2nd Intl' Conference on Advances in Engineering Sciences and Applied Mathematics (ICAESAM'2014) May 4-5, 2014 Istanbul (Turkey)

Optimum Design Procedures of Turbojet Combustion Chamber

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***Abstract*—**The modern gas turbine engine combustion chamber industry needs a simpler and faster optimum design methods to facilitate the development process. The combustion chamber design procedure requires the selection of optimum empirically derived formulas. This paper shows the optimum design procedure of a turbojet combustion chamber by identifying the main design requirements and the selection of best configuration that matches the design key features with optimum performance. The combustion chamber input data and geometry of annular type designed with central vaporizing unit is selected as an example for the design procedure.

***Keywords*—**Optimum testing; turbojet engine; combustion chamber.

I. INTRODUCTION

THE current and future applications of the aircraft engines have requirements presenting formidable challenges to the combustor designer. Reduced cost and fuel consumption and improved durability and reliability as well as higher temperatures and pressures are forecast. Coupled with these performance requirements is the demand to control the pollutant emissions from gas turbine engines, namely the oxides of nitrogen, carbon monoxide, smoke and unburned hydrocarbons. These technical and environmental challenges have made the design of the combustion system a very hard task.

Thus, modern gas turbine engine combustion chamber industry needs a simpler and faster optimum design methods to facilitate the development process. Accordingly, in the early design phase of this project, it was targeted to generalize a calculation method that enables to understand the fundamental concepts of these coupled processes and to identify the proper procedure that formulate and solve the problems in combustion fields as much simplified as possible and accurate manner. In addition, the design procedure should generalize methods that can be applied to similar combustion chambers, as in general, most of the new engine combustors are developed on the basis of the existing ones.

Thus the combustion chamber design procedure has to be optimized. This requires the selection of optimum empirically derived formulas. These formulas include the calculation procedure of the airflow rate required by each zone of the combustion chamber, the proper distribution of such airflow to attain a suitable gas temperature at the exit plane, the determination of liner diameter and liner length that meets high combustion efficiency and both pressure drop and temperature pattern factor requirements, the determination of chamber casing diameter that matches the allocated space with chamber performance goals, and finally, the determination of the accurate size and location of the air admission holes that properly distribute the airflow rate to ensure high holes discharge coefficients, best jet penetration and momentum flux ratios that promote the best mixing process between the cold inflow and hot flowing gas to yield the targeted combustion performance goals.

Thus, with the imposition of more rigorous design performance goals together with low cost and reasonable reliability, targeting an optimum design procedures that assure higher combustion efficiency, lower pressure losses and in turn lower fuel consumption, lower emissions and stable combustion over a wide range of operating conditions with much reduced size and weight are targeted.

The combustion chamber input data and geometry found in reference [2] is selected as an example for the design procedure. This chamber is of annular type designed with central vaporizing unit to deliver 516.3 KW of power. The geometrical constrains of the chamber are 142 mm & 140 mm overall and casing diameter respectively. The airflow rate is 0.8 kg/sec and the fuel flow rate is 0.012 kg/sec.

II. DESIGN PRINCIPLES AND CONSTRAINTS

In order to optimize the design procedure of the combustion chamber and to determine properly the design parameters, the design constraints have to be clarified and their effect on chamber performance should be considered in the early design stages.

The first constraint imposed by low cost involves the elimination of turbine blade cooling and limits the combustor exit temperature to 1100 K maximum in order to assure safe and long operation of turbine blades and nozzle guide vanes.

The overall engine dimensions of 500 mm maximum length and 145 mm maximum diameter dictated a short length and small diameter combustor and in turn will increase the difficulties of achieving an optimum design in terms of geometry and performance results. It was realized in the early design stages that a high temperature rises of about 600K in this short length is required together with a combustor efficiency of 98% minimum. Further more, a temperature pattern factor not higher than 0.45 is targeted to assure a satisfactory turbine section life and a combustor average exit gas temperature within 1100 K.

