# Temperature Prediction and Validation of V-Gutter for an Aeroengine Afterburner

Batchu Suresh, S. Kishore Kumar

**Abstract**— Military aircraft engines employ afterburner system for increasing the thrust required during combat and take-off flight conditions. V-gutter is employed in an aeroengine afterburner for stabilization of the flame during reheat. The hybrid methodology of V-gutter metal temperature prediction is discussed in the present work. Prediction methodology is highlighted considering the flame radiation and thermal barrier coating. The V-gutter metal temperature is measured at various reheat power setting during aero engine testing on the test bed. The metal temperature is measured with the help of thermocouples which are routed to the V-gutter from data acquisition system. The metal temperature data is acquired during aero engine testing on the test bed. The convective and radiative heat loads coming on the V-gutter are estimated depending on surrounding gas and its aerodynamic parameters like pressure, temperature and velocity. The heat loads estimated from the empirical correlations are used for Finite Element (FE) analysis to predict metal temperature. The coating thickness and its conductivity are considered for the analysis. The metal temperature prediction in the presence of gas temperature variation, flame radiation and thermal barrier coating is complex. The proposed method of thermal prediction is simple and economical. The predicted and measured metal temperatures of the V-gutter are found to be in good agreement at different reheat conditions with the maximum deviation being 7%.The influencing parameters like gas temperature, thermal barrier coating thickness and coating conductivity are considered for carrying out a sensitivity analysis for V-gutter thermal analysis. The sensitivity analysis helped in identifying the critical parameter affecting the metal temperature. This hybrid prediction methodology can be used for predicting V-gutter metal temperature for afterburner combustor system for an advanced fighter aircraft during initial development. V gutter will be experiencing criticality from thermal cycling point of view and metal temperature prediction is required at different reheat conditions. This prediction methodology will be very useful and necessary during design and development phase of aero engine.

**Index Terms**— Afterburner Combustor V-gutter, Thermal barrier coating, Prediction of V gutter metal temperature.

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## 1 INTRODUCTION

Current military aero-engines are designed for very high power, low specific fuel consumption, small engine size and high thrust to weight ratio. Afterburner provides significant thrust augmentation which is vital for the mission and performance of fighter aircraft. V-gutters are present in afterburners for flame stabilisation which is required to establish continuous source of ignition in a fuel air mixture. A V-gutter bluff body creates a recirculation zone that acts as an ignition source for incoming fuel/air mixture by recycling hot products from the burnt mixture. It is proven to be very effective in anchoring the flame created in the combustion environments [1]. V-gutter splits the gas stream coming from upstream to create a low velocity recirculation zone. V-gutters for aero engine afterburner are V shaped cross section with nose facing the upstream turbine. The V-gutters are exposed to very high gas temperature during full reheat. The flame is surrounded at the rear portion and the gas from the turbine impinges at the leading edge. V-gutter experiences radial variation of hot gas coming from the turbine and receives heat due to radiation from the flame .The V-gutter has thermal barrier coating on the downstream portion to restrict the heat flux coming on to the V-gutter. The metal temperature prediction during full reheat is significant for thermal creep, fatigue life estimation for reliability of the afterburner performance.

Although the V-gutter flame holder has been investigated for many years, the underlying physical phenomena are still not well understood due to the nature of the complexity in the chemically reacting turbulent flows [2]. Many experiments have been conducted by Robert[3] for afterburner to improve the combustion efficiency and lean blowout limits for circular and parallel array of V gutters. He concluded that circular array of V gutter provided higher combustion efficiency and parallel arrays provided higher leaner blowout limit.

