A TEST BENCH FOR GAS TURBINE COMBUSTOR COOLING INVESTIGATIONS

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ABSTRACT

Design and installation of a test bench for combustion chamber cooling investigations of gas turbines are carried out. The test bench mainly consists of a radial fan, an electrical heater, an air tunnel, a test section, and cooling air supply system. The combustor liner is presented by a flat test plate which is a scaled-up model of a real combustor geometry. Main flow can be provided at a temperature in the range of 298-573 K, which enables a wide range of density and blowing ratio between the main flow and the coolant. The surface temperature distribution of the test plate is measured by infrared thermography technique to determine the adiabatic cooling effectiveness. The test bench enables to investigate the effects of different geometrical and flow parameters on effusion and film cooling effectiveness.

INTRODUCTION

Gas turbine combustors operate at high temperature levels and some cooling techniques should be used to keep the liner material in the desired temperature range. Film, effusion, and impingement cooling are three main cooling techniques widely utilized for combustor liners. One important design criteria for combustor is to use minimum amount of air for cooling which should lead to an optimum cooling configuration. Flow conditions such as blowing ratio (BR), density ratio (DR), Reynolds number (Re) etc. and geometrical parameters of cooling holes are the main parameters which affect the cooling performance. Many experimental and numerical studies have been conducted to investigate the effects of different flow conditions and geometrical parameters on film and effusion cooling performance for gas turbine combustor.

NOMENCLATURE

t	[mm]	Test plate thickness
d	[mm]	Effusion hole diameter
L	[mm]	Effusion hole length
S	[mm]	Inter-hole distance
T	[K]	Temperature
x	[mm]	Axial distance
U	[m/s]	Velocity
BR	[-]	Blowing Ratio, $BR = \frac{(\rho U)_c}{(\rho U)_\infty}$
Special characters		
α	[°]	Effusion hole angle
η	[-]	Cooling effectiveness
ρ	[kg/m^3]	Density
Subscripts		
s	[-]	Pitch
p	[-]	Span
s	[-]	Surface
∞	[-]	Mainstream
c	[-]	Coolant
m	[-]	Mean

Film cooling

The effectiveness of film cooling methods on combustion chamber is investigated by different research groups during decades. Leger et al. [1] conducted an experimental study to investigate the effects of different geometric and flow parameters on adiabatic wall temperature for film cooled flat plate. Angle and diameters of holes, transverse and longitudinal pitch are the geometric parameters whereas pressure drop through holes, coolant temperature, coolant and hot gas mass flow rates are the aero-thermodynamic parameters studied. Their study also includes the development of an artificial neural network code to predict the hot side heat transfer coefficient and adiabatic wall temperature. Yuzhen et al. [2] investigated the adiabatic film cooling effectiveness on walls with inclined multi-holes at engine representative combustor conditions. Lateral hole pitch, streamwise hole spacing, and compound angle were the parameters changed for four different test pieces. Numerical study was also performed to understand the film cooling mechanism. The results showed that the blowing ratio ranging from 1 to 4 has negligible effect on the cooling effectiveness for the concurrent film injection configuration whereas for the counter-flow film cooling scheme blowing ratio within the same range has strong effect on effectiveness.

Scrittore et al. [3] presented the experimental results from a combustor tested in a low speed wind tunnel. Engine representative, non-dimensional coolant flows were tested for a full-coverage effusion plate. Detailed flow field characteristics of the effusion cooling was measured with a Laser Doppler velocimetry [3]. Additionally, the effect of dilution flow on film cooling performance was studied by the same research group [4]. Patil et al. [5] performed experiments and numerical computations to investigate the convective heat transfer characteristics of a gas turbine can combustor under cold flow conditions in a Reynolds number range between 50,000 and 500,000 with a characteristic swirl number of 0.7.

