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ONE DIMENSIONAL RADIATION HEAT FLUX CALCULATION FOR A TUBULAR COMBUSTOR

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ABSTRACT

Preliminary gas turbine combustor design requires quick evaluation tools that can apply reliable methods in liner metal temperature calculations where convection and radiation are the dominant heat loads. The first one is generally well known and relatively easy to consider. The latter one is flame side radiation and it is difficult to include in the simulations. Difficulty of calculation rise from the complexity of temperature distribution and mixture fractions of the combustion gases. It is necessary to evaluate radiation heat flux from the hot combustion gases to combustor liner in order to calculate liner metal temperatures. There are some numerical methods in CFD programs that can analyze radiation effects but solving combustion and radiation together requires a three dimensional geometry and also requires more analysis time. Therefore, preliminary analysis tools are essential and they generally utilize empirical correlations to calculate the radiation heat flux on combustor liners. It should be mentioned that, calculated heat flux may be specific to the analyzed combustor architecture and it may be necessary to calibrate with an experimental setup.

The scope of this work is validation of preliminary design tool using the experimental results for a literature case and application on a tubular combustor and comparison of radiation heat fluxes with the ones obtained from the 3D combustion CFD analysis using Discrete Ordinate method.

INTRODUCTION

Since one-dimensional calculations are used for finding the potential combustor configurations prior to the complex computational fluid dynamics calculations, gas turbine combustor design process requires validation of the one-dimensional analysis process. One-dimensional design tools have the advantage of short computational times and by the way, optimization of the geometry can be conducted easily. Design process begins with design envelope and performance requirements. For the given envelope, a generic liner geometry is obtained and then liner hole configurations are searched and cooling requirements are defined depending on the liner temperatures. Empirical correlations are utilized when calculating the metal temperatures. The critical issue for the tool is the reliability and validity of these empirical methods. As the metal temperatures get closer to the material limits, risk

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for liner integrity becomes bigger. In order to increase accuracy of predictions, each heat contribution to the liner temperatures should be evaluated.

In this study, one-dimensional radiation heat transfer correlations have been studied and flame side radiation heat flux has been calculated for a tubular combustor. Radiation is the most complicated mode of heat transfer in flame tube and therefore preliminary methodologies must be checked by three dimensional models and experimental data.

Combustor liner heat transfer

There are various combustor liner types with cooling features and thermal barrier coating but the same liner heat transfer calculation approach may be used for all of them. Basic heat transfer balance on a simple combustor liner is given in Figure 1, which means heat gain from the inner side is equal to the conducted heat and the heat loss from the cold side. At the upper side; there is heat loss by means of convection from liner to cold air and radiation from liner to casing. And, at the lower side; there is heat entry by means of convection from hot gases to liner and radiation from the combustion products. Steady state heat transfer analysis can be done by using conservation of energy (Equation (1)) in the radial dimension. Lefebvre [Lefebvre and Ballal, 2010] has been proposed empirical correlations for convective and radiation heat fluxes for combustors in equation (2) and (5). In these equations convective heat transfer coefficients are calculated by using a modified version of the Dittus Boelter correlation assuming that the air flow on combustor is similar to the straight pipe flow. Validity of this assumption has also been studied separately and it is not covered here.

Calculation of cold air side radiation heat flux, from combustor liner to the casing is a clear process since surface to surface radiation is well known. However gas side radiation is a complex phenomenon because of the emissivity of combustion products and variations in the temperature in real situations.

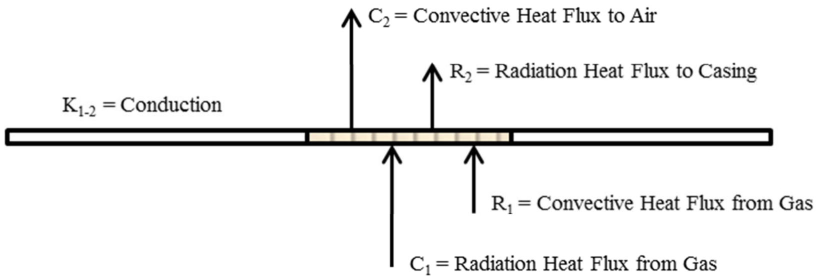

Figure 1: Basic heat transfer process in combustor liner

$$\boldsymbol{R_1 + C_1 = R_2 + C_2 = K_{1-2}} \quad (1)$$

$$\boldsymbol{R_1 = 0.5 \cdot \sigma \cdot (1+\varepsilon_w) \cdot \varepsilon_g \cdot {T_g}^{1.5} \cdot ({T_g}^{2.5} - {T_w}^{2.5})} \quad (2)$$