In the research by Sanquer et al.[4], the effects of the shape of the flame holder on the wake structure downstream was investigated. Recently, Cuppoletti et al. [5] measured the high frequency combustion instabilities with a radial V-gutter. Cheng-Xian Lin et.al [6] studied the effects of inlet turbulence intensity and angle of attack on the chemically reacting turbulent flow. The temperature distributions around a V-gutter in a flow channel were investigated in detail by a finite volume method. Emphasis was on the influence of the angled V-gutter on the reacting flow inside a flow channel and the channel walls could impact the flow around the V-gutter, at different inlet turbulence levels. Trovati[7] gave a survey of design process and described the development of afterburner problems encountered and their relevant solutions. Trovati mentioned that V- gutter is critical from thermal cycling which is proved by testing and prediction of metal temperature is required at all instants of the thermal transient cycles. S Ganesan et al[8] carried out experiments and compared with

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numerical simulations the flow features near V gutter region in afterburner. The predicted axial gas temperature variation across the afterburner shows that the increase in mass weighted gas temperature is more near the V-gutter compared to the later portion of the afterburner. S Kishore Kumar[9] presented their work of detailed numerical prediction of non-reacting flows in an afterburner .The flow field behind the V gutter showed that the axial length of the recirculation is 2.3 times the width of the V-gutter. Marek[10] presented the impact of thermal barrier coating on the turbine aerofoil and found the temperature drop from leading to trailing edge surface is from 200 to 700C. A long development process is required to optimize structure and shape of V gutter to obtain required life.

Basharat et al [11] highlighted the design of flame holder based on empirical correlation which are very useful for initial design process and serve as an effective and very economical approach as compared with CFD simulation that requires huge computer time and cost. The understanding of flow near the V-gutter is required for estimating the incoming heat loads. The V-gutter metal temperature prediction can be based on Conjugate Heat Transfer (CHT) or semi empirical correlation with FE hybrid methodology. CHT is computationally expensive and time consuming with different models for droplet distribution, combustion and turbulence. In the present work hybrid method of generic correlation and FEM is used. The correlations are tuned to validate temperature predictions with measured data during the engine testing.

During full reheat, gas radiation contributes to total heat load coming on the V-gutter and temperature drop across the thermal barrier coating is significant. Semi empirical correlations are used for estimation of convective and radiative heat fluxes coming on to V-gutter which are input for the FE model. 3D FE thermal analysis is carried out to predict the nodal temperature distribution for V-gutter. The thermal barrier coating with actual thickness is modelled in FE model and the temperature drop across the coating is estimated.

In this work, empirical correlations used for convective, radiative fluxes, and gas emissivity are highlighted. The predicted metal temperature are compared with measured data during engine runs at different reheat conditions. The measured data was consolidated for various engine runs at different engine setting and compared with predicted values. A sensitivity analysis is carried out to study the effect of various parameters like gas temperature, coating thickness and coating conductivity on V-gutter metal temperature.

## 2 OBJECTIVE

The objective of the current work is to predict the V-gutter metal temperature and validate the hybrid prediction methodology for an aero engine afterburner. V gutter metal temperature during testing is measured with help of thermocouples. Predicted the metal temperature using the methodology. Compared the predicted metal temperature with measured temperature data during in house aero engine testing at test bed. Carry out a sensitivity study to identify the critical parameter affecting the V –gutter metal temperature

## 3 ASSEMBLY DETAILS

The schematic layout of aero engine afterburner and its major components are shown in Fig.1. Afterburner is an exhaust system that is present at the exit of the turbine in the aero engine. The main components of afterburner are diffuser to reduce the flow velocity, screech liner to attenuate the pressure oscillations, fuel manifolds/fuel spray bars to provide proper fuel distribution and V-gutter to provide the recirculation zone for flame anchoring. The conventional flame holder widely used in afterburner is of a bluff body type. It consists of V-shaped gutter with the apex of the gutter pointing towards the incoming gas stream. The detailed configuration of the V- gutter is shown in Fig.2. It has one central circular ring to which six inner and twelve outer radial gutters are attached. The hot gas from turbine comes and impinges on the leading edge and flows along the side walls of the V gutter. Gas passes through the four impingement holes present on the leading edge of outer radial gutter and impinges on the plate present at the rear side of V-gutter. The wake side of the V gutter will be facing the hot flame and thermal barrier coating is present on the rear side of the V–gutter.

