EXPERIMENTAL INVESTIGATION OF EFFUSION AND FILM COOLING FOR GAS TURBINE COMBUSTOR

Inanli, S.[1]* Yasa, T.[2] and Ulas, A.[3]
*Author for correspondence
[1]Tusaş Engine Industries, Inc.
Eskişehir, 26003, Turkey,
E-mail: sinan.inanli@tei.com.tr
[2]Department of Mechanical Engineering
Anadolu University
26555, Eskisehir, Turkey
[3]Department of Mechanical Engineering
Middle East Technical University
06800, Ankara, Turkey

ABSTRACT

Experimental study was conducted to understand the heat transfer characteristics of film or effusion cooled test plates that represent the gas turbine combustor liner. Two effusion cooling test plates having different hole angles (30 and 75° with horizontal) were used. Film cooling tests were conducted by six different slot geometries. Test geometries were the scaled-up model of real combustor liner. Three different blowing ratios were applied for each test plate geometry. Surface cooling effectiveness was determined for each test condition by measuring the surface temperature distribution by infrared thermography technique. Effects of geometrical and flow parameters on cooling effectiveness were investigated.

INTRODUCTION

Gas turbine combustor liner life is highly dependent on the metal temperature distribution on it. Film and effusion cooling techniques are the most pronounced ones that are used to protect the liner and to keep the metal temperature at desired levels. The name film cooling is usually reserved for those schemes that employ a number of annular slots through which air is injected axially along the inner wall of the liner to provide a protective film of cooling air between the wall and the hot combustion gases [1]. In effusion cooling, large amount of holes with small diameters are drilled on the liner to provide a protective layer of coolant on the inner surface. Due to the high l/d ratio of effusion holes, convective heat transfer from liner to coolant along the hole has also important contribution to cool the liner.

Cooling air, especially for reversed flow combustors, can reach up to 50% of the total engine mass flow rate. Providing reliable cooling scheme by using minimum amount of air is one design consideration for combustors. Flow conditions such as blowing ratio (BR), density ratio (DR), Reynolds number (Re) etc. together with geometrical parameters such as cooling hole diameter, hole angle, p/d, s/d etc. have strong effects on cooling performance. Many experimental and numerical studies have been carried out to reveal the physics underlying the heat transfer and flow field characteristics of film or effusion cooled combustor liner.

NOMENCLATURE

t	[mm]	Test plate thickness
d	[mm]	Effusion hole diameter
D	[mm]	Film Cooling Diameter
L	[mm]	Streamwise distance
S	[mm]	Inter-hole distance
T	[K]	Temperature
U	[m/s]	Velocity
BR	[-]	Blowing Ratio, $BR = \frac{(\rho U)_c}{(\rho U)_\infty}$

Special characters

α	[°]	Effusion hole angle
η	[-]	Cooling effectiveness , $\eta = \frac{T_\infty - T_s}{T_\infty - T_c}$
ρ	[kg/m^3]	Density

