Investigation of Film Cooled Rough Surfaces using Large Eddy Simulation

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Abstract

The use of "dirty" fuels with increased particulate concentrations leads to enhanced surface deposition and erosion on airfoil surfaces and can produce rough surfaces that can alter film cooling characteristics significantly. Both large scale and small scale roughness has been observed as a result of deposition and erosion. The study of film cooled rough surfaces has been predominantly experimental till now. For computational investigations, the resolution and meshing requirements of surface asperities is a major challenge. In the present paper the effect of roughness on the film cooling has been investigated numerically using Large Eddy Simulation. Effect of small scale (micro) roughness and large scale (macro) roughness have been studied. Macro roughness is modeled using an Immersed boundary method, and a roughness element model is used for micro roughness over immersed surfaces. Results of different roughness scenarios are analyzed and compared with the baseline smooth case.

Introduction

Significant changes in the film cooling performance due to roughness has been reported in the published literature[1][2]. Goldstein et al.[3] have reported a decrease in adiabatic film cooling effectiveness at lower blowing ratios and a significant improvement in adiabatic film cooling effectiveness at higher blowing ratios (in the range where jet lift off is observed). Bogard et al.[1] reported 50-60 % increase in heat transfer rate to the blade due to surface roughness. Due to these significant effects, predicting the cooling performance on rough surfaces is necessary to properly design cooling circuits.

The topography of realistic rough surfaces is quite complex and may contain multiple scales simultaneously. Exact roughness modeling therefore is extremely difficult. In earlier studies, Reynolds-Averaged Navier Stokes (RANS) and Detached Eddy Simulation (DES) approaches, with adaptive grids, have been used to study the effect of roughness[4]. However, restrictions arise in the 3D modeling of exact surface roughnesses by using a body fitted grid due to the large number of mesh points required and mesh quality due to the rough-surface topography.

Roughness elements and 2D ribs (grooves, d or k type roughness) have been the most popular approaches in roughness modeling. A Roughness Element Model was used to model roughness effects in a channel flow by Miyake at al. [5] in which the effect of roughness is modeled by the equivalent drag produced by an array of virtual cones introduced in the flow field. Bogard et al.[1] have used scaled conical roughness elements to simulate effect of roughness on heat transfer rate to the turbine blade.

In this paper, we present a computationally cost-effective procedure of undertaking simulations over rough surfaces and apply this to film cooled rough surfaces to better understand the impact of roughness on film cooling.

Roughness Element Models and Computational Methodology

Large Eddy Simulation (LES) is used in the present study. The spatially filtered governing equations for mass and momentum for an incompressible flow in curvilinear coordinates are solved. For modeling the near-wall surface roughness, a combination of Immersed Boundary Method (IBM) and roughness element model has been used. Roughness is decomposed to have a macro- and a micro- component based on the ability of the mesh to resolve the peak to peak magnitude of the roughness elements. The micro-roughness, not resolved by the grid, is represented by a roughness-element model, while the macro-roughness is represented by the IBM.

In the roughness element model used to model micro-scale roughnesses, the effect of additional drag due to roughness is modeled using additional body force term corresponding to a regular sandgrain type roughness elements (conical element is considered in the present study). Additional drag term is given as,

$$f_i = 0.5 C_d \rho u^2 \frac{u_i}{|u|} \frac{A}{V} \tag{4}$$

where A and V are frontal area and volume of the immersed part of the cone in computational cell. A $C_d = 0.2$ is assumed throughout the calculations.

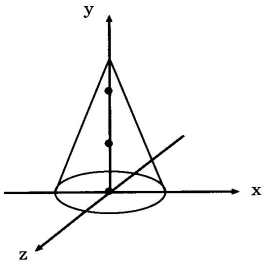


Fig. 1: Conical Roughness Element[2]

The dimension and distribution of these roughness elements is determined based on statistical roughness data due to Bons et al. [2]. Key roughness parameters include a measure of the roughness height (k), cone diameter (d), and inter-cone spacing (s). For all the simulations k/Ra = 5[1] is assumed where Ra is a measure of the average roughness height. Various values of k/θ are considered here resulting in different Ra values.

