Numerical Investigation of Forward/Backward Coolant Injection for Effusion Cooling Method

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Abstract

Combustor liner cooling has been more challenging for aircraft engines due to the development trends over the last decades. In the present study, the effect of the inclination angle in both forward and reverse directions on the cooling effectiveness and the flow characteristics was investigated numerically for the effusion cooling technique, an advanced cooling concept for gas turbine combustors. CHT simulations were carried out on a simplified plate under non-reacting conditions for the simplification of complex combustor structure. The numerical results were compared with the experimental results of Inanli et al. [1]. SST k-ω model provided better match with the experimental results. 20° inclined holes showed the best cooling performance with low coolant amount. On the other hand, the effect of the backward coolant injection on the cooling effectiveness and the flow structure depends on the blowing ratio. The backward coolant injection provided more effective cooling with increasing blowing ratio.

Keyword: *Effusion cooling, CHT, Combustion chamber*

1. Introduction

Many aircraft engine manufacturers tend to update their combustion chamber concepts towards to lean burn combustion chamber technology promising to decrease NOx emissions due to strict environmental regulations concerning NOx from civil-aero engines. Since cooling air availability for liners reduces with increasing air mass flow rate in the primary zone for lean burn combustion chamber technology, the liner cooling design has been more challenging [2,3]. Previous works published in the literature showed that inclination angle is one of the most effective parameters on the cooling performance for effusion cooling method, an advanced cooling concept for gas turbine combustors. Vishal et al. [4] carried out Conjugate Heat Transfer (CHT) analysis to investigate the inclination angle (30°, 45°, 60° and 90°) effect on the cooling effectiveness in a combustion chamber domain with an effusion cooled wall and a coolant chamber. They showed that lower angles provided better cooling performance at upstream locations and steeper angles provided better performance at downstream locations. Singh et al. [5] studied angles varying from 30° to 60° in both forward and reverse directions numerically and experimentally on a flat plate. Cooling air is injected such that its axial velocity component is in the reverse direction to that of the mainstream flow for the backward coolant injection. This paper stated that reverse (backward) holes showed better film cooling performance than forward holes. Park et al. [6] investigated the inclination angle (35° and 145°) effect on the cooling performance with the experiments using pressure sensitive paint method. Their results showed that combination of backward and forward injection holes enhanced the cooling performance. Depending on the tests using pressure sensitive paint technique in a three-sector gas turbine combustor rig with a realistic swirling flow they performed, Andreini et al. [7] showed that 20° inclination angle has the best film cooling performance. The studies mentioned above were carried out under non-reacting conditions. On the other hand, similar to the non-reacting conditions, Ji et al. [8] stated that the backward injection will show the highest cooling performance with adequate coolant amount under reacting conditions as well.

The aim of the present work is to investigate the effect of the inclination angle in both forward and reverse directions on the cooling effectiveness numerically, thus determining the configuration that enhances the cooling performance. The investigation in the current study was conducted on a simplified plate under non-reacting conditions for the simplification of complex combustor structure. Inclination angles evaluated in this work were chosen based on the previous works in the literature. 20° and 60° inclination angles were studied in both forward and reverse directions for the staggered array with CHT simulations. Also the combination of forward and backward holes (the combination of 20° and 160° inclined holes, the combination of 60° and 120° inclined holes) was evaluated. Since the cooling performance is related to the flow characteristics, the investigations in the current study were carried out not only for the cooling effectiveness but also for the flow characteristics. The flow structure was visualized with the numerical study.

2. Numerical Setup

Inanli et al. [1] studied the inclination angle effect (30° and 75°) on the cooling effectiveness using a test bench, see Fig. 1, for effusion cooling test plates under non-reacting conditions. They used Infrared Thermography method for the wall temperature measurements. The thermal camera results for the effusion cooled plate including 30° inclined holes that simulate gas turbine combustor liner cooling system for BR (Blowing ratio) = 2.30 condition was used for the validation of CHT methodology in this work. The geometry of the test bench [1] was replicated for CHT simulation. A full CHT model, see Fig. 2a, was generated in order to include side-wall effects. Polyhedral mesh was generated with the prism layers on the liner. Mesh refinement was conducted at the region of the coolant holes and near to the liner. The commercial software ANSYS Fluent, using Release 2019 R3, was used for the study. Turbulence was modelled by means of the Realizable k-ε model with Enhanced Wall Treatment and SST k-ω model. The COUPLED pressure velocity coupling was used with a second order spatial discretization. The y+ value was kept lower than 1 on the liner walls to be aligned with the selected turbulence models and wall treatments.

