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Research article

Numerical investigation of mist/air impingement cooling on ribbed blade leading-edge surface

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ABSTRACT

The working gas turbine blades are exposed to the environment of high temperature, especially in the leading-edge region. The mist/air two-phase impingement cooling has been adopted to enhance the heat transfer on blade surfaces and investigate the leading-edge cooling effectiveness. An Euler-Lagrange particle tracking method is used to simulate the two-phase impingement cooling on the blade leading-edge. The mesh dependency test has been carried out and the numerical method is validated based on the available experimental data of mist/air cooling with jet impingement on a concave surface. The cooling effectiveness on three target surfaces is investigated, including the smooth and the ribbed surface with convex/concave columnar ribs. The results show that the cooling effectiveness of the mist/air two-phase flow is better than that of the single-phase flow. When the ribbed surfaces are used, the heat transfer enhancement is significant, the surface cooling effectiveness becomes higher and the convex ribbed surface presents a better performance. With the enhancement of the surface heat transfer, the pressure drop in the impingement zone increases, but the incremental factor of the flow friction is smaller than that of the heat transfer enhancement.

1. Introduction

Gas turbine has been widely used in vehicle and aviation, electricity generation, refrigeration and other aspects. With the increase in the inlet temperature of gas turbine, the efficiency and output power of gas turbine are rising obviously. Now the turbine inlet temperature can be up to 2000 K with advanced technologies (Liao et al., 2014). The extreme operating conditions can shorten the lifespan and reduce efficiency of the blade (López-Abente et al., 2014). Especially, the blade leading-edge is directly impinged by hot gas and suffers a great thermal load. The frequent replacement of the blades results in massive material wastes and the low efficiency causes more emissions of NOx (Javed et al., 2007). Therefore, the advanced cooling method for protecting the blade leading-edge has received high attentions. Conducting many experimental tests can also cause environmental and economic concerns, such as material waste and air pollution. Many environmental regulations have been made by the government to demand the different industries to follow the stringent requirements to solve those problems. The widely used Computational Fluid Dynamics (CFD) method can provide the design details based on the operating conditions to satisfy those regulations (Mikulčić et al., 2016; Baleta et al., 2017) and shows great promise in the environmental science field. For example, Wania et al. (2012) simulated an effect of vegetation on atmospheric processes. Kafle et al. (2015) investigated two down-flow wood bark-based biofilters under the actual swine farm conditions. All of their studies obtained good results by using the CFD techniques.

Numerical results by using the CFD method are also obtained to predict effects of the cooling technologies on the protection of turbine blades. Now the two most widely used cooling techniques are the film cooling and the composite cooling. Kanani et al. (2009) numerically proved that many factors had important effects on the film cooling effectiveness and film shrouded homogeneity, such as the film holes shape, the holes arrangement and the blowing ratio. Chang et al. (2015) compared film cooling with composite cooling under the same coolant conditions and they found that the

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Nomenclature

A_d	Surface area of the particle, m^2
c_p	Specific heat, J/(kg K)
$c_{p,d}$	Specific heat of the particle, J/(kg K)
C_D	Drag coefficient
d_d	Diameter of the particle, m
f_i	Mass force, m/s^2
f_i'	Volumetric momentum source, kg/(m^2 s^2)
f'	Interaction forces, m/s^2
h	Enthalpy, J/kg
$H_{lat_{ref}}$	Latent heat at reference conditions, J/kg
h_d	Particle enthalpy, J/kg
h_{fg}	Latent heat of particle, J/kg
k_c	Mass transfer coefficient, m/s
M	Volumetric mass source, kg/(m^3 s)
$\dot{m}_d$	Mass flow rate of the particles per cell, kg/s
m_d	Average mass of the particle on cell entry, kg
Δm_d	Mass exchange of the particle per cell, kg
$m_{d,in}$	Mass of the particle on cell entry, kg
$m_{d,out}$	Mass of the particle on cell exit, kg
p	Pressure, Pa
Re	Relative Reynolds number
Re_d	Reynolds number of the particle
t	Time, s
Δt	Time step, s
T	Temperature, K
T_{in}	Temperature of the particle on cell entry, K
T_{out}	Temperature of the particle on cell exit, K
T_{ref}	Reference temperature for enthalpy, K
T_d	Particle temperature, K
T_R	Radiation temperature, K
u_i, u_j, u_k	Velocity, m/s
u_d	Velocity of the particle, m/s
x_i, x_j, x_k	Coordinate directions, m
$Y_{i,s}$	Vapor mass fraction at the surface
$Y_{i,\infty}$	Vapor mass fraction in the bulk gas

