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A DESIGN TOOL FOR THE PRELIMINARY ANALYSIS OF GAS TURBINE COMBUSTORS

Ahmet Topal[1]
TUSAŞ Engine Industries, INC., Eskişehir, 26003, Turkey

Sıtkı USLU[2]
TOBB University of Economics and Technology, Department of Mechanical Engineering, Ankara, 06520, Turkey

Önder TURAN[3]
Anadolu University Faculty of Aeronautics and Astronautics, Department of Civil Aviation, Eskişehir, 26470, Turkey

ABSTRACT

A crucial task in the design process of a gas turbine combustor is the conceptual and preliminary design studies. Because of the different phenomena included in combustor design, there is significant number of design parameters to take into consideration. Number of these design parameters must be decreased prior to the detail design that is a time and money consuming phase. In preliminary design; combustor basic flow path, liner hole configuration, flame temperature and liner metal temperatures can be investigated and optimization can be performed by using empirical correlations. Rapid execution times have a critical importance for the flow path studies of the combustor that needs numerous design iterations. A more accurate initial design means shortening the detail design phase. Objective of this study is to develop a preliminary combustor design tool (***PreCoDe***) that includes all of the conceptual and one-dimensional preliminary design process in an automated way. The present methodology divides the combustor flow path (both, the annulus and flame tube) into small segments with varying fuel equivalence ratios and hence with different flame temperatures resulting into different liner metal temperatures. It differentiates from the known network approaches in the way that it involves more and finer details for calculating the combustor liner temperatures. Liner wall temperatures have been calculated using empirical correlations and compared with thermal paint test results.

INTRODUCTION

Gas turbine combustor design includes a huge number of design parameters. This situation requires detailed investigations in conceptual and preliminary design phases. In order to decrease development time and costs, combustor engineers need better design tools. An effective conceptual and preliminary design tool is critical for tuning the combustor geometry prior to 3D CFD (Computational Fluid Dynamic) studies.

In the past decades, various studies have been carried out to create design tools for gas turbine conceptual and preliminary studies. Pipe network solver is the most practiced methodology for preliminary design studies. Rogero [1] developed a combustor preliminary design simulation tool named as Flownet. It can be described as a geometry-independent, semi-empirical, network model. The Flownet provides information about mass flow splits, pressure drop, heat release and liner wall temperatures. Gouws [2] also created a one-dimensional empirical solver to predict pressure losses, flow distributions, and temperature distributions across gas turbine combustion chambers and studied

[1] Combustion Discipline Expert, Email: ahmet.topal@tei.com.tr
[2] Asst. Prof. Dr. in Dept. of Mechanical Eng., Email: suslu@etu.edu.tr
[3] Asst. Prof. Dr. in Dept. of Airframe and Powerplant Maintenance, Email: onderturan@anadolu.edu.tr

T56 turboprop engine combustor. A combustor design program named as DEPTH is developed by Murthy [3] to carry out a preliminary design along with prediction of the cooling slots for a given metal temperature limit or to evaluate heat transfer and temperatures for an existing combustion chamber. Stuttaford [4] studied a versatile design tool able to model all conceivable gas turbine combustor types. A network approach provides the foundation for a complete flow and heat transfer analysis to meet this goal.

In this paper, the newly developed preliminary design tool, ***PreCoDe***, and application to a small scale gas turbine combustor is presented. Code uses combustor performance parameters, design requirements and geometrical constraints as design inputs. It provides information about mass flow split, heat release, flame temperatures and combustor liner temperatures for 1 millimetre segments by using empirical correlations. Related outputs are automatically plotted and optimization studies can be easily performed by simple interface. Both of the through flow and reverse flow combustor types can be examined. Moreover, combustors that have different fuel supply systems such as vaporizer or air-blast atomizer can be analysed.

METHODOLOGY

The Microsoft Excel based code is written in combination between spread sheet neuron cells, visual basic, and macrocode. These three combinations provide user-friendly interface and easy pre-processing and post-processing. Analysis starts with the definition of performance and design parameters and geometrical constraints. After that the basic sizing of combustor is done and an initial liner hole configuration is used to be iterated on for further optimization. The *PreCoDe* calculation process initiate with flow split calculation. After performing this step, the flame temperature and liner metal temperature calculations are performed automatically. Finally, code prints the pre-defined data and relevant output plots.

