Numerical and Experimental Investigations on Film Cooling Performance of Trench Model Embedded with Compound Angle Film Hole Jets

V. G. Krishna Anand and K. M. Parammasivam

Abstract The Trench film cooling is a cooling technique where film cooling holes are embedded within a cut slot made on the surface with the application of thermal barrier coatings. The goal of the present investigation is to compare the cooling effectiveness of trench model embedded with compound angled film hole viz. 45°, 90°, 135° through numerical and experimental investigation at two different blowing ratios. The width and depth of trench are maintained at 2D and 0.7D, respectively, with *D* as the hole diameter. Results of the study show that trench model embedded with 90° compound angled film hole delivered highest cooling effectiveness for two tested ratios of blowing between coolant and mainstream flows. Experimental results on film cooling effectiveness produced good agreement with computational results.

Keywords Compound hole jets · Trench model · Cooling effectiveness

1 Introduction

Film cooling is a widely employed cooling technique for aircraft gas turbines, rocket nozzle, thrust chamber, marine and industrial gas turbine components. The downsides of flat model cooling are injectant jump off at higher BR, less lateral spreading of injected coolant. In trench film cooling, the film holes are embedded within cut slot made on the film cooling surface with the application of thermal barrier coatings. Dorrington et al. [1] performed an experimental study on various trench configurations. Their results concluded that height of trench of 0.75 times the film hole size offered higher cooling effectiveness and width of trench 2D and 3D provided a comparable film cooling performance, and they also reported that film effectiveness provided with trench is higher than shaped holes at high blowing ratios. Kross and Pfitzner [2] carried out an experimental and numerical study on trench configuration at high blowing ratios with tetrahedral obstructions placed at leading-edge regions of trench. They concluded that trench configuration provided better performance even at high

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blowing ratios and also additional tetrahedral obstruction provides further improved cooling performance. Goldstein and Jin [3] performed investigations to determine the behavior of cylindrical film hole with compound angles. They reveal that lateral averaged effectiveness offered with compound angle is higher than streamwise film hole injection because of better span side spreading. Taslim and Khanicheh [4] conducted experimental investigation with compound angling on round and expanded shaped hole models to study the impact of FCE. They conclude as diffuser shaped compound hole provides better cooling effects due to wide span side coverage with low momentum and increased film coolant concentration at hole exit. Chandran et al. [5] carried out studies to understand the behavior of different hole shapes on FCE. The study reported as the shaped and trenched models offered better film coverage than other configurations and also trench shaped film hole offered higher effectiveness only for increased BR of injected coolant. Anand and Parammasivam [6] performed optimization studies on trench film cooling parameters to optimize and identify the significant trench film cooling parameters. They conclude that the height of trench, film hole compound angle and BR have significant influence on trench FCE and the study also optimized these significant parameters.

Lu et al. [7] conducted an experimental study of FCE on various trench width of 2D and 3D with trench depth kept constant at 0.75D also incorporating some modification on trench trailing edge. They reported that the trenched film hole offered better film effectiveness compared with cylindrical film hole non-trench case, and downstream trailing edge modification of trench provided a very small performance improvement. Oguntade et al. [8] performed numerical investigation with modified trailing edge shape of trench and conclude that fillet shaped trench outlet offered highest effectiveness compared with other trench outlet tested configurations. Computational results predicted on trench film cooling model with realizable k-ε model with EWT produced close results with experimental data. Mcgovern and Leylek [9] performed computational study with compound oriented film holes on flat plate model.

Lot of studies performed on trench model utilized streamwise oriented film cooling holes embedded in trenches. The studies [3, 4] reported on film cooling surface without trench and embedded with compound angled film hole reported higher FCE. Hence, the present investigation aimed to compare the cooling performance of trench model embedded with compound angled film hole viz. 45°, 90°, 135° through numerical and experimental investigation at two different BR of 1.2 and 2.

2 Numerical Investigations

Numerical investigation is performed through a series of steps viz. computational domain modeling, model mesh generation, numerical solution, post process of results. The computational model used in present study is based on experimental domain dimension. The domain used in computation is shown in Fig. 1. It consists