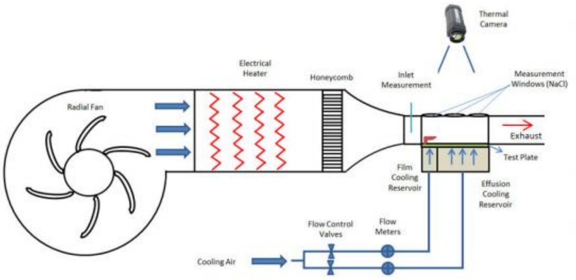

Fig. 1 Test Bench [1]

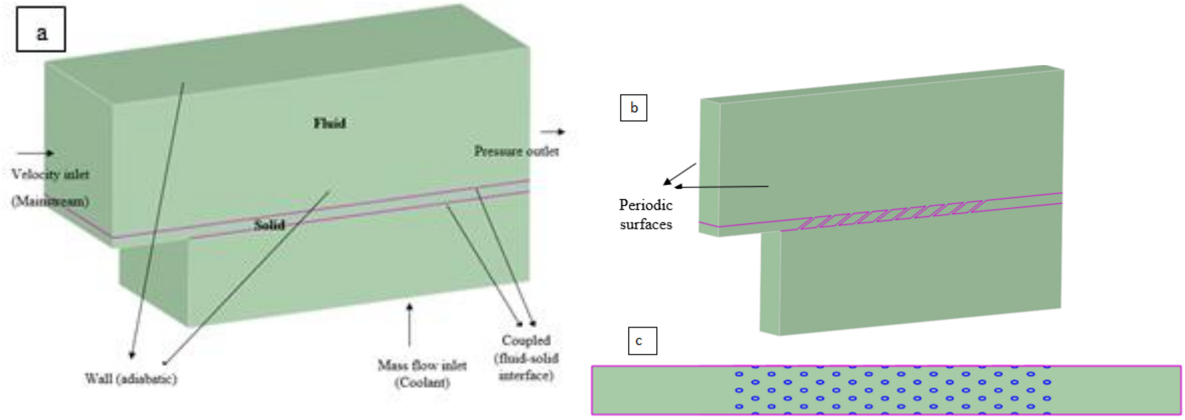

Fig. 2 a) Full CHT model, b) Periodic CHT model

A periodic model, see Fig. 2b, was created to reduce the computational time. The mainstream conditions were assigned in terms of total temperature, turbulence quantities and velocity magnitude at the main inlet for the full model, and mass flow rate, total temperature and turbulence quantities were specified at the coolant inlet. While velocity inlet was defined as the mainstream inlet for the full model, mass flow inlet was used for the mainstream inlet of the periodic model. Thermal conductivity value was taken as 0.4 W/m.K. The boundary conditions shown in the Table.1 were determined depending on the test conditions.

Table.1 Boundary Conditions

Boundary types	BR = 2.30 (Full model)	BR = 2.30 (Periodic model)
Mainstream temperature	338 K	338 K
Mainstream velocity - mass flow rate	3.7 m/s	0.016 kg/s
Mainstream turbulence	1.6 % turbulence intensity	1.6 % turbulence intensity
Coolant temperature	298 K	298 K
Coolant mass flow	0.00668 kg/s	0.00191 kg/s
Coolant turbulence	1.6 % turbulence intensity	1.6 % turbulence intensity

Six different configurations (20°, 60°, 160°, 120°, combination of 20° and 160° inclined holes, combination of 60° and 120° inclined holes) were investigated with the CHT methodology. While the inclination angle and directions were changed for the configurations, other geometrical parameters (spanwise pitch (Sp=11 mm), streamwise pitch (Ss=11 mm), hole diameter (2.25 mm), plate thickness (10 mm) and the number of rows (20)) remained the same. These geometrical parameters except inclination angle were determined depending on the test setup. The plates including 20° inclined holes in the forward and reversed directions are shown in Fig. 3.

