

Development of an augmented conceptual design tool for aircraft gas turbine combustors

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ABSTRACT

Combustor design is the most unreliable and challenging portion in the design process of a gas turbine. To ensure the proper performance, many experimental tests must be performed on a combustor in the industry. The above mentioned design phase is costly and time consuming. This paper focused on an automated and augmented conceptual design methodology for conventional combustors. The design tool developed for this study employs empirical and semi-empirical models which include two main parts of the combustor, the reference diameter and area as well as the component design. The necessity of this work arose from an urgent need for comprehensive and fast generation data in the conceptual design phase of a combustion chamber. This automated and comprehensive tool, equipped with the capacity to provide many details, has a considerable impact on the reduction of further experimental effort. Also, the said tool is equipped with a geometrical model generation section that has application in the future design phases, e.g., detail design.

1. INTRODUCTION

The designing of gas turbine combustors and the analyzation of combustion creates fundamental challenges for designers. Since combustion is a complex phenomenon and its modeling seems problematic, there are a large number of design requirements that must be observed. The combustor is known as a heat machine that transfers the potential chemical energy of fuel into thermal energy of process air by taking into consideration the maximum possible efficiency, flame endurance, stability, and reliability, even in the most unfavorable conditions. Reaching the collective values for the purported terms should be taken into account during the design process. Also, the temperature profile at the exit and emission level should be considered in this process.

The engineering design problems may include conceptual, preliminary, detail, and experimental design phases. In the initial phases of the classic design procedure, a combustor model is built upon a series of calculations used in acquiring the required amount of fuel flow to reach a target temperature while only considering some of the general geometrical parameters. Then, the remaining design phases become increasingly complicated and more expensive. In other words, most of the achievements in combustor

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design is dedicated to the experimental phase which is costly and time consuming. Nowadays, the increased use of fossil fuel and strict laws for engines to be ever more environmentally friendly, push the gas turbine designers to modify the existing designs or to develop new generations of combustors. A conceptual design tool may assist the designers by targeting more features of the combustor in the initial design phases, and thus reducing the number of trials during the experimental tests.

Combustor design is known to be governed by semi-empirical models. These relations are well documented for conventional combustors [1-5]. In addition to having a considerable effect on the final specifications of the combustor, these models are usually incorporated into the manufacturer's design philosophy. In addition, the combustor design is often discussed at a more fundamental level in the available literature. Due to the existing varieties of gas turbine engine types and applications, there are several methods used in designing gas turbine combustors. Therefore, different approaches and considerations of combustor design are presented in the above cited references. Large numbers of general combustor design methodologies have been reported in the literatures [6-13]. A more detailed design process for conventional combustors is presented by Pegemanifar and others [14-16] where a non-extensive statistical effort has been implemented. This effort is assisted by an automated tool chain consisting of CAD files and CFD (Computational Fluid Dynamics) mesh generation and analysis to optimize the design. Although the CFD has high fidelity, it is costly in terms of time and money; also the results may vary dramatically by changes in user settings. Therefore, this approach is not suitable for the automated process in the conceptual design phase.

In this work, a comprehensive study of the gas turbine combustor design was performed to derive a general method that included all the recommendations and considerations of previous works. This provides potential users with the most allocable parameters and details. This paper focused on an automated, augmented conceptual design methodology for conventional combustors. Also, this methodology with some minor modifications can be used for any new types of combustors such as DLE (Dry Low Emissions) or RQL (Rich Quench Lean) combustors. Furthermore, the acquired data from the current study were used to develop an automated tool to generate the conceptual 2D geometry of a designed combustion chamber.

2. DESIGN TOOL STRUCTURE

The procedure proposed in this paper is a design methodology for a combustor as described in Figure 1. This method is based on analytical and experimental correlations.

Before starting the design process, it is necessary to define the required inputs. The design inputs can be divided into two main categories: engine cycle thermodynamic data (at on-design and off-design conditions) and constraints and variables of design space.

The input data are used to estimate the reference diameter and area. The calculated dimensions and other input data are required for a component design module. Also, the results of the chemical equilibrium analysis code are used in this step. Finally, all the calculated geometrical data are used for producing a two-dimensional drawing of a combustor at the conceptual design phase.

3. COMBUSTOR REFERENCE DIAMETER AND AREA

The reference area (A_{ref}) is defined as the maximum cross section area of the combustion

chamber casing without taking the burner into consideration; similarly, the normal length of that area is known as the reference diameter (D_{ref}). Figure 2 illustrates the reference diameter and the liner or flame tube diameter (D_{ft}) for different types of turbine engine combustors.

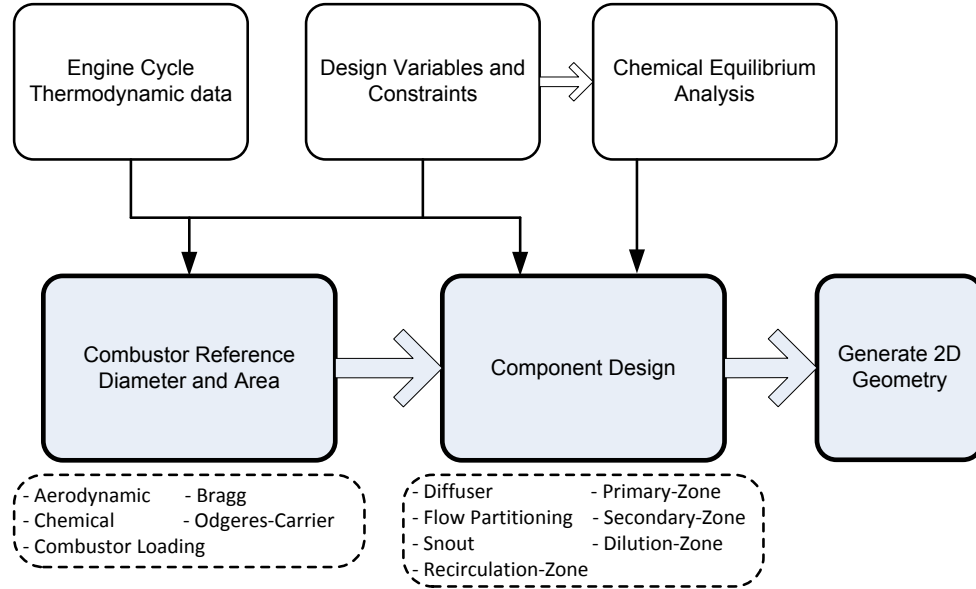


Figure 1: Flowchart of the combustor design procedure

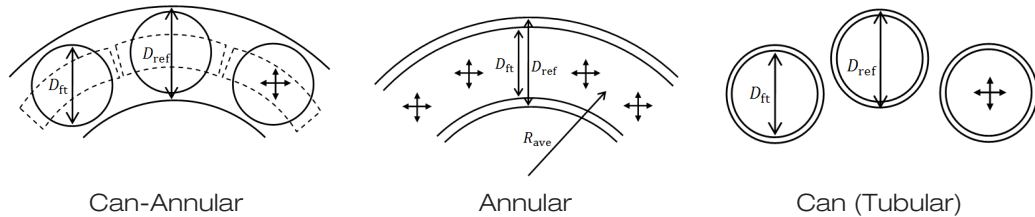


Figure 2: Reference diameter for different combustor configurations

As shown in Figure 2, there is a minor difference in the calculation of the reference area between annular and other types of combustors:

$$A_{ref} = \begin{cases} \pi D_{ref}^2/4 & \text{Can and Can-Annular} \\ 2\pi R_{ave} D_{ref} & \text{Annular} \end{cases} \quad (1)$$

The reference area is selected by considering the possibility of either the chemical or pressure loss (aerodynamic) limitations [1]. Each operating condition is considered and, from the tabulated answers, the optimum value is assessed. This method is presented in the following sections.