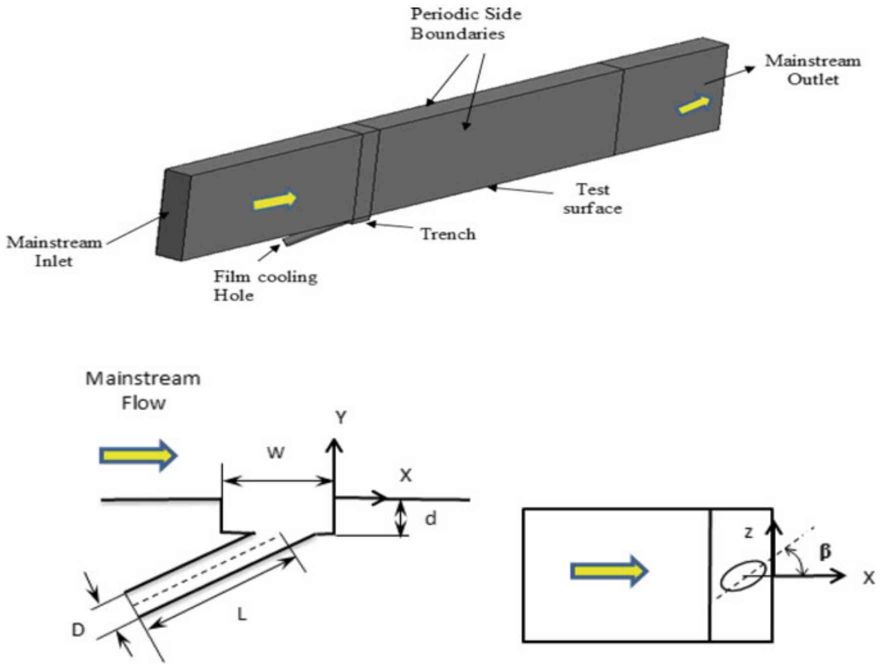

Fig. 1 Details of computational domain with trench and film hole compound angle (β)

of mainstream region, trench region and film hole region. The vertical lateral boundaries are specified with periodic boundary condition. The co-ordinate system origin of the computational domain is at the end of the trench side. The details for trench and compound angle are shown in Fig. 1. The width and depth of trench are maintained at 2D and 0.7D, respectively, with *D* of 4 mm for cooling hole. The modeling of computational domain is followed by mesh generation. Hybrid mesh system was employed for the computational domain.

The surface close to the wall was the change in temperature and velocity gradients occur, hence a wall clustered mesh system is generated close to the surface and also higher mesh concentration is introduced in the area of the computational domain with higher temperature and velocity gradients. Grid independence study is performed with three different mesh system viz. 0.8, 2.1, and 4.05 million cells with lateral averaged film cooling effectiveness used as assessment parameter for grid independence study. The Re No-based calculation on the mainstream inlet reveals that the flow is turbulent. The realizable k-ε model turbulence with EWT and thermal effects is used. The FCE predicted with turbulence model R-k-ε show good agreement on experimental results. Mainstream is specified with constant velocity 13 m/s and the temperature ratio of the hot air to coolant air is 0.883. The film coolant hole velocity is changed as per the change in BR and the temperature of the coolant stream was maintained constant. All the lateral side vertical boundaries are specified with periodic boundaries.

The sides of the domain are specified with non-heated and non-slip walls. Turbulence intensity for mainstream inlet and film hole inlet is 5% and 2%, respectively. The hydraulic diameter calculated based on mainstream and film hole inlet are specified at their respective boundaries. The continuity, momentum, energy equation and turbulence closure terms are solved in segregated method for three-dimensional steady incompressible flows. The SIMPLE scheme is adapted for coupling the pressure and velocity terms and SOUS is used for space discretization terms. The convergence criteria were set for scaled residuals to drop five orders of magnitude for continuity, momentum, turbulence equations and nine orders of magnitude for energy equation.

3 Experimental Investigation

The experimental study was performed on a custom fabricated suction type film cooling facility. The experimental set up comprises of different sub modules starting with air inlet whose sides are contoured to allow uniform air entry through inlet. Adjacent to the air inlet section is a heater assembly for rising the temperature of air entering the section and the heater element used is tubular finned type air heater with power of 12 kW. The temperature of heater module is controlled with a PLC temperature controller assembled adjacent to heater module. The heater module is covered with heat insulation blanket to reduce the heat loss to atmosphere. The test section is a C- shaped arrangement where the test plates with plenum can be inserted from behind the test section. Except the test section, all other modules are fabricated with MS plates of thickness 3 mm. The rubber gaskets are used to seal and connect the test section with adjacent modules, and asbestos fiber gasket sheet is used to seal the gap and prevent the leakage between all other assembled modules. The test section is followed by square to circular transition section that connects a diverging circular duct to inlet section of the blower unit. The film cooling air is supplied from air storage tank which receives pressurized air from a high power compressor. The air for film cooling is supplied through pipeline and controlled with check value. The orifice plate assembly is utilized for mass flow measurement of film cooling air, and a digital manometer is used to measure the pressure difference between upstream and downstream location of orifice assembly. Temperature measurement was performed with thermocouples embedded on the test surface with trench film cooling model.

