Procedure of Combustion Chamber Airflow Rate Distribution

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Abstract— **Combustion systems are the least amenable of all gas turbine components to analyze. Among the literature overview made, it was realized that even though significant steps have been made in improving the combustor design procedure via the use of computational fluid dynamics, much of the design process still relies upon empirically derived rules. These rules include the calculation procedure of the required airflow rate by each zone of the combustion chamber to attain a suitable gas temperature, high values of combustion efficiency, low concentrations of pollutant species together with the determination of liner geometry that matches the chamber required performance goals with the constraints imposed by the engine dimensions [1,2,3, and 4]. The main target of this research work is to identify the proper procedure to distribute a predetermined airflow rate in annular type combustor and to generalize an effective calculation method that formulate and solve the problems in as much simplified and accurate manner as possible. The combustor dimensions and airflow rates in each zone is found in reference [5] and shown in Figure 1. It is designed with central vaporizing unit to deliver 516.3 KW of power with a geometrical constraint of 142 mm & 140 mm overall length and casing diameter, respectively, while the airflow rate is 0.8 kg/sec and the fuel flow rate is 0.012 kg/sec [5, 6]. The airflow rate to be distributed in the liner primary zone is 0.0798 kg/sec, while in the secondary zone is 0.133 kg/sec and in the dilution zone is 0.367 kg/sec [5]. The relevant design equations are programmed by using MathCAD language for ease and speed up of the calculation process.**

Index Terms: **gas turbine, airflow rate, annular type combustor, combustor design procedure.**

I. INTRODUCTION

In a gas turbine engine, the location of the combustion section is directly between the compressor and the turbine sections. It houses the combustion process, which raises the temperature of the air passing through the engine. The chamber liner is divided into three main zones; the primary, secondary and dilution zone, as shown in Figure 2. The primary zone known also as the main burner or the combustion zone, its function is to anchor the flame and to provide sufficient time, temperature, and turbulence to achieve rapid air-fuel mixing which promote complete combustion of the fuel.

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provide a region where dissociation losses in the gas flow can be recovered, and the burning of any imperfectly mixed fuel rich pockets of gas can be completed before then this gas enters the dilution zone; second at high altitudes, i.e. low ambient pressures, the rate of reaction in the primary zone is slower, owing to the low concentration of fuel and air, and thus combustion is far from complete at exit from the primary zone. In the dilution zone, as the gas temperature at the outlet from the intermediate zone is still too high to be tolerated by the turbine section, air is added for cooling this gas. A sufficient turbulence must be introduced so that the dilution air and hot gas are mixed to give a uniform temperature distribution at the chamber outlet [2, 7, 8, and 9]. The primary function of a combustion chamber is then to burn the fuel/air mixture, thereby adding heat energy to the air. To do this efficiently, the combustion chamber should provide means for proper mixing of the fuel and air to assure good combustion, burn this mixture efficiently, cool the hot combustion products to a temperature that the turbine inlet guide vanes/blades can withstand under operating conditions, and deliver the hot gases to the turbine section [5,9, and 10]. This entails dividing the air entering the combustion chamber by proper holes into the three main streams; primary, secondary and dilution air. The primary or combustion air is directed inside the liner at the front end, where it mixes with the fuel and is burned. Secondary and dilution air passes between the outer casing and enter the liner through proper holes. Dilution air (known also as cooling air) joins the combustion gases through larger holes at the rear of the liner, cooling the combustion gases from about 1500°C to near 800°C (for un-cooled turbine blades). Thus in order for each zone to perform its function perfectly, the airflow rate should be perfectly distributed and the proper number, size and location of the air admission holes should be found.

II. LINER AIRFLOW DITRIBUTION

Effective control of the predetermined airflow rate distribution is vital to the attainment of complete combustion, stable operation, required gas exit temperature and acceptable liner temperature distribution [1, 2, and 9]. Generally, the flow through the liner holes does not depend only on their size and the corresponding pressure drop but also on the duct geometry and flow conditions in the vicinity of the hole, which can strongly influence its effective area. The semi-empirical formulas found in references [2, 9, and 10] for determining the number, size, shape and disposition of the air admission holes within the liner that were derived on the basis of promoting an airflow pattern ensuring easy light up, efficient and stable combustion, adequate wall cooling, and delivery of uniform gas temperature profile to the turbine section; form the major design steps for this work.