Effusion cooling

Effusion cooling methods recently become popular for the combustor cooling design. Gustafsson [6] performed a parametric study of surface temperature distributions on effusion cooled plates by means of infrared thermography. The effects of different temperature ratios, velocity ratios, Reynolds numbers, hole spacing, injection angles, and thermal conductivity of the wall material were investigated. The experiments were designed to scale with a combustion chamber condition of a real gas turbine. A linear relationship between surface temperature and temperature ratio between the hot cross-flow and the coolant was found. A complete mapping of the 3D velocity and turbulence fields near one of the injection holes in the third row of holes was obtained by laser- doppler anemometry. Wurm et al. [7] introduced a new test rig with planar geometry that includes three swirlers in the lateral direction. Operating Reynolds number and temperature ratio is simulated based on the real engine conditions. The test channel is rectangular and equipped with large windows for easy accessibility for laser optical measurements like PIV and 3-component LDA. In the test rig the starter flow (cooling flow supplied under heat shield) and effusion cooling air can be controlled independently. Infrared thermography technique is used for surface temperature measurements. Experimental results are presented in terms of static pressure distributions on the combustor liner and PIV contour plots of the swirl flow. Ceccherini et al. [8] experimentally investigated the combustor liner cooling scheme on a test article having large dilution central hole and effusion holes. The adiabatic cooling effectiveness was measured by means of a steady-state Thermochromic Liquid Crystals (TLC) technique, considering the combined effects of slot, effusion, and dilution holes. CFD RANS calculations were also performed with the aim of better understanding of interactions between coolant exiting from the slot and injected by effusion cooling rows. Numerical analysis revealed a large dependency on effusion velocity ratio. Andreini et al. [9] carried out an experimental study composing of two campaigns to determine the heat transfer coefficient over effusion cooled plate. Air and CO_2 are used as coolant. Steady state TLC technique is used to measure the temperature distribution over the heated surface to determine the heat transfer coefficient. Results of the two campaigns were finally combined to calculate the Net Heat Flux Reduction and the overall effectiveness. The work reported by Wurm et al. [10] is aimed at quantifying typical effusion-cooling performance at a range of combustor relevant free-stream conditions (high turbulence), and also to assess the importance of modelling the coolant to free-stream density ratio. For a typical combustor effusion geometry that uses cylindrical holes, spatially resolved measurements of adiabatic effectiveness, heat transfer coefficient, and net heat flux reduction are presented for a range of blowing ratios (0.48 to 2), free-stream turbulence conditions (4 and 22 %) and density ratios (0.97 and 1.48). The effect of two different turbulence levels at two different density ratios, with the cooling flow using air for low density and CO_2 gas for higher density ratio, on the adiabatic effectiveness and heat transfer coefficient is studied.

Elevated temperature

Most of the experimental works were carried out at low main stream temperatures due to economic reasons. However, some groups also performed research at elevated temperatures to verify the results of low temperature experiments. Juhasz and Marek [11] carried out film cooling experiments in a rectangular gas turbine combustor section operated at atmospheric inlet pressure conditions and high temperature (1367 K) for different slot configurations. They compared measured cooling effectiveness to the results obtained by different proposed correlations and found high discrepancy between experimental results and some of the predictions. Coolant mass flow rate and free-stream turbulence intensity were found to be the two parameters, which have more importance in the correlations. Behrendt et al. [12] introduced a new test rig for the investigations of gas turbine combustor cooling concepts characterization. The rig has the capability of conducting the combustor cooling experiments at realistic engine conditions at elevated pressures (up to 10 bars) and temperatures (2000 K). The goal of the test rig is to offer a testing environment for metallic and ceramic test samples with operating conditions which are realistic for modern and future gas turbine combustors.

Other cooling methods

Wurm et al. [13] performed an experimental study on combustor liner cooling using coolant ejection from both effusion cooling holes and a starter film. The experimental setup consists of a generic scaled three sector planar rig in an open loop hot gas wind tunnel. Experiments are performed without combustion. Realistic engine conditions are achieved by applying engine-realistic Reynolds numbers, Mach numbers, and density ratios. As the main focus of the study is a deeper understanding of the interaction of swirl flows and near wall cooling flows, wall pressure measurements are performed for the definition of local blowing ratios and to identify the impact on the local cooling performance. For thermal investigations, an infrared thermography is employed on the effusion cooled liner surface. The effects of different heat shield geometry on the flow field and performance of the cooling films are investigated in terms of near wall velocity distributions and film cooling effectiveness.