Table 1 Roughness Case Matrix

Case	k/θ	k	d	s	k/Ra
R4-M05D2	1	0.6e-3	3.0e-4	4.6e-4	5
R7-M05D2	2	1.2e-3	3.0e-4	4.6e-4	5
R5-M05D2	4	2.4e-3	3.0e-4	4.6e-4	5
R6-M05D2	6	3.6e-3	3.0e-4	4.6e-4	5

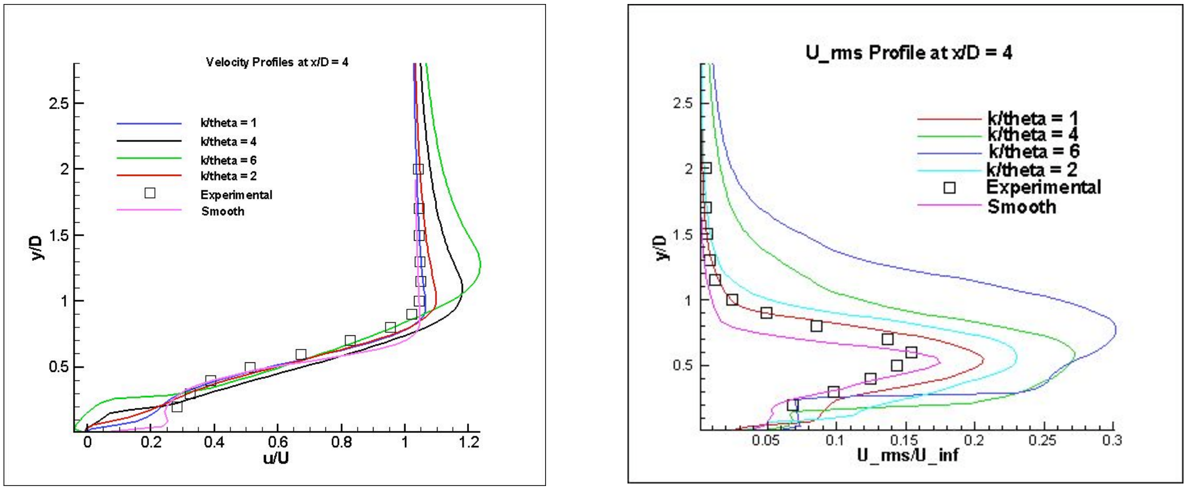
Macro-scale roughness is modeled using an IBM where the nodal points adjacent to the roughness interface are "forced" to satisfy the interface boundary condition[6].

These macro-scale roughness elements can be though to arise from preferential deposition rates, spallations etc.

Representative Results

Calculations are reported for a film cooling configuration of a single inclined hole with a 35-degree simple injection and a range of blowing ratios (BR) from 0.5 to 2. Experimental data for this configuration is provided by Pietzryk et al.[7] for a smooth surface. Representative results for a BR of one are provided here in this abstract.

Figure 2 shows the streamwise velocity and rms profile at x/D=4 for the smooth case and for surface roughness values of k/θ of 1-6. The predictions for the smooth case are in good agreement with the measured data of Pietzryk et al[7]. Note that k/θ values of 6 represent significant levels of roughnesses with θ/D of the order of 0.1 about 2 hole diameters upstream of the coolant hole. Figure 2a plotted at x/D=4 shows that the main roughness effects on the velocity field include a defect-velocity behavior near the surface, and a thickening of the boundary layer. This behavior is increasingly accentuated at higher roughness levels. Figure 2b shows the near wall turbulence profile which displays a significant increase in the rms across the entire vertical extent of the flowfield. At the highest roughness levels, rms levels are amplified by a factor of nearly 2.



(a) (b)

Fig. 2: Comparison of (a) velocity and (b) rms velocity components with experimental measurements by Pietrzyk et al. [7] *(smooth case)*

Figure 3 shows the spanwise averaged cooling effectiveness for the smooth and the various roughness cases. Roughness clearly has a significant effect on the cooling effectiveness with a decrease in peak effectiveness values from 0.5 for the smooth cases to below 0.2. For the lower k/θ values the predominant effect appears to be amore rapid dispersal of the coolant over the surface and a reduction in the cooling effectiveness. With increasing k/θ values the velocity defect behavior and a thickening of the boundary layer upstream of the coolant injection begins to play an important role leading to a sharp decay in the cooling effectiveness downstream of the coolant injection.

Detailed results over a range of blowing ratios and roughness parameters will be presented in the full paper.

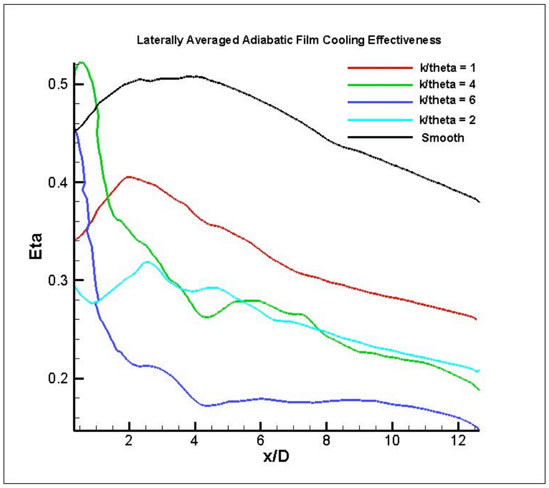


Fig 3: Laterally Averaged Adiabatic Film Cooling effectiveness

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