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http://dx.doi.org/10.15242/IIE.E0514026

Also in order to limit the exit gas temperature to be within the required value, to protect the liner walls and to obtain good ignition characteristics coupled with high combustion efficiency at low power conditions, the equivalence ratio in primary zone of combustion chamber entails a range of values in order of 0.7 to 0.95 to be considered [2,4].

The constraint imposed by the combustion products dissociation losses due to chemical instabilities, namely the carbon dioxide and water vapor in the intermediate zone entails to distribute the air properly to achieve an equivalence ratio of 1.7 and in turn a gas temperature limited to 1700 K and thus recombination of the dissociated products can be made feasible [3, 4, 5].

Finally, in order to lower the production costs, the combustor chamber can be made of SST 321 material.

TABLE I
COMBUSTOR INLET FLOW CONDITIONS

Design parameter	Design value
Inlet air mass flow rate (m_a)	0.8 kg/sec
Inlet total pressure (P_3)	2.85×10^5 Pa
Inlet total temperature (T_3)	423 K

TABLE II
COMBUSTOR OUTLET FLOW CONDITIONS

Design parameter	Design value
Outlet total temperature (T_4)	1100 K
Fuel flow rate (m_f)	0.012 kg/sec
Overall combustor F/A ratio	0.015

III. PHYSICAL MODEL AND DETAILED PARAMETERS

In order to match with the required design performance goals of good ignition, wide combustion stability limits and relatively high combustion efficiency at low power conditions, the primary zone of the combustor is designed to operate with approximately stoichiometric air-fuel ratio in the primary zone at an equivalence ratio of 0.95.

The chamber is designed with a central vaporizer unit. The vaporization method involves the injection of the fuel along with the pre-determined amount of air that flows through the vaporizer tube in order to vaporize the fuel as well to cool the tube. With this air allocation, fuel coking is precluded and carbon formation in the combustor primary zone is minimized. The fuel is directed from the fuel tube and injected into the vaporizer with low injection velocity. The fuel mixes with the air in the vaporizer tube and then directs in a reverse flow direction towards the combustor head plate (dome). Fuel vaporization and combustion with the remaining primary zone airflow introduced into the liner air injection ports occurs in the primary zone. Strong recirculatory flow patterns are then expected to setup in this zone by the interaction of the axial and radial flows issuing from the liner primary air injection ports. The remaining airflow is used for diluents air mixing and for cooling of the liner.

Also, the combustion chamber should be equipped with an air swirler to assure high mixing rates of air and fuel to result a uniform mixture in a vapor form on the vaporizer exit. This is required to complete the burning of the fuel within the main zone of combustion and to assure then the achievement of optimum performance results.

In order for the chamber design to match with the required performance goals of complete combustion and in turn high combustion efficiency, good temperature traverse quality with a tolerable pattern factor, stable combustion and low exhaust emissions, the airflow has to be carefully distributed through out the chamber that every zone will perform the intended optimum task. The calculation procedure of the airflow distribution together with sizing of the air admission holes for each zone of the combustor will be discussed in details bellow.

Figure 1 relates the combustor efficiency with combustor loading.