3.1 Aerodynamic and Chemical Considerations

The reference diameter of a combustor might be determined by either aerodynamics or by reaction rate control. Generally, if the combustor is sized to meet a specific pressure loss, it will be large enough to accommodate the chemical reactions [1].

Equation (1) can be used in calculating the reference area considering aerodynamic (pressure-loss) terms in SI units [1, 2]:

$$A_{ref} = \left(143.5 \left(\frac{\dot{m}_3 T_3^{0.5}}{P_3} \right)^2 \left(\frac{\Delta P_{3-4}/q_{ref}}{\Delta P_{3-4}/P_3} \right) \right)^{0.5} \quad (2)$$

In which \dot{m}_3 is the total mass flow rate, T_3 is the inlet temperature, P_3 is the inlet total pressure, ΔP_{3-4} is the combustor total pressure loss, and q_{ref} is the dynamic pressure at the reference cross section (diffuser outlet). The $\Delta P_{3-4}/q_{ref}$ parameter is known as the pressure loss factor. The pressure loss factor is a fixed property of the combustor. It represents the sum of two separate sources of pressure loss: (1) pressure drop in the diffuser, and (2) pressure drop across the liner.

The reference area calculation formulas from the chemical (combustion) considerations are as follows [1, 2]:

$$A_{ref} = \left(\frac{\dot{m}_3 \theta}{(4/\pi)^{3/8} P_3^{1.75} \exp(T_3/b)} \right)^{8/11} \quad (3)$$

where b is the temperature correction factor that is estimated by the empirical equations that is presented in the flowcharts of Figure 3. Also, θ is a correcting parameter. All types of turbine engine combustors have combustion efficiencies (η_c) close to 100% at a value of θ equal to 73×106 (SI units) [1, 2].

Figure 3 represents a calculation flowchart of the aerodynamic and chemical considerations for the reference area and diameter.

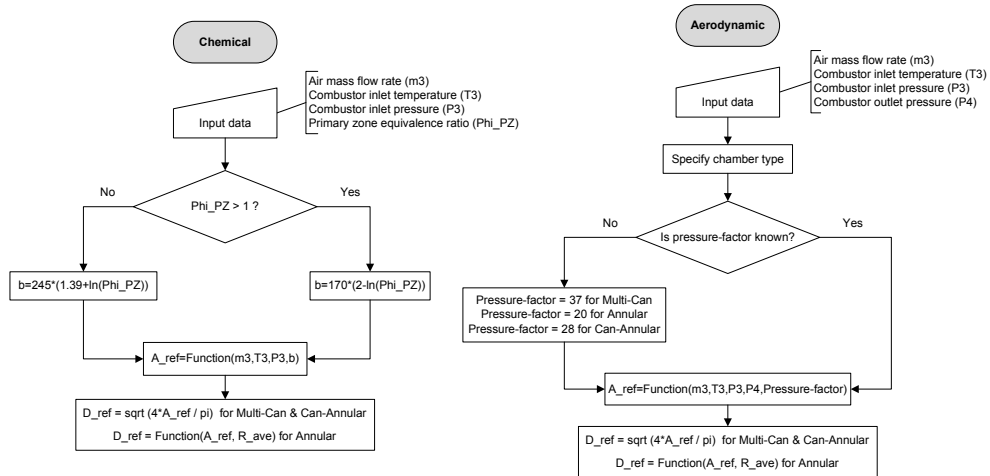


Figure 3: Calculation procedure of aerodynamic and chemical considerations

3.2 Combustion Loading Approach

The combustor volume (V) can be calculated by considering loading at different operational conditions. The combustion loading in SI units is:

$$\text{Loading} = \frac{\dot{m}_3}{V P_3^{1.8} 10^{(0.00145 \cdot (T_3 - 400))}} \quad (4)$$

In the above equation, combustor volume (V) represents the Liner (flame tube) volume. At the on-design operation (sea level static maximum rating), loading should be less than 10 kg/s atm1.8m3, and preferably less than 5 kg/s atm1.8m3. For industrial engines, a greater volume is practical and values as low as 1 kg/s atm1.8m3 may be attainable [3].

The calculated value of the combustor volume from Equation (4) must be checked by combustion intensity limitation:

$$\text{Intensity} = \frac{\dot{m}_f \eta_c LHV}{V P_3} \quad (5)$$

where \dot{m}_f is fuel mass flow rate and LHV is fuel lower calorific value (kJ/kg). Similar to loading, the smaller values of the combustor intensity is desirable. For the on-design operation, intensity should be less than 60 MW/m3 atm.

The flowchart for the sizing procedure by means of the combustion loading approach is illustrated in Figure 4. For the sake of brevity, some of the relations and equations are not included and can be found in [3].

3.3 Other Methods

In this section, two other alternative methods for combustor size prediction is proposed. Bragg suggests the following equation for determining the flame tube area [17]:

$$A_{ft} = 1.621 \times 10^{-2} \frac{\dot{m}_f T_3^{0.5}}{PR} \left(\frac{P_3}{\Delta P} \right)^{0.5} \quad (6)$$

where PR is the pressure ratio of the compressor.

On the other hand, by utilizing the proposed equation of Odgers and Carrier [18], the flame tube diameter can be determined. The main equation in the cited methodology is:

$$\log \psi_{300} = -1.39 - 4.40 n - 1.10 D^* \quad (7)$$

where ψ is kinematic fuel loading, n is reaction order that is equal to 2ϕ (lean) or $2/\phi$ (rich). The term D^* is a constant empirical coefficient that is obtained from:

$$D^* = 0.736 - 0.0173 (P_3/\Delta P) \quad (8)$$

It is necessary to mention that the D^* parameter is only calculated at the on-design condition.

The calculated values of ψ_{300} is corrected using the following equation:

$$\psi_{T_3}/\psi_{300} = (10^{-3.054 y^{-1.205}}) (T_3^{1.2327 y^{-1.205}}) \quad (9)$$

where $y = 1$ (for lean mixture) or $y = \phi$ (for rich mixture).