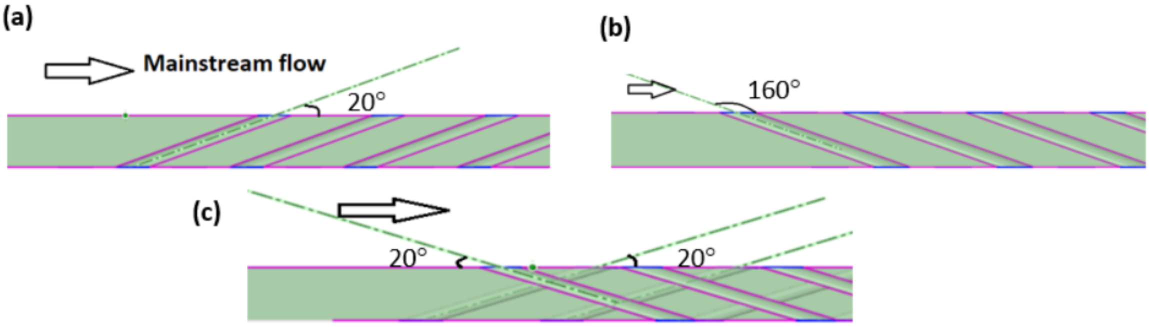

Fig. 3 a) The plate including 20° inclined holes, b) The plate including 160° inclined holes, c) The plate including combination of 20° and 160° inclined holes

3. Results & Discussions

3.1 Comparison of Numerical and Experimental Results

SST k-ω model provided better match with the experimental results despite the certain differences at the entrance when side-wall effects were included in the numerical results, see Fig. 4. Axial location was specified as L/Def where L is the length of the plate and Def is the hole diameter. Several reasons have been considered for the differences between the experimental and numerical results at the entrance. The wall was defined as adiabatic up to the point where L/Def was approximately 40 where the cooling air began to be supplied. This condition may affect the heat transfer at the entrance of the plate.

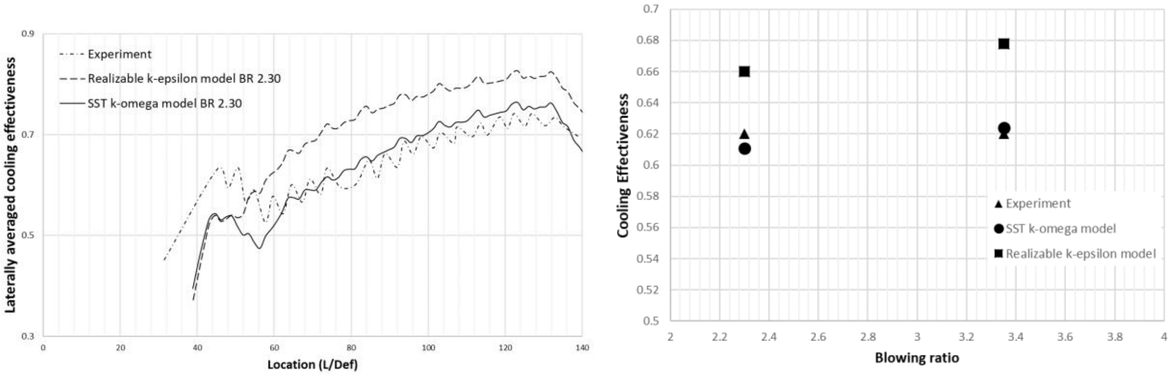

Fig. 4 Comparison of numerical and experimental results for laterally averaged cooling effectiveness and area weighted average cooling effectiveness

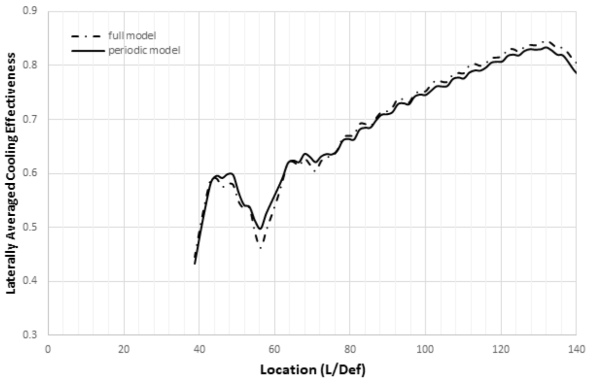

Fig. 5 The comparison of full and periodic models

The results obtained with the periodic model created in order to decrease the computational time were compared to the results obtained on a plane generated in the middle of the effusion plate for the full model, see Fig. 5. Due to the fact that the results obtained from full and periodic models are approximately the same, the periodic model was used for the study investigating forward/backward coolant injection.

3.2 Numerical investigation of forward/backward coolant injection

The coolant flow rate was kept at a low amount in order to simulate more challenging conditions. The blowing ratio was selected as 0.5 for the first investigation. The cooling effectiveness results are shown in Fig. 6 and Fig. 7. 20° in the forward direction has the best cooling performance between all configurations for BR=0.5. While the backward coolant injection did not improve the cooling performance for 20° inclined holes, the backward coolant injection achieved better cooling effectiveness than the forward coolant injection for 60° inclined holes. Combining the holes in both directions did not show a significant positive effect for either angle.