Subscripts

s	[-]	Pitch
p	[-]	Span
s	[-]	Surface
∞	[-]	Mainstream
c	[-]	Coolant

Juhasz and Marek [2] carried out film cooling experiments in a rectangular gas turbine combustor section operated at atmospheric inlet pressure conditions and exit temperature up to 1367 K for different slot configurations. They compared measured cooling effectiveness to the results obtained by different proposed correlations. They developed a turbulence mixing model to improve the correlation accuracy. Leger et al. [3] conducted an experimental study for film cooled flat plate. Different geometrical parameters and aerothermal properties were the main concern of their investigation on cooling effectiveness. Their study also includes the development of an artificial neural network code to predict the hot side heat transfer coefficient and adiabatic wall temperature. Gustafsson [4] performed an experimental study on effusion cooling. The effects of different mainstream and coolant flow conditions together with hole geometry and thermal conductivity of the wall material were investigated. A complete mapping of the 3D velocity field and turbulence fields near one of the injection holes was also obtained by laser-doppler anemometry. Yuzhen et al. [5] investigated adiabatic film cooling effectiveness on four full-coverage inclined multihole walls with different hole arrangements experimentally and numerically. Experimental results showed that for the concurrent film injection configuration blowing ratio ranging from 1 to 4 has negligible effect on the cooling effectiveness whereas for the counterflow film cooling scheme blowing ratio within the same range has strong effect on effectiveness. By numerical simulations, they obtained consistent results with experiments. Scrittore et al. [6] presented the experimental results of effusion cooled flat plate tested in a low speed wind tunnel. Engine representative, nondimensional coolant flows were tested for a full-coverage effusion plate. In addition to cooling effectiveness measurements, detailed flow field characteristics of the plate was measured with a Laser Doppler velocimetry. Combustor liner including both the dilution and film cooling jets was experimentally investigated also by the same research group [7] to reveal the heat transfer and flow field characteristics of the plate. Behrendt et al. [8] 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 and temperatures. The inlet pressure of the combustor can reach up to 10 bars and global flame temperature can reach up to up to 2000 K. Ceccherini et al. [9] experimentally investigated the combustor liner cooling on a test plate having large dilution central hole and effusion holes. Combined effects of slot, effusion and dilution holes were experimentally and numerically studied. Effusion cooling air exit velocity was found as a critical parameter on cooling effectiveness. Andreini et al. [10] carried out an experimental study composing of two campaigns to determine the heat transfer coefficient over effusion cooled plate with typical blowing and velocity ratios of real aero engine conditions. Results of the two campaigns were finally combined to calculate the Net Heat Flux Reduction and the overall effectiveness. Wurm et al. [11] experimentally investigated the effusion-cooling at high turbulence levels and especially concerned with the density ratio effect on cooling effectiveness. Their experiments cover the blowing ratios between 0.48 to 2, at free-stream turbulence conditions 4 and 22 %, and density ratios between 0.97 and 1.48. Same research group [12] also performed experiments for combustor liner to see the combined effect of both film and effusion cooling. Realistic engine conditions are achieved by applying engine-realistic Reynolds numbers, Mach numbers, and density ratios. 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.

This study aims at experimentally investigating the effects of different aerothermal flow conditions and geometric parameters on effusion and film cooling performance.

EXPERIMENTAL SET-UP

The test bench mainly consists of a radial fan, air tunnel and test section. The air tunnel is directly connected to the radial fan and contains an electrical heater, honeycomb arrangement and sections with turbulence generators. The test section includes the testing model (in this case an effusion and/or film cooled test plate), coolant reservoir, and measurement stations. Test section has cross-secitonal area of 150x120 mm^2 and 400 mm length. The test setup is depicted in Figure 1. The cooling reservoir is designed to have enough volume for the stagnation of coolant flow. It is located below the test plate so stagnated cold air directly supplied to the test plate to ensure uniform coolant flow distribution. The surface temperature distribution is one of the parameters to compute the surface cooling effectiveness. In the current setup, it is measured by using infrared thermography system (FLIR A645). Such system requires a special optical access which transmit IR bandwidth to visualize the model surface. Hence, three circular NaCl windows with a diameter of 100 mm are installed on the top wall of test section with inter-distance of 120 mm (center-to-center). The NaCl windows are preferred due to its high IR transparency and resistivity to the high temperatures.