Finally, the values of the flame tube diameter can be obtained from:

$$D_{ft} = \left(\frac{4 \dot{m}_f}{\pi \psi_{T_3} P_3^n} \right)^{1/3} \quad (10)$$

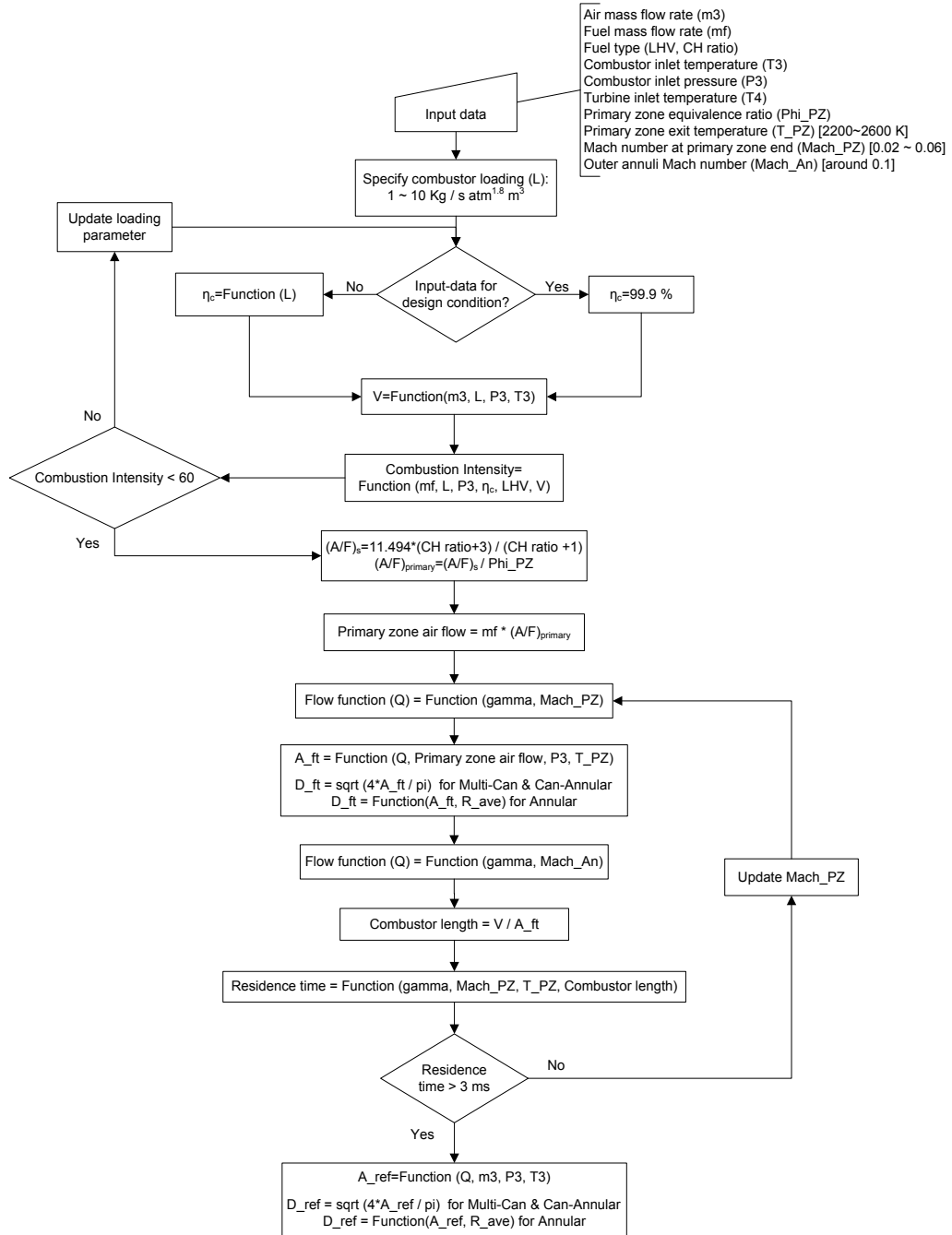


Figure 4: Calculation procedure of the combustion loading sizing approach

3.4 Selection of Appropriate Combustor Diameter and Area

In sections 3.1 to 3.3, five different methods for determining the reference diameter and area of combustors is presented. In Bragg's as well as Odgeres-Carrier's method, the liner section dimensions are proposed instead of the outer casing. The following recommendations for the relation between the liner and outer casing (reference) dimension of gas turbine combustors are as follows [1]:

$$A_{ft}/A_{ref} = 0.7 \quad (11)$$

and in order to maximize the ratio of dilution jet penetration per jet diameter, the following equation is suggested [19, 20]:

$$A_{ft}/A_{ref} = 1 - \left(\frac{\dot{m}_{Annulus}}{\dot{m}_3} \right)^{2/3} \left(\frac{\Delta P_{3-4}}{q_{ref}} \right)^{-1/3} \quad (12)$$

Due to variations in the theoretical and empirical background of the previously mentioned sizing methods, a valid deviation in the output metrics would be significant as expected. Therefore, it is desirable to establish a comprehensive method by which constrains of the design is met while considering the results of different methods.

4. COMPONENT DESIGN

4.1 Diffuser

A diffuser is a diverging flow passage that slows the air flow coming from the compressor and provides a smooth and well-distributed flow toward the combustor core and annulus. Normally, the exit Mach number of the diffuser is expected within a range of 0.05 to 0.1 [5]. Combustor diffusers can be classified as having a flat or curved wall, gradual or sudden expansion, and single or multiple passages. Nowadays, most diffuser types in conventional gas turbine combustors are categorized as “dump” or “step” diffusers. The latter consists of a short straight-wall diffuser in which the air velocity is reduced to almost half of its inlet value. At its outlet, the air is then “dumped” and sent to the snout section. This configuration is mechanically simple and aerodynamically efficient [2, 5].

The diffuser component is sized for an on-design condition to slow the flow down to the desired Mach number at the diffuser exit. Figure 5 shows the step diffuser model and its design parameters.

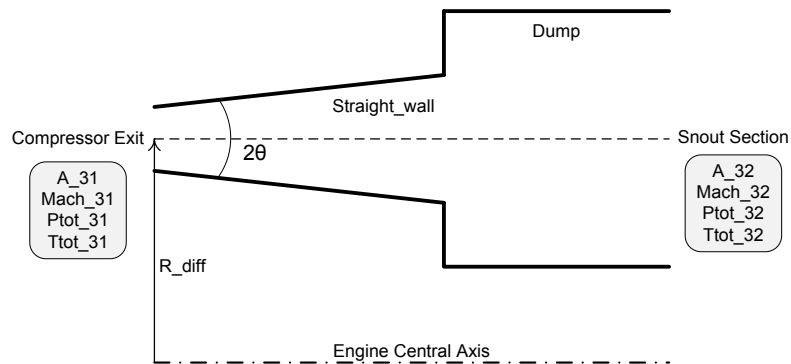


Figure 5: Model and design parameters of an annular step diffuser

The procedure of diffuser design starts from the calculation of the straight-wall diffuser efficiency [21]:

$$\eta_{straight-wall} = 1.1138 - 0.017701(2\theta) + 1.9925 \times 10^{-4}(2\theta)^2 - 9.3068 \times 10^{-7}(2\theta)^3 + 1.5722 \times 10^{-9}(2\theta)^4 \quad (13)$$

In the above equation, 2θ is the diffuser divergence angle in degrees (Figure 5).