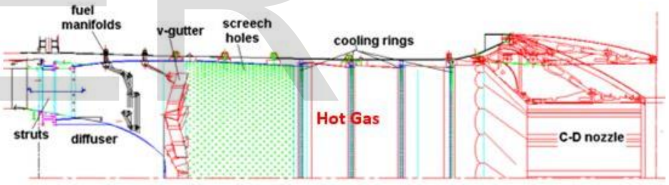

Fig.1.Schematic Layout of Aero Engine Afterburner

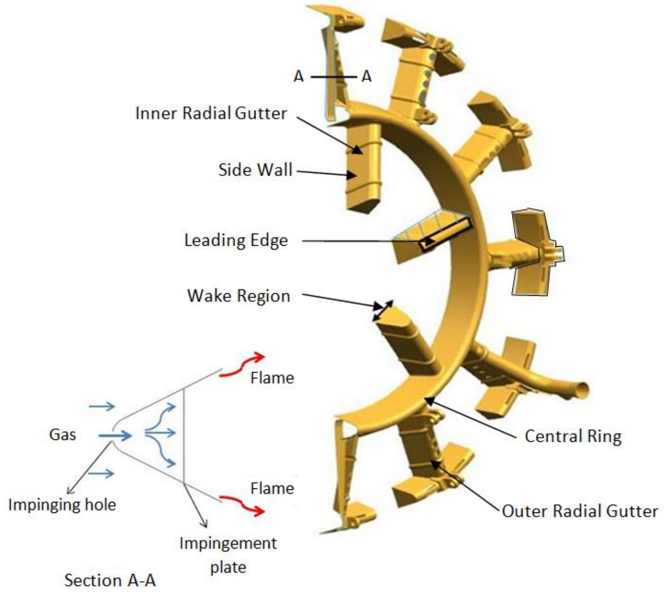

Fig.2.Regions considered for V-gutter thermal Analysis

## 4 REGIONS OF HEAT TRANSFER MODELLING

Various regions on the V gutter are identified for the heat transfer modeling depending on the flow pattern and gas temperature .The regions considered for the thermal analysis are shown in Fig.2 the regions are,

i. Leading edge

ii. Side Wall

iii. Wake region

iv. Impingement plate.

## 5 HYBRID PREDICTION TECHNOLOGY

Afterburner V-gutter is exposed to convective and radiative heat transfer from hot gases during reheat operations. The heat fluxes coming on the V gutter depends on its geometry and gas stream condition. Semi empirical correlations are used for estimating convective and radiative heat fluxes. These heat fluxes are given as input to model and FE analysis is carried out. 3D Finite element thermal analysis is carried out using commercial software ANSYS to estimate the nodal temperature distribution across the V-gutter. The analysis is carried out for the actual reheat aero engine test conditions. The measured V-gutter metal temperature data is consolidated at different conditions which are specified by Pilot Lever Angle. The PLA angle will control fuel flow rate and thus the reheat gas temperature. The estimated V-gutter metal temperatures are compared with measured metal temperature.

## 6 EMPERICAL CORRELATIONS

i)Leading edge

The heat transfer at the leading edge of V gutter depends mainly on the mainstream condition such as Reynolds number and turbulence intensity. Leading edge heat transfer can be considered as a flow past the cylinder hence Lowery and Vachon [12] correlation is used. The Reynolds number is based on leading edge diameter and the turbulence intensity is taken as 5%.

$$\frac{Nu}{\sqrt{\mathrm{Re}}} = 1.01 + 2.624\left(\frac{Tu\sqrt{\mathrm{Re}}}{100}\right) - 3.07\left(\frac{Tu\sqrt{\mathrm{Re}}}{100}\right)^2 \qquad \text{...(1)}$$

ii) Side wall

As the flow diverges in the leading edge, flow over the side wall is assumed as a turbulent flow over a flat plate. To estimate the heat transfer coefficient on the side wall region turbulent flow over a flat plate [13] equation is used. The fluid properties are evaluated at Eckert's reference temperature on the hot gas side for side wall region. Re is based on length of the side wall.