A segmented architecture of a small scale turboprop engine combustor is shown in Figure 1. Each segment of the combustor flow path is defined by coordinates to define dimensions of flow segments. By using coordinates of these segments, flow and heat transfer calculations can be performed specific to each combustor segment.

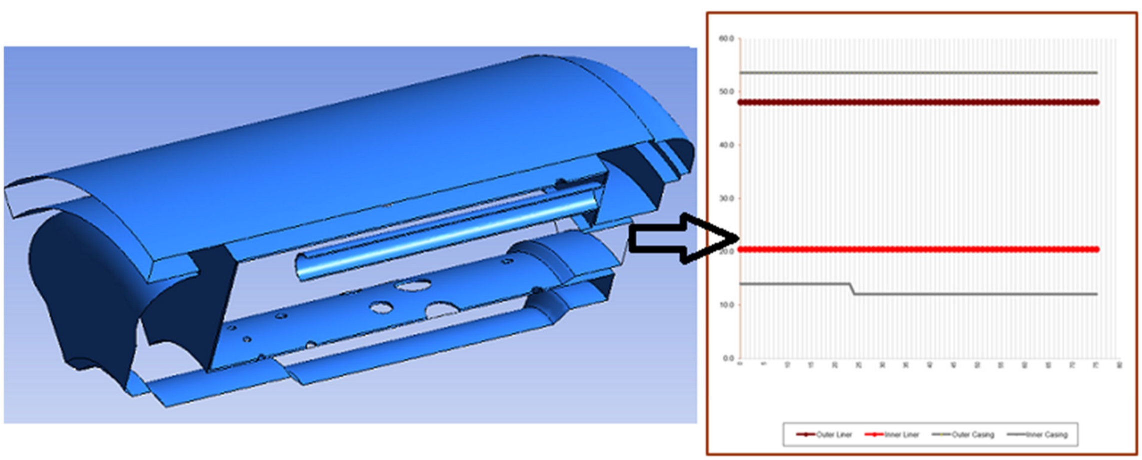

Figure 1: 2D flowpath of combustor and flow segments

Liner hole configuration is the primary factor that specify the flow split all over the combustor. Total hole area must be determined by the pressure drop design parameter. Therefore; prior to calculations, combustor pressure drop is given by the engine cycle. Combustor total pressure drop is a sum of cold and hot pressure losses and hot part of the pressure losses come from the combustion process. *PreCoDe* calculates the diffuser and hot pressure losses and subtracts them from the total pressure drop to obtain the pressure drop across the liner. The knowledge of pressure drop through the liner combustion air and cooling air holes allows us to compute the mass flow rate through the mentioned holes.

Mass flow split over the outer and inner liners of the combustor in Fig. 1 is shown in Figure 2**.** This mass flow split determines the flame tube mass flow, air to fuel ratio and hence flame temperature to be used for wall temperature calculation in each segment. (Figure 3).