The diffuser design procedure is presented in Figure 6. According to the computational algorithm for diffuser design, if the calculated value of A_{32} reaches values bigger than the maximum value assigned for the straight-wall diffuser (sweet-spot, A_m), the diffuser will be considered as a step diffuser (combination of straight-wall and dump diffusers). The following equation can be utilized to calculate the total diffuser efficiency [4, 19]:

$$\eta_{total} = \frac{\eta_{straight-wall}AR(1 - AR_m) + 2(AR_mAR - 1)}{AR^2 - 1} \quad (14)$$

where AR is the total diffuser area ratio (A_{32}/A_{31}) and AR_m is the area ratio of the straight-walled section of the diffuser (A_m/A_{31}).

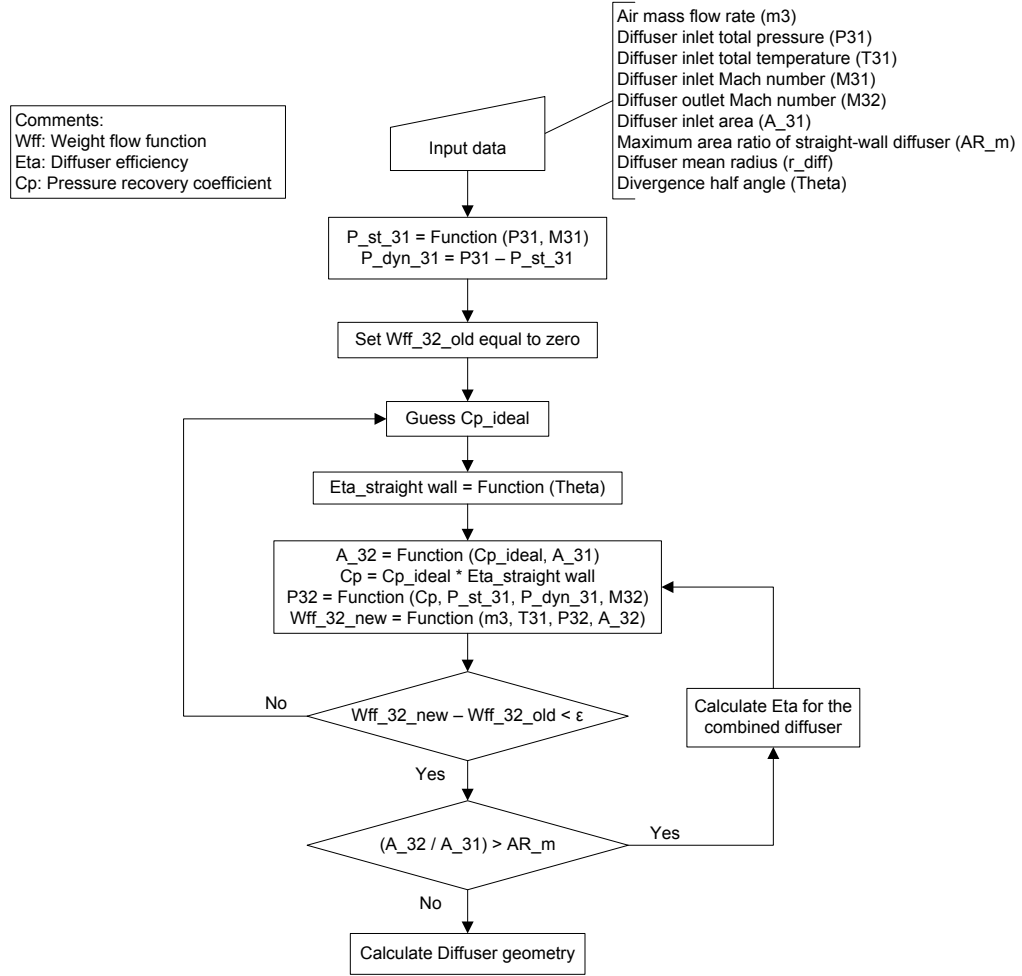


Figure 6: Calculation procedure of diffuser design

4.2 Flow Partitioning

The flow partitioning code calculates the fraction of the total air flow that goes to each of the combustor sections. The total flow that enters into the combustor after passing the diffuser is divided into two parts. The first part goes to the core section (burner) and is determined by the required equivalence ratio in the primary zone (PZ). The second part is diverted around the main burner to the annulus section and is then added to the core section.

The procedure of estimating the different flow fraction in the conventional turbine engine combustors is presented below.

The cooling flow effectiveness parameter (ϕ_{cool}) is used for estimating the cooling flow fraction (μ_{cool}) [4]:

$$\phi_{cool} = \frac{T_{PZ\ Max} - T_{liner\ Max}}{T_{PZ\ Max} - T_{annulus}} \quad (15)$$

$$\mu_{cool} = \frac{\dot{m}_{cool}}{\dot{m}_3} = \gamma \frac{\phi_{cool}}{1 - \phi_{cool}} \quad (16)$$

where γ parameter is the cooling mechanism factor, $T_{annulus}$ is the cooling flow temperature and equals to T_{32} , and $T_{liner\ Max}$ is the maximum allowable liner temperature.

A portion of the annulus air flow is utilized for wall cooling purpose, and the remaining is directed through the dilution orifices in order to burn off the unburnt fuel or UHC and provide the equivalence ratio (ϕ) and the exhaust target temperature.

The following equations are used in determining the flow fractions of the combustor zones [4]:

$$\mu_{PZ} = \frac{\dot{m}_{PZ}}{\dot{m}_3} = \frac{\phi_{total}}{\phi_{PZ}} \quad (17)$$

$$\mu_{SZ} = \frac{\dot{m}_{SZ}}{\dot{m}_3} = \frac{\phi_{total}}{\phi_{SZ}} - \frac{\phi_{total}}{\phi_{PZ}} \quad (18)$$

$$\mu_{DZ} = \frac{\dot{m}_{DZ}}{\dot{m}_3} = 1 - \mu_{cool} - \mu_{PZ} - \mu_{SZ} \quad (19)$$

4.3 Snout

The snout section is located between the diffuser and the combustor primary zone. The function of the snout is to regulate the streamlines of the flow coming from the diffuser toward the combustor annulus and core section (Figure 7). The snout supplies the adequate amount of the flow rate that is required at the annulus section and accelerates it to the desired Mach number at the annulus section entry (MachAnnulus).

The following equation is used for calculating the snout cross section area [1]:

$$\frac{A_{snout}}{A_{32}} = \frac{\dot{m}_{snout}}{\dot{m}_3} \frac{1}{C_{d,s}} \quad (20)$$

where $C_{d,s}$ is the snout discharge coefficient and for a uniform compressor delivery, this coefficient approaches unity. For conventional combustors snouts, the mass flow rate

(\dot{m}_{snout}) is approximately equal to half of the primary zone air flow. The snout pressure loss is calculated using the following equation:

$$\frac{\Delta P_{snout}}{q_{ref}} = 0.25 \frac{q_{snout}}{q_{ref}} = 0.25 \left(\frac{A_{ref}}{A_{32}} \right)^2 \quad (21)$$

4.4 Swirler and Atomizer

The main role of the swirler is to convert the axial flow stream of the core flow to the tangential ones. Imposing a tangential motion on the flow creates a flow recirculation that brings the hot gases back to the flame front which increases flame stability and prevents flame blow-off. Another role of the swirler is to enhance the mixing quality of the fuel and air, while the toroidal motion of the flow reduces the flame length [19, 22].