$$\boldsymbol{C_1 = 0.020 \cdot \frac{k_g}{D_L^{0.2}} \cdot \left(\frac{m}{A_L \cdot \mu_g}\right)^{0.8} \cdot (T_g - T_w)} \quad (3)$$

$$\boldsymbol{R_2 = \sigma \cdot \frac{\varepsilon_w \varepsilon_c}{\varepsilon_c + \varepsilon_w (1-\varepsilon_c) D_L / D_{ref}} \cdot ({T_w}^4 - {T_g}^4)} \quad (4)$$

$$\boldsymbol{C_2 = 0.020 \cdot \frac{k_a}{D_{an}^{0.2}} \cdot \left(\frac{m}{A_{an} \cdot \mu_a}\right)^{0.8} \cdot (T_w - T_3)} \quad (5)$$

Effects of temperature distribution in the hot gas side can be evaluated with probabilistic methods. Here it is assumed that the temperature inside the flame tube concentric with combustor axis. Flame side radiation can be calculated using the equation (2) or alternatively equation (6). Equation (7) provides a relation between the gas and wall temperatures and absorptivity of the wall and emissivity of the gases. In the hot gas, water vapor and carbon dioxide are considered as the main participating mediums. The radiation from water vapor and carbon dioxide gases present in combustion mixture is classified as Non-Luminous and emissivity for the nonluminous gases can be calculated by using the equation (6).

$$\boldsymbol{\varepsilon_g = 1 - exp(-290 \cdot P \cdot (f \cdot l_b)^{0.5} \cdot T_g^{-1.5})} \quad (6)$$

Where P is Pressure (Pa), f is fuel to air ratio, l_b is beam length (m) and T_g is gas temperature (K). The beam length is shaped by the size and shape of the gas volume and can be approximated by the equation 7. For a cylindrical flame tube it can be assumed as 0.6 < l_b < 0.9 depending on the length/diameter ratio. A reasonable value for primary zones can be assumed as 0.6d [Lefebvre and Herbert, 1960]. For secondary and dilution zones, a value of 0.9 can be used.

$$\boldsymbol{l_b = 3.4 \frac{volume}{surface\ area}} \quad (7)$$

If there are sooth particles inside the hot gases, additional radiation is emitted by these particles. This kind of radiation is classified as Luminous. Sharma has stated that, at higher pressures luminous radiation can contribute much more than non-luminous radiations [Sharma, 2015]. Luminous radiation can be calculated with equation (8) by adding a luminosity factor "L". Then equation (6) changes to equation (8). Luminosity factor is defined as the C/H ratio of the fuel by mass [Kretschmer and Odgers, 1979].

$$\boldsymbol{\varepsilon_g = 1 - exp(-290 \cdot P \cdot L \cdot (q \cdot l_b)^{0.5} \cdot T_g^{-1.5})} \quad (8)$$

$$\boldsymbol{L = 0.0691(C/H - 1.82)^{2.71}} \quad (9)$$

In the preliminary analysis everything considered as axially symmetric however in reality there are local hot spots that strongly affect the radiation heat flux distribution. Hot spots are difficult to simulate in one dimensional analysis. Therefore, in the flame side radiation calculation, gas side temperature should be corrected in respect of the experimental results or 3D CFD studies of the similar architectures.

Preliminary design tool calculates gas temperature variation in axial direction for the specified inlet boundary conditions and liner holes configuration. Consequently, emissivity value of the gases is calculated using equation (8), based on the pressure, luminosity factor, fuel air ratio, beam length and gas temperature. Luminosity factor depends on C/H mass ratio which is characteristic of the fuel and it can be calculated by using the chemical formulas defined in Table 1 [SAE ARP 1533, 2004].