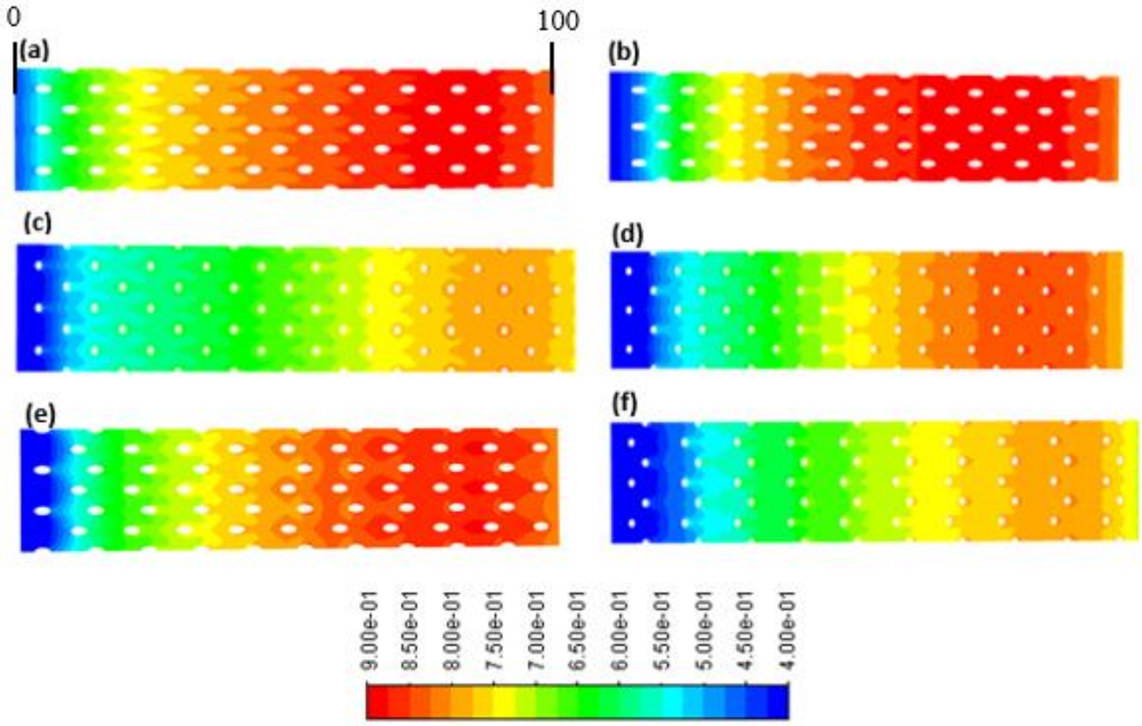

Fig. 6 The cooling effectiveness distribution the plates including a) 20°, b) 160°, c) 60°, d) 120°, e) 20°-160°, f) 60°-120° inclined holes for BR=0.50

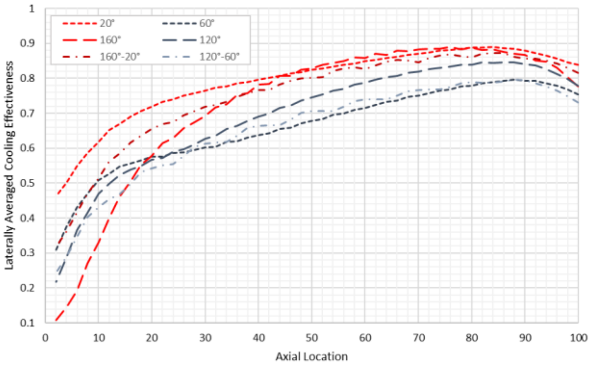

Fig. 7 Laterally averaged cooling effectiveness for all configurations

3.3 Blowing Ratio Effect

The investigation was repeated for the plates including 20° and 160° inclined holes at BR=1.5 condition to evaluate the blowing ratio effect on the cooling performance and the flow characteristics. The blowing ratio affects the coolant jet penetration depth. Since the coolant jets penetrated further with an increase in the blowing ratio, the cooling effectiveness decreased especially at the downstream region of the plate for 20° inclined holes, see Fig. 8a, c and d. On the other hand, the backward coolant injection provided better cooling performance with increasing blowing ratio, see Fig. 8b.