4 Results and Discussions

The numerical results need to be validated with experimental results to gain confidence in the computational methodology. Figure 2 shows the validation study performed at blowing ratio (BR) of 1.2 and trench depth of 0.7D with film hole compound angle of 90°. Computational results are close to experimental results. The film cooling performance of trench model embedded with compound angled film

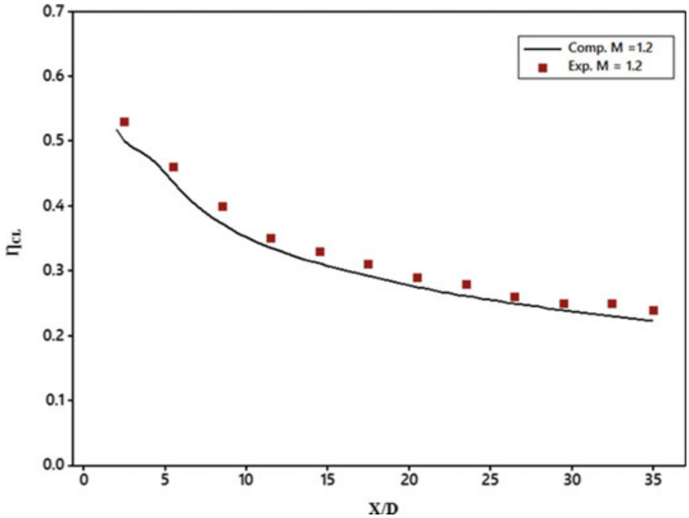

Fig. 2 Comparison of centerline FCE along test surface for numerical and experimental results

cooling hole is investigated with three major film cooling effectiveness parameters viz. local, lateral averaged and centerline FCE.

The lateral averaged FCE of 45°, 90° and 135° compound angles on test surface for BR of 1.2 as in Fig. 3, here the 90° compound angle film hole delivers higher FCE when compared to other compound angled hole models.

The 135° compound angle film hole delivers lower lateral averaged FCE. For higher BR 2, the lateral averaged FCE of different film hole compound angle is shown

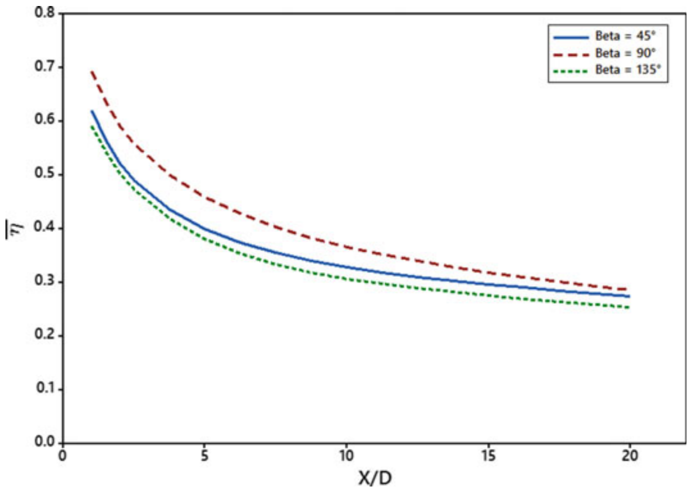

Fig. 3 $\overline{\eta}$ of different film hole compound angles at blowing ratio 1.2

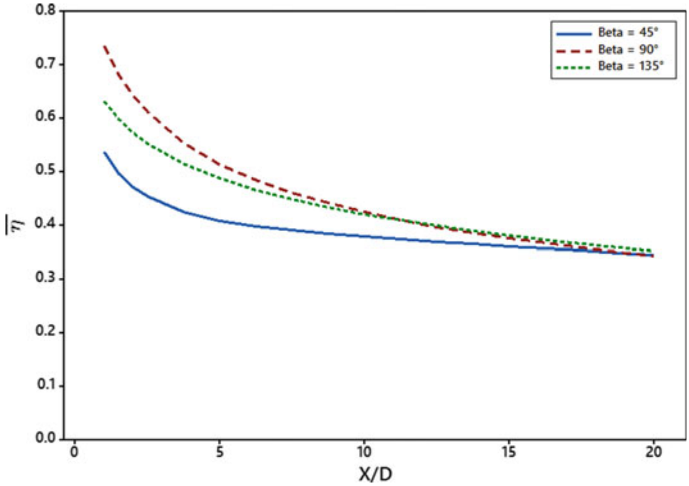

Fig. 4 $\overline{\eta}$ for various tested compound angle holes at BR 2

in Fig. 4, near the end of trench a significant level variation of lateral averaged FCE is observed.