Table 1. Chemical formulas of the jet fuels

Jet A	$C_{11.6}H_{22}$
JP-4	$C_{8.5}H_{16.9}$
JP-5	$C_{7.16}H_{18.37}$
JP-8	$C_{10.9}H_{20.9}$
JP-10	$C_{10}H_{16}$

EMPIRICAL RADIATION MODEL AND VALIDATION

In order to evaluate radiation calculation methodology of the developed in house code, the following literature case has been selected. Stuttaford and Rubini has been presented radiation heat flux results for a case in their study [Studdaford and Rubini, 1997]. In the experiment, they have used a cylindrical enclosure with 2 m diameter and 6 m long. Walls of cylinder are black (ε_w = 1) and all have constant uniform temperature of 500 K (Figure 2). Inside the cylinder case, hot gas was generated in cylindrical form, since there is no sooth formation only non-luminous radiation is considered. Hot gases were divided into 18 segments with different temperatures as shown in figure (2); that is increasing from 1000 K to 2000 K (0 meter to 3.5 meters) and then decreasing to 1300 K (from 3.5 meters to 6 meters) with 100 K steps.

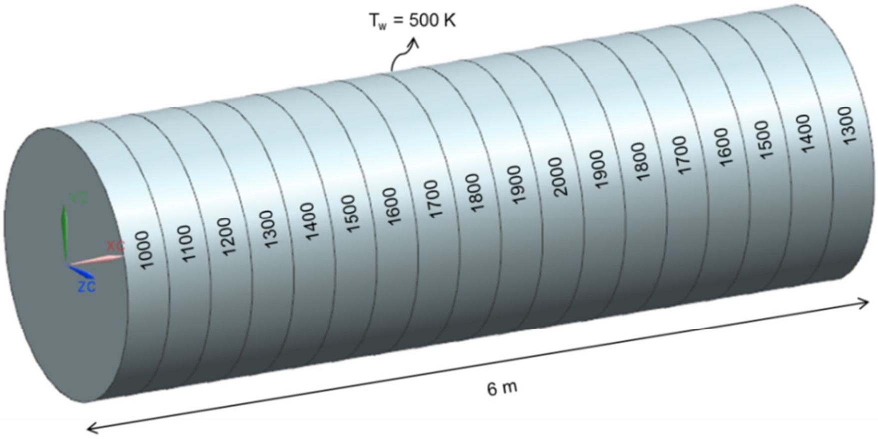

Figure 2: Case 1 (Cylinder geometry and gas temperature distribution)

This case has been modeled in a commercial CFD code and radiation heat flux distribution was calculated using "Discrete Ordinates" radiation model. Absorption coefficient is used for CFD calculation and gas emissivity value has been calculated by using equation (10).

$$\boldsymbol{\varepsilon_g = 1 - \exp(-kL)} \qquad 10$$

In Figure 3 and Figure 4, experimental, CFD and empirical calculation comparison is shown for the k=1 m^{-1} (ε_g = 0.817) and k=0.1 m^{-1} (ε_g = 0.156). In this case, it is assumed that radiation emits only perpendicularly in each segments. As it can be seen in figures, when this assumption is used, there is obtained high values of flux at the maximum gas temperature location. This situation shows that the effect of gas domain in two dimensions by using view factor should be taken into consideration.