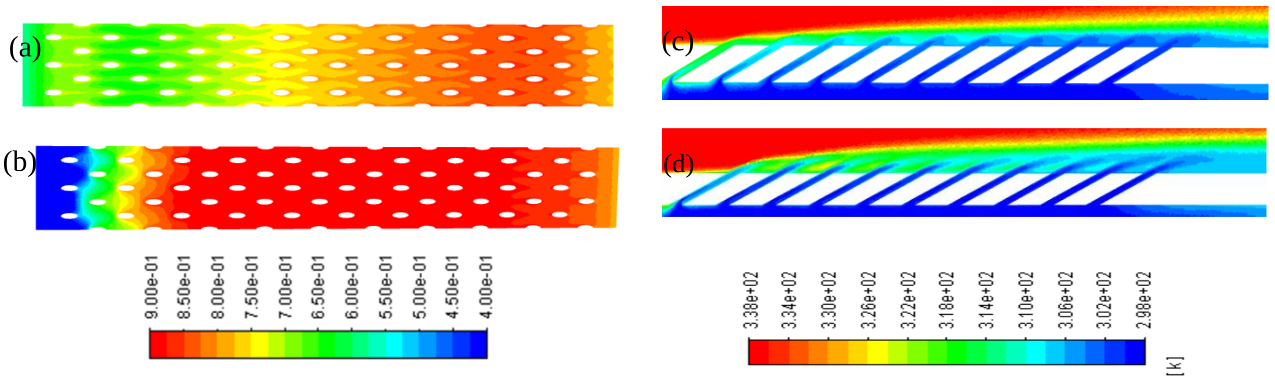

Fig. 8 The cooling effectiveness for a) 20°-BR=1.5, b) 160°-BR=1.5, Total temperature (K) for c) 20°-BR=0.5, d) 20°-BR=1.5

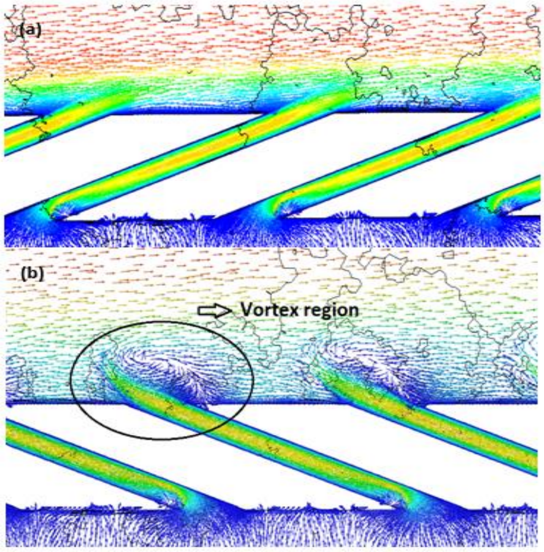

Fig. 9 Velocity vectors for a) 20° inclined holes, b) 160° inclined holes at BR=0.5 condition

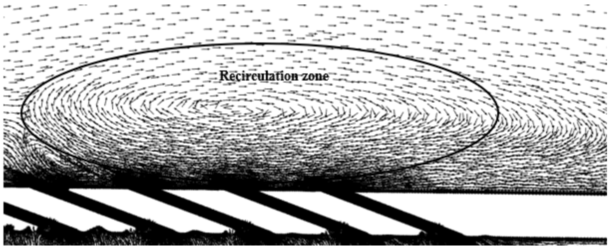

Fig. 10 Velocity vectors at the downstream region of the liner for 160° inclined holes and BR=1.5 condition

While the vortex structures were generated around the region of the effusion holes for the backward coolant injection at BR=0.5 condition, a large recirculation zone was observed at the downstream region of the liner for 1.5 blowing ratio condition. These results show that the effect of the backward coolant injection on the cooling effectiveness and the flow structure depends on the blowing ratio.

4. Conclusions

The aim of this work is to investigate the effect of the inclination angle in both forward and reverse directions on the cooling effectiveness and the flow structure numerically. The main findings can be summarized as follows:

(1) 20° inclined holes had the best cooling performance with low coolant amount.
(2) The backward coolant injection did not improve the cooling performance for 20° inclined holes with low coolant amount. On the other hand, the backward coolant injection provided better cooling performance than the forward coolant injection for 60° inclined holes at BR=0.5 condition.
(3) The backward coolant injection improved the cooling performance with increasing blowing ratio.
(4) The effect of the reversed holes depends on the blowing ratio.
(5) A large recirculation zone was observed at the downstream region of the liner with an increase in the blowing ratio for the backward coolant injection.

The flow structure inside the flame tube of a gas turbine combustion chamber is crucial for the combustion stability. Since the backward coolant injection has the significant effect on the flow characteristics, whether or not the reversed holes are used for the combustion chamber should be evaluated by taking into account the combustion stability under the reacting conditions.

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