A. Primary zone airflow distribution

In this zone, the combustion air is introduced through the dome (head plate) and through the first row of the liner air holes in the annulus, as shown in Figure 3, with a total amount of 0.0798 kg/sec [5,6]. An amount of 33.4% of the total primary air i.e. 0.0266 kg/sec flows through the holes located in the dome section that surrounds the vaporizer for both purposes of film cooling and participating in the combustion process [5]. While the rest 66.6% i.e. 0.0531 kg/sec of this primary airflow will then flow in the annulus section and enters through the next set of primary holes for the same purposes of liner wall film cooling and to participate in the combustion process [5]. Apart from the manner by which this amount of airflow is admitted to this zone, an efficient and easy light up of the combustible mixture together with a stable combustion remains the primary task to be considered in distributing the airflow through this zone. These combustion tasks can be met by matching the requirements of the jet penetration, the initial angle of the jet and its subsequent mixing with the hot following gas that can result in an accurate holes dimensioning together with best distribution and positioning. The condensed experimental work carried out by Lefebvre [2] and other researchers established the theory of jet flow phenomena issuing from these holes and the factors affecting the mixing process with the hot gas flowing in the combustion chamber. Their experimental analysis includes different hole shapes, numbers and initial jet angles for different chambers configuration. Their derived empirical formulas were found very useful and then used for distributing the airflow in this zone.

B. Primary zone airflow distribution in the dome section

Lefebvre [2] studied experimentally the configuration of multiple-jet penetration and their effect on the mixing process. Then he estimated the maximum penetration depth that assures the best mixing process and he came up with useful empirical formulas that relate; the maximum jet penetration with the jet diameter and momentum flux ratios; the jet diameter with the hole discharge coefficient and hole diameter; and the number of admission holes and jet diameter with the liner pressure drop, the air mass flow rate immerging from the jet and the combustor inlet pressure and temperature. It is worth to notice that Lefebvre [2] studies were concerned with round air jets flowing air into the combustion chamber and his derived empirical formulas are the one used to size the primary zone holes of the current combustion chamber. The empirical formula that relates the maximum jet penetration with the jet diameter and momentum flux ratios is found useful to estimate the jet diameter and as follows [2]:

$$\frac{Y_{\max}}{d_j} = 1.25 \times J^{0.5}\left(\frac{m_g}{m_g + m_j}\right) \qquad (1)$$

Where, mg, is the total gas flow rate, equals 0.18 kg/sec [5]. m_j, is the amount of the airflow rate to be admitted through the chamber dome section, 0.0266 kg/sec [5]. And *J* is the momentum flux ratio, defined as:

$$J = \frac{\rho_j \times U_j}{\rho_g \times U_g} \qquad (2)$$

Equation (1) above is useful to estimate the diameter of the jet (d_j) on the basis of a specified maximum jet penetration depth since all the other terms are readily calculated. In order to achieve the best performance results, typical maximum penetration (Y_{max}) for large annular combustion chambers in the range of 0.14-0.2 of the liner diameter is encountered [2, 8, 9, and 10]. For the design calculations of the current combustor, and because it is an outstanding combustion chamber designed to match specific performance requirements with such dimension constraints, an iterative calculation procedure was required to find the total number of the admission holes can be then found by the continuity equation as follows [6]:

$$m_j = \frac{\pi}{4} \times n \times d_j^{\,2} \times \rho_{inL} \times U_j \qquad (3)$$

Where, *n*, is the total number of the primary zone circumferential air admission holes. ρ_{inL}, is the combustor inlet density, equal to 2.223 kg/m3 [5,6]. And U_j, can be calculated as:

$$U_j = \left(\frac{2 \times \Delta P_L}{\rho_{inL}}\right)^{0.5} \qquad (4)$$

- ΔP_L, is the liner pressure drop in the dome section, equal to 1.072x104 Pa [5]. Equations (4) and (3) are rearranged and following useful expression results [2, 9, and 10]:

$$n \times d_j = \frac{15.25 \times m_j}{\left(P_{inL} \times \Delta P_L / T_{inL}\right)^{0.5}} \qquad (5)$$