The current paper describes a new wind tunnel that is designed and manufactured to study film and effusion cooling interaction on combustor liner geometries. The main stream flow speed can be varied by a variable speed fan to study different flow Re whereas the cooling cavities are supplied by pressurized air where the line pressure is regulated by a valve. The heater at the entrance of the tunnel increases the main stream temperature up to 573 K. The tunnel has three IR windows to measure the surface temperature distribution. A test case from the literature is studied as a first test campaign for system checkout and validation purpose.

EXPERIMENTAL SET-UP

Figure-1 shows the cross sectional areas of test sections of different wind tunnels obtained from literature. The cross-sectional areas range between 100x100 mm to 150x150 mm. In this study, the tunnel cross sectional area is selected as 150x120 mm by maximizing the measurement resolution of infrared camera and preventing side wall effects on measurements.

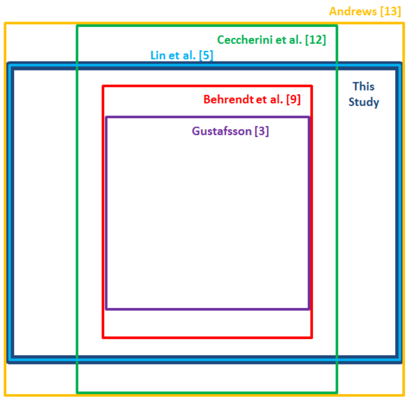


Figure 1 Comparison of Existing Wind Tunnel Cross Sections

Temperature ratio and blowing ratio are the two important parameters affecting the cooling effectiveness. Experiments are mostly conducted at lower temperature ratio values as compared to real engine conditions because of higher investment and operational costs and difficulty of ensuring flow temperature uniformity. Figure 2 shows temperature ratios used by different research groups. The new tunnel in this study is capable of reaching the temperature ratio of 1.92 to investigate the effect of thermal boundary layer on effectiveness.

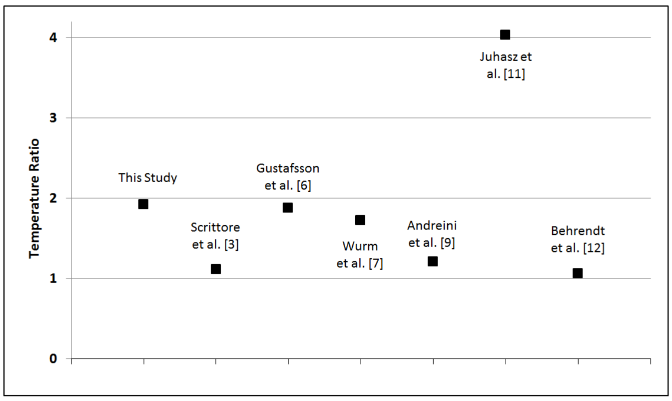
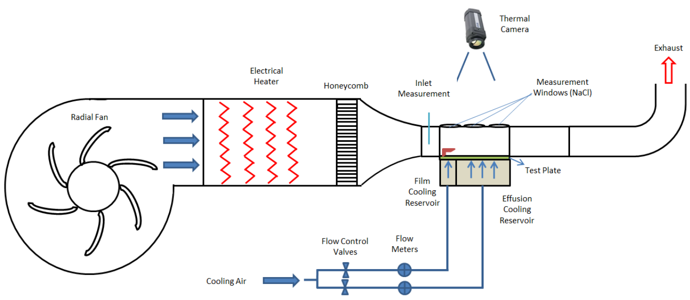