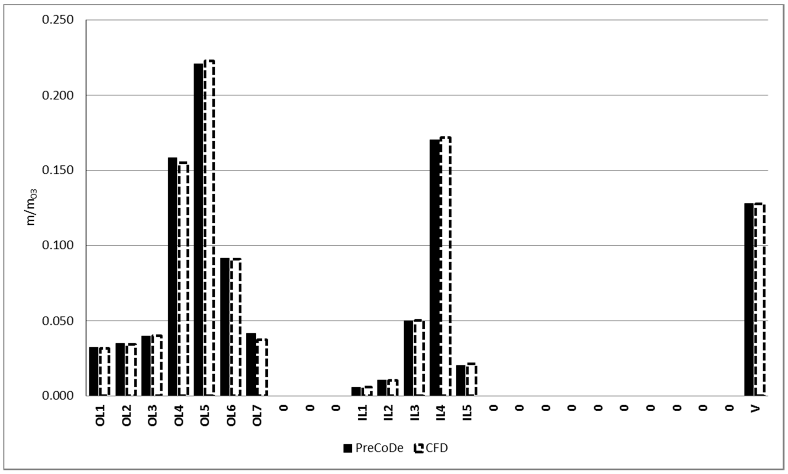

Figure 2: Normalized mass flow split for the small turbojet engine combustor

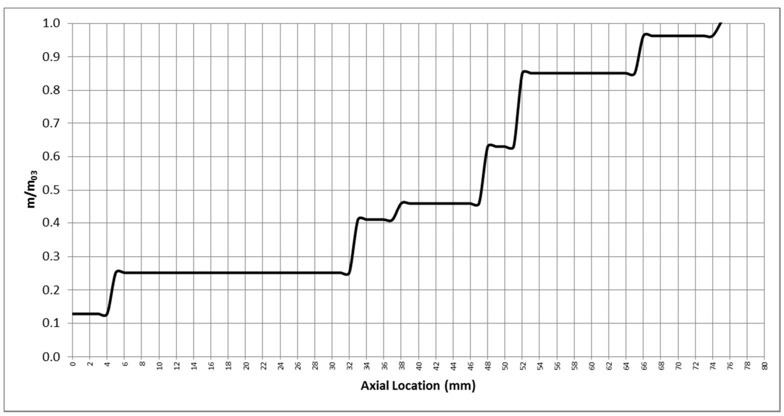

Figure 3: Normalized mass flow through the flame tube

Look-up tables are used to determine adiabatic flame temperatures for each segment [2]. Adiabatic flame temperature is calculated from the air fuel ratio, inlet temperature and pressure. Therefore, flow split values are used to calculate air to fuel ratio at each segment.

In order to accurately predict the flame temperatures, combustion efficiency must be taken into account. Combustion efficiencies of primary and secondary zones are calculated from the empirical correlations of Odgers [1]. However, correlations give the maximum efficiency value and do not take the effects of unmixedness of fuel and air into account. Therefore combustion efficiency increase along each segment and the maximum efficiency is obtained at the end of the zone.

$$\eta_{PZ,max} = 0.72 + 0.29 \tanh[1.5475 \cdot 10^{-3}(T_a + 108 ln P_a - 1863)] \quad 1$$

$$\eta_{SZ,max} = 0.80 + 0.29 \tanh[1.5475 \cdot 10^{-3}(T_a + 108 ln P_a - 1863)] \quad 2$$

Calculated gas temperature is the mean gas temperature of the flame tube segment. However, near wall gas temperatures must be estimated for a more accurate liner metal temperature calculation. In order to account for this phenomenon, a radial temperature distribution factor is defined for each zone and near wall gas temperature value over the liner is evaluated. In Figure 4, comparison of the mean and near wall gas temperature is shown.

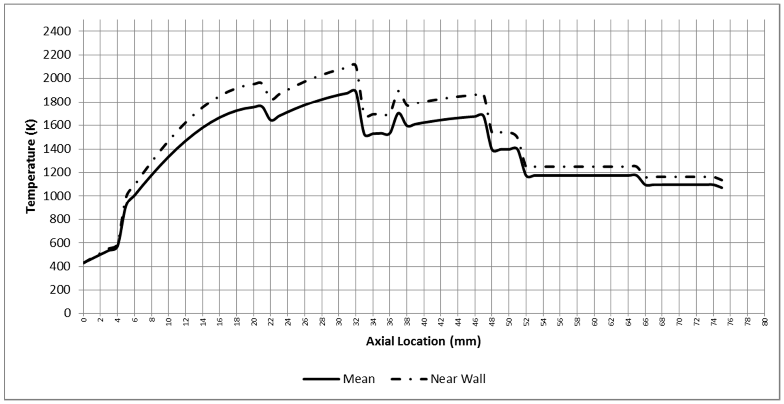

Figure 4: Mean and near wall gas temperature distribution along the axis of the combustor segment

A methodology of wall temperature calculations is well explained in Lefebvre [6]. It takes both modes of heat transfer, namely, convection and radiation, into account. Heat is transferred from the hot gasses to the liner by convection and radiation on hot side and is removed away by the same processes of heat transfer on the cold annulus side. To simplify the methodology and because of the thin liner walls, *PreCoDe* assumes that wall inner temperature equals to outer temperature. Basic heat transfer process is given in Figure 5.