Once the jet diameter is defined, the hole diameter can be easily found as [2, 9, and 10]:

$$d_h = \frac{d_j}{\sqrt{C_D}} \qquad (6)$$

- C_D, is the hole discharge coefficient and for best performance air admission holes should be designed with values in the range of 0.56-0.65. The hole discharge coefficient can be calculated by the following empirical formula [2]:

$$C_D = \frac{a_1 \times (K-1)}{\left[4 \times K^2 - K(2-\alpha_h)^2\right]^{0.5}} \quad (7)$$

Where,

- α_h, is known as the hole bleed ratio, , equal to 0.04 [5].
- a_1, is a constant and equals either to 1.25 or 1.65, depending upon the cooling holes types and shapes [2, and 6]. - K, is the hole pressure drop coefficient and can be given as [2]:

$$K = 1 + \frac{\Delta P_L}{q_{an}} \quad (8)$$

- q_{an}, is the annulus flow dynamic head, Pa, equal to 8.867x103 Pa [5].

In order to obtain the optimum number and size of the air admission holes that result high hole discharge coefficient and enough static pressure drop to ensure all holes in the same row pass the same amount of airflow, an iterative calculation process is required. This involves guessing the liner pressure drop; accordingly the hole pressure drop and the hole discharge coefficient are estimated by using equations (7) and (8), respectively. Then, the maximum penetration depth is guessed and accordingly equation (1) is used to calculate the jet diameter. Next, using equations (5) and (6) to estimate the number of the admission holes and the hole diameter, respectively. Then checking if the targeted hole pressure drop coefficient (0.6 or higher) is obtained with the attainment of optimum hole number and size. If not, new values of the liner pressure drop and maximum penetration depth are guessed and the calculation procedure is repeated till the desired value of hole pressure drop coefficient is matched with the correct number of holes and hole size. The distribution of the primary zone air in this section by the procedure detailed above entail a maximum penetration to liner diameter ratio of 0.088136, a jet diameter of 1.705 mm and 52 holes of 2.2 mm in diameter each is found satisfactory (i.e. a hole discharge coefficient of 0.6 is maintained) and as shown in Figure 4.

C. *Primary zone airflow distribution in the in the annulus section*

The amount of the primary zone airflow rate that has to be admitted through the annulus is 0.0531 kg/sec [5]. It is then required to distribute properly this amount through a number and size of holes that can assure best combustion performance. The procedure is based on the same principles detailed above; of achieving the maximum jet penetration that assures the high mixing rates. The empirical formulas were already detailed above, and in a similar manner, the ratio of the maximum penetration of the jet to the liner diameter is iterated and the proper distribution of the primary zone air in this section entails, a maximum penetration to liner diameter ratio of 0.076282, a jet diameter of 1.708 mm and 102 holes of 2.2 mm in diameter each is found satisfactory (i.e. a hole discharge coefficient of 0.6 is maintained). And in order to achieve better penetration and mixing process, these holes has to be distributed in two rows [2]. Thus the total number of holes calculated in this section is distributed in two rows of 51 holes each, and as shown in Figure 4.

D. *Secondary zone airflow distribution*

In order to complete the reaction process and to consume the high levels of primary zone products such as the unburned hydrocarbon (UHC) and carbon monoxide (CO), an intermediate air is introduced through a second raw of the liner holes. If these dissociated products are not recovered here, the hot gas will pass to the dilution zone and to be rapidly cooled by a massive addition of the dilution air that the gas composition will be frozen and CO and UHC, which are potentially fuel, would be discharged unburned and thus the combustion efficiency will be lowered with increased concentrations of pollutant species. It is worth to mention that, even if the combustion of the fuel is normally complete, at temperatures of 2200-2400 K prevailing in the primary zone, dissociation of carbon dioxide (CO_2) to carbon monoxide (CO) and oxygen occurs [2,8,and 10]. Thus the intermediate zone must allocate the proper length to consume these dissociated species and accordingly, the airflow has to be distributed properly to ensure the achievement of the targeted performance goals. This involves proper sizing of the air admission holes together with finding out their appropriate number. The secondary zone airflow rate is 0.133 kg/sec [5]. The procedure found in Lefebvre [2] and detailed above will be also followed to determine the optimum number, size and distribution of the secondary holes. As discussed earlier, this procedure is based on achieving the maximum jet penetration that assures the best mixing process of the secondary air with the primary zone products. Round air jets configuration is also selected to admit the air to this zone. Accordingly, the maximum jet penetration to this zone is iterated and the ratio of the maximum jet penetration to liner diameter of 0.047058 is found to match with the required hole pressure drop and hole discharge coefficient values i.e. 8.775 x 10^3 Pa and 0.6, respectively. Once the maximum jet penetration is found, the jet diameter d_j and in turn the number of the air admission holes together with the appropriate hole size can be easily determined by the procedure detailed above in Section 2.1.1. The total number of secondary holes in the annulus and their sizing are found 304 with 2.2 mm in diameter, respectively. These holes are distributed in two sets containing 4 rows of 76 holes each in the manner shown in Figure 5.