$$\mathrm{Nu} = 0.037\ \mathrm{Re}^{0.8}\ \mathrm{Pr}^{0.3} \qquad \ldots(2)$$

iii)Wake Region

Wake region during reheat mode will be exposed for both convective and radiative heat transfer from hot gases. Nusselt number in separated flow on the rear of the bluff bodies is proportional to (2/3) power of the Reynolds number and is given by Andrew [14] and Hajime [15]

$$Nu = 0.172\,\mathrm{Re}^{\left[\frac{2}{3}\right]} \qquad \ldots(3)$$

iv)Impingement Plate Region

The gas from the turbine flows through 4 holes present at the leading edge of V-gutter and impinges on the impingement plate. The heat transfer coefficient is estimated using the correlation for Impingement on a flat plate by Katti and Prabhu [16]

$$\mathrm{Nu} = 0.0436\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.333}\left(\frac{z}{d}\right)^{0.0976}\left(\frac{r}{d}\right)^{-1.0976} \qquad \ldots(4)$$

The flame is characterized by predominance of luminous radiation in aero engine combustors. Lefebvre and Herbert [17] have given the gas emissivity εg for luminous radiation as

$$\varepsilon_g = 1 - \exp^{\left\{-290 * P_g * L * \left[\left(1/\left(A/F\right)\right) * L_b\right]^{0.5} * \left(T_g\right)^{-1.5}\right\}} \qquad \ldots(5)$$

## 7 FINITE ELEMENT ANALYSIS

3D thermal Finite element analysis is carried out using commercial software ANSYS ver.14.5 to estimate the nodal temperature distribution.$30^0$ sectorial model is considered for the analysis because of geometric symmetry. Fig.3 shows the full view of FE model of V-gutter assembly. The model consists of 22056 3D shell elements, 22762 nodes. 3D Shell is used for the analysis which is a multi-layered, 4 nodded shell element having in-plane and through thickness conduction capabilities. In this model the thickness of base metal and thermal barrier coating thickness is modelled. The convective and radiative fluxes estimated are applied on the FE model. There is a radial gas variation at the inlet of V gutter which are measured with thermocouple probes during testing. Measured radial gas temperature variation at inlet of the V-gutter is considered for load application on FE model. Fig.4 shows front and rear view of V gutter where thermal loads in the form of gas temperatures and heat transfer coefficients are applied. Radiative loads are estimated and are applied on the gas side. The base material is Nickel based alloy and thermal barrier coating is Yittria stabilized Zirconia. The variation of thermal conductivity with temperature for materials are considered for the analysis.[18] The convective loads in form of heat transfer coefficients are applied which are obtained from the governing equation mentioned earlier. At the wake side of the V gutter the gas temperature is estimated from the amount fuel and gas flow and is applied.

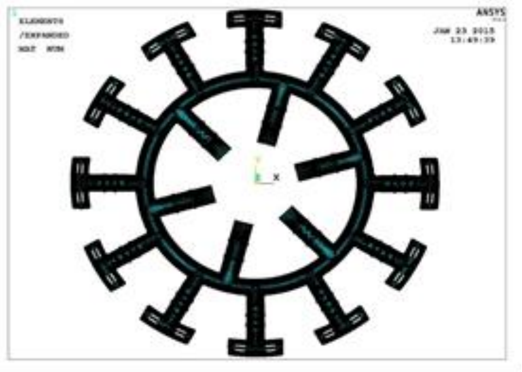

Fig.3. Finite Element model of V-gutter assembly

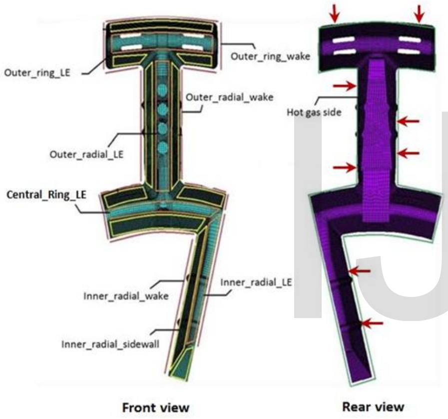

Fig.4 Various zones of V-gutter where loads are applied.

