_{dif}/P_3$= 1% .

The area is determined from equation (9) [12].

$$\frac{A_S}{A_0} = \frac{\dot{m}_s}{\dot{m}_3} \frac{1}{C_{ds}}$$

(9)

Where C_{ds} is the snout coefficient of discharge.

7. Length of the combustion zone

The lengths of the combustion zone L_{pz} and L_{sz} primary and secondary zone are calculated using the following equations, respectively [7].

$L_{pz} = 0.75\ \times D_l$ And L_{sz}=0.5× D_l (10)

The length of the dilution zone is a function of Temperature Traverse Quality (TQ) in the combustor exit and Pressure Loss

Factor($\Delta P_{3-4}/q_{rf}$). The value of TQ can be calculated by: $TQ = (T_{max} - T_4)/(T_4 - T_3)$ and it is usually in the range between 0.05 and 0.30 [4].

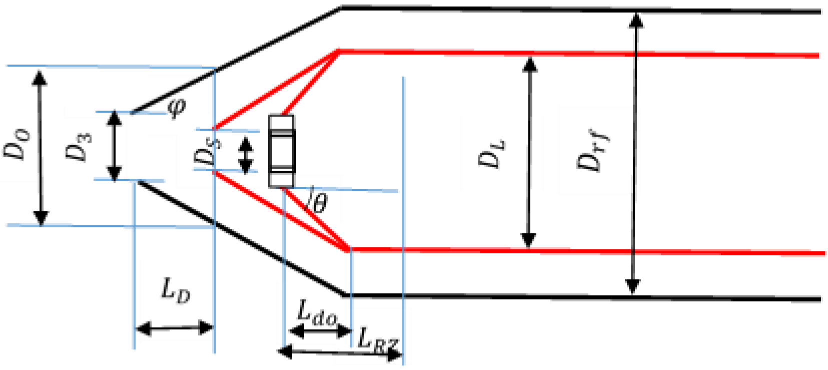

Figure 3. Combustor Front Geometry

8. Length of the Recirculation Zone

In this work, the length of the recirculation zone L_{RZ} is assumed to be twice the swirler diameter and smaller than the length of the primary zone. The swirl area is calculated from equation (11) [4].

$$A_{sw} = \sqrt{\frac{{A_{rf}}^2}{\left[\frac{\Delta P}{q_{rf}} / K_{sw} \left(\left(\frac{\dot{m}_3}{\dot{m}_{sw}}\right)\right)^2 + \left(\frac{A_{rf}}{A_L}\right)^2\right] cos^2\beta_{sw}}} \qquad (11)$$

Where K_{sw} Is the swirling constant, which is 1.3 for flat vanes and 1.15 for curved vanes [7]. In this work flat vanes are used and β_{sw} is assumed to be 45, the ratio $\Delta P/qrf$ is 3.33%, the Swirl Diameter is 0.03m, $L_{Rz} = 0.06m$, and $L_{Dom} = 0.018m$.

The length of the dilution zone was taken from [7] and is approximated to be $1.5 \times D_L$. Whereas, the angle θ is assumed to be 45^o.

9. Temperature Calculation

As mentioned in the previous section, the CC is divided into four zones: recirculation zone, primary zone, secondary zone, and dilution zone. The temperature is assumed to vary linearly between T_{in} and T_{out}. For every zone, the outlet temperature is calculated by equation (12) [13].

$$T_{out} = T_3 + \eta . \Delta T \qquad (12)$$

By assuming $T_{in} = T_3$ and ΔT is the temperature rise from T_3 to the adiabatic flame temperature at an equivalence ratio equal to one, and η is the combustion efficiency in the recirculation zone [12].