Figure 2 Comparison of temperature ratio of different research groups

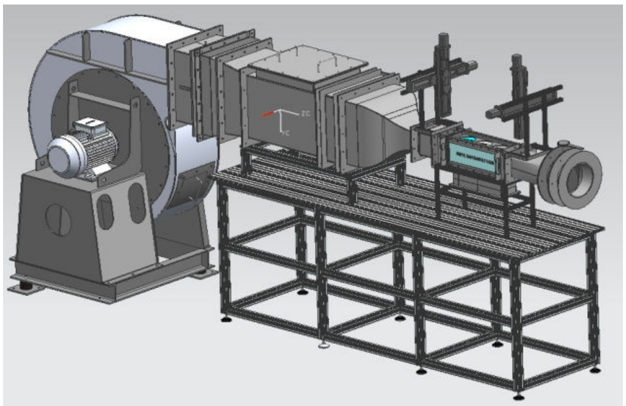
The test bench mainly consists of a radial fan, an air tunnel including an electrical heater, a honeycomb and a turbulence grid, a test section including an effusion and/or film cooled test plate, coolant supply system, data acquisition system, and an infrared camera as depicted in Figure 3. The main flow in the tunnel is provided by a radial fan working in the blowing mode. A 120 kW electrical heater placed downstream of the radial fan can heat the main flow up to 300 °C. Coolant is supplied at room temperature by a compressor. A cooling reservoir is designed below the test plate which reduces the cooling air speed to ensure uniform coolant air supply. The cooling air reservoir is split into two cavities to allow studying two different cooling schemes and their interaction. The surface temperature distribution of the test plate is measured by FLIR A645 sc thermal camera to determine the effects of different geometrical and flow parameters. The infrared thermography requires an IR transparent window. The selection of the material for this window is challenging due to the high main stream temperature. NaCl window is selected for the IR windows and located on the top surface of the test section. Turbulence grid is used just before the test section to adjust the desired turbulence intensity. Table 1 shows the main geometrical parameters and flow conditions of the test bench. 2D and 3D views of the set-up are presented in Figure 3.

Table 1: Test bench main characteristics

Parameter	
Test Section Cross Sectional Area (mm^2)	150x120
Total Length (mm)	4000
Mainstream Temperature Range (K)	298-573
Coolant Temperature (K)	298
Mainstream Velocity Range (m/s)	0-30
Mainstream Reynolds Number Based on D_h	0-1630
Coolant Reynolds Number	0-16500
Temperature Ratio	1-1.92
Test Section Length (mm)	400



(a)



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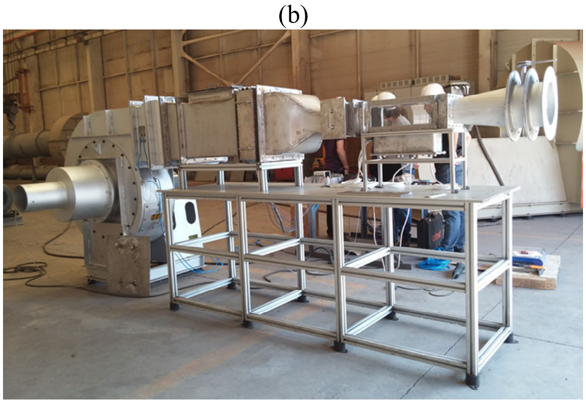

(c)

Figure 3 Wind Tunnel in this study; (a) Sketch of the tunnel, (b) CAD Model of the tunnel, (c) Picture of the tunnel after manufacturing

Bidirectional traversing system is installed at the inlet station just before the test section to characterize the main stream flow. 2D characterization of the tunnel is performed when the tunnel is installed. Then, a pitot probe is located at the center of the channel to set the desired operating condition. The main stream temperature is also measured at each test at the inlet station by using a K-type thermocouple. The thermocouple is located at 50% of the tunnel height on the centreline. The coolant mass flow rates are separately measured by thermal mass flow meters and the coolant temperature is measured by a thermocouple.

VALIDATION OF THE TEST BENCH

A well-known literature test case from Scrittore et al. [3] is selected for the first test model. They experimentally investigated the cooling effectiveness and detailed flow field on a scaled-up effusion test plate which represents the combustor liner. The reference model is scaled down by about 2.5 in order to fit it to our current test section. The model is manufactured from the balsa wood, which has a thermal conductivity of 0.05 W/m^2K. Comparison of the two models is presented in Table 2. Figure 4 shows the test plate used in this study, which has 210 holes with 2.25 mm diameters structured in a staggered manner. The plate thickness is 10 mm and holes have 30° angle with horizontal.