## 8 RESULTS AND EXPERIMENTAL VALIDATION

Fig.5 shows the thermal contours of the V-gutter interface metal temperature at the front view for a typical maximum reheat condition tested during the engine run. The maximum condition is corresponding the to the maximum PLA position during reheat operation where maximum gas temperature is encountered. The thermal contours are non-dimensionalised with respect to maximum metal temperature for all the figures mentioned in this work. Interface is the location between the coating and base metal. The maximum metal temperature is at the trailing portion of outer radial V-gutter and is within the allowable material temperature limit. The maximum metal temperature distribution at this area is due to the flame anchoring, presence of turbulent eddies at the wake side and higher incoming gas temperature at outer radial gutter. The temperature is lower at the leading edge of inner radial gutter due to higher heat transfer coefficient and lower incoming gas temperature. The thermal barrier coating brings down the heat flux coming on to the metal due to increase in thermal resistance.

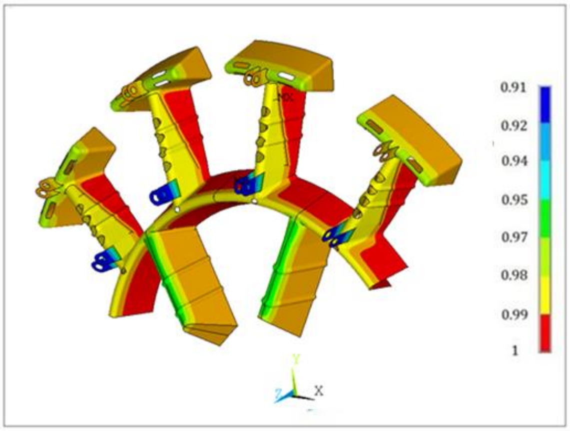

Fig.5 Thermal contours of V-gutter at the interface metal temperature with coating.

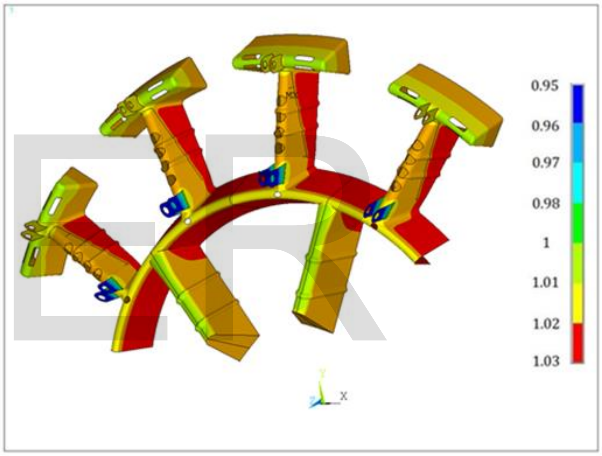

Fig.6 Thermal contours of V-gutter at the interface without coating.

Fig.6 shows the non-dimensional thermal contours of V-gutter without coating at the rear view which is carried out for the same reheat condition. The range of non-dimensional metal temperature is increased from 1 to 1.03 without coating. This is due to the increase in the incoming flux from the wake side. The thermal barrier coating has brought down the maximum metal temperature by $32^0$C. The temperature drop depends on the heat load coming on to the V-gutter, thickness and conductivity of the coating. In this case also the temperature drop is at highest at the location maximum temperature.