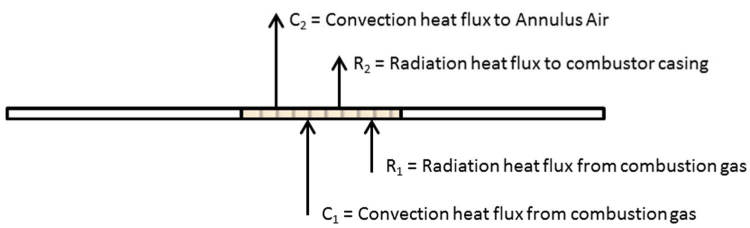

Figure 5: Basic heat transfer process in the combustor liner

Radiation and convection heat flux correlations are given by;

$$R_1 = 0.5 \cdot \sigma \cdot (1+\varepsilon_w) \cdot \varepsilon_g \cdot {T_g}^{1.5} \cdot ({T_g}^{2.5} - {T_w}^{2.5}) \quad 3$$

$$C_1 = 0.020 \cdot \frac{k_g}{D_L^{0.2}} \cdot \left(\frac{m}{A_L \cdot \mu_g}\right)^{0.8} \cdot (T_g - T_w) \quad 4$$

$$R_1 = \sigma \cdot \frac{\varepsilon_w \cdot \varepsilon_c}{\varepsilon_c + \varepsilon_w \cdot (1-\varepsilon_c) \cdot (A_w/A_c)} \cdot ({T_w}^4 - {T_3}^4) \quad 5$$

$$C_2 = 0.020 \cdot \frac{k_a}{D_{an}^{0.2}} \cdot \left(\frac{m}{A_{an} \cdot \mu_a}\right)^{0.8} \cdot (T_w - T_3) \quad 6$$

Code uses an iterative approach to calculate heat balance between combustion gas and air sides. In each iteration, wall temperature is updated to obtain the heat flux balance.

$$R_1 + C_1 = R_2 + C_2 \quad 7$$

Gas emissivity (with the account of Luminosity factor) is calculated by;

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

The following correlation for Luminosity factor has been suggested by Lefebvre [2] for modern aero engine combustors;

$$L = 336/H \quad (9)$$

where H is the fuel hydrogen content (by mass) in percent.

The beam length is determined by the size and shape of the gas volume. Lefebvre defines it by the expression;

$$l_b = 3.4(volume)/(surface\ area) \quad (10)$$

Kadoya et al. [8] presented correlation about the viscosity and thermal conductivity of air in the gaseous phase over a wide range of temperature and pressure. The range covered is from 85 to 2000 K for temperature and up to 100 MPa for pressure. Because of the difficulty of estimating combustion gas composition in one-dimension, combustion gas is approached as dry air and same correlations have been used to calculate viscosity and thermal conductivity. Correlation is assumed as applicable above to 2000 K. Following equation was used for the calculation of viscosity.

$$\eta(T_r, \rho_r) = H.[\eta_0(T_r) + \Delta\eta(\rho_r)] \quad (11)$$

where

$$\eta_0(T_r) = A_1 T_r + A_{0.5} T_r^{0.5} + \sum_{i=0}^{-4} A_i T_r^i$$

$$\Delta\eta(\rho_r) = \sum_{i=1}^{4} B_i \rho_r^i$$

$$T_r = T/T^*$$

$$\rho_r = \rho/\rho^*$$

Moreover a similar equation was used for the calculation of thermal conductivity.

$$\lambda(T_r, \rho_r) = \Lambda.[\lambda_0(T_r) + \Delta\lambda(\rho_r)] \quad (12)$$

where

$$\lambda_0(T_r) = C_1 T_r + C_{0.5} T_r^{0.5} + \sum_{i=0}^{-4} C_i T_r^i$$

$$\Delta\lambda(\rho_r) = \sum_{i=1}^{5} D_i \rho_r^i$$

$$T_r = T/T^*$$

$$\rho_r = \rho/\rho^*$$

Constants for equation 11 and 12 are given in Table 1.