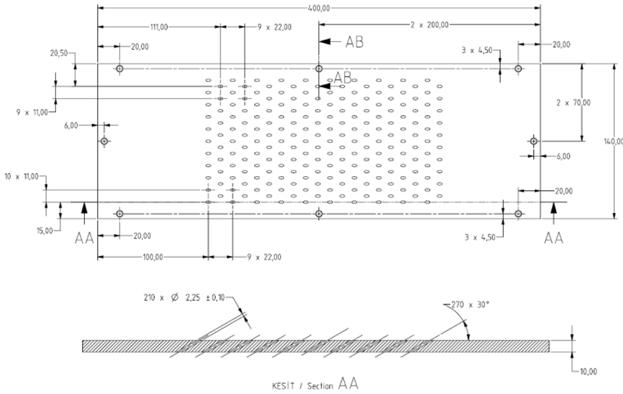

Figure 4 Model drawings of TEI test model

The reference experiment was conducted at the following flow condition: Re=17574, BR=3.35, TR=1.05. Due to the variation of tunnel cross section between our current wind tunnel and the reference wind tunnel, all flow conditions cannot be met. Table 2 lists the geometric parameters of the two test cases.

Table 2: Comparison of geometric parameters of this study and reference models

	t	d	L/d	t/d	Ss	Sp	Ss/d	Sp/d	α
Scrittore et al.	25.4	5.7	8.9	4.5	27.9	27.9	4.9	4.9	30
This study	10	2.25	8.89	4.44	11.0	11.0	4.9	4.9	30

Temperature profile at the test section inlet is measured by using a bidirectional traversing and a thermocouple. Figure 5 shows the temperature profile obtained along the height of the tunnel from five different lateral sections. Temperature on the x-axis is given as the ratio of the temperature measured at a point over mean temperature at the inlet.

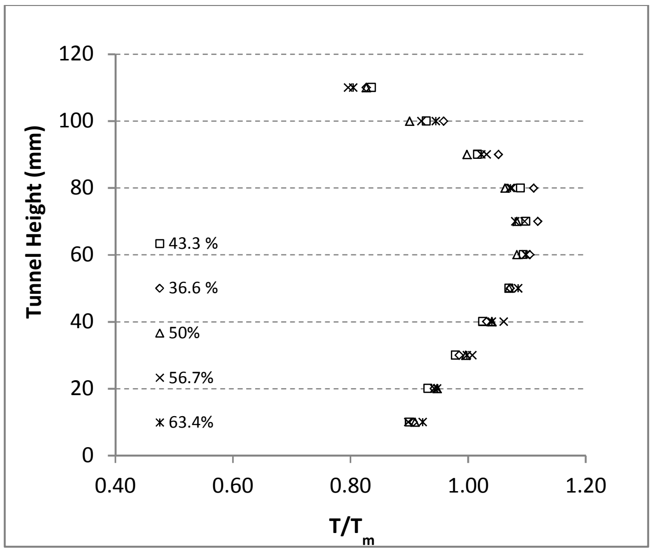

Figure 5 Test Section Inlet Temperature Profile

RESULTS

It takes about 6 hours to reach steady-state conditions inside the wind tunnel. The IR images captured from three measurement windows are presented in Figure 6. The flow close to the lateral walls affects the near wall temperature distribution. At least two holes close to near wall region are affected by the near wall flow. The temperature distribution outside the near wall is assumed to be uniform in lateral direction. Therefore, it is assumed that cooling air is equally distributed to the holes. Some part of the images taken from window 2 and window 3 are overlapping with some section of the previous image. These three images are merged into a single image to obtain the overall effectiveness on the surface.