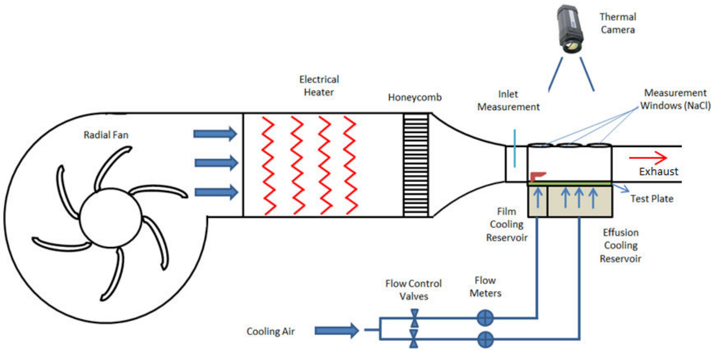


Figure 1 Test Bench 2D Model

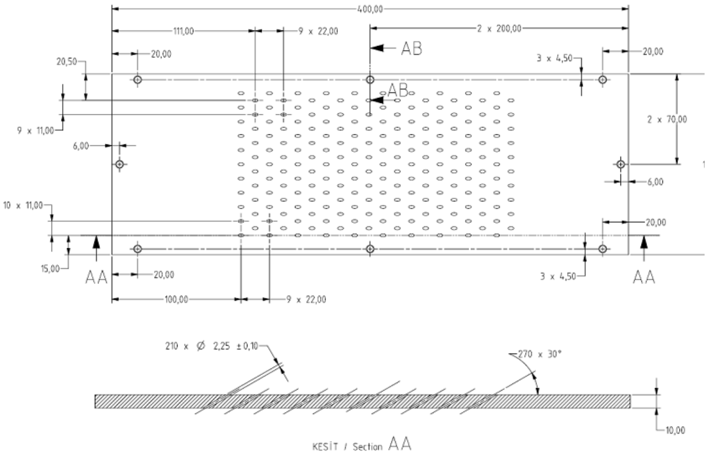
Bidirectional traversing system is installed at the inlet of the test section to characterize the main stream flow. The temperature and velocity fields are characterized once in both directions (along the height and width) using a K-type thermocouple probe and a pitot probe, respectively. Then, a thermocouple probe is installed at the inlet plane at the mid-section of the inlet to monitor air temperature for each test. Coolant mass flow rate is measured by a thermal mass flow meter and the coolant temperature is measured by a thermocouple for each test. Turbulence grid is used just before the test section to adjust the desired turbulence intensity. Turbulence measurements were conducted by hot-wire anemometry (DANTEC Mini CTA). Mean turbulence intensity at the test section inlet is 1.6% for all experiments.

Effusion Cooling

Effusion cooling tests are carried out by flat plates. The test model is generated by scaling up a real combustor liner. The scaling-up of the models enhance the spatial resolution of the measurements. Beside the flow periodicity must be satisfied by placing enough number of holes to a row for the reliability and accuracy of the measurements. The scaling-up is performed in such a way that critical parameters like the blowing ratios, hole length to hole diameter ratio, distance between holes to hole diameter ratio are respected. By considering the measurement resolution of the thermal camera and the dimensions of the test section, scale-up factor is determined to be 8.5 for the effusion and film cooling test plates. Plexiglass is used for the manufacturing of the model due to its low thermal conductivity (0.4 W/m^2K) and good machinability properties. Figure 2 shows the two different test plates. Both of them have 210 holes with a diameter of 2.25 mm. They distributed on the plate in staggered manner. Plate thickness is kept as 10 mm for both configurations whereas the hole angle is changed as 30° (H30) and 75° (H75) degrees (relative to the horizontal plane). Table 1 shows the geometrical parameters of two plates. Each test plate is painted to the black to have black body condition during the measurement of surface temperature. The air temperatures are set to 338 K for mainstream and 298 K for the coolant flow. The mainstream velocity is kept constant at 3.7 m/s for all tests while the coolant air velocity is varied to three different values, 5.06, 6.75 and 8.44 m/s to investigate the effect of blowing ratio on coolant performance. Blowing ratios are determined by considering blowing ratios encountered at real engine conditions. Mainstream Reynolds number is 28352 whereas coolant Reynolds numbers based on cooling hole diameter are 726, 969 and 1211 for each corresponding coolant velocity.

Table 1: Geometric parameters of H30 and H75 plates

	t [mm]	d [mm]	t/d	Ss [mm]	Sp [mm]	Ss/d	Sp/d	α [deg.]
H30	10	2.25	4.44	11.0	11.0	4.9	4.9	30
H75	10	2.25	4.44	11.0	11.0	4.9	4.9	75