E. Dilution zone airflow distribution

The amount of the air available in the annulus should be carefully distributed to properly mix with the hot gas in order to lower its temperature and to tailor the exit temperature profile to achieve moderate turbine section life and optimum performance requirements [2, 8, 9, and 10]. The proper amount of the airflow rate to participate in the dilution process is 0.367 kg/sec [5]. The design variable remains then to find out the appropriate size of the dilution air admission holes, coupled with the correct number of jets to form sufficient localized mixing regions to ensure a satisfactory temperature profile on the chamber outlet with an adequate penetration of the dilution air jets. Lefebvre [2] investigated the effect of the hole size on jet penetration and mixing process and concluded that if the total dilution hole area is spread over a large number of small holes, the jet penetration will be inadequate and a hot core will persist through this zone. On the other hand, the use of a small number of large holes will result in a cold core, due to over-penetration, and unsatisfactory mixing. Thus the first step is to find out the optimal number and size of the dilution holes. The correlations and design charts found in references [2,10] were useful to perform this task. These design charts were generated on the basis of a condense experimental work, showing that for any given value of the ratio of the dilution air to approach gas stream mass (mj/mg), the best pattern factor is obtained for specific value of the following parameter group:

$$\left(2D_L + D_i\right)^2 \big/ nd_j D_L \qquad (9)$$

Where,
- D_L, is the liner height.
- D_i, is the liner inner diameter, 34.5 mm
- n, is the number of dilution holes
- d_j, is jet diameter, mm

Figure 6 shows one of the charts of concern for single-sided annular combustors developed by Lefebvre [2]. Since the ratio of the dilution air to approach gas stream mass ratio (m_j/m_g) is already known, the parameter group $(2D_L+D_i)^2\ /nd_jD_L$ can be read off. Then this parameter in conjunction with equations (5) and (6) derived earlier in Section 2.1.1 to relate the product of the number of holes with jet diameter *(nd_j)* and the hole diameter, respectively, leads to find out the number and size of the dilution holes together with the optimum total dilution-hole area. The number of dilution holes is found to be 4 with a hole diameter of 34 mm. It was soon realized that this combination cannot be use of a small number of large holes will result in a cold core, due to over-penetration, and unsatisfactory mixing. Instead, the total dilution hole area will be then found on the basis of achieving adequate penetration of the air jets and in turn high mixing rates with the hot gas combustion products. High values of static pressure drop and hole discharge coefficient perform the task. A targeted hole discharge coefficient of 0.6 is selected. Both continuity and Bernoulli equations are then used:

$$A_h = \frac{m_{adj}}{C_D\sqrt{2\rho_{an}\Delta P_{Ldz}}} \qquad (10)$$

Where,
- C_D, is the hole discharge coefficient and set to a desired value of 0.6.
- ΔP_{Ldz}, is the required pressure drop, Pa, equal to 7.744 x 103 Pa [5].
- m_{adj}, is the dilution air flow rate and already calculated as 0.367 kg/sec [5].
- ρ_{an}, is the air density in the annulus and equal 2.155 kg/m3 [5].