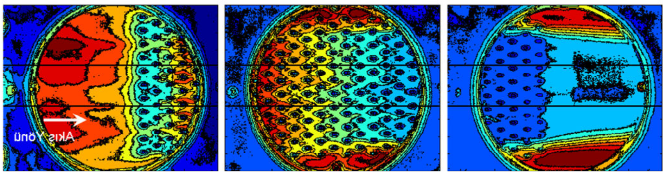

Figure 6 Raw temperature distribution captured by IR camera from three IR windows

The cooling effectiveness value is computed using the data obtained from the center of the plate. Three hole space is considered for the calculation which is depicted in Figure 6. IR data located in between the two black lines in Figure 6 and on the same streamwise distance are averaged to obtain a single representative wall temperature value (T_s). Then, Equation 1 is used to calculate the cooling effectiveness distribution in flow direction. The data obtained from our current wind tunnel is compared with the reference case in Figure 7.

$$\eta = \frac{T_\infty - T_s}{T_\infty - T_c} \quad (1)$$

Both cases start with effectiveness value of around 0.5 and decrease to around 0.4 for the first three-to-four holes and then it shows an increasing trend for the remaining holes . Although the temperature and blowing ratios are the same for each test case, due to the dimensional differences in the cross-section of the two test sections, Reynolds number of mainstream and cooling air do not match and this leads to some discrepancy between the two results given in Figure 7, especially for the second half of the test plate in the flow direction. Difference in turbulence intensity levels for two cases also contributes to the discrepancy in the results. Nonetheless, the two results are qualitatively very similar.

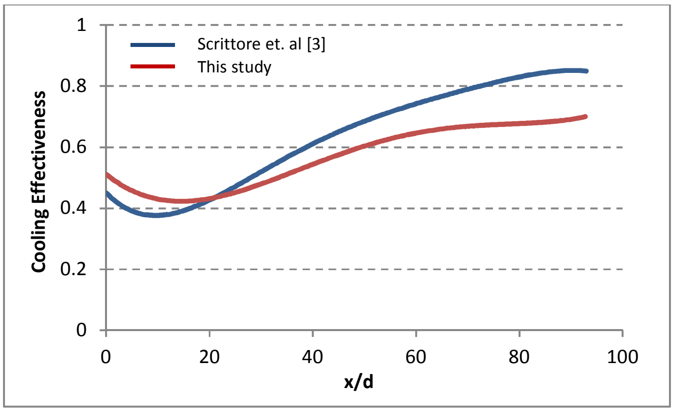

Figure 7 Cooling Effectiveness Distribution along the Plate

Figure 8 shows the repeatability of the measurements. Two experiments conducted at the same conditions end up with very close results as can be depicted from the figure.

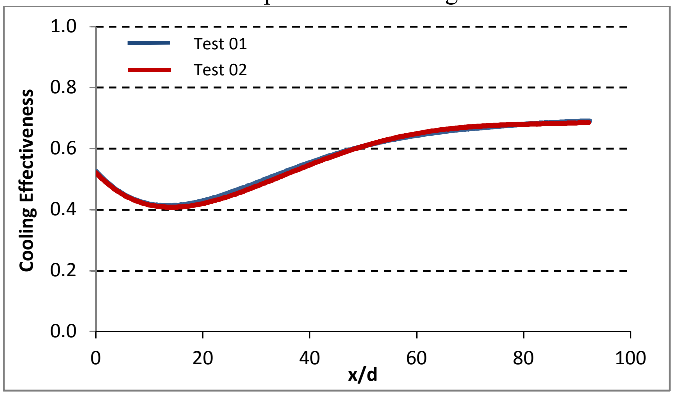

Figure 8 Repeatability of the Measurement

CONCLUSION

A test bench is designed, manufactured, and installed for gas turbine combustor film and effusion cooling investigations. Its dimensions and flow conditions (velocity, temperature etc.) are selected after a detailed research on our requirements and literature review. It allows cooling studies in a wide range of temperature ratio, blowing ratio, and Reynolds number for both mainstream and coolant. Although the bench is designed for combustor cooling studies, it can also be used for turbine cooling research. Since it has two separate coolant reservoirs, the hybrid cooling tests (film and effusion cooling together) can also be carried out.