The swirler design is based on providing the given amount of the pressure drop that is obtained from the engine cycle analysis. Knight and Walker [23] proposed the following pressure loss relation for calculating the swirler area (A_{SW}):

$$\frac{\Delta P_{SW}}{q_{ref}} = K_{SW} \left[\left(\frac{A_{ref}}{A_{SW}} \right)^2 \sec^2 \beta_{SW} - \left(\frac{A_{ref}}{A_{ft}} \right)^2 \right] \left(\frac{\dot{m}_{SW}}{\dot{m}_3} \right)^2 \quad (22)$$

where β_{SW} is the turning angle of the air flow. The swirler discharge parameter (K_{SW}) is 1.30 for thin straight blades and 1.15 for thin curved blades. Experiments have shown that the combustor will perform well for amounts of swirler airflow (\dot{m}_{SW}) ranging from 3% to 12% of the total air [1].

In order to calculate the swirler pressure loss, the combustor total pressure loss, diffuser, and snout pressure loss have to be known:

$$\frac{\Delta P_{SW}}{q_{ref}} = \frac{\Delta P_{3-4}}{q_{ref}} - \frac{\Delta P_{snout}}{q_{ref}} - \frac{\Delta P_{diff}}{q_{ref}} \quad (23)$$

After determining the overall dimensions of the swirler, it is necessary to check the Swirl number value. Flow recirculation is obtained for a Swirl number greater than 0.6 [4].

$$Swirl_number = \frac{2}{3} \tan \beta_{SW} \frac{1 - (D_{hub}/D_{SW})^3}{1 - (D_{hub}/D_{SW})^2} \quad (24)$$

where D_{hub} and D_{SW} are the inner and outer swirler diameter, respectively.

Figure 8 presents the design algorithm of the swirler for conventional gas turbine combustors.

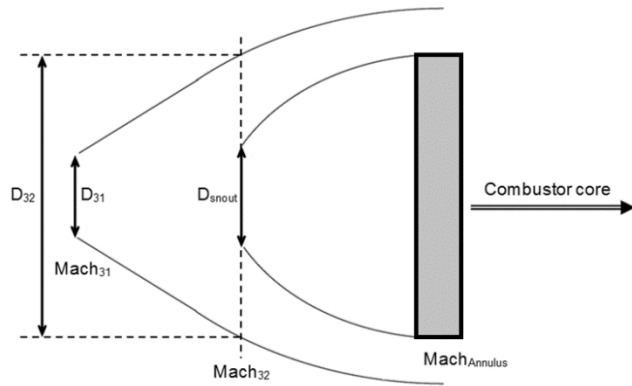


Figure 7: Schematic of the snout

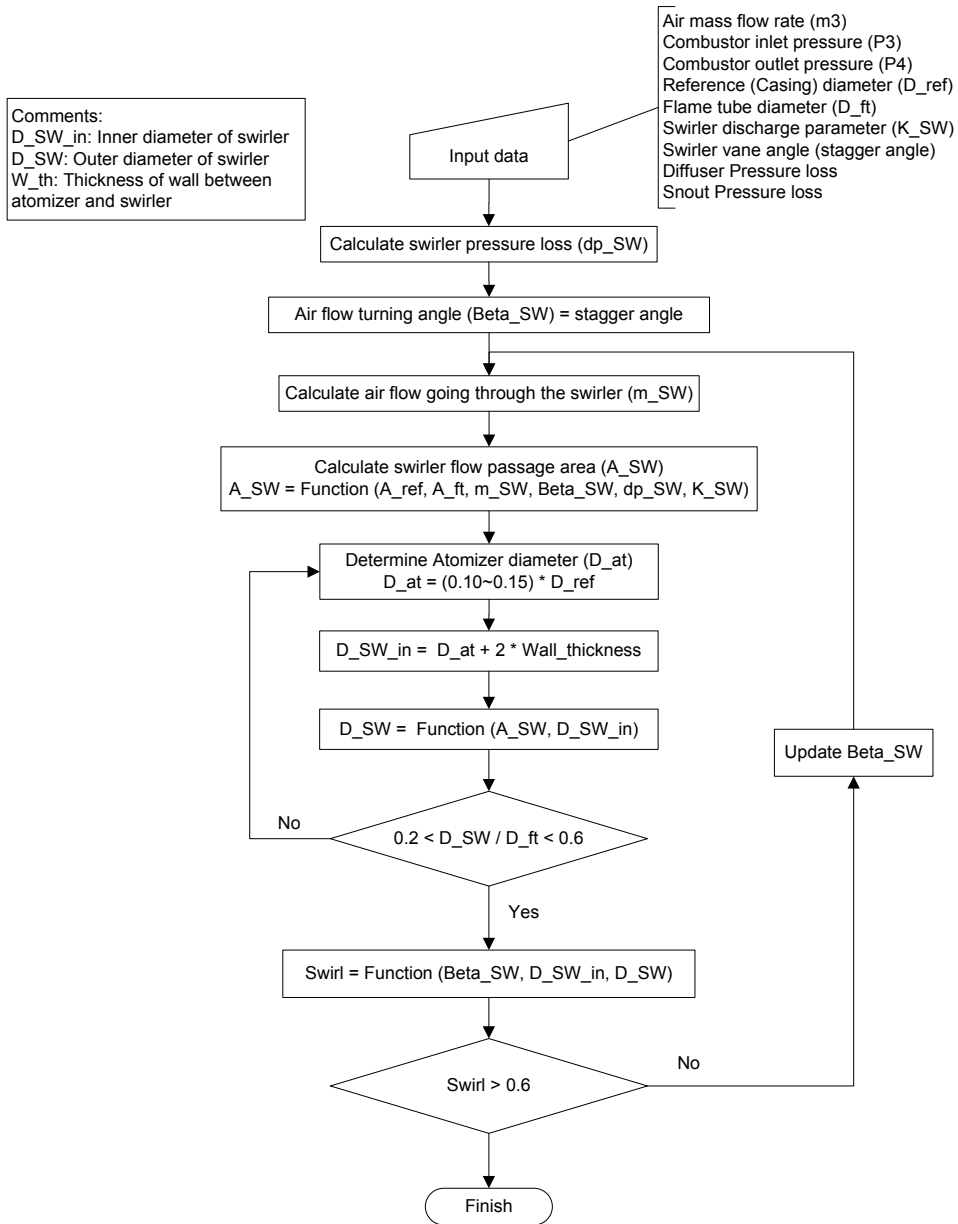


Figure 8: Calculation procedure of the swirler design

4.5 Recirculation-Zone and Primary-Zone

The schematic of the recirculation zone and igniter position is shown in Figure 9. The recirculation zone is defined based on the concept of “Magic Circles”. These circles, with a diameter equal to half of those of the flame tube, are placed inside the liner where it touches the dome wall, the liner wall, and the liner centerline. The Magic Circles attempt to capture the recirculation patterns inside the liner [24].