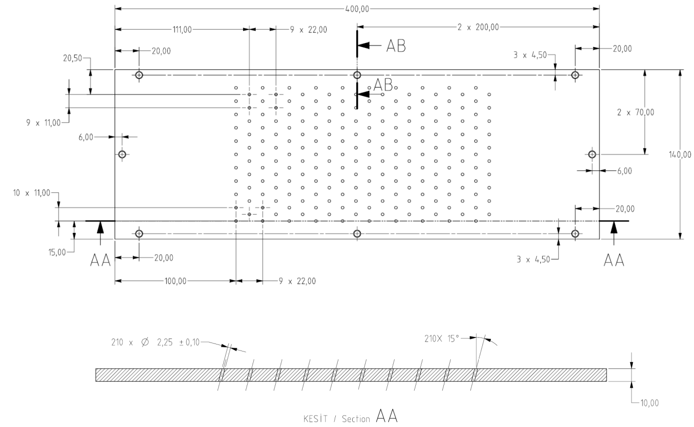


Figure 2 Model drawings of test plates

Film Cooling

Film cooling test plates have one row of holes. Seven holes are drilled with a diameter of 8.5 mm and an angle of 75° degree respect to the horizontal plane which results in a pitch to diameter ratio of 2.3. Similar to the effusion cooling configuration, Plexiglas plates with a thickness of 10 mm is used. Two different leap geometries (flat and angled) are tested for three different slot heights (7.5, 10 and 12.5 mm). Tests are conducted for each plate at three different coolant air velocity that corresponds to the blowing ratios (1.0, 1.5 and 2.0). The mainstream velocity is 4.14 m/s and kept constant for all test conditions. The air temperatures are set to 338 K for mainstream and 298 K for the coolant flow. Mainstream Reynolds number is 26848 for all test conditions. Figure 3 shows the models and leap configurations used in the test campaign.

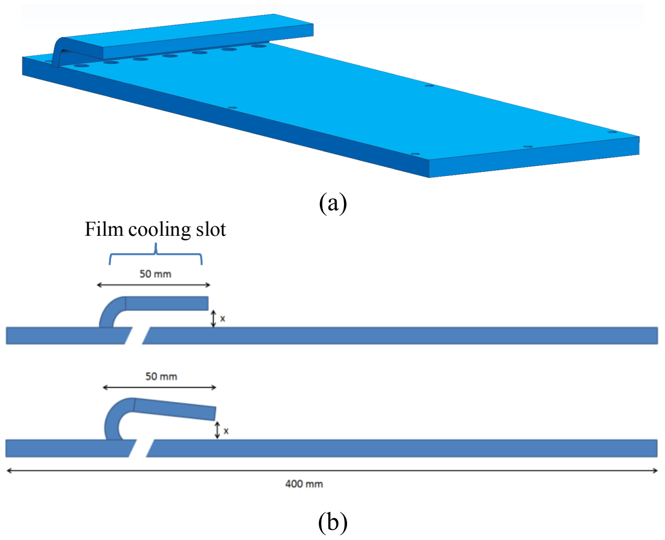


Figure 3 (a) 3D Model of film cooling test plate (b) Cross sections of test plates with flat and angled leap geometries

RESULTS

Effusion Cooling

The surface temperature distribution of the effusion cooled test plate is shown in Figure 4. The temperature distribution shows a gradual variation in streamwise direction at the centre of the plate whereas the region close to outer edge of the plate is influenced by the side walls of the test section. Therefore, temperature values corresponds to three hole pitches (in between two black lines which as indicated in Figure 4) are considered for the cooling effectiveness calculations.

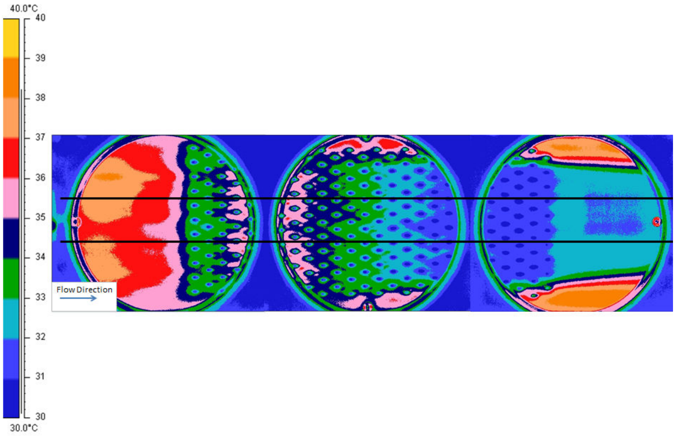


Figure 4 Surface temperature distribution of effusion plate from three optical access for test H30-BR3.35

