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Effects of surface deposition and droplet injection on film cooling

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ABSTRACT

In the present research, the influence of the particle dispersion onto the continuous phase in film cooling application was analysed by means of numerical simulations. The interaction between the water droplets and the main stream plays an important role in the results. The prediction of two-phase flow is investigated by employing the discrete phase model (DPM). The results present heat transfer characteristics in the near-wall region under the influence of mist cooling. The local wall temperature distribution and film cooling effectiveness are obtained, and results show that the film cooling characteristics on the downstream wall are affected by different height of surface deposits. It is also found that smaller deposits without mist injection provide a lower wall temperature and a better cooling performance. With 2% mist injection, evaporation of water droplets improves film cooling effectiveness, and higher deposits cause lateral and downstream spread of water droplets. The results indicate that mist injection can significantly enhance film cooling performance.

1. Introduction

In order to maintain high thermal efficiency and high power output, Benini [1] indicated that modern gas turbine engines should operate at high temperatures (1200–1600 °C). Since such temperatures are much higher than the allowable metal temperatures, it is necessary to cool the turbine components for the safe and durable operation. In order to cool the turbine blade internally and externally, the coolant air is usually extracted from the engine compressor. Polezhaev [2] presented that the transpiration gas-cooled blade concept had demonstrated its ability to provide protection from high temperatures. Hao et al. [3–5] numerically analysed uncoupled thermoelasticity using the Discontinuous Galerkin (DG) finite element method and presented an unconventional formulation for conjugate heat transfer (CHT) problems in gas turbines.

Air film cooling is nowadays commonly employed for the external turbine blade cooling. Discrete holes or several rows of holes with different shapes and inclination angles were investigated in the film cooling technology. Maiteh and Jubran [6] indicated that a favourable pressure gradient reduces the film cooling protection. Koc et al. [7] found that the film cooling effectiveness of a given curved surface depends on the optimum selection of the blowing ratio and maximum curvature height. Asghar and Hyder [8] carried out an analysis of averaged film cooling effectiveness from a row of semi-circular holes, and they found it is almost similar to that of circular holes. Bayraktar and Yilmaz [9] found that maximum cooling efficiency is obtained at the inclination angle of 30° and blowing ratio of 2.0. Shine et al. [10] showed that increase in the tangential angle may not provide an improvement in film cooling.

However, the air film cooling approaches its limitation. The coolant flow with water mist injection, also called mist cooling, can enhance the film cooling effectiveness due to the following mechanisms [11]: the latent heat of droplet evaporation, direct contact of droplets with the cooling wall and a higher specific heat of both the water steam and water compared to that of air. Li et al. [12] investigated a mist/steam slot jet impinging on a concave surface and simulation results showed that water injection of the 2% coolant flow rate can enhance the adiabatic cooling effectiveness for about 30–50%. Recently, Dhanasekaran and Wang [13,14] revealed the phenomenon of mist secondary flow interaction at bend portion and also performed simulations on both stationary and rotating turbine blades. Jiang et al. [15,16] investigated the effect of various parameters, including mist concentration, droplet diameter (5 μm, 10 μm and 15 μm) and different particle–wall interaction conditions on the improvement of cooling performance. In order to evaluate cooling enhancement, conjugate simulation for the C3X gas turbine vane with leading film holes was also carried out by them. Now scholars point potential merit out in

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Nomenclature

d	slot width, m
h	height of deposition, m
M	blowing ratio, $= \rho_j V_j / \rho_\infty V_\infty$
T	temperature, K
x, y, z	local coordinates, m
Greek symbols	
α	Inclination angle, deg
η	adiabatic film cooling effectiveness, $= (T_i - T_{aw})/(T_i - T_j)$
Subscripts	
aw	adiabatic wall
i	mainstream flow
j	coolant jet

injecting mist into the film-cooling flow, although there are existing problems, such as erosion and corrosion of the turbine components. Mohapatra and Sanjay [17] focused on the comparison of impact of vapour compression and vapour absorption cooling integrated to a cooled gas turbine, and the two methods of inlet air cooling improve the efficiencies of gas turbine cycle by 4.88% and 9.47%, respectively.