In addition to heat transfer measurements, the bench allows flow visualization at the test section by transparent side walls. It is crucial to know the detailed flow field in the investigation of heat transfer characteristics of different cooling techniques. Film, effusion, and hybrid cooling tests are planned as a next step for the test bench. Different geometrical and flow parameters will be used and their effects on cooling effectiveness will be investigated.

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REFERENCES

[1] B. Leger, G. Schott, G. Grienche, Experimental Study of Geometric Effect for Design of Multihole Cooling for Combustion Chamber Walls, *RTO AVT Symphosium, Advanced Flow Management: Part B – Heat Transfer and Cooling in Propulsion and Power Systems*, held in Loen, Norway, 7-11 May 2001

[2] Yuzhen Lin, Bo Song, Bin Li, Gaoen Liu and Zhiyong Wu, Investigation of Film Cooling Effectiveness of Full-Coverage Inclined, *Proceedings of ASME Turbo Expo 2003*, June 16-19, 2003, Atlanta,Georgia, USA

[3] J. J. Scrittore, K. A. Thole and S. W. Burd, Investigation of Velocity Profiles for Effusion Cooling of a Combustor Liner, *Journal of Turbomachinery*, v129, pp. 518–526, July 2003

[4] J. J. Scrittore and K. A. Thole, Experimental Characterization of Film-Cooling Effectiveness near Combustor Dilution Holes, *Proceedings of GT2005, ASME Turbo Expo 2005*, June 6-9, 2005, Reno-Tahoe, Nevada, USA

[5] Sunil Patil, Santosh Abraham, Danesh Tafti, Srinath Ekkad, Yong Kim, Partha Dutta, Hee-Koo Moon and Ram Srinivasan, Experimental and Numerical Investigation of Convective Heat Transfer in a Gas Turbine Can Combustor, *Proceedings of ASME Turbo Expo 2009*, June 8-12, 2009, Orlando, Florida, USA

[6] K.M. Bernhard Gustafsson, Experimental Studies of Effusion Cooling, *Chalmer University of Technology, PhD. Thesis*, Göteborg, Sweden, 2001

[7] B. Wurm, A. Schulz, H.-J. Bauer, A New Test Facility for Investigating the Interaction Between Swirl Flow and Wall Cooling Films in Combustors, *Proceedings of ASME Turbo Expo 2009*, June 8-12, 2009, Orlando, Florida, USA

[8] Alberto Ceccherini, Bruno Facchini, Lorenzo Tarchi, Lorenzo Toni and Daniele Coutandin, Combined Effect of Slot Injection, Effusion Array and Dilution Hole on the Cooling Performance of a Real Combustor Liner, *Proceedings of ASME Turbo Expo 2009*, June 8-12, 2009, Orlando, Florida, USA

[9] A. Andreini, G. Caciolli, B. Facchini, L. Tarchi, Density Ratio Effects on the Cooling Performances of a Combustor Liner Cooled by a Combined Slot-Effusion System, *Proceedings of ASME Turbo Expo 2012,* June 11-15, 2012, Copenhagen, Denmark

[10] B. Wurm, A. Schulz, H.-J. Bauer, A New Test Facility for Investigating the Interaction Between Swirl Flow and Wall Cooling Films in Combustors, *Proceedings of ASME Turbo Expo 2009*, June 8-12, 2009, Orlando, Florida, USA

[11] Albert J. Juhasz and Cecil J. Marek, Combustor Liner Film Cooling in the Presence of High Free-Stream Turbulence, *NASA TN* D-6360, July 1971

[12] Thomas Behrendt, Christoph Hassa, A Test Rig for Investigations of Gas Turbine Combustor Cooling Concepts Under Realistic Operating Conditions, *25th International Congress of The Aeronautical Sciences*, 2006

[13] B.Wurm, A.Schulz, H.-J. Bauer, Impact of Swirl Flow on the Cooling Performance of an Effusion Cooled Combustor Liner, *Proceedings of ASME Turbo Expo 2012*, June 11-15, 2012, Copenhagen, Denmark