Table 1: Constants in equations 11 and 12

T*	132.5 (K)	T*	132.5 (K)
ρ*	314.3 (kg/m^3)	ρ*	314.3 (kg/m^3)
H	6.16090 (Pa.s)	Λ	6.16090 (W/mK)
A_1	0.128517	C_1	0.128517
$A_{0.5}$	2.60661	$C_{0.5}$	2.60661
A_0	-1	C_0	-1
A_{-1}	-0.709661	C_{-1}	-0.709661
A_{-2}	0.662534	C_{-2}	0.662534
A_{-3}	-0.197846	C_{-3}	-0.197846
A_{-4}	0.00770147	C_{-4}	0.00770147
B_1	0.465601	D_1	0.465601
B_2	1.26469	D_2	1.26469
B_3	-0.511425	D_3	-0.511425
B_4	0.2746	D_4	0.2746
		D_5	-0.0201725

Wall temperature results for inner and outer liners of the given annular combustion chamber obtained from *PreCoDe* calculations are shown in Figure 6.

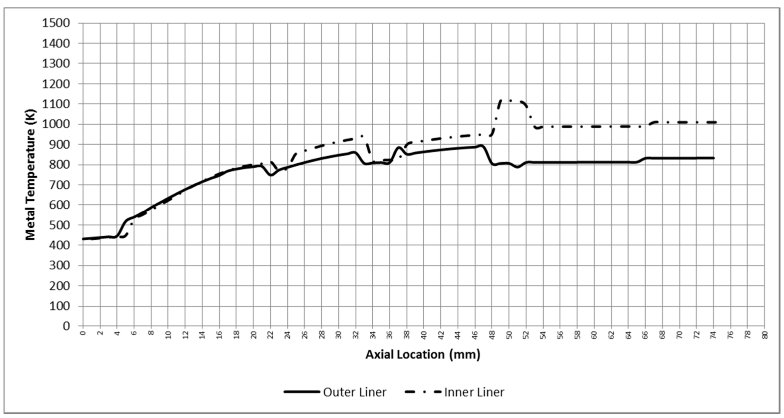

Figure 6: Wall temperatures for outer and inner liners

In addition to the liner wall temperatures, outer and inner annulus secondary air temperature was calculated and shown in Figure 7.

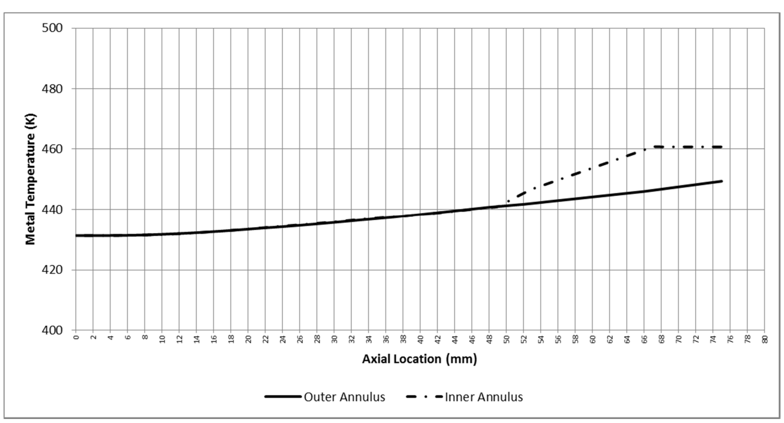

Figure 7: Air Temperatures at Outer and Inner Annulus

Also both air and combustion gas side heat transfer coefficients were calculated and plotted (Figure 8). *PreCoDe* uses same parameters for outer and inner liner gas heat transfer coefficient calculations.

Therefore two parameters have the same values. The value of heat transfer coefficient is very high compared to the experimental results. Abraham [9] performed experimental studies on a can type combustor and has shown a peak value of 160 W/m^2K heat transfer coefficient. This situation clearly explains the lower metal temperature values of simulated combustor.