10. Cooling Air and Holes Size

To estimate the cooling air film and its effectiveness, the density of hot gases ρ_g and gas velocity U_g are evaluated as a function of the liner tube area A_{ft} that is calculated from the relation

$$U_g \rho_g = \frac{\dot{m}_g}{A_{ft}} \qquad (13)$$

Where $\dot{m}_g$ is the hot gases mass flow rate inside the combustor tube. The percentage of total air that shall be used for cooling through the liner is computed using the following equation [7]

$$\frac{\dot{m}_{cooling}}{\dot{m}_3} = 0.10 T_3 - 30 \qquad (14)$$

The air in other zones is calculated using the overall equivalence ratio of the air and fuel. The air distribution in the primary zone is computed using the following relationship [4, 20, and 21]:

$$\frac{\dot{m}_{pz}}{\dot{m}_3} = \frac{\emptyset_{overall}}{\emptyset_{pz}} \qquad (15)$$

And for the secondary zone

$$\frac{\dot{m}_{pz} + \dot{m}_{sz}}{\dot{m}_3} = \frac{\emptyset_{overall\,rich}}{0.8} \qquad (16)$$

According to Ballal and Lefebvre [4], the following values were assumed: $\emptyset_{overall} = 0.38$, $\emptyset_{overall\,rich} = 0.6$, and $\emptyset_{pz} = 0.6$. For the design and the size of the cooling holes, the following equation is recommended [4, 7, and 21]:

$$\frac{\Delta P_h}{P_3} = \frac{143.5\, \dot{m}_h^2 T_3}{P_3^2 C_{dh}^2 A_h^2} \tag{17}$$

Where $\Delta P_h/P_3$ =0.6

After knowing the amount of air that enters through the primary zone, the secondary zone, and the dilution zone, it is then possible to obtain the area of the holes A_h for each row as follows: First find the bleed ratio β which is the ratio between holes' mass flow rate $\dot{m}_h$ and the total mass flow rate in the annular area $\dot{m}_{an}$, assuming that the value of C_{dh} is 0.5 and $\Delta P_h/P_3$ is 6 %. Once the value of A_h is calculated, the area ratio α and bleed ratio β can be calculated along with the ratio μ which is the ratio between the bleed ratio and the area ratio. That is orifice Area ratio $\propto = A_h/A_n$, bleed ratio $\beta = \dot{m}_h/\dot{m}_{an}$, and $\mu = \beta/\propto$.

To calculate the hole coefficient of discharge C_{dh}, the factor of pressure loss K should be calculated from equation (18) [4].

$$K = 1 + \delta^2\{2\mu^2 + [4\mu^4 + (\mu^2/\delta^2)(4\beta - \beta^2)]^{0.5}\} \tag{18}$$

δ is the factor of momentum loss and its value varies between 0.75 -0.9 [4, 14] then:

$$C_{dh} = \frac{(K-1)}{\delta[4K^2 - K(2-\beta)^2]^{0.5}} \tag{19}$$

The value of C_{dh} must be close to the estimated value. Also, the number of holes can be determined from equation (20).

$$d_h = 2\sqrt{\frac{A_h}{\pi N_h}} \tag{20}$$

11. Design Parameter and Calculation Summary

The predicted dimensions and the designed parameters of the combustion chamber are listed in table 2. On the other hand, a schematic drawing of the CC which consists of an air jacket and a flame tube is shown in Figure.4.

Table 2. Combustion Chamber Design Parameter

Compressor isotropic efficiency	75%
Compressor inlet temperature	298 K
Compressor outlet temperature	447 K
Compressor outlet pressure	2 bar
Outlet mass flow rate	0.6 kg/sec
Fuel flow ratio	0.0067
Fuel type	Neutral gas Ch_4

The chamber inlet and outlet were fixed to match the inlet and outlet of the compressor and turbine. The most important geometries are the outer diameter and the flame tube diameter which were in the range of 13.5 and 10 cm. This was important to leave suitable jacket space in the range of 1.5cm. The flame tube has a different row of hole sizes, from 0.5 to 1 cm, distributed along the flame tube including the chamber's three zones (Primary, secondary, and dilution zones). The number of holes in each zone were 10, 8, and 8 respectively. The holes in the combustion tube can be tuned later experimentally by trial and error. Excess air passes around the liner tube and then continues into the turbine housing. The main purpose of this air layer is to cool the hot gases entering the turbine. Lastly, the mathematical model presented above was applied to calculate the final design parameters of the combustion chamber and they are listed in Table 3.