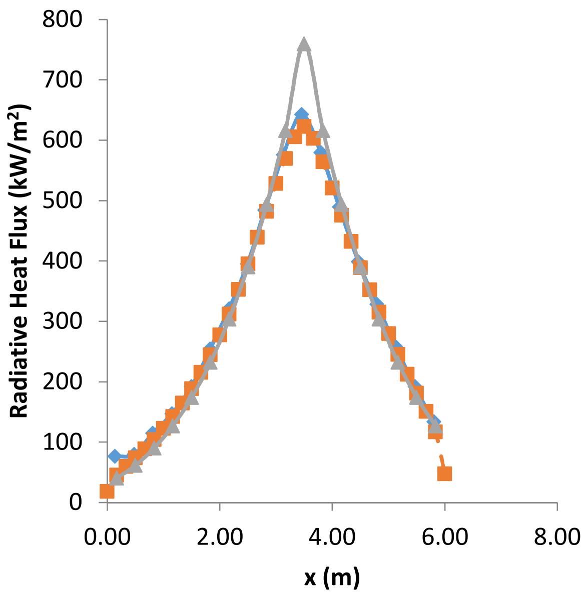

Figure 3: CFD and empirical calculation comparison for k=1 m^{-1}

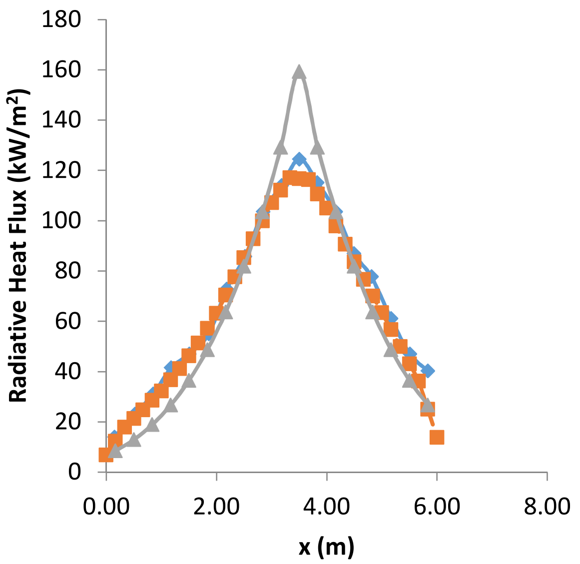

Figure 4: CFD and empirical calculation comparison for k=0.1 m^{-1}

As it can be seen in Figure 5, view angle is calculated for each wall segment for a gas domain and view factor can be calculated by using equation (11). Sum of the all view factor should be equal to one therefore; calculated view factor is divided to sum of all view factors. After calculation of the view factor of gas domains for each wall segments are used to calculate radiation heat fluxes (Equation (12)). Sum of the all radiation heat flux over the each wall segments give the total flux value.

$$VF = \frac{(Cos(\theta))^2}{{z_j}^2} / \sum_{0}^{j} \frac{\left(Cos(\theta)\right)^2}{{z_j}^2} \qquad 11$$

$$R = VF \cdot 0.5 \cdot \sigma \cdot (1+\varepsilon_w) \cdot \varepsilon_g \cdot {T_g}^{1.5} \cdot ({T_g}^{2.5} - {T_w}^{2.5}) \qquad 12$$

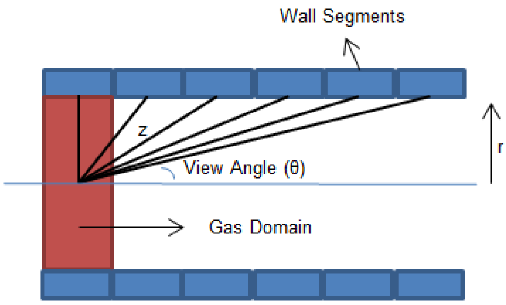

Figure 5: View angle calculation

Empirical results by using view factor and the CFD calculations for absorption coefficients of 1 m^{-1} and 0.1 m^{-1} have been presented in Figure 6. As it can be seen, radiation flux is calculated more accurately at the peak temperature locations when view factor is used.