The cooling effectiveness parameter (η) is calculated by using test plate surface temperature measurement, gas and coolant temperature readings. To avoid sidewall effects, effectiveness value is calculated by using the surface temperature obtained in between two black lines shown in Figure 4. Laterally averaged effectiveness is calculated in the streamwise direction. The averaged cooling effectiveness data are presented in Figure 5 as function of streamwise direction. The blowing ratio slightly changes the cooling effectiveness for both plates although the variation of cooling effectiveness is more pronounced for H75 case. Due to the higher coolant exit angle of H75 plate, coolant flow penetrates more into the mainstream and behaves like a solid obstacle which enhance the mixing downstream of it. Instead of generating an insulation layer, mixing allows more interaction between the main stream flow and the model surface which reduces the cooling effectiveness. For H30 plate, coolant flows more parallel to the test plate surface and penetration into the mainstream is less noticeable. The effectiveness value decreases when the blowing ratio is increased for H75 case. For both cases, the cooling injection from the first hole increases the effectiveness value rapidly. Then, the effectiveness value shows a decreasing trend along the first four holes. Starting from the fifth hole, the effectiveness value increases continuously up to the end of the plate. H30 configuration gives higher results up to L/D value of about 70 then the H75 configuration starts to give slightly better performance compared to the H30 configuration. All temperature measurements were performed with ±0.1 °C which leads to uncertainty of ±3% in effusion cooling effectiveness calculations.

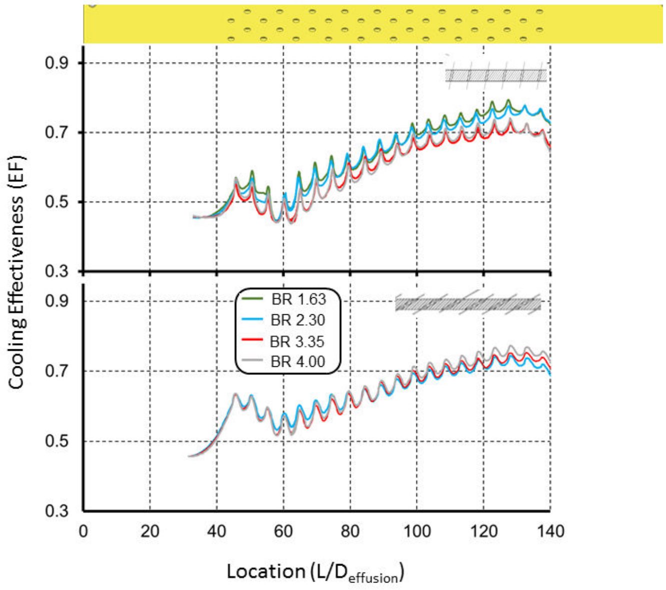


Figure 5 Cooling effectiveness distribution in streamwise direction upper: H75 plate lower: H30 plate

Figure 6 presents the comparison of mean cooling effectiveness values calculated for the L/D ratio of between 35-120 for each test condition. Negligible increase on cooling effectiveness value is observed for the H30 test plate as the blowing ratio increases from 2.3 to 4.0. On the other hand, the performance of H75 test plate reduces when the blowing ratio is increased.

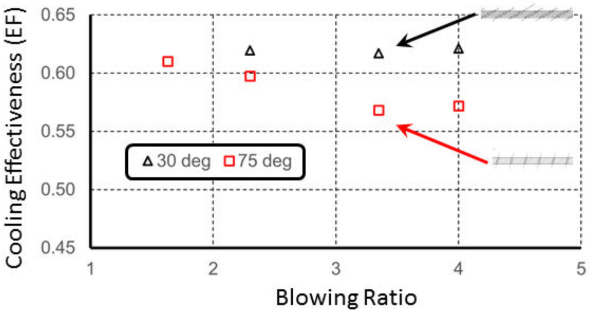


Figure 6 Comparison of mean cooling effectiveness (effusion)

Film Cooling

The surface temperature distribution over the film cooled test plate obtained from three measurement windows is shown in Figure 7. The lowest surface temperature is measured just downstream of the cooling slot and it increases along the streamwise direction mainly due to fact that film layer over the plate loses its effect due to the turbulent mixing of coolant and mainstream. The method used for the calculation of cooling effectiveness of effusion cooled plate is applied for the film cooling investigation. The calculation is performed for the same region that is used for the effusion cooling test (indicated with two black lines in Figure 7).