Table 3. Calculation Summary

Referance area A_{rf}	0.0138844 m^2	Snout diameter D_s	0.025 m
Referance diameter D_f	0.132 m	Length of diffuser L_d	0.064 m
Liner area A_l	0.00971 m^2	Length of primary zone L_{pz}	0.08 m
Liner diameter D_l	0.1112 m	Length of secondary zone L_{sz}	0.055 m
Annulus area A_{an}	0.0138844 m^2	Length of dilution zone L_{dz}	0.16 m
Snout area A_s	0.0016 m^2	Length of liner tube	0.298 m
Snout outer diameter D_0	0.045 m	Swirl diameter D_{sw}	0.03 m
Diameter of primary holes d_{ph}	0.005 m	Number of primary holes	10
Diameter of secondary holes d_{sh}	0.012 m	Number of secondary holes	8
Diameter of dilution holes d_{Dh}	0.008 m	Number of dilution holes	8

In part II of this study, the combustion and the flow inside the chamber will be simulated using ANSYS FLUENT software. The preliminary design geometry calculated in this work (listed in Table 3) will be used as input data in the ANSYS FLUENT simulation.

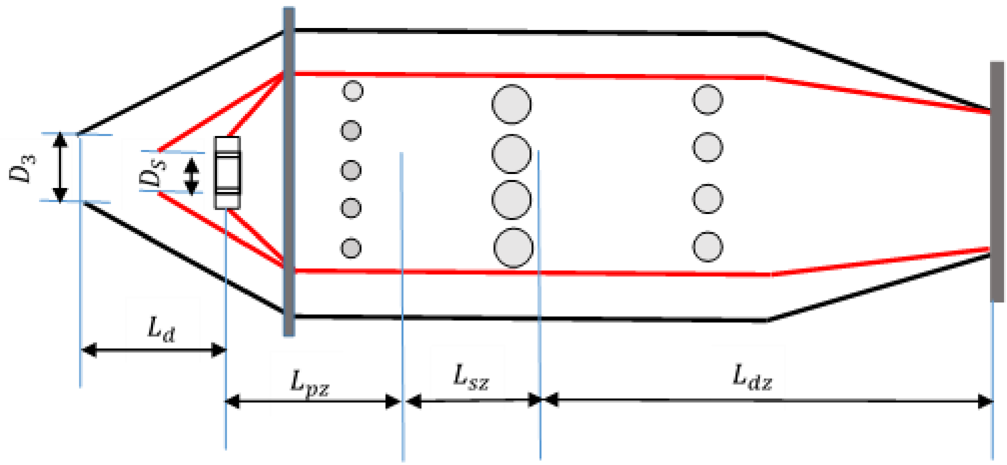

Figure 4. The Designed Combustion Chamber and Holes Distribution

12. Conclusion

This work presented the first part of designing a combustion chamber for micro gas turbine engines based on automotive turbochargers. The primary procedure for planning and calculations of the combustor geometry was presented. The methodology used for this design emphasizes mainly the practical rather than theoretical aspects of combustion chamber design. This method is suitable for this type of combustion chamber and requires minimum development time. Also as the design method depends on the experimental test for more improvement. Some geometries, such as the inlet air swirl and fuel burner, weren’t included in the calculations and for simplicity will be adopted from published articles. On the other hand, the inner and outer tube diameter, combustion zones area, hole numbers, hole dimensions and other chamber parts geometry were calculated in this paper and presented in Table 3.

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