The igniter must be placed in a predicted position that is rich in fresh fuel/air mixture. The location where the magic circles touch the liner wall is proposed for the quoted feature:

$$L_{ig} = \frac{D_{ft}}{4} \left[1 + \cot \left(\frac{\pi - \theta_{dome}}{2} \right) \right] + L_{dome} - \frac{D_{ft}}{4} \quad (25)$$

In most cases of conventional combustors, the combustor dome angle (θ_{dome}) is approximately equal to 60 degrees. Therefore, the dome length is equal to:

$$L_{dome} = \frac{D_{ft} - D_{SW}}{2 \tan(\theta_{dome})} \quad (26)$$

Taking into consideration the parameters in Figure 9, the recirculation zone length is equal to:

$$L_{RZ} = L_{igniter} + \frac{D_{ft}}{4} \quad (27)$$

It is necessary to note that the recirculation zone is a portion of the primary zone and must be smaller than the primary zone. The primary zone length can be estimated using the Swirl number value [2, 4]:

$$L_{PZ} = D_{SW} \times Swirl_number \quad (28)$$

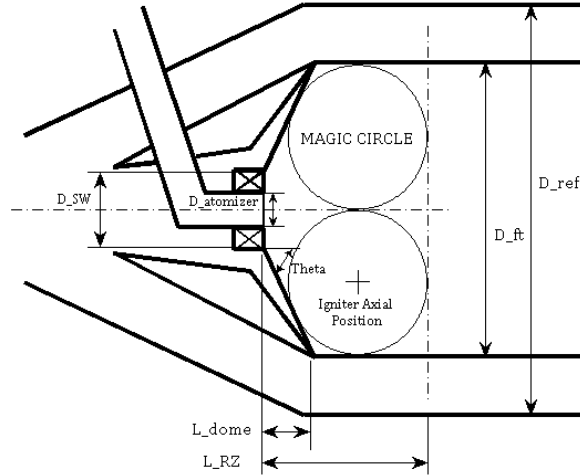


Figure 9: Schematic of the recirculation zone

4.6 Secondary-Zone and Dilution-Zone

In the secondary and dilution zones of the conventional combustors, the dilution jets from the holes (orifices) penetrate to the hot core flow. The pressure differences between annulus and core flow drives the latter. The procedure for specifying the number of dilution orifices and diameter (for SZ or DZ) are presented below.

The sizing of the orifices is based on the ratio of maximum penetration depth (Y_{max}) to the dilution jet diameter (d_j), which is equal to [2]:

$$Y_{max}/d_j = 1.15 J^{0.5} \sin \theta \quad (29)$$

where θ is the jet penetration angle, and J is the momentum flux ratio that is defined as [2]:

$$J = \frac{q_{jet}}{q_g} = \rho_{jet} U_{jet}^2 / (\rho_g U_g^2) \quad (30)$$

In accordance with the definition of the above equation, the q parameter is momentum flux; *jet* and *g* subscripts are corresponding to jet flow and core flow, respectively.

As the physical fluid properties at station 32 (snout section) is known, rewriting the equation (29) for the secondary zone would lead to:

$$(Y_{max}/d_j)_{sz} = 1.15 \sqrt{\frac{q_{jet}}{q_{32}} \left(\frac{q_{sz}}{q_{32}}\right)^{-1}} \sin \theta_{sz} \quad (31)$$

Equation (31) could also be rewritten for the dilution zone.

By specifying the (Y_{max}/D_{ft}) parameter, the dilution jet diameter value is obtained as follows:

$$d_j = \left(\frac{Y_{max}}{D_{ft}}\right) \left(\frac{Y_{max}}{d_j}\right)^{-1} D_{ft} \quad (32)$$

Normally, the dilution jet diameter is smaller than the orifice diameter; thus the dilution orifice diameter can be express as follows:

$$d_{orifice} = \frac{d_j}{\sqrt{c_d}} \quad (33)$$

in which c_d is the flow coefficient factor and its value is considered between 0.6 ~ 0.65.

The number of dilution orifices is obtained by dividing the total flow that goes through the orifices (secondary or dilution flow) by the flow that goes through a single orifice.

$$n_{orifices} = \frac{\dot{m}_{dilution}}{\dot{m}_{tot}} \frac{\dot{m}_{tot}}{\dot{m}_{jet}} = \frac{\dot{m}_{dilution}}{\dot{m}_{tot}} \frac{4 A_{32} V_{32}}{\pi d_j^2 V_j} \quad (34)$$

Since the flow velocity inside the combustor core is much slower than the jet flow, it is assumed that the total pressures drop is the same as the difference between the static pressures of the annulus and the core flow; therefore, the density in the annulus section is almost constant. The jet velocity can be obtained from the following equation [19]:

$$V_j = \sqrt{\frac{\Delta P_{3-4}}{\frac{1}{2} \rho_{32}}} = V_{32} \sqrt{\frac{\Delta P_{3-4}}{\frac{1}{2} \rho_{32} V_{32}^2}} = V_{32} \sqrt{\left(\frac{\Delta P_{3-4}}{q_{ref}}\right)} \quad (34)$$

The jet penetration angle can be determined using the following equation [2, 19]:

$$\sin \theta = \sqrt{1 - \frac{q_{Annulus}}{q_{jet}}} \quad (36)$$

The calculation procedure of the features of the secondary and dilution zones are presented in Figure 10.

The length of the secondary and dilution zones is frequently expressed as the length to diameter (height) ratio in the references. The value of the mentioned parameter is recommended to be in a range of 0.5 to 1.0 [1, 4, and 19].

Since certain requirements exist in the design of turbine engines, the inlet and exit radii of the combustors would often be different. Taking into consideration Equation (1), to keep

the cross-section area fixed in the annular combustors, the height of the zones increase or decrease depending to the combustor displacement away from or toward the engine's centerline.