Thus, when substituting with all of these values into the above equation, the total dilution hole area is 3.217 x 10^{-3} m^2. Once the total dilution hole area is known, the next step will be to find out the optimum dilution hole number and size. It is worth to notice that on the basis of his experimental research in dilution zone performance, Lefebvre [2] concluded that the jet penetration increases with increasing the hole diameter, but the extent of this increase is influenced by the hole spacing, as closely spaced holes tended to inhibit penetration. The total dilution area has to be then spread over a reasonable number and size of admission holes in order to match with the performance goals, thus the hole diameter is then given as:

$$d_h = \sqrt{\frac{4A_h}{\pi\, n}} \qquad (11)$$

The calculation procedure involves iterating with different number of dilution holes till optimum hole spacing is found. The combination of 16 holes of 16 mm diameter each is found to perform the task as shown in Figure 7. The above equations with the calculation procedure are programmed using MathCAD language for ease of achieving results and the program flow-chart is shown in Figure 8. This chart highlights the main steps to be followed in the design calculations and clarify the solution procedure followed to obtain the optimum number of the air admission holes with the correct size that guaranties the achievement of the best performance results.

III. CONCLUSIONS

The semi-empirical formulas found in literature were gathered and used to determine the optimum number, size, shape and disposition of the air admission holes within a pre-sized combustion liner. These formulas were derived on the basis of promoting an airflow pattern ensuring easy light up, efficient and stable combustion, adequate wall cooling, and delivery of uniform gas temperature profile to the turbine section. In the primary zone, 52 holes of 2.2 mm diameter will be located in the dome section to distribute an airflow rate of 0.027 kg/sec in this section, while the rest 0.531 kg/sec flows in the annulus and will enter through 102 holes with 2.2 mm diameter arranged in two rows of 51 holes each. The interaction of the radial flow issuing from the primary air injection ports located at the dome section and the axial flow issuing from the primary holes located in the annulus together with the vaporized air and fuel mixture that is directed towards the combustion chamber dome in a reverse flow direction will set a strong recirculatory flow patterns that are of benefits for combustion stability, efficiency and ignition process. In the secondary zone, 0.133 kg/sec of the airflow will enter through a total number and size of injection holes 304 and 2.2 mm diameter each, respectively. Then these holes are in turn distributed in a manner that every set contains 152 holes arranged in two rows of 76 holes in order to provide better penetration and mixing processes. In the dilution zone, the number of dilution holes and size by using the standard design charts found in literature is found to be 4 with a hole diameter of 34 mm each to admit 0.367 kg/sec. This combination cannot be used, as small number of large holes in this zone will result in a cold core, due to over-penetration, and unsatisfactory mixing. The reasons can be due to these charts that were developed for conventional large chambers and as this chamber is compact and an outstanding one designed to meet specific performance requirements. Instead, the total dilution holes area is then found on the basis of achieving high values of static pressure drop and holes discharge coefficient to yield adequate air jets penetration and in turn high mixing rates with the hot gas combustion products. The use of continuity and Bernoulli equations yield 16 holes of 16 mm diameter each located on the outer liner to admit the required amount of the airflow rate. It is worth to notice that the dilution air entry was only feasible through the combustor outer liner, since the available annular space between the inner liner and the engine shaft is precluding reasonable flow rates or velocities in the passage to the inner diluent station. This geometrical constraint will definitely increase the difficulties in providing the targeted low exit temperature distortion. The obtained results are summarized in Table 1 and shown in Figures 9 and 10.

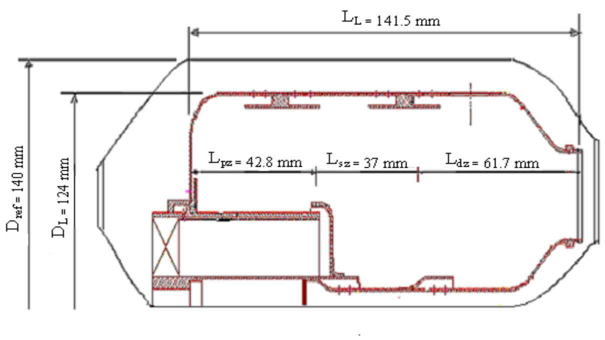

Figure 1. Chamber Main Dimensions.

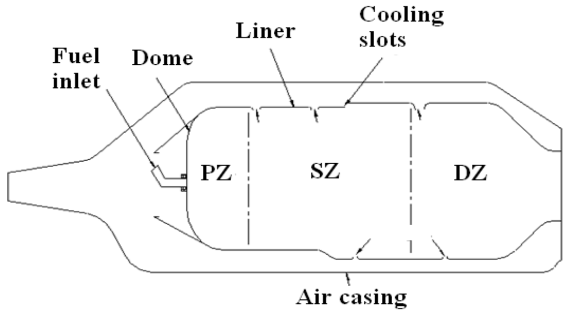

Figure 2. Combustion Chamber Zones.