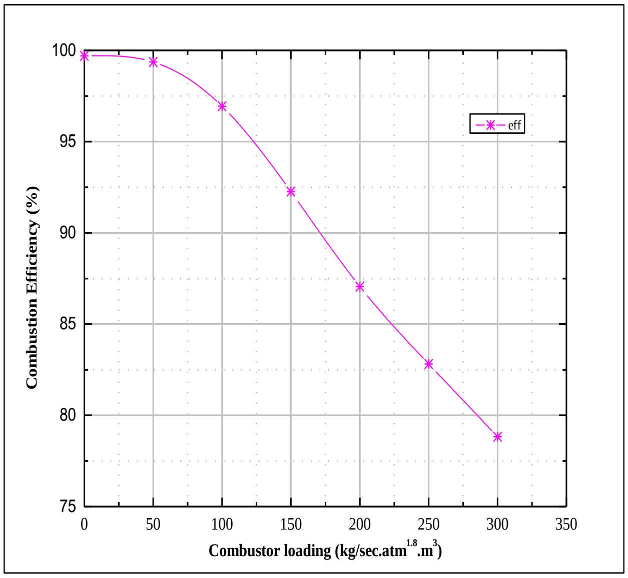


Fig. 1 Combustor efficiency versus loading

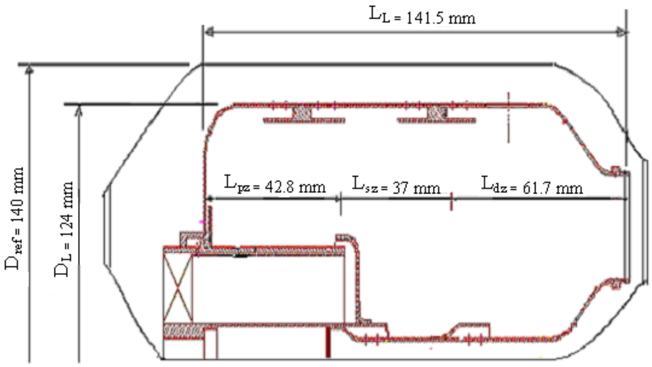


Fig. 2 Main dimensions of combustion chamber

IV. RESULTS

In order to match with the required design goals, the combustor primary zone is designed with fuel rich mixture at an equivalence ratio of 0.95. A primary zone airflow rate of 0.1684 kg/sec was found to perform good ignition performance, and promising low NO_x emissions and high combustion efficiency at low power conditions with the expenses of increased exhaust smoke and reduced volumetric heat release rate [3].

An airflow rate through the vaporizer tube in the order of 0.0886 kg/sec is used for both purposes of vaporizing 0.012 kg/sec of gasoline fuel as well as to cool the tube. With this air allocation, fuel coking is precluded and carbon formation in the combustor primary zone is minimized. The fuel is directed from a tube into the vaporizer inlet and mixes with this air in the vaporizer tube. Then this mixture flows in a reverse flow direction towards the combustor head plate. Both of fuel vaporization, mixing with primary zone airflow and then complete combustion process is intended to occur in this zone of the combustion chamber.

The distribution of the primary zone air is such that 33.34% i.e.0.027 kg/sec enters through 52 holes of 2.2 mm diameter located in the dome section and the rest 66.6% i.e. 0.0531 kg/sec, flows in the annulus and enters through 102 holes with 2.2 mm diameter each and 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 sets a strong recirculatory flow patterns that are of benefits for combustion stability, efficiency and ignition process.

The remaining airflow is used for both secondary and dilution zones as The remaining airflow is used for both secondary and dilution zones as well as for film cooling of the liner at the outer and inner locations. In the secondary zone, 0.133 kg/sec of air was necessary to achieve an equivalence ratio of 1.7, to complete the reaction process that has been already started in the primary zone and to consume the high levels of primary zone carbon monoxide and unburned hydrocarbon (fuel) that ensures the elimination of such dissociated products from entering the dilution zone and this in turn assures the achievement of higher combustion efficiency. The total number and size of the secondary zone air injection holes are found 304. Then these holes are in turn in a manner that every set contains 152 holes arranged in two rows of 76 holes of 2.2 mm diameter each.

In the dilution zone, an amount of 0.367 kg/sec of air enters through 16 holes of 16 mm diameter each located on the outer liner. This amount of air is distributed to assure maximum penetration and high mixing rates, that the turbine section can tolerate the gas exit temperature distribution. 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 a low exit temperature distortion.

In order to protect the liner walls form overheating, it was necessary to introduce an amount of airflow that will form a barrier against the hot following gas. Accordingly, 6.58% of the chamber total airflow rate i.e. 0.053 kg/sec enters in the annular space between the inner liner and engine shaft to film cool the liner wall at this location and distributed through 96 holes total of 2.3 mm in diameter each, as shown in Figure 3. These holes are in turn arranged in two sets of 48 holes each that each set in turn contain two rows of 24 holes. This arrangement assures the proper air distribution and guaranties maximum protection to the inner liner wall.

