Detached Eddy Simulation of Film Cooling over a GE Flat Plate

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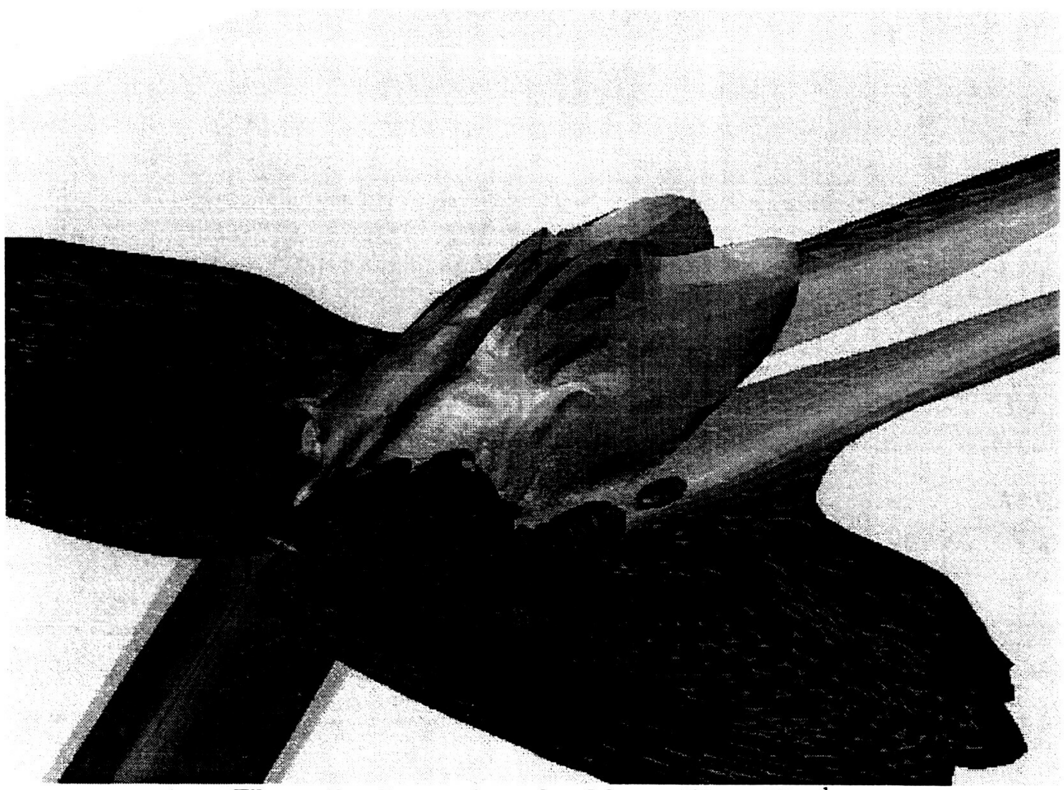

Film cooling flow vortices colored from +50k to –50k s^{-1}.

The detached eddy simulation of film cooling has been utilized for a proprietary GE plate-pipe configuration. The blowing ratio was 2.02, the velocity ratio was 1.26, and the temperature ratio was 1.61. Results indicate that the mixing processes downstream of the hole are highly anisotropic. DES solution shows its ability to depict the dynamic nature of the flow and capture the asymmetry present in temperature and velocity distributions. Further, comparison between experimental and DES time-averaged effectiveness is satisfactory. Numerical values of span-averaged effectiveness show better prediction of the experimental values at downstream locations than a steady state Glenn HT solution. While the DES method shows obvious promise, there are several issues that need further investigation. Despite an accurate prediction in the hole vicinity, the simulation still falls short in the region x = 10d to 100d. This should be investigated. Also the model used flat plate. Actual turbine blade should be modeled in the future if additional funding is available.