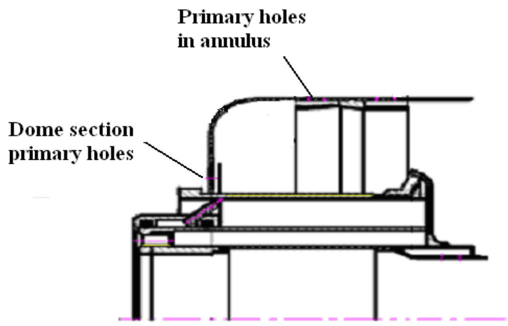

Figure 3. Primary Zone Airflow.

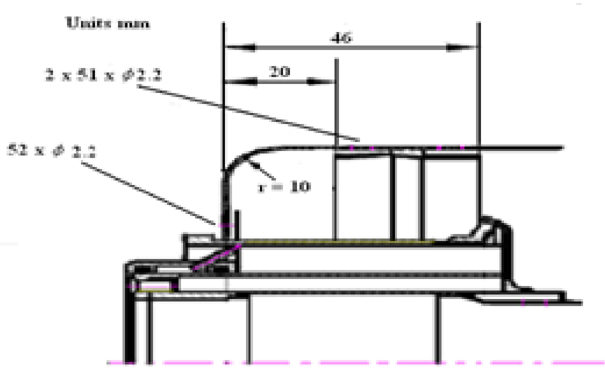

Figure 4. Primary Zone Airflow Distribution.

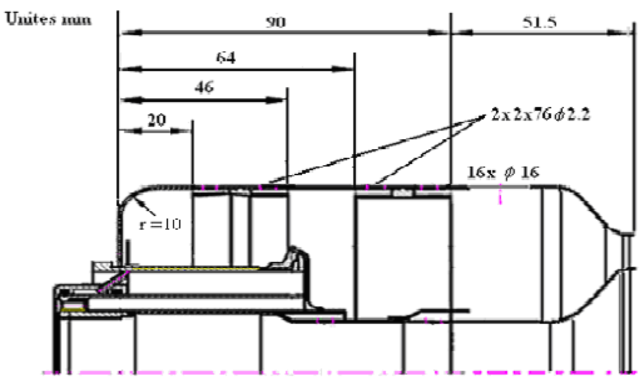

Figure 5. Secondary Zone Airflow Distribution.

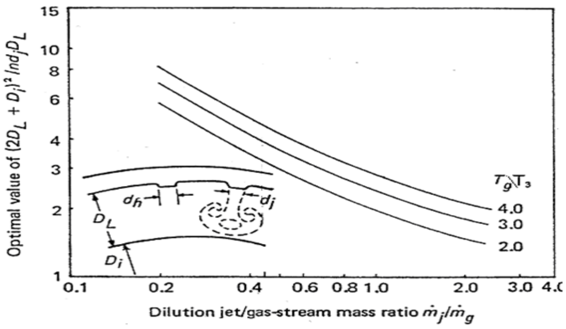

Figure 6. Dilution Zone Design Chart.

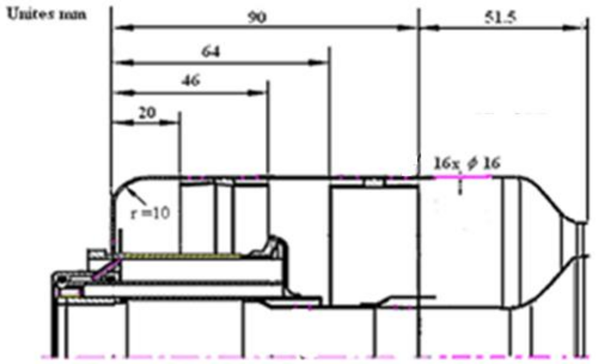

Figure 7. Dilution Zone Airflow Distribution.

