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Numerical prediction on mist/steam cooling in a square ribbed channel at real gas turbine operational conditions

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ABSTRACT

Flow and heat transfer characteristics of mist/steam cooling in a square channel with 60° rib angle at elevated gas turbine operational conditions featured by high temperature, pressure and Reynolds number are numerically investigated. The heat transfer enhancement of mist/steam at elevated conditions is compared with that at laboratory conditions with the identical mist mass ratio and droplet size. The 3D steady Reynolds-averaged Navier–Stokes equations with a standard k-ω turbulent model are solved by using commercial software ANSYS CFX. The CFD model has been validated by experimental data for both steam-only and mist/steam cases with a good agreement. Distribution and evolution of secondary flow in the ribbed channel as well as its effect on heat transfer are analyzed by vortex core technology. The results show that the strength of longitudinal secondary flow has a great influence on Nusselt number distribution on the ribbed surface. When injecting 2–8% mist into steam coolant, the heat transfer enhancement of 6.8–25.7% with average wall temperature reduction of 21–71.2 K is achieved at elevated conditions, while that of 11.2–34.3% with average wall temperature reduction of 23–71 K is obtained at laboratory conditions. The heat transfer enhancement and thermal performance of mist/steam at elevated conditions increase with Reynolds number, mist mass ratio and droplet size, but the thermal performance of steam-only gradually decreases with Reynolds number. The maximum heat transfer enhancement of mist/steam is 19.8% with 20 μm mist at elevated conditions, while that is 41.6% with 15 μm mist at laboratory conditions. The key of heat transfer performance of mist/steam is the survivability of droplets in the ribbed channel.

1. Introduction

Aiming at lower carbon dioxide emission, higher thermal efficiency and power output requests continuous elevation of the gas turbine inlet temperature (TIT). TIT for most advanced gas turbines has risen to about 2000 K, which is far beyond the allowable long-term operation temperance of gas turbine blades and vanes material. As a result, various cooling technologies such as air film cooling, impingement cooling, internal convective cooling, thermal barrier coating, transpiration cooling, are developed to effectively protect the gas turbine blades and vanes from high temperature corrosion and creep, etc. In order to improve the durability and reliability of gas turbine hot components. Among these cooling technologies, internal convective cooling is an established solution to effectively remove the heat load on gas turbine blades and vanes; various rib configurations in internal cooling channels play an important role in convective heat transfer enhancement.

Over the past decades, extensive studies of both numerical simulations and experimental measurements have been performed to explore heat transfer performance of air coolant in internal cooling ribbed channels. In the 1980s, Han et al. [1–3] and Park et al. [4] began to experimentally study the heat transfer characteristics of air in internal cooling ducts with commonly used parallel ribs. The ribbed ducts with five aspect ratios (W/H = 1/4, 1/2, 1/1, 2/1 and 4/1), four rib angles (α = 30°, 45°, 60°and 90°), two rib pitch-to-height ratios (p/e = 10 and 20) have been tested in their experiments. Their results indicated that generally the best heat transfer performance was obtained in narrow aspect ratio channels (W/H < 1) and rib angle of 45°/60°, while rib angle of 30°/45° was recommended for large aspect ratio channels (W/H > 1). Up to now, although the heat transfer performance of traditional air cooling has been gradually improved, the net benefit is approaching its limit to meet the requirement of advanced gas turbines.

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Nomenclature

D	hydraulic diameter of channel, mm
e	rib eight, mm
f	dimensionless friction coefficient
f_o	friction coefficient for fully developed region in a smooth tube
H	height of channel, mm
ΔL	length of channel, mm
L_e	extended entrance section, mm
L_h	length of heated section, mm
$L_\circ$	extended outlet section, mm
Nu	Nusselt number
$Nu_\circ$	Nusselt number for fully developed region in a smooth tube
p	rib pitch, mm
P	static pressure
ΔP	pressure loss of channel, Pa
Pr	Prandtl number
q	heat flux, W/m^2
Re	Reynolds number
TD	wall temperature difference between mist/steam and steam-only, K
T_w	temperature of the ribbed side wall, K
T_b	bulk temperature at x-direction, K
u	inlet velocity of channel, m/s
W	width of channel, mm

Greek letter

μ	fluid dynamic viscosity, m^2/s
α	rib angle, °
λ	thermal conductivity, W m^{-1} K^{-1}
η	thermal performance factor
$\boldsymbol{\Omega}$	anti-symmetric components of velocity gradient tensor
$\boldsymbol{S}$	symmetric components of velocity gradient tensor