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INTRODUCTION

Gas turbines require proper cooling mechanism to protect the airfoils from thermal stresses generated by exposure to hot combustion gases. The problem becomes aggravated by the growing trend to use higher turbine inlet temperature to generate more power. Thus, film cooling is used as a cooling mechanism and it works in the form of row of holes located in the spanwise direction, through which cold jets are issued into the hot crossflow. The penetration of cold jet into the main flow creates a complex flowfield. Systematic investigation of such flowfield started in late 50s. Figure 1 shows the schematic of a single round jet injected in the crossflow. Figure also describes the boundary conditions applied at different faces. Even though use of symmetry boundary condition at the hole centerline would reduce the computational time by half, its use is avoided as it prevents the possibility of capturing the unsteady asymmetric vortical flow patterns. This geometry is well accepted for the gas turbine community and has been extensively studied[1] for cooling performance for a wide range of blowing ratios, M= $\rho_{fs}V_{fs} / \rho_j V_j$, where ρ and V are density and normal velocity, respectively for jet (j) and freestream (fs). The film cooling effectiveness η is defined as the ratio $(T_{fs} - T)/(T_{fs} - T_j)$, where T_{fs}, T and T_j are the temperatures of crossflow, blade and jet respectively. Sinha et al.[1] carried out experimental work to study the relationship between the fluid-thermal parameters of jet and film cooling effectiveness using a row of inclined holes.

The mixing of a jet in a cross-stream is a fully three-dimensional phenomenon[2,3]. Garg and Rigby[4] resolved the plenum and hole pipes for a three-row showerhead film cooling arrangement with Wilcox's k-ω turbulence model. Heidmann et al.[5] used RaNS to compute the heat transfer for a realistic turbine vane with 12 rows of film cooling holes with shaped holes and plena resolved. Several numerical studies[3-6] based on RaNS, k-ε, Wilcox's k-ω, RST and LES turbulence models and even DNS provide good details of the flow. However, these methods either lack anisotropic dynamic nature of the spanwise vortices (e.g. RaNS or RST) or they become computationally too intensive to be viable[6]. As a remedy, Roy et al.[7] and Kapadia et al.[8] have documented a detached eddy simulation (DES) based hybrid modeling of film cooling flow for the three-dimensional geometry in Figure 1. The geometric dimensions and physical data used are given in Table 1. Proposed by Spalart et al.[9], DES is a hybrid model which combines the efficiency of RaNS and the accuracy of LES length scales to work under a single framework. DES works by applying a variable length scale that varies as a function of the distance to the nearest wall (d_w) in the attached boundary layer and conforms with sub-grid scale in the rest of the flow including separated regions and near wake[10]. Spalart-Allmaras[9] based DES model is used in the present study. S-A is a one equation RaNS model. A detailed information about S-A one equation model, which is used in the presented DES simulation is given in Kapadia et al.[8].

Spalart-Allmaras based DES model has been developed in such a way that the model works as a standard S-A turbulence model inside the numerically predicted boundary layer. In the regions, far from the wall, the length scale becomes grid-dependent and the model performs as a subgrid-scale version of the S-A model for eddy viscosity. When production and destruction terms balance each other, this model reduces to an algebraic mixing-length Smagorinski-like subgrid model.

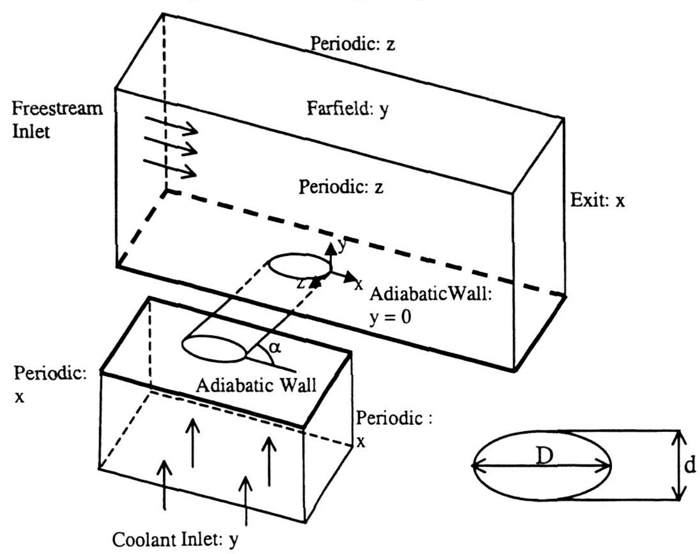


Figure 1. Schematic of the film cooling flow. Actual geometry definition and boundary conditions.