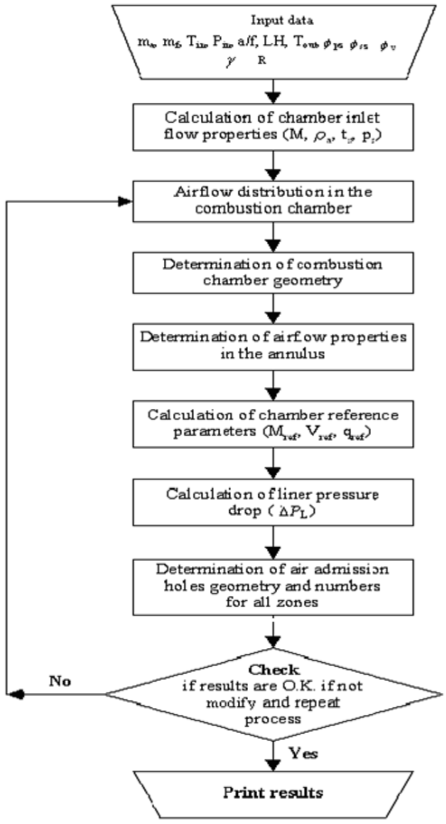

Figure 8. Physical Model Program Flow Chart.

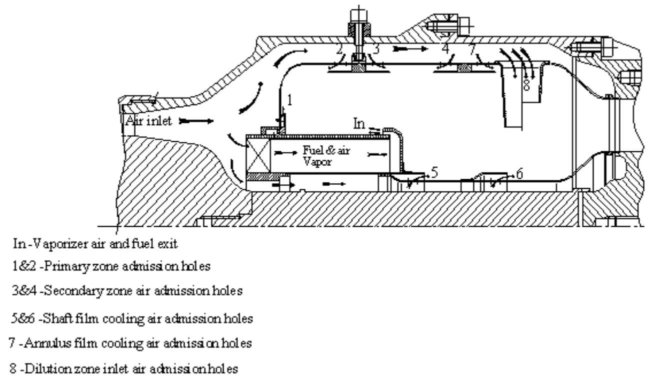

Figure 9. Air Admission Holes Location.

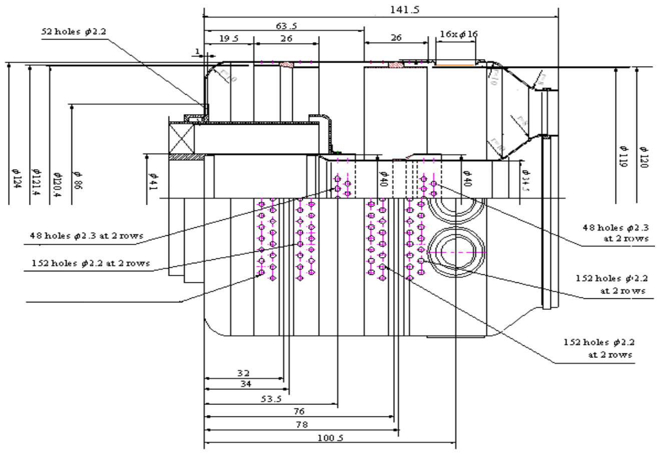

Figure 10. Combustion Chamber Dimensions and Air Distribution Summary.

Table 1. Air Admission Holes Design Calculations Summary

Location	Primary zone at chamber dome	Primary zone at chamber annulus	Secondary zone	Dilution zone
Number of holes	52	102 (two rows of 52 each)	304 (two rows of 104 each)	16
Hole diameter (mm)	2.2	2.2	2.2	16

IV. NOTATION

- Y_{max} Maximum penetration depth, m
- d_j Jet diameter, mm
- n Number of holes
- m_g Total gas flow rate, kg/sec
- m_a Total air flow rate, kg/sec
- m_h Hole air flow rate, kg/sec
- m_{an} Air flow rate in the annulus, kg/sec
- ρ_{an} Air density in the annulus, kg/m3
- m_j Airflow rate in the chamber dome section, kg/sec
- D_L Liner height, mm

-Δ_{PL} Liner pressure drop, Pa
-C_D Hole discharge coefficient
-α_h Hole bleed ratio, $\alpha_h = m_h / m_{an}$
- a_1 Constant
- K Hole pressure drop coefficient
-q_{an} Annulus flow dynamic head, Pa
-D_i Liner inner diameter, mm
-ΔP_{Ldz} required pressure drop, Pa
-m_{adj}, Dilution air flow rate, kg/sec

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