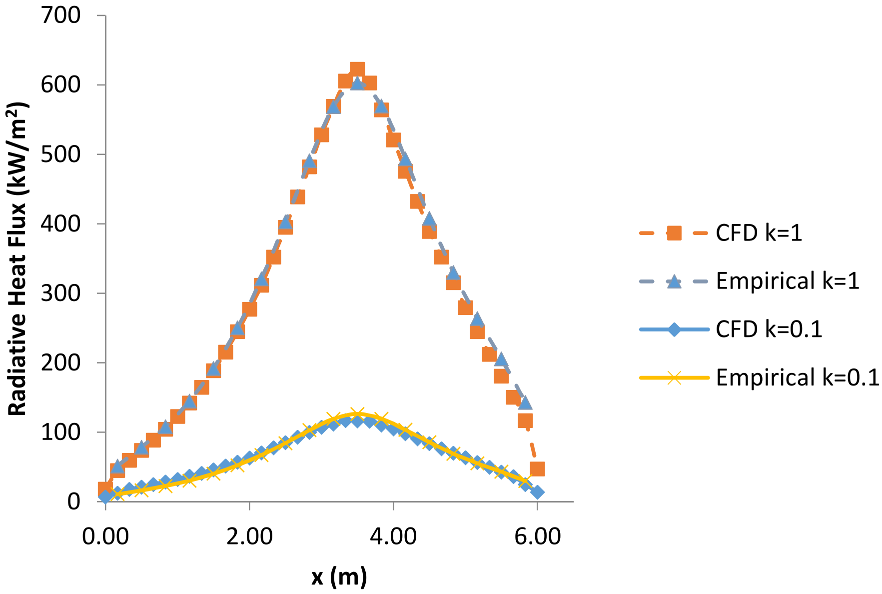

Figure 6: CFD and empirical calculation (by using view factor) comparison

RADIATION HEAT FLUX IN A TUBULAR COMBUSTOR

Applied methodology has provided satisfactory results with the simple cylindrical geometry. As a next step same methodology was applied the same methodology on the combustor geometry. For this purpose; a basic, axi-symmetric, through flow tubular type combustor has been selected. This is an experimental combustor with air-blast atomizer and straight liner. There are three rows of holes on the liner which are providing the necessary circulation, mixing and dilution for the fuel combustion process. Number and diameters of these holes have been defined with a flow split analysis.

CFD fluid domain is shown in Figure 7. Air enters to from the inlet, passes through the liner holes and mixes with the fuel injected from the air-blast atomizer. Then the fuel is burned and the released heat increases gas temperatures. Finally hot gases leave the domain through the outlet.

The region where the combustion occurs is called as “Flame tube” or “Flame side”. During the combustion, gas temperatures may reach up to 2500 K. Naturally; radiation heat transfer takes place from hot gases to liner inner surfaces. Flame side radiation heat flux calculations have been performed for a fixed liner temperature both by using empirical calculations and CFD.

Discrete ordinates radiation model is used for the CFD calculations and a constant value of 474 K is given for the wall temperatures. To simplify the validation problem, soot model is not included to model and therefore only non-luminous radiation is calculated. In CFD model there is output parameter which is gives the radiation heat flux value on the liner inner wall. This data is extracted from the CFD results and circumferentially average values were found.

Similarly hot gas temperatures from the CFD analysis results were extracted and used for the empirical calculations. Mean and maximum flame temperature and fuel to air ratio distributions through the flame tube are given in Figure 8 and Figure 9. As it can be seen in Figure 8, there are local high temperatures through the flame tube.