The high temperature region located at the beginning of plate corresponds to the top of the film-cooling leap, which is made by Plexiglas, a material that is non-transparent to IR wavelength. Therefore, the sudden drop of temperature in Figure 7 shows two different locations (cooling leap top and the plate itself). The coolant flow injection reduces the surface temperature in the first IR window but the wall temperature rises constantly in streamwise direction.

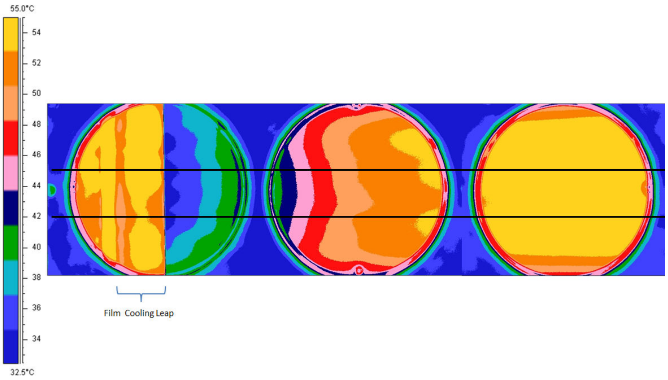


Figure 7 Surface temperature distribution of film cooling plate

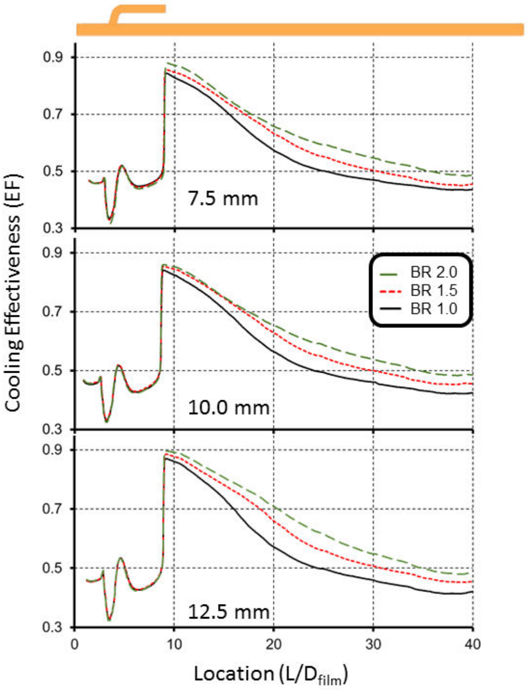


Figure 8 Cooling effectiveness of straight film cooling leap for three different leap height

Figure 8 shows the cooling effectiveness distribution of straight film cooling leap configuration for three different slot height tested at three blowing ratios. For all three slot height, increasing of blowing ratio has a positive effect on the cooling effectiveness parameter. This effect is more pronounced for the further distances from the slot. Independent from the leap height, the cooling effectiveness value is about the same for all cases at the slot outlet. The decay of cooling effectiveness can be split into two different zones for all cases. Starting from the leap outlet plane up to the L/D of about 18 the cooling effectiveness decays almost linearly and from this point on the decay shows a non-linear trend up to the end of the plate.

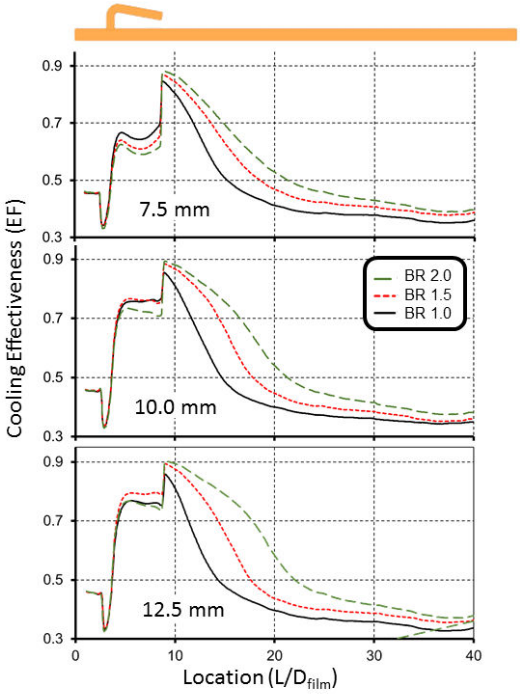


Figure 9 Cooling effectiveness of angled film cooling leap for three different leap height