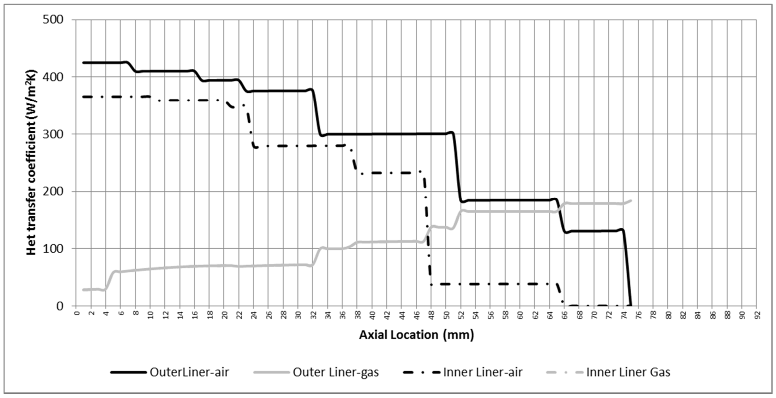

Figure 8: Heat transfer coefficients at the air and combustion gas side

THERMAL PAINT TESTS

In order to validate the wall temperature results predicted by the *PreCoDe* software, thermal paint test was applied to the outer liner of the combustor. Thermal paint, that is also known as Temperature Sensitive Paint, when applied correctly, it creates an irreversible visual record of the temperature contour patterns[7]. Thermal paint does not affect the thermal behaviour of the component during the test.

KN3 type product of the Thermal Paint Temperature Technology Company was applied to the combustor. This type has a wide colour range and the temperature level for each gradient is appropriate for expected liner temperatures. In Figure 9, application of the thermal paint can be seen. Combustor was masked prior to the painting and a very thin coat was applied to required areas. Thermal paint application needs expertise and therefore special care is required for painting process.

Figure 9: Thermal paint application on combustor

Although no special instruments are required for a thermal paint testing, a crucial testing procedure must be carefully followed for precise measurements. The thermal paint testing is time dependent and the testing time at maximum operating conditions must match to the available paint calibrations. During testing, thermal paint changes its colour irreversibly depending on the combustor liner temperature which reveals a signature pattern on the painted surfaces. Thermal paint has a 10 minutes calibration time to reach the specified colours. Combustor was tested in design point and calibration time conditions. To evaluate thermal paint results accurately, special coupons has been prepared. Each painted coupon has been heated up to specified colour change temperature level in a special furnace. A temperature scale was created for evaluating the measured wall temperature data. Thermal paint results of the combustor and temperature scale coupons of the KN3 type thermal paint can be seen in Figure 10.

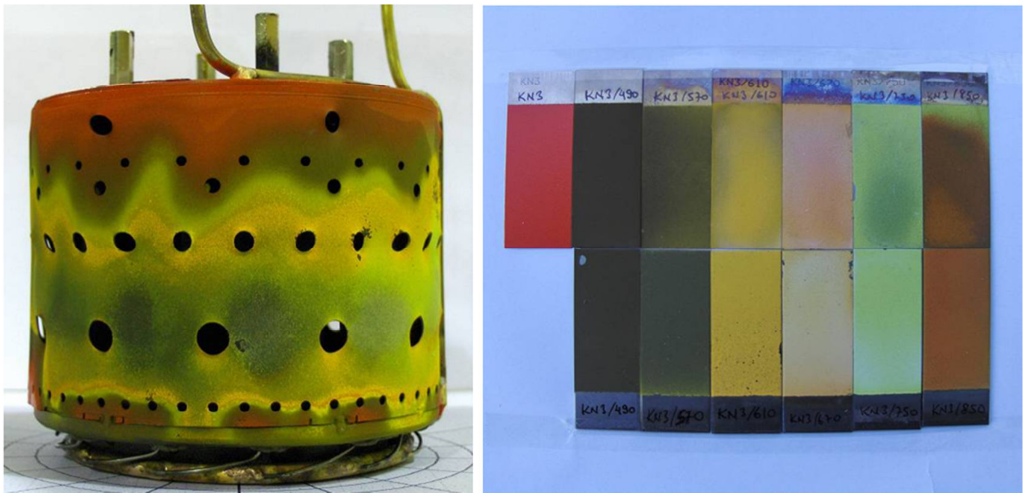

Figure 10: Thermal paint results of combustor and coupon scales

Panoramic photo of outer liner was taken and each thermal gradient was specified carefully. As it can be seen from the results, it was not reached to orange colour band. It means that the maximum liner temperature did not exceed the 670 °C (943 K). Thermal map of the outer liner is presented in Figure 11.

