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Study on flow and heat transfer characteristics of the mist/steam two-phase flow in rectangular channels with 60 deg. ribs

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A B S T R A C T

Flow and heat transfer characteristics of mist/steam two-phase flow in a high temperature square channel with 60 degreed ribs are studied experimentally and numerically. First, a 3-D fluid–solid coupled numerical model was established for this channel cooled by mist/steam. The numerical results are in good agreement with the experimental results and the maximum temperature deviation of bottom wall centerline is less than 4.6%. Then, the effect of longitudinal vortex and the distribution of the "mainstream influenced zone" and the "vortex influenced zone" on the channel wall temperature distribution were analyzed qualitatively according to the simulation results. Finally, the influence of the key factors *Re* number, mist/steam mass ratio, water droplet diameter and heat flux on the flow and heat transfer characteristics were studied using this numerical method. The following conclusions can be reached: When *Re* increases from 74,000 to 170,000, the average centerline *Nu* number rises from 376.3 to 882.2, under the condition of $q = 8000\ W/m^2$ and mist/steam = 3%. As the mist/steam mass ratio increases from 0.5% to 9%, the average *Nu* number rises from 636.3 to 996.3 at the condition of inlet *Re* = 147,000, $q = 8000\ W/m^2$. The ratio f/f_∞ is increased by nearly 22% when *Re* rises from 74,000 to 170,000 under the condition of $q = 8000\ W/m^2$. Mist/steam mass ratio has little influence on f/f_∞, and the ratio f/f_∞ is slowly increased with wall heat flux. When the heat flux and the mist/steam ratio are certain, the heat transfer enhancement increases with the increasing of the friction resistance.

1. Introduction

As the gas turbine inlet temperature is raised to 1500 °C, the conventional cooling technologies using air or steam as the coolant are increasingly difficult to meet the cooling requirement because of the low cooling efficiency, which hinders further improvement of the gas turbine efficiency and power output [1]. To solve this problem, many researchers are committed to finding more effective coolants to increase the cooling efficiency of gas turbine vane.

Using mist/steam two-phase flow as gas turbine blade coolant is an important research direction for the next generation gas turbine blade cooling technology. The application process of this cooling technique is as follows. First, draw a certain amount of steam out from the bottom steam cycle. Then, inject fine water droplet into the cooling steam and form mist/steam mixture. Finally, transport the mixture into the cooling system of turbine blade [2]. The main advantages of mist/steam cooling compared to steam cooling can be summarized as follows: (1) absorbs a large amount of latent heat in the water mist evaporation process, (2) increases the specific heat of the coolant after mixing water mists, (3) reduces the coolant bulk temperature during the mixing process, (4) increases the temperature gradient near the heated walls, (5) enhances the heat and mass transfer near the heated wall when water droplets evaporate, (6) disturbs the thermal boundary layer near the walls [3]. For the reasons above, cooling by the mist/steam two-phase flow can achieve higher cooling efficiency of the gas turbine blade compared to cooling by steam or air. At the same time, the consumption of steam or air coolant can be reduced and the output power and thermal efficiency of the gas turbine can be improved greatly.

Although the idea of using water as gas turbine components coolant has been discussed over the past 60 years [4], and Pedersen experimentally studied water droplets cooling hot surfaces in 1970 [5], it was only in the past twenty years that more and more research focused on two phase flow cooling techniques. In 1998, Nirmalan et al. experimentally studied the heat transfer of water/air coolant in the gas turbine vane. Their results proved that the cooling air consumption can be reduced by more than 50% when the water droplets are injected into the air coolant [6]. Wang Ting et al. conducted experiments of mist/steam cooling in a horizontal tube and a 180-degree bend tube [7–9]. They also studied the

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Nomenclature

D	hydraulic diameter of passage, mm
e	rib eight, mm
f	dimensionless friction coefficient
f_∞	friction coefficient for fully developed region in a smooth tube
H	height of passage, mm
ΔL	length of passage, mm
L_{in}	length of inlet section, mm
L_h	length of heated section, mm
L_{out}	length of outlet section, mm
m_s	mass flow rate of main stream
Nu_{mist}	Nusselt number with mist/steam cooling
Nu_{steam}	Nusselt number with steam cooling
p	rib pitch, mm
P_{in}	inlet Pressure, MPa
ΔP	pressure loss of passage, Pa
q	heat flux, W/m^2
Re	Reynolds number
t	passage wall thickness, mm
T_{in}	inlet temperature, K
$T_{sat,s}$	saturation temperature of steam, K
$T_{w,s}$	local wall temperature, K
$T_{b,s}$	bulk temperature of steam, K
u_{id}	water mist velocity, m/s
W	width of channel, mm
z	position in channel at z-direction, mm