Radiation heat transfer from the flame contributes to incoming total heat load for V-gutter. Radiative heat transfer flux is estimated using Lefebvre[17] approach. The analysis is carried out without giving the radiative heat load. Fig.7 shows the non-dimensional thermal contours of V-gutter without radiation. The radiative heat transfer increased the V-gutter metal temperature by order of $20^0$C.Radiative heat flux is of the order of 10% of the total incoming heat flux.

The V-gutter metal temperature is measured using calibrated 'K' type thermocouples during engine testing. The thermocouples are routed to the location of measurement from data acquisition systems. Special provisions are made on the hardware to facilitate this temperature measurement. Different radial locations marked Ch-33 and Ch-35 are shown in Fig.8 for measuring the V-gutter metal temperature. Ch -33 is spot welded at the central circular ring and Ch-35 at the outer radial gutter. The metal temperatures reach steady state within few milliseconds and the response of the metal temperatures are almost instantaneous and follow the gas temperature. The thermocouples are spot-welded and data is acquired over 2 samples per second using data acquisition. The incoming gas temperature is measured using temperature probe at different radial heights. The analysis is carried out for many engine runs and reheat conditions to check the repeatability of results.

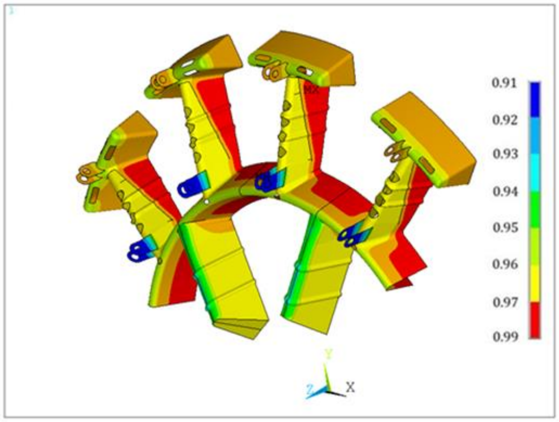

Fig.7 Thermal contours of V-gutter at the interface without radiation

Fig.9 and Fig.10 shows the comparison of non-dimensional predicted and measured metal temperature at Ch- 33 and Ch-35 at different pilot lever angle (PLA) position. The V-gutter metal temperature distribution is predicted using the same hybrid prediction methodology. Using the above procedure the predicted metal temperature data is in agreement with the measured metal temperature data and variation is within +7% for Ch-33 and within +1% for Ch-35 at all the eight reheat conditions. This variation may be because of the uncertainty in estimation of some of the parameters like gas temperature, coating thickness and coating conductivity values.

## 9 SENSITIVITY ANALYSIS

To understand the importance of each parameter on V-gutter temperature a sensitivity analysis is carried out with respect to gas temperature and thermal barrier coating thickness and conductivity thickness. The sensitivity analysis is carried out for V-gutter metal temperature by repeating the analysis for different values of gas temperature near wake region, thermal barrier coating and conductivity around the baseline parameters. V-gutter metal temperature variation with 10% variation of gas temperature, conductivity and thermal barrier coating are shown in Table-1. With increase in gas temperature the metal temperature increases due to increase of incoming heat flux on the V-gutter from the hot gas. With 10% increase of gas temperature from the baseline gas temperature the metal temperature is increased by 6%. With decrease in gas temperature the metal temperature reduces. With increase in coating thickness the conductive resistance increases, so heat load on to the V-gutter reduces thus reducing the V-gutter temperature. For 10% increase in coating thickness with 0.5 mm baseline thickness the reduction in metal temperature is 0.3%.With increase in thermal conductivity of the coating the conductive resistance decreases increasing the metal temperature. With increase in coating conductivity by 10% the increase in metal temperature is .4%. It is evident from the Table-1 that with 10% variation of gas temperature the V gutter metal temperature increases by 6% which is higher than other parameters considered.