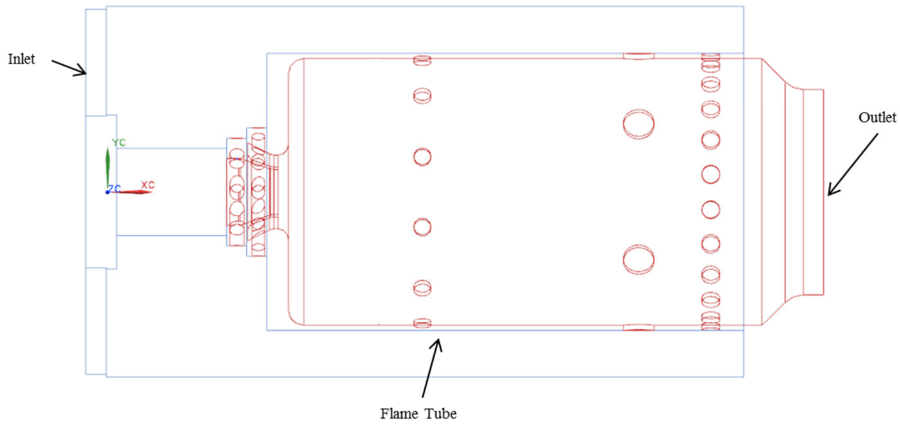

Figure 7: CFD Boundary Conditions

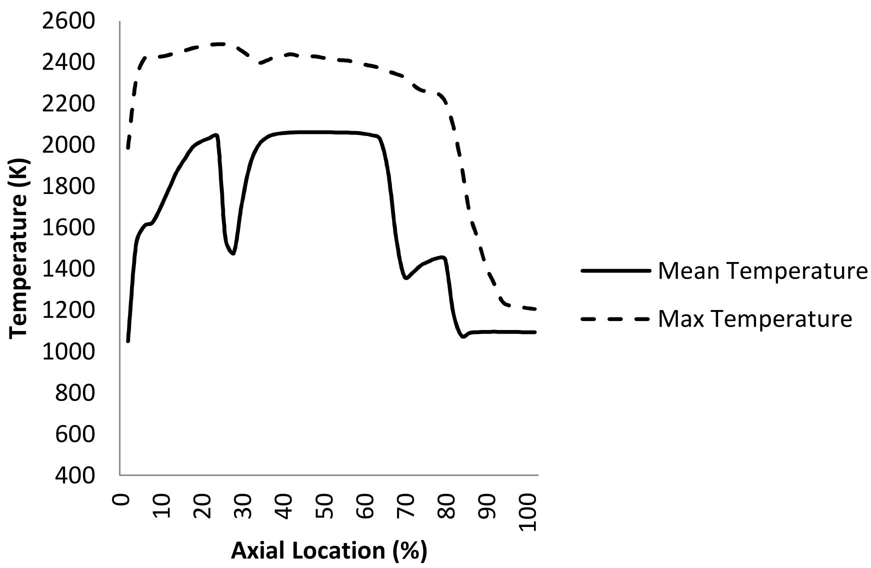

Figure 8: Mean and Maximum Gas Temperatures in the Flame Tube

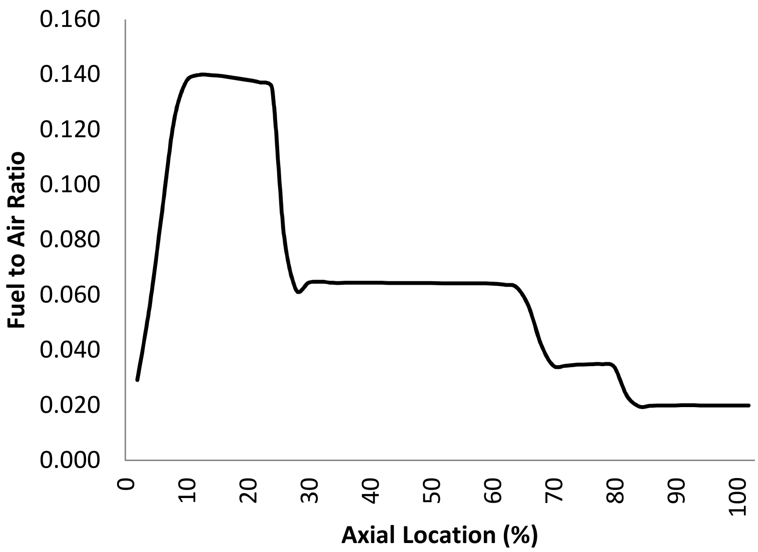

Figure 9: Fuel to Air Ratio Change through the Flame Tube

Empirical calculations have been performed based on the CFD flame temperature and fuel to air ratio values. Emissivity values have been calculated based on the mean gas temperature and fuel to air ratio values.

In the Figure 10, comparison of the CFD and empirical calculations for radiation heat flux There is two method for the empirical calculations as classical method (without view factor) and by using the view factor approximation. As it can be seen in graph, each of the empirical method gives underestimated results for radiation heat flux but view factor approximation gives a better trend. These results show that the effect of the maximum temperatures regions in the gas domain must be considered to get a more exact solution.

In order to consider maximum temperatures and hot spots, there is a need for a correction factor.