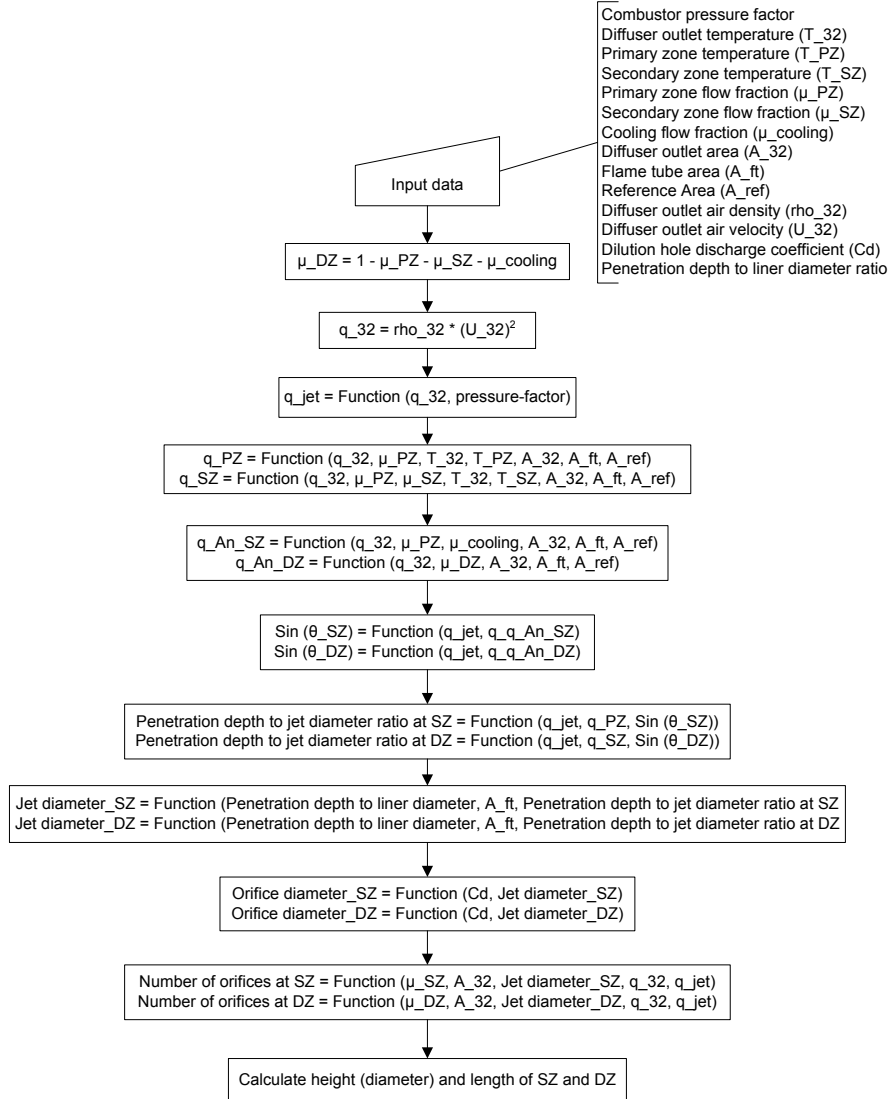


Figure 10: Calculation procedure for features of secondary and dilution zones

5. 2D GEOMETRY GENERATION

The parameters acquired through the procedures presented in the Component Design section of this study facilitate a fully defined state space in which this series of adequate data could be used to create the geometrics of a conceptual model. These data along with the primary geometrical constrains are applied in an automated code that sequentially generates a 2D drawing for a longitudinal cross section of a designed combustor.

6. RESULTS AND DISCUSSION

To evaluate the calculated output of the developed methodology for the combustor conceptual design, the results were compared with the data of a selected engine. To achieve this goal, due to the accessibility of the thermodynamic data of the engine operation and also the combustor sketch in the open resources, the single annular combustor of a CFM56-7B27 engine was selected (Figure 11). The engine was built by the CFM International Company.

The main dimension of the CFM56 engine combustor is presented in the references [6, 14]. Using this data and a drawing of the combustor, other actual dimensions of the combustor can be estimated by scaling.

Table 1 shows the cycle parameter values of the CFM56 engine for different operating conditions [6]. These parameters have been calculated by comprehensive modeling of the engine.

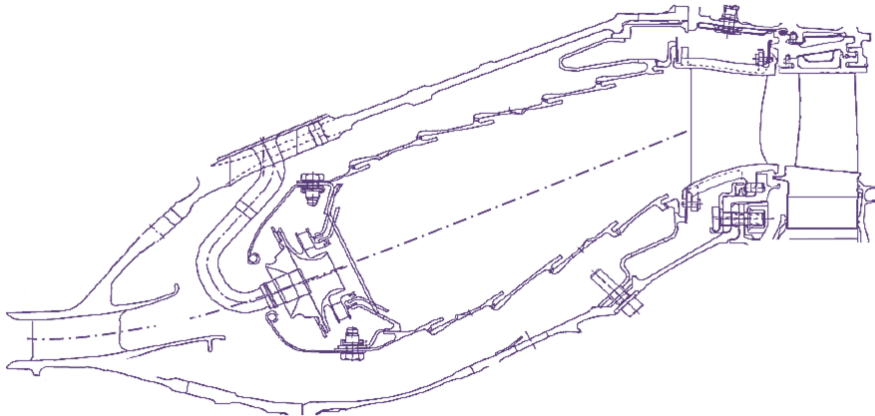


Figure 11: 2D drawing of the CFM56 engine combustor [6, 14]

Table 1: Cycle parameter of CFM56 engine combustor [6]

Condition	\dot{m}_3 (kg/sec)	\dot{m}_f (kg/sec)	P_3 (kPa)	T_3 (K)	Overall ϕ
Take-off (design point)	44.52	1.276	2900	800	0.42
Climb	39.10	1.040	2477	764	0.39
Approach	20.87	0.349	1132	613	0.245
Ground idle	12.12	0.119	559	505	0.144

Some of the input parameters utilized for the “Combustor Reference Diameter and Area” methods and for the “Component Design” sub-sections are listed as Table 2. Portions of this information were determined through the Monte Carlo filtering process that was performed by Rezvani [6].

The initial phase in the design procedure of a gas turbine combustor is determining its reference diameter and area. To determine this, the input data presented in Tables 1 and 2 were applied on every previously mentioned method for each operating condition. The

results are illustrated in Table 3. Consequently, from the tabulated answers, the final (optimum) value of the mentioned parameters would be chosen.

Table 2: Set of input data and parameters for a CFM56 engine combustor

Parameter	Value
Pressure factor ($\Delta P_{3-4}/q_{ref}$)	45
Pressure loss ratio ($\Delta P_{3-4}/P_3$)	0.05
PZ equivalence ratio in on-design condition (ϕ_{PZ})	1.05
SZ equivalence ratio in on-design condition (ϕ_{SZ})	0.8
Mach number at Outer annuli	0.015
Mach number at the end of PZ	0.05
Inlet mean radius (compressor exit)	275.8 mm
Exit mean radius (turbine entrance)	344.4 mm
Number of injectors	20
Divergence half angle of diffuser	1.2 degree
Diffuser inlet height	19.6 mm
Maximum area ratio of straight wall diffuser (sweet-spot)	1.25
Diffuser inlet Mach number (M31)	0.2
Diffuser exit Mach number (M32)	0.04
Combustor exit Mach number (M40)	0.075
Fuel inlet temperature	309 Kelvin
Maximum allowable liner temperature	1139 Kelvin
Cooling mechanism factor (γ)	0.29
Swirl angle (β_{SW})	61.5 degree
Swirler discharge parameter (K_{SW})	1.30
Ratio of atomizer diameter to reference diameter	0.10
Burner dome angle	60 degree
Dilution holes discharge coefficient (cd)	0.6
Penetration depth to flame tube diameter at SZ	0.46
Penetration depth to flame tube diameter at DZ	0.41

Table 3: Combustor reference diameter values (meter)

Condition	Aerodynamic	Chemical	Bragg	Odgers	Combustion Loading
Take-off (design point)	1.05E-01	1.14E-02	1.26E-01	1.99E-01	1.22E-01
Climb	1.05E-01	1.37E-02	N.A.	1.93E-01	1.24E-01
Approach	1.09E-01	1.63E-02	N.A.	4.75E-01	1.36E-01
Ground idle	1.14E-01	3.70E-03	N.A.	6.05E-01	1.49E-01

Even though the calculated values for each working condition may differ, the on-design values (i.e., take-off condition) have greater importance. The selected value of the reference diameter must comply with aerodynamic and chemical considerations. Regarding the calculated values, the reference diameter of the CFM56 engine combustor is equal to 1.26E-1 (m); also, the flame tube diameter of the CFM56 engine combustor is equal to 8.61E-2 (m).