Greek letter

μ	fluid dynamic viscosity, m^2/s
α	rib angle, °
λ	thermal conductivity, W m^{-1} K^{-1}
Ω	anti-symmetric components of velocity gradient tensor
S	symmetric components of velocity gradient tensor
ρ	fluid density, kg/m^3

cooling efficiency of mist/steam two-phase flow in a film cooling structure using the numerical method [10]. After that, Wang Ting et al. experimentally studied mist/steam heat transfer of multiple rows of impinging jets. They found that the maximum local heat transfer increased up to 800% when 3.5% was injected in low heat flux condition. The heat transfer characteristic is improved enormously by injecting water mist into steam coolant [11].

Many researchers have studied the heat transfer enhancement of the mist/steam cooling in different cooling structures of gas turbine blade. Dhanasekaran and Wang studied the effect of mist film cooling on rotating gas turbine blades by the numerical method and found that the average heat transfer enhancements are increased by 15–35% under laboratory and elevated conditions [12]. Jiang et al. studied the air/mist cooling in heavy-duty C3X gas turbine vane through numerical methods and found out that the cooling efficiency and the cooling performance location can be controlled by manipulating the size of injected mist [13]. This research group also numerically investigated the heat transfer characteristics of mist/air coolant in swirl and impingement cooling structure of a blade leading edge. The influences of the mist ratio and inlet *Re* number on vortex structure, heat transfer enhancement, pressure loss and thermal uniformity were studied at the same time. Their results show that the heat transfer increases by 46.2% and 51.5% for impingement and swirl cooling through adding 8% mist, but the pressure loss coefficient increases by 19% [14]. Moreover, Wang and Dhanasekaran studied the mist/steam impinging jets cooling of the gas turbine blades, results show that under the working conditions the cooling efficiency increases up to 20% and 100% when mixing 1.5% and 5% mist, respectively [3]. After that, they studied mist/steam cooling with jet impingement onto a concave surface with the numerical method under elevated operating condition [15].

As one of the most important parts of the blade cooling techniques, the flow and heat transfer characteristics of coolant in blade internal cooling passage have always been the research hotspots. Dhanasekaran and Wang analyzed the mist/air cooling in a two-pass rectangular rotating channels with 45 degree angled ribs through the numerical method. The results show that in the first passage the mist cooling enhancement is about 30% at the trailing surface and about 20% at the leading surface with 2% mist injection. In the second passage, a 20% enhancement is reached for both surfaces [16]. Kanani et al. numerically studied the gas and water droplet flows and film cooling efficiency with and without mist on a flat plate [17]. Wang et al. studied the influence of the key factors such as inlet *Re* number, mist diameter and rotating speed on heat transfer characteristics in the channel with 45° angled ribs using the mist/steam two phase flow as the coolant [18]. Besides, Gao and Zeng et al. numerically studied the mist/steam cooling in an internal cooling passage with 60° angled ribs. In their study, the numerical model was validated by the experiment data from Wang Ting's study on mist/steam cooling in a smooth tube [19]. Shi et al. experimentally researched the heat transfer of mist/steam coolant in a smooth square tube [20].

Although the heat transfer of the mist/steam cooling in a horizontal tube has been experimentally studied, the cross sections of most cooling passages in gas turbine blade are rectangular with angled ribs on the sidewalls. Compared with a smooth tube, the flow and heat transfer of mist/steam coolant in a rectangular channel are quite different. Therefore, it is necessary to carry on the experimental study of forced convection heat transfer of mist/steam coolant in an internal cooling passage with angled ribs.

In this article, the influences of inlet *Re* number, mist/steam mass ratio and wall heat flux on the flow and heat transfer characteristics of mist/steam cooling in a rectangular channel with 60° ribs were investigated through the experimental method. In order to deeply analyze the heat transfer characteristics under different mist diameters, mist/steam mass ratio, and the flow field concurrently, a 3-D fluid–solid coupled numerical model for mist/steam coolant in internal cooling passage with ribbed walls was developed. This study can provide some theoretical basis for the development of mist/steam cooling blade techniques.

2. Experimental methodology

2.1. Experimental facility

The experimental facility is composed of a steam subsystem, a mist subsystem, a mixing chamber, a test section with the heating system, a data acquisition system, a control system and an exhaust system. The steam subsystem consists of a water softener, an evaporator and a steam superheater. The softened water was heated in the evaporator and became the saturated steam. Then the saturated steam was heated in the super heater and became superheated steam with certain temperature and pressure. The mist system consists of a water tank, a heater, a metering pump, valves