Table-1 Sensitivity Analysis

| Variable | For + 10 % Variation, % variation in Metal Temperature | For - 10 % Variation, % variation in Metal Temperature |
|---|---|---|
| Gas Temperature | +6.0 | - 6.0 |
| Coating Thickness | - 0.3 | +0.3 |
| Coating Conductivity | +0.4 | -0.4 |

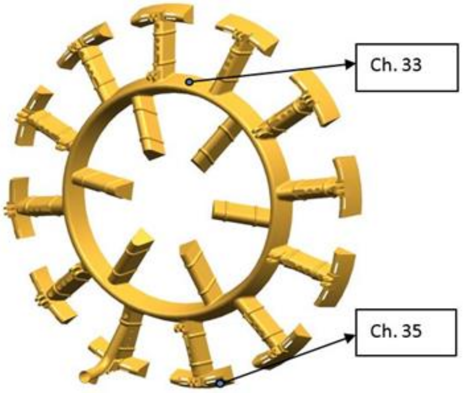

Fig.8 V-gutter with different thermocouple locations

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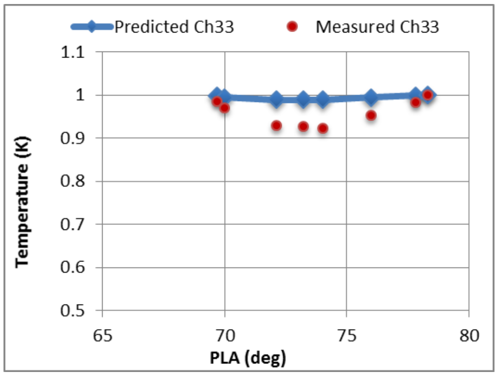

Fig.9 Comparison of predicted and measured metal temperatures for Ch 33

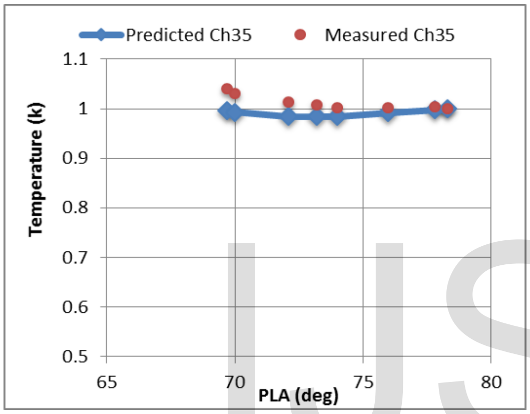

Fig.10 Comparison of predicted and measured metal temperatures for Ch 35

## 10 CONCLUSIONS

The hybrid methodology of correlative and FE based approach is used for prediction of V -gutter metal temperature at reheat steady conditions. The methodology proved to be reliable and accurate from the comparisons made with measurements. The estimated values of V-gutter temperatures were in good agreement with measured temperature during engine testing. The metal temperature predictions are within +7% of the measured temperature values for different operating conditions. The V-gutter temperature is within the allowable limits of the material at the peak condition. Thermal barrier coating has brought down the peak metal temperature by 32$^0$C. The effect of radiation during full reheat on V-gutter metal temperature is of the order of 20$^0$C. Sensitivity analysis has shown that the gas temperature is the critical parameter affecting the V-gutter metal temperature of all the parameters considered. The hybrid methodology can be adopted for design of cooled configuration for V gutter for advanced fighter aircraft where the order of gas temperature is very much beyond the allowable metal temperature. This hybrid prediction methodology of V gutter temperature prediction will be reliable and fast especially for abnitio development of gas turbine afterburner combustor.

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### Nomenclature

| | |
|---|---|
| d | diameter of impingement hole, m |
| F/A | Fuel air ratio |
| L | Luminous factor |
| Lb | Beam Length, m |
| Nu | Nusselt Number |
| Pr | Prandtl Number |
| Pg | Gas side pressure |
| Re | Reynolds Number |
| r | distance from the normal line, m |
| Tg | Gas total temperature |
| Tu | Turbulence intensity |
| z | distance between impingement holes and impingement surface m |
| εg | Gas Emissivity |

## REFERENCES

[1] Longwell, J. P., "Flame Stabilization by Bluff Bodies and Turbulent Flames in Ducts," Proc. Combust. Inst., 4, pp. 90–97, 1953.