The ratio of the flame tube area to the reference area is equal to 0.68 and has an acceptable agreement with the results of Equations (11) and (12). Regarding the two main calculated parameters, it is possible to proceed to the component design procedure. Table 4 presents

elements of the component design outputs that are comparable with the extracted data of CFM56.

Table 4: Comparing of the calculated values and actual geometrical data of the CFM56 engine combustor

Geometrical parameters	Calculated data	Measured data	Unit
Straight wall diffuser length	0.0803	0.0795	meter
Diffuser length	0.1209	0.1189	meter
PZ length	0.0546	0.0531	meter
SZ length	0.0497	0.0597	meter
DZ length	0.0769	0.0648	meter
Dome length	0.0131	0.0140	meter
Snout length	0.0298	0.0307	meter
Burner length	0.2110	0.2083	meter
Combustor axial length	0.3205	0.3073	meter
Dump diffuser height	0.0812	0.0800	meter
Snout height	0.0252	0.0265	meter
Atomizer diameter	0.0126	0.0130	meter
Swirler hub radius	0.0146	0.0145	meter
Swirler tip radius	0.0203	0.0230	meter
SZ height	0.0828	0.0749	meter
DZ height	0.0769	0.0625	meter
SZ orifices number	80	80	no.
DZ orifices number	122	120	no.

Using the results of Table 4 and the other outputs of the Component Design, it is possible to generate the 2D conceptual geometry of the gas turbine combustor. Ordinarily, the inlet and exit radii of the combustor are not equal because the combustor has an inclination angle with the engine's central axis. The developed tool can handle the above mentioned issue and, moreover, it considers the different axis for the diffuser and outlet part of combustor. Figure 12 shows a sample output result of the mentioned automated code that is generated for input data of the CFM56 engine combustor.

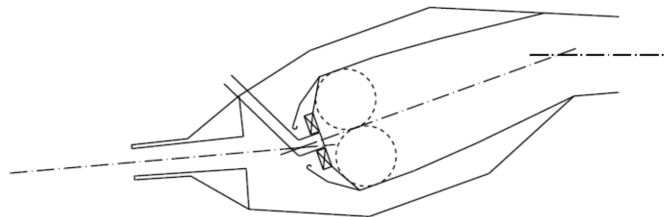


Figure 12: 2D drawing of conceptual geometry for the CFM56 engine combustor

It is accepted that design procedures could be iterative by nature; thus the experimental evaluation of the design procedure is a necessity. Hence, providing valid limitations toward output design space and/or providing more precise values during the early design procedure that could lead to less experimental efforts is justified, i.e., by considering more details and parameters using in the augmented conceptual design phase. Therefore, the early allocation of the parameters due to the multidisciplinary conceptual design leads to significant shrinkage of the total time and cost of the design phase, which is a main objective of this work by providing an efficient mapping of inputs on a considerably limited output state space.

Even though the design space of an experimental tests phase can be reduced, it is not expected to be exact in covering all considerations and requirements of the final product during the conceptual design phase. In examples of such issues, flame stability and structural considerations can be addressed. In other design phases, e.g. detail design, their complexity and/or computational and experimental effort may be diminished by receiving more outputs from the conceptual design phase.

Chemical equilibrium analysis is used in calculating the temperature of the air and burned mixture of the combustor. This study determines the axial variation of the total temperature in different combustor zones. These data are used for input of the Component Design segment. Figure 13 shows the axial temperature variation of the CFM56 engine combustor.

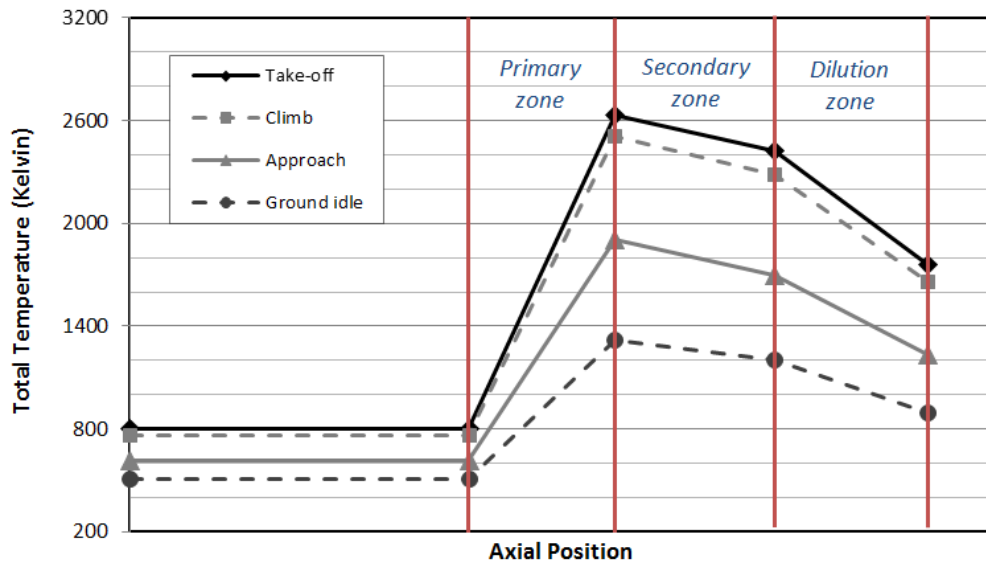


Figure 13: Axial temperature variation of CFM56 engine combustor for different operating conditions

7. CONCLUSIONS

An overview of this work shows that the integration of various design strategies has advantages both technically and systematically over the classic designs. The proposed strategy only consists of modules in the conceptual design phase. The key properties of the proposed augmented conceptual design approach are presented below:

- The method of augmented conceptual design is dedicated to providing the most achievable combustion chamber parameters. The available conventional early design methods are also

implemented. The results of this method provide a well-constrained output space state which is a good platform to provide the final product configurations of any components; these configurations are not covered in the scope of this study.

- Based on available literature methodologies, the differences in the perspectives and approaches of various authors evoke an inconsistency among their findings. This paper focused on the issue and the integrated so-called methods.
- The base parameter in the combustor design is the maximum diameter of the outer casing that is defined by a reference value. In this work, a code has been constructed which is capable of calculating the reference diameter based on the non-extensive statistical data of previous methods. Also, the output space of the augmented conceptual design method includes the numerous details of the components; this leads to less effort during the detailed design and experimentations.
- One of the key advantages of the so-called integration is providing an automated computational code that follows equations and correlations. This automated and comprehensive code (by mean of providing most details) has a considerable impact on the shrinkage of further experimental effort. Also, the provided code is equipped with a geometrical model generation section that has application in the future design stages, e.g., detail design.
- Although the augmented conceptual design method is only applied to conventional combustion chambers, it can be implemented to other recent configurations with minimal change.
- Predicting and/or calculating the performance parameters such as spray quality, SMD of fuel droplets, pattern factor quality, and pollutant emission prediction are out of the scope of this paper.

As could be obvious to an expert in the art, the approach leading to the automated and augmented conceptual design tool is not limited to the design of the combustor and can be implemented for designing new and modern design strategies.

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