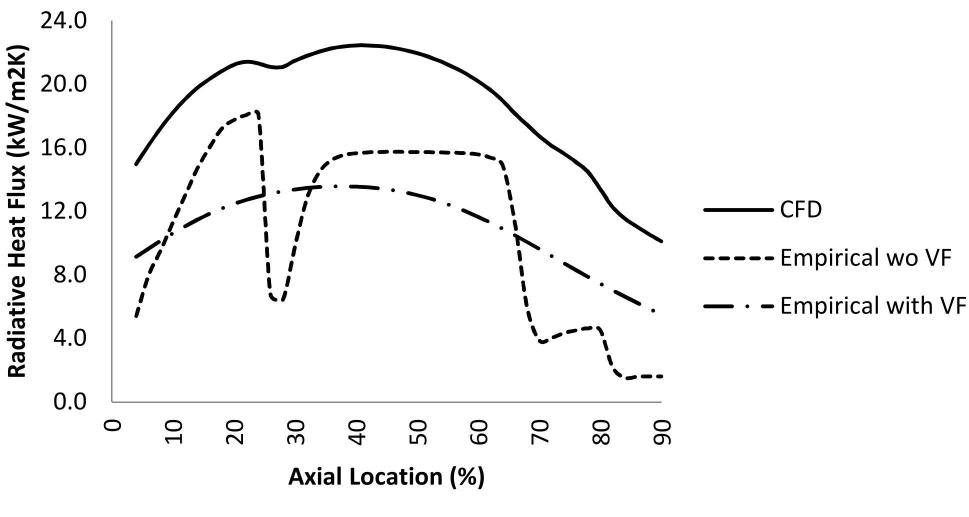

Figure 10: Axial Radiation Heat Flux Change Based on Mean Gas Temperatures

As a known methodology from the literature, these corrections are made based on the test results of the similar combustor architectures. However, in the absence of test data some assumption can be done. Therefore mean gas temperatures of each zone have been revised by constant coefficients (Figure 11) and by using these values empirical radiation heat fluxes have been recalculated. As it can be seen in Figure 12, view factor approximation gives a good match with CFD results.