For a typical gas turbine, components operate under high temperature, high pressure and high velocity. The harsh environment causes thermal oxidation and surface deterioration, thus reducing component's life. Deposits are formed by various contaminants present in the combustion gases and tend to adhere to surface region around the film cooling holes due to the lower wall temperature in this region. Part of deposits can detach from the surface, peeling off the thermal barrier coating (TBC). Hence, it is important to understand the effect of surface deposition on the performance of film cooling. Bohn and Krewinkel [18] investigated the effect of oxide formation on the cooling effectiveness. They found that the effects of the oxidation on the cooling effectiveness seem to be minimal for the different blowing ratios and that the oxidation layer shows significant influence on the flow field both in the cooling holes and on the plate. Sundaram and Thole [19] indicated that deposits near the hole exit can sometimes improve the cooling effectiveness at the leading edge, but with increased deposition height the cooling deteriorates. Ai et al. [20,21] studied deposition in an accelerated test facility with finely ground coal ash particulates at 1180 °C and 180 m/s. In addition, hole spacing influence on the deposition was studied. Sundaram et al. [22] showed a systematic study of factors affecting the delamination energy release rate. They found that transient thermal gradients induce stress gradients through the coating and substrate. Kistenmacher et al. [23] investigated film cooling effectiveness with a thermal barrier coating and deposition in a realistic trench configuration. The results showed that this configuration was more prone to deposition within the trench, although the trench designs are more helpful to reduce the deposition formation than the round holes.

Since there is almost no literature reporting effects of TBC surface deposition on the film cooling with water droplet injection, present results from the 2D model are compared with the 2D cases without deposition from [12]. Additionally, this work investigates the deposition effect on the film cooling. Moreover, 3D models are also employed to give detailed insights into observed phenomena. Finally, for both 2D and 3D models with mist injection the adiabatic film-cooling effectiveness with different deposition height is investigated.

2. Numerical model and validation

In order to investigate the film cooling effectiveness, both 2D (two-dimensional) and 3D (three-dimensional) meshes are used in numerical simulations as shown in Fig. 1. The computational domain is $80d \times 20d$ and the 2D model has a slot width (d) of 4 mm. The slot is positioned 60d from the exit of the mainstream and vertical height of the jet hole is 1.74d. An inclined angle (α) of 35° is here considered having the optimal value according to [24,25]. A curved cross section is used as an approximation of TBC surface deposition of various heights (0.4–0.8 h). The streamwise deposit length (w) was 2d for all simulated cases. In the case of 3D model, the domain has a lateral depth of 8d and diameter of the film hole is 8 mm (2d). Similar configurations can be found in [12]. Different curved cross sections representing deposits are used with a varying height of 0.4d, 0.6d and 0.8d. The commercial computational fluid dynamics software ANSYS 15.0 was employed for numerical calculations. The simulation uses the segregated solver, which employs an implicit pressure-correction scheme. The pressure and velocity were coupled by the SIMPLE algorithm. Discrete phase model (DPM) was used to investigate interaction with continuous phase, where DPM sources are updated every iteration. A second-order upwind scheme was used for spatial discretization of the convective terms and species. The Lagrangian trajectory calculations were adopted for modelling the dispersed phase of droplets, while the impact of the droplets on the continuous phase was handled through the source terms of governing equations.

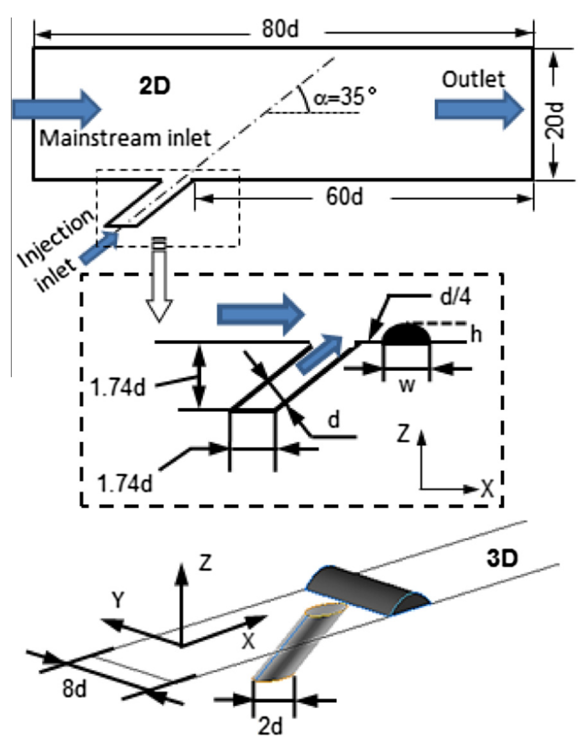

Fig. 1. Computational domain and hole configurations for 2D and 3D.

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