[2] Lin,C.,Sekar,B., Holder,R.,Zelina,J., and Thronburg,H,"Numerical Simulation of inter-Turbine Burner(ITB) flows with inclusion of V-gutter Falme Holders" ASME paper no.GT2008-50337,2008.

[3] Robert Branstetter and Gregory M Reck "Afterburner performance of circular V –gutter and sector of parallel V gutter for a range of inlet temperautres to 1255K.",NASA TN D-7212, March 1973.

[4] Sanquer, S., Bruel, P., and Deshaies, B., "Some Specific Characteristics of Turbulence in the Reactive Wakes of Bluff Bodies," AIAA J., 36_6_, pp. 994–1001, 1998,

[5] Cuppoletti, D. R., Kastner, J., Reed, J., Jr., and Gutmark, E. J., 2009, "High Frequency Combustion Instabilities with Radial V-Gutter Flameholders," AIAA Paper No. AIAA-2009-1176,2009.

[6] Cheng-Xian Lin, Richard Jack Holder," Reacting Turbulent Flow and Thermal Field in a Channel With Inclined Bluff Body Flame Holders" J. Heat Transfer, Vol. 132 / 091203-1, 2010.

[7] Trovati A ,F Turrini and C Vinci " Afternurner design and Deveolpement" presented at RTO AVT Symposium on "Design,principles,and methods for aircraft gas turbine engines."11-15 May 1998

[8] S.Ganesan, S.Kishore Kumar &Venkataraman Shankar, "Prediction of model gas turbine afterburner performance using CFD"ISABE -2007,18th ISABE Conference, held at Beijing,China, Sept2-7 2007

[9] S Ganesan , S Kishore Kumar & V Ganesan , "CFD study of isothermal flow in an afterburner system" Indian Journal of Engineering and Material SciencesVol.12, pp 487-497, December 2005 .

[10] Marek Lazazyk, Roman Domanski ,"Numerical simulation of thermally loaded aircraft engine turbine blade covered with thermal

barrier coating-TBC" Journal of Kones powertrain and transport vol.19,No.3 2012.

[11] Basharat Ali Haider ,Nikola Davidovie and Naveed Durrani,"Preliminary Design of short Afterburner for single –spool Expendable Turbojet Engine" AIAA 2011-574 ,49th AIAA Aerospace meeting and Aerospace Exposition, Oriando Florida, 4-7 Jan 2011

[12] Lowery, G.W., and Vachon, R.I., "The effect of turbulence on heat transfer from heated cylinders", International Journal of Heat and Mass Transfer, Vol.18, pp.1229-1242.

[13] Y. A. Cengel, Heat Transfer: A Practical Approach, 2nd edition, McGraw-Hill, 2003.

[14] Andrew E., Potter "Effect of Pressure and Duct Geometry on Bluff-body Flame Stabilization", NACA TN 4381, Sep-1958

[15] Hajime Nakamura and Tamotsu Igarashi, "Variation of Nusselt No. with flow regimes behind a circular cylinder for Re from 7 to 30000", Int. J of Heat and Mass Transfer 47 , 5169-5173, 2004

[16] Vadiraj Katti & S.V. Prabhu "Experimental study and theoretical analysis of local heat transfer distribution between smooth flat surface and impinging air jet from a circular straight pipe nozzle" International Journal of Heat and Mass Transfer -51,4480-4495,2008.

[17] Lefebvre,A.H., and Herbert,M.V.,"Heat Transfer Processes in Gas Turbine Combustion Chambers", Proceedings of the Institution of Mechanical Engineers, Vol.174, No.12, pp.463-473, 1960.

[18] Henry Wiggin and company limited, England, Publication:3463, May 1976