Geometric Dimensions		Physical Variables	
Hole diameter, d	0.0185 in.	Blowing ratio, M	2.02
Flowfield height: y	1.25 in	Velocity ratio	1.26
Flowfield width: z	0.067 in	Temperature ratio	1.61
Upstream of leading edge: x	1.6115 in	Inlet freestream total temperature	1121.0 deg. R
Downstream of leading edge: x	6.037 in	Coolant total temperature	695.7 deg. R
Flowfield total length: x	7.6485 in.	Inlet freestream total pressure	34.466 psi
Plenum height: y	0.375 in.	Exit static pressure	27.057 psi
Plenum length: x	0.375 in.		
Plenum width: z	0.067 in.		
Hole angle, α	30 deg		

Table 1. Important dimensions and variable details used in the simulation of schematic in Fig. 1.

Grid information and Computational approach

Present study implements Cobalt[11], a parallel, implicit, unstructured finite-volume based flow solver that uses second-order accurate spatial and temporal Godunov schemes. A multi-block computational grid was initially developed using the GridPro Multiblock grid generator. Gridgen14.03 is used to convert this grid into Cobalt compatible unstructured grid. The final grid used in the solution contains single block and 4 million cells. Viscous clustering was employed at all solid walls with a y^+ value less than 1.0 at all locations. Stretching ratios less than 1.2 were used normal to the viscous walls. Iteration convergence was considered achieved when all residuals reduce by four orders of magnitude. Size of the time-step is a function of CFL. Present case is run on the cluster of 16 parallel processors on Blue Horizon supercomputer at the San Diego

Supercomputing Center (SDSC). The aggregate CPU time requirement for the entire DES solution is about 37 seconds/iteration and that for one cell is approx 18 micro seconds/iteration.

RESULTS AND DISCUSSION

Figure 1 describes schematic control volume. All dimensions and physical variables used are iven in Table 1. All data have been converted to the SI unit. Fixed mass flow rate and stagnation temperature inlet boundary conditions are employed for the plenum and freestream. Fixed static pressure boundary condition is applied at the exit. Adiabatic no-slip conditions are applied at all solid walls, including the inner surface of the film hole and the plenum. A maximum Mach number not exceeding 0.3 was achieved in the flow field. Figures 2-6 described in this section correspond to the time-averaged DES solution when the solution reaches at quasi-stationary state.

Film cooling is a strongly coupled fluid-thermal process. Figure 2 shows the temperature distribution on the plate a slight asymmetry is observed around and near the hole. The color patterns ranges from 620K (red) to 385K (blue). Figure 3 plots the three dimensional collage of temperature distribution on several two dimensional planes with overlay of streamlines of cool jet penetrating the hot gas crossflow. Figure 4 shows the predicted penetration of the cool jet in the central z-plane cut along the major axis of the hole. The thermal effect on flow structures is described in Figure 5. The asymmetry is dominant just beyond the trailing edge of the hole (x = 3d) than further downstream (x= 10d).

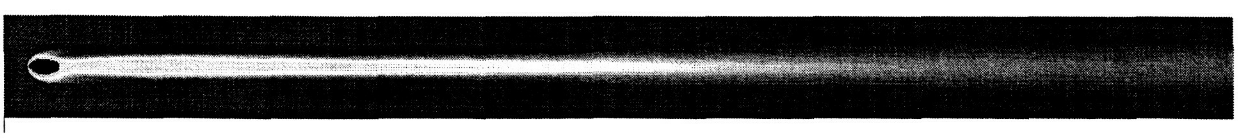


Fig. 2 Film cooled blade temperature distribution.