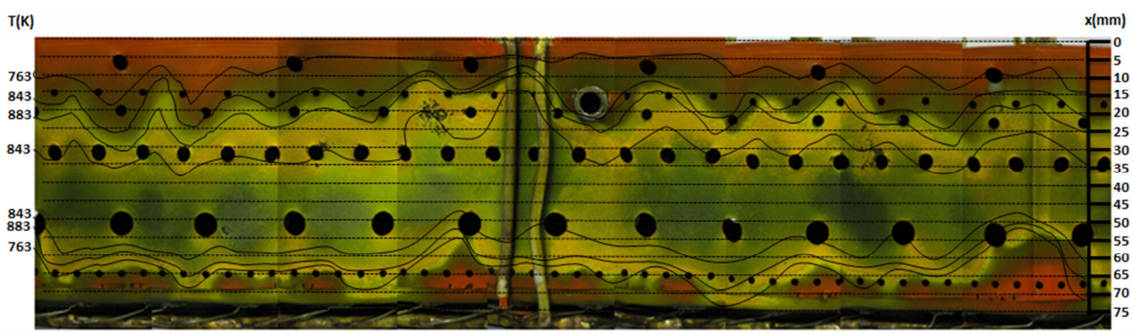

Figure 11. Thermal gradients of the combustor outer liner

Outer liner was divided in 5 mm segments to get approximate temperature data. These temperature values were compared with the one-dimensional results obtained by the *PreCoDe*. As seen in Fig. 12 the wall temperature results predicted by the *PreCoDe* are in reasonable agreement with the data with exception of the last segment for the reason that is explained in conclusion part.

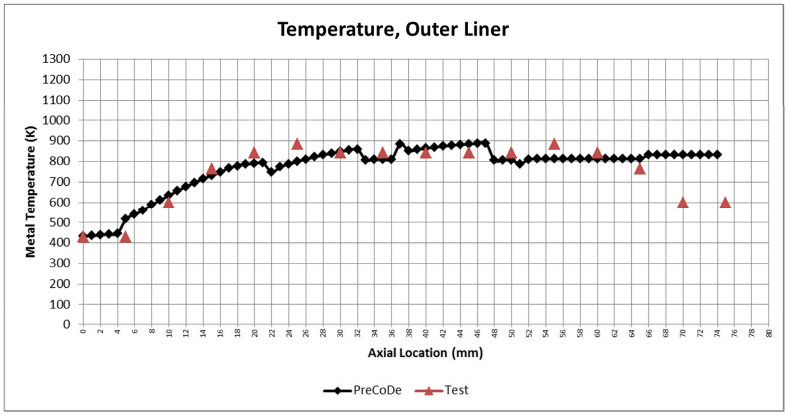

Figure 12: Comparison of PreCoDe and thermal paint test results

CONCLUSION

PreCoDe simulation and thermal paint test of a small scale gas turbine combustor has been performed. It has been observed that the simulation results are acceptable compared to thermal paint measurements. However, there is a large difference between the predictions and measurements at the end of the combustor. It is purely due to the prediction of high gas temperatures by *PreCoDe*. In the combustor experiments, rear flange dilution holes create a cold zone that is not estimated correctly by the adiabatic flame temperature calculations in the code and this results in highly over-predicted wall temperatures at the end of the liner.

In addition to thermal paint, simultaneous thermocouple measurements at different locations are planned as future work. In near future different size and type of combustors where measurements are available will also be used for wall temperature calculations in order to validate the predictive capability of the *PreCoDe*.

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