Greek symbols

δ	Heat transfer enhancement coefficient
δ_V	Cell volume, m^3
δ_{ij}	Kronecker's delta
μ	Dynamic viscosity coefficient, Pa s
ρ	Density, kg/m^3
ρ_d	Density of the particle, kg/m^3
λ	Thermal conductivity, W/(m K)
Φ	Volumetric energy source, W/m^3
ε_d	Emissivity
σ	Stefan Boltzmann constant, 5.67×10^{-8} W/(m^2 K^4)
Δ	Convection heat transfer enhancement coefficient
θ	Enlargement factor of flow friction
Γ_j	Viscous stress tensor, Pa

composite cooling effectiveness was higher than the film cooling. Nirmalan et al. (1998), Li and Wang (2005) and, Wang and Li (2008) found that the film cooling effectiveness of the steam/mist two-phase flow was higher than that of the steam flow only. Nirmalan et al. (1998) experimentally investigated heat transfer of the turbine vane with water-air cooling method. Li and Wang used the CFD technique to study the film cooling, they found that the cooling effectiveness enhanced with mist injection (Li and Wang, 2005) and then investigated the blade cooling using that method under the real turbine operating conditions (Wang and Li, 2008). Jiang et al. also used the numerical method to study the steam/mist film cooling on the heavy-duty gas turbine vane (Jiang et al., 2014) and further explored the film cooling enhancement techniques on the leading-edge surface and downstream surface of turbine blade (Jiang et al., 2015a). Wang et al. added ribs on the cooling passage to enhance the flow disturbance, which showed good cooling protection for the blade (Wang et al., 2015, 2016a). The similar configuration was used to investigate the effect of the inclined flow angle on film cooling (Wang et al., 2016b). The application of composite cooling and multiphase film cooling can greatly improve the cooling effectiveness near the blade leading-edge. With the increase in turbine inlet temperature, the usage of the coolant increases quickly in order to protect the blade. Meanwhile, a large quantity of coolant flowing into turbine results in losses of benefits (Shi et al., 2015a). In addition, the hole configurations would result in complicated flow distributions around the turbine blades, and some challenges emerge to the stability of the working equipment (Jun et al., 2015).

Two-phase impingement cooling method has been gradually introduced into protection of the blade leading edge for the characteristics of high cooling efficiency. Shi et al. (2015b) found that the efficiency of the steam/mist impingement cooling was much higher than that of the steam cooling only. Li et al. (2003) proved that the concave surface had a better impingement cooling effect than the flat surface by the slot steam/mist impingement experiments. Dhanasekaran et al. conducted a two-phase flow impingement simulation on the surface of a 180° bend pipe and compared the results with the experimental data (Dhanasekaran and Wang, 2012), besides, they also numerically investigated the cooling effect of the surface with 45° angled ribs (Dhanasekaran and Wang, 2013). Jiang et al. (2015b) studied the cooling characteristic of the leading-edge surface of turbine blade using air/steam two-phase impingement cooling method and they found that it was a promising method. But how to further enhance impingement cooling efficiency and bring it into commercial application are still unclear.

In this study, the air/mist impingement cooling model of the leading-edge is presented and validated. The cooling effectiveness on rough surfaces with convex/concave ribs is then investigated after the smooth leading-edge surfaces are studied and benchmarked. In addition, the pressure drop characteristics of the impingement zone are also obtained to investigate the benefit of the ribbed surface.

2. Numerical model formulation

2.1. Physical and computational domain descriptions

Numerical method has been used to study the cooling characteristics of ribbed surfaces and a few assumptions are made to simplify the present model as follows:

1) One blade is included in the computational domain and the periodic boundary condition is used to simulate the annular cascades;
2) The solid zone of the blade only involves the leading edge part and others are neglected;
3) Air/mist mixing zone is ignored and droplets are injected from the inlets of the impingement zone directly;
4) The hot air is used instead of the combustion gas;

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