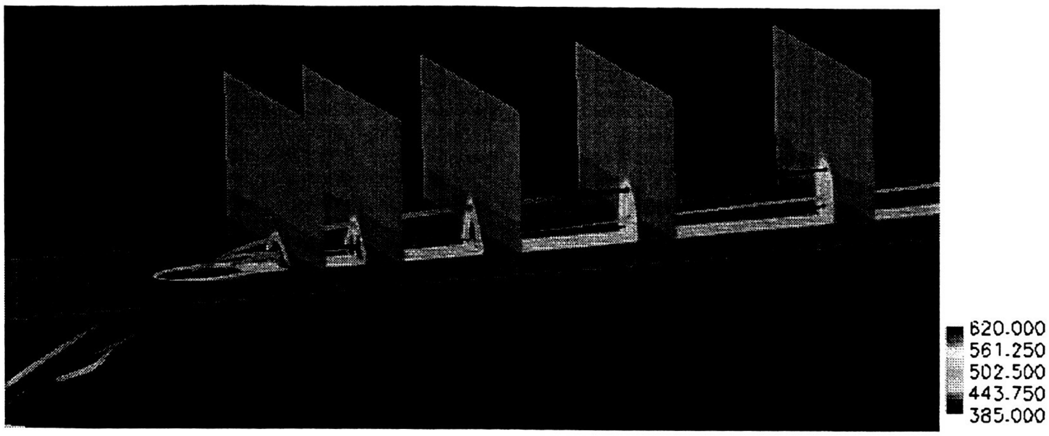


Fig. 3. Collage of different 2-D temperature planes with streamlines of film cooling jet.

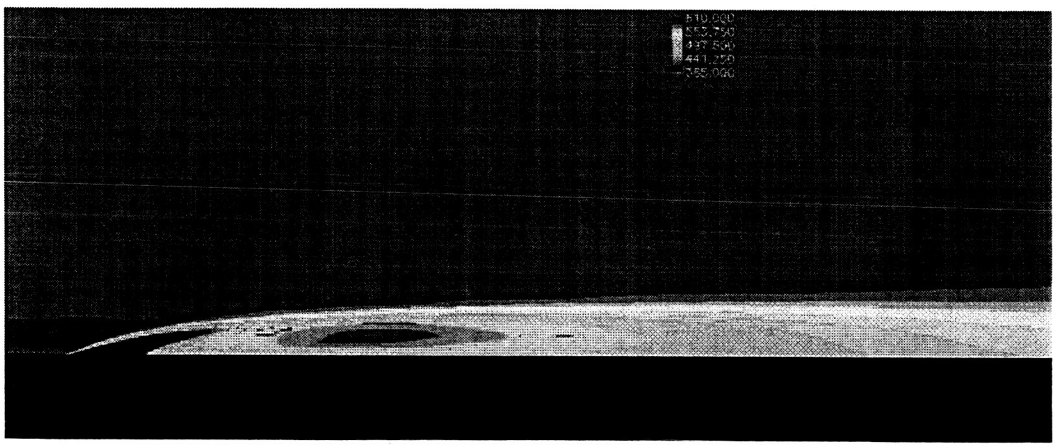
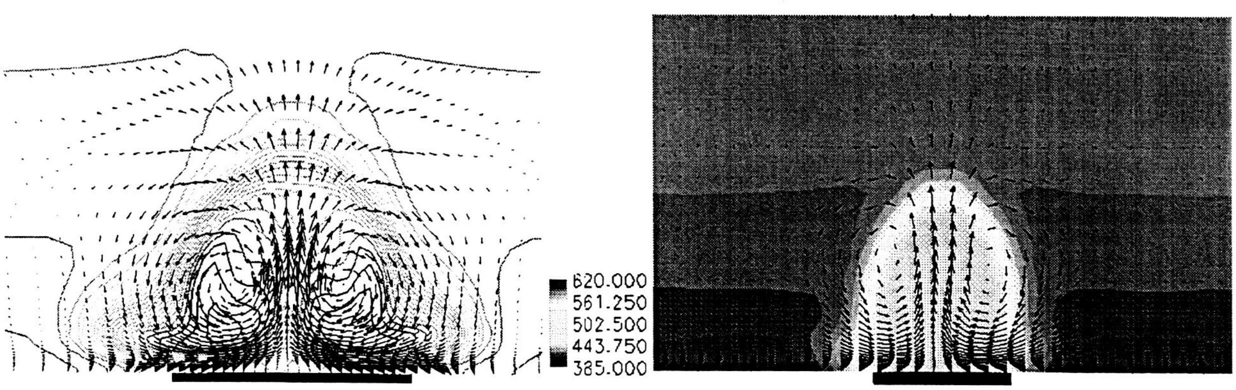


Fig. 4. Temperature distribution at the symmetry plane.



(a) **(b)**

Fig. 5. Flow vectors plotted on temperature contours. (a) At x/d = 3 shows asymmetry; (b) x/d=10 shows more symmetry.