Figure 99 shows the cooling effectiveness distributions of curved leap configurations for three different leap height tested at three blowing ratios. Differently from the straight configuration the blowing ratio has a significant effect on the cooling effectiveness distribution even starting from the leap outlet plane. Overall blowing ratio on the test plate surface is much more noticeable for curved leap as compared to the straight leap as blowing ratio is increased. Better cooling performances are observed when the blowing ratio increases independent from the leap height. Similar to the straight cooling configuration, the effectiveness decays almost linearly up to the L/D ratio of about 15. However, when the curved leap is used the decay occurs more rapidly compared to the straight leap configuration. Based on the results, one can say that the straight leap configuration results in a better performance compared to the curved leap configurations. For better understanding of the leap geometry effect on effectiveness, detailed flow field measurements or CFD analysis should be performed. Flow structure downstream of the leap is mostly influenced by the leap geometry and it has strong effect on heat transfer characteristics in this region.

Figure 10 compares average cooling effectiveness values of all film-cooling configurations. The distance used in the effusion cooling comparison is respected also for the comparison of the film cooling performance. The straight configuration results in better cooling performance regardless from the blowing ratios. At low blowing ratio (BR=1) all straight configurations provide similar average cooling effectiveness values. The slot height of 7.5 mm and 10 mm results in similar performance for all three blowing ratios. The slot height of 12.5 mm gives the best cooling performance for the straight leap configuration. Although it gives similar cooling effectiveness for the low blowing ratio (BR=1.0), the performance of highest slot significantly increases when the blowing ratio of 1.5 and 2.0 is used. The cooling performance of angled leap increase parallel to the blowing ratio for all slot heights The short slot performs better when the blowing ratio is 1.0. However, the trend turns into opposite direction (highest slot height results in better cooling effectiveness values), when the blowing ratio is increased to 2.0. All temperature measurements were performed with ±0.1 °C which leads to uncertainty of ±1.2% in film cooling effectiveness calculations.

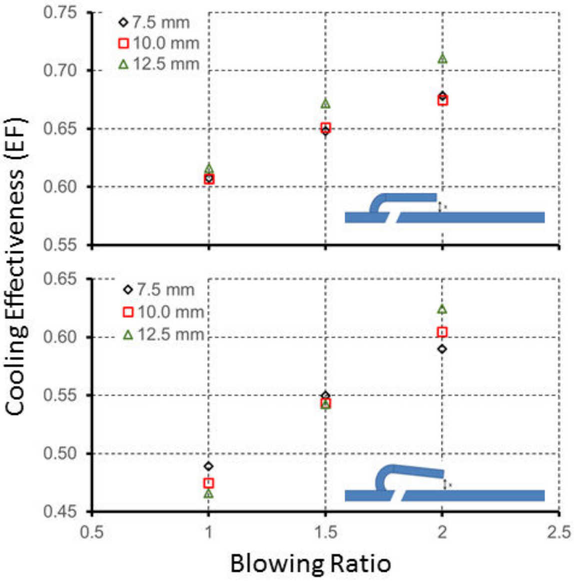


Figure 10 Comparison of mean cooling effectiveness (film)

CONCLUSION

Effusion and film cooling tests were conducted to understand the effects of different flow conditions and geometric parameters on cooling effectiveness. Effect of blowing ratio is more pronounced for effusion cooled test plate having 75 degree hole angle as compared to the plate with 30 degree hole angle. This phenomenon is due to the more coolant penetration into the mainstream and less coolant layer formation on the surface. Straight film cooling leap configurations result in higher mean cooling effectiveness values than angled leap configuration for all leap heights and all corresponding blowing ratios. Leap height of 12.5 mm for straight geometry gives better effectiveness for all blowing ratios and increase in blowing ratio makes higher leap height more advantageous. Test plates with 7.5 and 10.0 mm leap heights for straight configuration ends up with almost the same mean cooling effectiveness. For angled leap geometry, maximum effectiveness is obtained by 7.5 mm leap height for BR=1 whereas for BR=2, 12.5 mm leap height results in highest mean effectiveness value.

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