In comparison to air coolant, steam has a higher specific heat capacity and a lower thermal conductivity, which results in the heat transfer performance of steam being much better than that of air. The closed-loop steam cooling scheme has been successfully employed in heavy frame land-based gas turbines and corresponding research work regarding heat transfer performance of steam coolant has been done by several researchers. Generally, the key factors influencing the flow and heat transfer characteristics of steam coolant can be divided into two categories: (1) geometric configuration parameters, such as aspect ratio, rib angle, pitch ratio and blockage ratio; (2) operational conditions, such as inlet Reynolds number, superheat of steam, operating pressure, heat flux of ribbed surface. Liu et al. [5] and Shi et al. [6] experimentally investigated the effects of geometric configuration parameters on heat transfer performance of steam coolant in internal cooling channels with aspect ratios $W/H = 1/4$, 1/2, 1/1 and rib angles $\alpha = 30°$, 45°, 60° and 90°. The results demonstrated that the best heat transfer performance was obtained in rectangular channel with aspect ratio of 1/2 and rib angle of 60°. With regard to the influence of operating conditions, Gao et al. [7] experimentally studied the influences of inlet Reynolds number varying from 30,000 to 140,000, operating pressure from 0.2 MPa to 0.5 MPa, heat flux of the ribbed surface from 5 kW/m^2 to 20 kW/m^2 and superheat of steam coolant from 13 °C to 51 °C on heat transfer performance of steam in a 60° ribbed channel. Thereafter, Shui et al. [8] numerically investigated the effects of elevated operating conditions with high pressure, temperature and Reynolds number on the thermal performance of steam coolant.

Although, closed-loop steam cooling has the potential of better performance than air, one of the disadvantages is that excessive steam coolant will be extracted from steam turbines, which results in degrading the thermal efficiency of steam turbines [9]. To address above issues, an effective and potential approach to greatly augment heat transfer is to inject a small amount of mist into the steam flow. The benefits of two-phase flow mist/steam cooling are mainly attributed to the latent heat of droplet evaporation, a lower bulk temperature, an increased turbulence mixing induced by gas-droplet interaction and droplet dynamics. In the 2000s, Guo et al. [10–12] initially conducted experimental studies on heat transfer performance of mist/steam in a smooth straight tube and in a 180° bend tube, respectively. They demonstrated that an average heat transfer enhancement of 50–100% was obtained with 5% mist in the smooth straight tube and that of 40–300% was observed by adding 1–2% mist in the 180° bend tube. Subsequently, Dhanasekaran et al. [13,14] verified their numerical scheme with experimental data in a smooth straight tube and in a 180° bend tube. The results indicated that the predicted values matched well with experimental data within 8% deviation for steam-only and 16% deviation for mist/steam.

For two-phase flow mist/steam or mist/air internal cooling, numerical simulations were conducted by Elwekeel et al. [15] and Liao et al. [16] to compare the heat transfer performance of four coolants including mist/steam, steam, mist/air and air in a 90° ribbed channel and in a wedge duct with pin-fins, respectively. The results demonstrated that mist/steam obtained the best thermal performance among all the coolants. Additionally, the heat transfer performance of mist/steam and mist/air in 90° ribbed channel with several kinds of rib configurations including square rib, triangular rib and trapezoidal rib was numerically investigated by Elwekeel et al. [17,18]. Similarly, the heat transfer characteristics of mist/air cooling in a two-pass 45° ribbed channel with or without rotation were numerically studied by Dhanasekaran et al. [19]. It was found that an average heat transfer improvement of 20–30% was obtained on leading and trailing surface by injecting 2% mist into air coolant.

For two-phase flow mist film cooling, Li et al. [20] firstly investigated the mist/air film cooling effectiveness on a flat surface by numerical scheme. They showed that the adiabatic mist film cooling effectiveness was increased by about 30–50% with 2% mist injection. Thereafter, the experimental measurement of mist/air film cooling effectiveness on a flat plate was conducted by Zhao et al. [21,22]. The results indicated that the mist film cooling effectiveness enhancement of 190% locally with average value of 128% was observed at the centerline of the flat plate. The studies in Refs. [20–22] showed a promising mist/air film cooling effectiveness under laboratory operational conditions with low temperature, pressure and Reynolds number. However, the gas turbines actually operate at elevated operational conditions with high temperature, pressure and Reynolds number. The huge challenges of utilizing mist/air film cooling are the survivability of droplets at such harsh working conditions and whether the droplets can be transported from internal cooling channel to the desired places, such as the sites of film holes. Wang et al. [23,24] explored the feasibility of applying mist/air film cooling to gas turbine vanes and blades at elevated operational conditions by zero-dimensional model and numerical scheme. Results showed that theoretically, it is feasible to transport droplets with sufficient size and mist concentration to the needed locations. Considering the limit and cost of conducting