An amount of airflow rate was required to enter the annulus passage of the combustor to film cool the outer liner at this location and 9.53% of the chamber total airflow rate i.e. 0.079 kg/sec is admitted through 152 holes total with 2.2 mm diameter each. And in order to distribute this air properly to perform the required task of the liner wall protection from overheating, these holes are in turn arranged in two rows of 76 holes of 2.2 mm diameter each.

The calculation of the combustion zone length (primary zone length) is based on the chamber volume, inlet velocity and combustion products residence time. The combustion chamber volume is in turn determined on the basis of the stirred reactor model found in [3, 5] that stands on the requirement of achieving an altitude combustion efficiency of 85%, and accordingly, the combustion volume is found 0.0005175 m3 and the corresponding liner inner diameter is 124 mm.

The calculation of the combustion chamber reference diameter was determined on the basis of the reaction rate (θ) parameter that is originally found in [1, 3] and on the basis of a targeted altitude efficiency of 85%, the chamber reference diameter of 140 mm is found satisfactory.

The combustion chamber length is calculated on the basis to match with the required pattern factor and to provide enough distance that controls the time and mixing process. This length was found 141.5 mm and expected to be enough to provide flame stabilization, complete combustion, and through mixing process with the dilution air.

The primary zone length is determined by the procedure that is based on achieving the optimum gas products residence time to complete the combustion process and in turn to obtain higher values of combustion efficiency, to assure wider stability limits and better ignition characteristics. Thus, the primary zone products residence time is found 1.317 ms, while the air velocity at the inlet to this zone is 32.5 m/sec. While, the primary zone length is found 42.8 mm.

The secondary zone length is determined by the procedure found in [3] i.e. on the basis of achieving just enough residence time to complete the reaction process and to consume the high levels of primary zone carbon monoxide and unburned fuel before the gas enters the dilution zone. And accordingly, the gas residence time in the secondary zone is found 1.003 ms, while the gas velocity at the inlet to this zone is 36.915 m/sec. Thus the secondary zone length is found 37 mm.

Once the optimum liner overall length together with the optimum primary and secondary zones lengths were already determined, the dilution zone length is obtained by subtracting from the total chamber length, the primary and secondary zone lengths and found 61.7 mm.