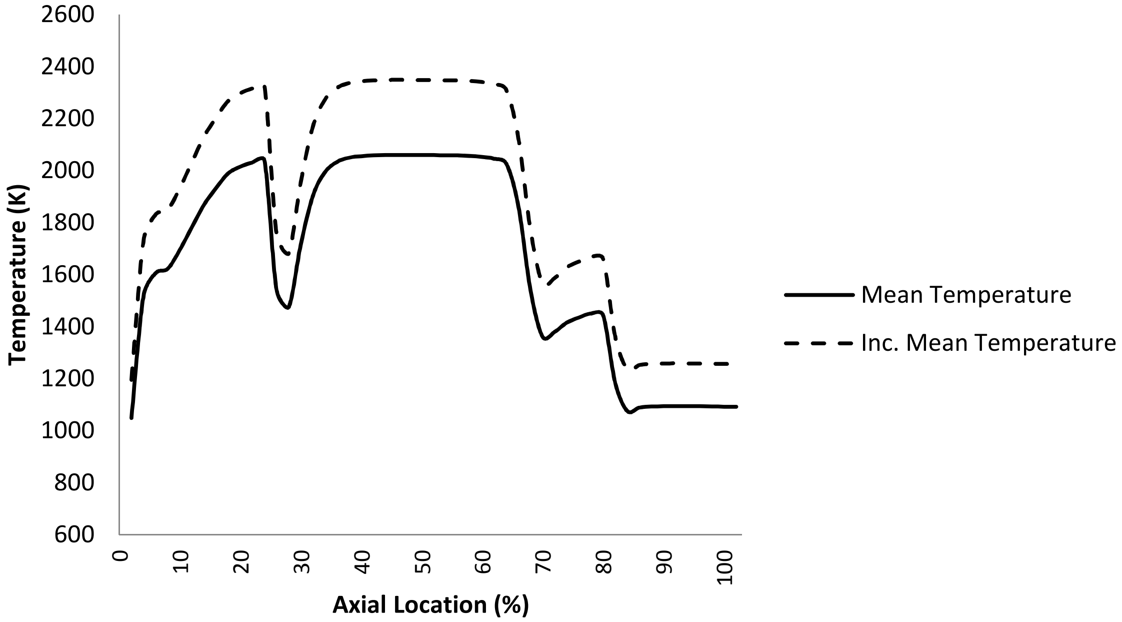

Figure 11: Modified Mean Gas Temperatures

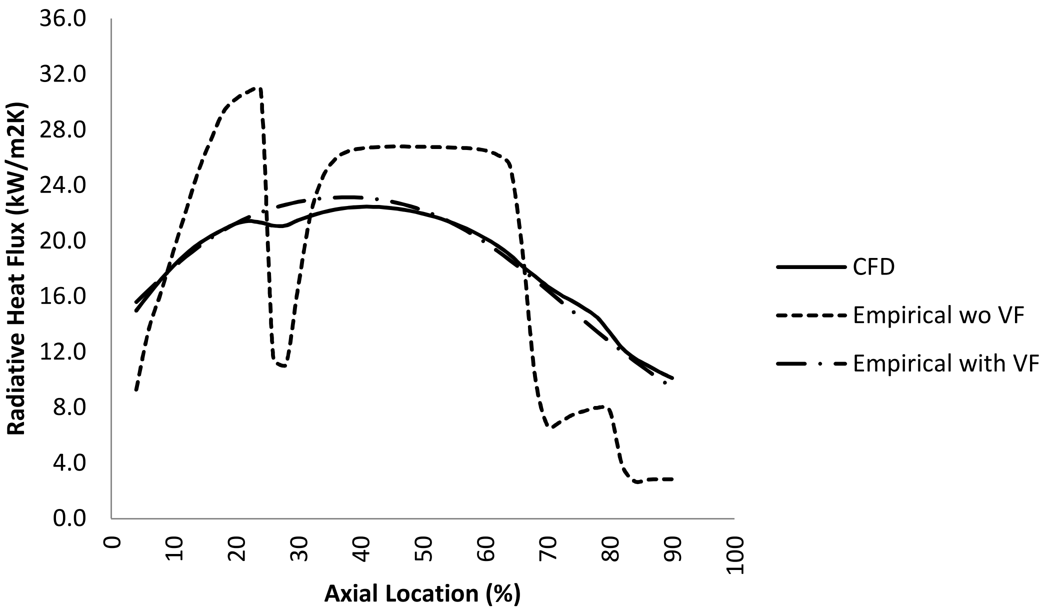

Figure 12: Radiation Heat Flux Change Based on Modified Mean Gas Temperatures

RESULTS AND DISCUSSION

One-dimensional calculation is an important process of the preliminary design phase of the gas turbine combustor and validated methodologies is required for that. While calculating the liner temperatures the most complicated heat load comes from the flame side radiation and by the way, it is required some approximation. In this study, one-dimensional radiation heat flux calculation methodology has been applied on a literature case and also a combustion CFD analysis case. It has been observed that using view factor approximation gives good heat flux distribution trend. In the simple cylindrical case when hot gas temperature is uniform there is no need for modifications. However in a combustor, where the hot gas temperatures is not uniform, mean gas temperatures should be incremented in accordance to the experimental or CFD studies for more realistic solutions.

Validity of this methodology should be further investigated for different boundary conditions and different combustor geometries. In the scope of tool and methodology development, CFD is a very powerful tool however it is necessary to investigate all analysis results with experiments.

NOMENCLATURE

A	Area, m^2
C_1	Convection heat flux from combustion gas to liner, W/m^2
C_2	Convection heat flux from combustion liner to casing, W/m^2
C/H	Mass based carbon to hydrogen ratio of fuel
D	Hydraulic diameter, m
f	Fuel to Air Ratio
k_g	Thermal conductivity of gas, W/(mK)
L	Luminosity factor
l_b	Mean beam length of radiation path, m
m	Mass flow rate, kg/s
P	Total pressure, Pa
q	Fuel/air ratio by mass
R_1	Radiation heat flux from combustion gas to liner, W/m^2
R_2	Radiation heat flux from combustion liner to casing, W/m^2
T	Temperature, K
VF	View Factor
ε	Emissivity
η	Combustion efficiency
ρ	Density, kg/m^3
μ	Dynamic viscosity, kg/(ms)
σ	Stefan-Boltzmann constant, 5.67×10^{-8} $W(m^2K^4)$
θ	View Angle, °

Subscripts

3	Combustor inlet station
a	Air
an	Annulus
c	casing
g	gas
L	liner
Ref	reference
w	wall

References

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