Cooling effectiveness ($\overline{\eta}$) for three different film hole compound angle, however at downstream location the span averaged FCE of three tested hole compound angles (β of 45°, 90°, 135°) is uniform. The 90° compound angled film hole delivers higher span averaged FCE in comparison on other compound angles (45°, 135°) throughout the test surface and the 45° oriented film hole delivered lower $\overline{\eta}$ at higher blowing ratio 2. The 135° model produced lateral averaged FCE slightly lower than 90° oriented film hole. The variation of centerline FCE (η_{CL}) for three tested hole compound angles (45°, 90° and 135°) along longitudinal axis for BR 1.2 is shown in Fig. 5.

The compound angle film hole (90°) delivers higher centerline FCE near to trailing region of trench and film hole, however the centerline effectiveness of 90° oriented film hole is slightly reduced between X/D—1.25 to 3.25 and after that 90° model deliver higher FCE along the test surface. The 135° oriented compound angled film hole delivers lower centerline film cooling effectiveness. For higher BR of 2, the centerline FCE of test surface for three different film hole compound angle is shown in Fig. 6 and the 90° compound angle film hole delivers higher centerline FCE along central axis on test surface.

5 Conclusion

Film cooling performance of trenched model embedded with three different compound angle (45°, 90° and 135°) film cooling holes was investigated. The local, lateral averaged and centerline film cooling effectiveness were used as assessment

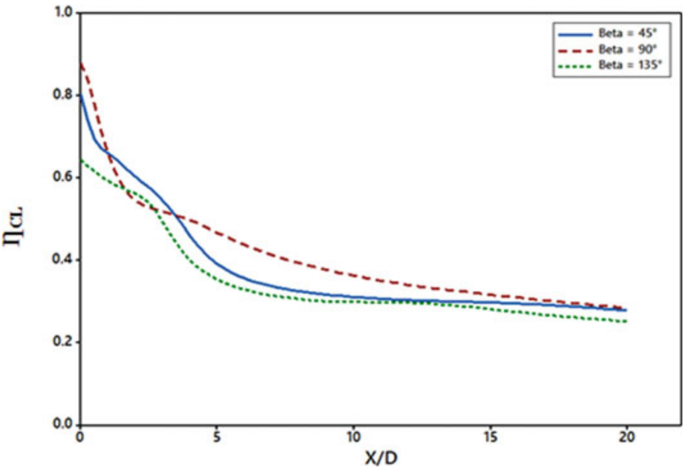

Fig. 5 η_{CL} for different film hole compound angles at blowing ratio 1.2

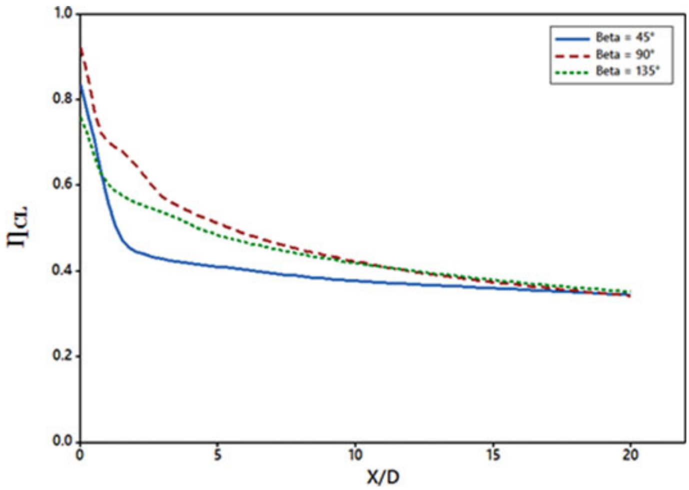

Fig. 6 η_{CL} for different film hole compound angles at blowing ratio 2

parameter to study the behavior on cooling effectiveness. Experiential studies performed on custom fabricated film cooling facility with 90° oriented film hole for blowing ratio of 1.2 shows close agreement with computational results. The film cooling hole oriented at compound angle 90° delivers higher local, lateral averaged and centerline FCE for two tested BR (1.2 and 2). 90° oriented compound angle film hole delivered uniform coolant coverage along lateral and longitudinal axis of test surface and this phenomenon results in higher film cooling effectiveness.

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