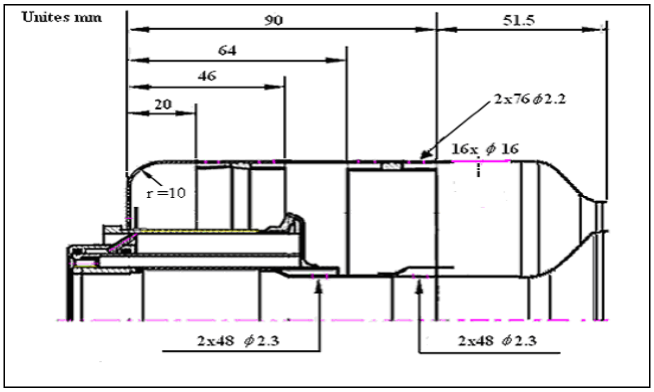


Fig. 3 Dilution zone and film cooling airflow distribution

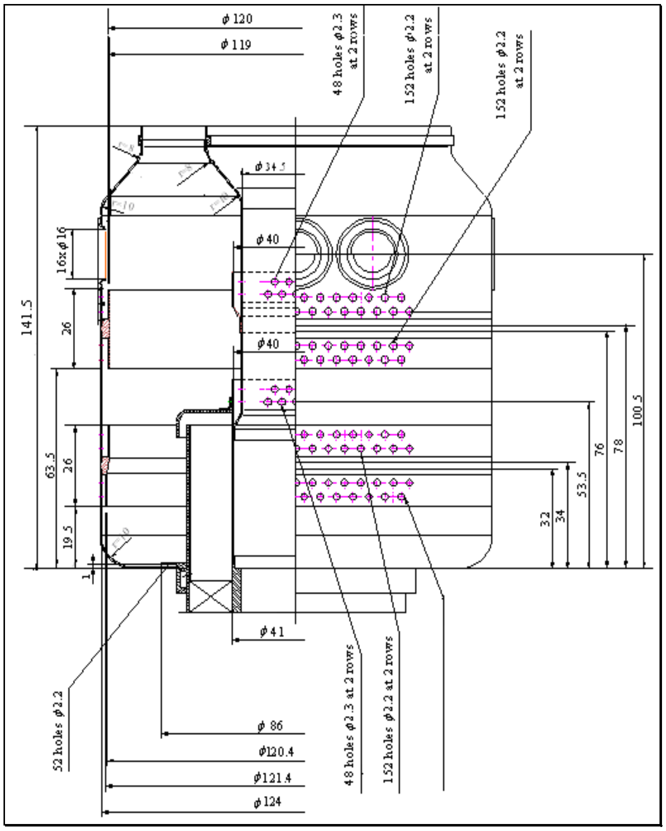
The values of the chamber flow reference quantities, such as the reference velocity, i.e. the mean velocity across the plane of maximum cross-section, the reference dynamic head, the reference flow Mach number and the chamber overall pressure loss factor are found as, 23.634 m/sec, 0.059, 620.905 Pa and 5.1%, respectively. These values when compared with the design data available in the wide literature found very reasonable.

Finally, Figure 4 shows the chamber configurations, Also the chamber geometry is detailed in Figure 5

Fig. 4 Combustion chamber configuration

V. CONCLUSIONS

In order to investigate the validity of design rules, an annular combustion chamber equipped with a central vaporizing unit found in [2] and designed to deliver 513.6 KW of power is selected as an example. The chamber outer dimensions are of 142 mm and 141.5 mm diameter and length, respectively. The performance goals targeted combustion efficiency not less than 98%, a temperature profile factor not exceeding 0.3, a liner pressure drop of 6% maximum. The chamber envelope constraints increased the difficulties to achieve the required 670 K high temperature rise in such short length combustor with high performance requirements.



(All dimensions in mm)

Fig. 5 Combustion chamber dimensions summary

The chamber inlet flow conditions are such, the inlet air and fuel mass flow rates is 0.8 kg/sec and 12 g/sec, respectively, the inlet air total pressure and temperature are 285000 Pa and 423 K, respectively. While the targeted chamber outlet flow conditions were of total gas exit temperature 1100 K maximum with an overall combustor fuel/air ratio of 0.015.

The chamber primary zone was designed with fuel rich mixture strength at an equivalence ratio of 0.95 to guarantee good ignition performance coupled with high combustion efficiency at low power conditions, while in the secondary zone, an equivalence ratio of 1.7 was selected in order to determine the proper amount of the secondary airflow rate that promotes the recombination process of the dissociated primary zone products.

Meanwhile, the calculation of a number of reference flow parameters was performed in order to facilitate the analysis of combustor flow characteristics and to allow a good judgment for the aerodynamic performance by comparing with previous designs carried out in this field. Accordingly, The values of the reference velocity, i.e. the mean velocity across the plane of maximum cross-section, the reference dynamic head, the reference flow Mach number and the chamber overall pressure loss factor are found as, 23.634 m/sec, 0.059, 625.24 Pa and 5.1%, respectively. These values when compared with the design data available in the wide literature sound very reasonable.

REFERENCES

[1] Gordon, C. Oates Aircraft Propulsion Systems Technology and design, AIAA education series1988.

[2] Nikola Davidović Mathematical Model of Turbojet Engine Combustion Chamber Primary Zone, May 2007

[3] Arthur H. Lefebvre Gas Turbine Combustion, Hemisphere Publishing, USA 1983.

[4] Gordon C. Oates Aero thermodynamics of Aircraft Engine Components, AIAA education series New York, 1985.

[5] P.P. Walsh & P. Fletcher Gas Turbine Performance, Black well Science, England 1998.

[6] Jack D. Mattingly, William AIAA Educations series, 1987.