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Study on heat transfer performance of steam-cooled ribbed channel using neural networks and genetic algorithms

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This work aims to optimize the steam-cooled ribbed channels to achieve the best heat transfer performance. The combined effects of channel aspect ratio ($W/H = 0.25–4$), rib angle (α = 30–90°) and Reynolds number (Re = 10,000–100,000) on the heat transfer characteristics of steam-cooled ribbed channels were analyzed. The semi-empirical heat transfer correlation related to W/H, α and Re was developed. The back propagation neural network (BPNN) combined with genetic algorithm (GA) was used to predict the heat transfer coefficients and optimize the structural parameters of steam-cooled ribbed channels based on 90 groups experimental data, and an excellent BPNN model with a maximum prediction error of 1.9% was obtained. Flow fields in the steam-cooled ribbed channels were numerically calculated to explore the heat transfer enhancement mechanism of optimized channels. The results show that the average heat transfer coefficients of steam-cooled ribbed channels increase at first and then decrease with the increase of W/H and α. The optimized neural network has better prediction accuracy than that of the fitted empirical correlation. Reynolds number has a great influence on the optimal aspect ratio and rib angle of the steam-cooled ribbed channel. The optimal W/H and the optimal α increase from 2.23 to 3.35 and 41.12° to 60.89°, respectively, with the increase of Re. Large α within the range of 41.12–60.89° should be selected for cooling channels with relatively larger W/H in the range of 0.25–4. The enhancement of longitudinal secondary flows and the suppression of main secondary flows result in the heat transfer enhancement of the optimized channels.

1. Introduction

Effective cooling technology for vane/blade is essential as the gas turbine rotor inlet temperature continues to increase [1]. Repeated ribs have been widely used in modern advanced turbine cooling vanes/blades to enhance internal heat transfer [2]. Ribs have various forms, such as straight ribs, angled ribs, V-shaped ribs, W-shaped ribs, intermittent ribs and grid ribs. The parallel rectangular ribs on two opposite walls are the most studied issue. The factors affecting the flow and heat transfer performance of ribbed channels mainly include the Reynolds number (Re), inlet pressure (p) and temperature (T), channel aspect ratio (W/H), rib angle-of-attack (α), rib height-to-hydraulic diameter (e/D), and rib pitch-to-height ratio (P/e).

A large number of experimental and numerical studies have been carried out for the air-cooled ribbed channels. Han et al. [3–5] developed the semi-empirical correlations of heat transfer and friction related to W/H, α, e/D, P/e and Re for air-cooled ribbed channels by experimental studies. Yongsiri et al. [6] numerically examined the heat transfer and thermal performance of the inclined detached-ribs with different attack angles, and found that the inclined ribs with angles of 60° and 120° yielded the highest heat transfer rate at high Re. Moon et al. [7] conducted a numerical study on the heat transfer performance of 16 different shaped ribs and reported that the heat transfer performance of the cooling channel strongly depends on the cross-sectional shape of ribs. Ravi et al. [8] reported that the thermal hydraulic performance of V-shaped and 45° ribs were significantly better than that of W-shaped and M-shaped ribs. Han et al. [9] experimentally investigated the heat transfer enhancement effect of a ribbed channel with dimples or protrusions. As can be seen from the above literature, the structure of the air-cooled ribbed channel becomes so sophisticated that it may extremely increase the manufacturing costs. This problem can be improved by the following two

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Nomenclature

A	cross-sectional flow area of the test channel, mm^2
D	channel hydraulic diameter, mm
e	rib height, mm
H	channel height, mm
I	current of the electric heater, A
L	channel length, mm
M	mass flow rate, kg s^{-1}
Nu	Nusselt number
Nu_a	average Nusselt number
P	rib pitch, mm
p	static pressure, kPa
Pr	Prandtl number
q	heat flux, kW/m^2
Q_h	electric heater power, W
Q_{loss}	heat loss of test system to the environment, W
Q_v	internal heat source strength, W/m^3
Re	Reynolds number
S_{in}	heat transfer surface area, mm^2
T	temperature, °C
T_f	reference temperature, °C
T_{in}	steam temperature at the inlet of test channel, °C
T_{out}	steam temperature at the outlet of test channel, °C
T_w	local temperature of channel inner walls, °C
T_{wo}	local temperature of channel outer walls measured by thermocouples, °C
U	voltage of the electric heater, V
u_{in}	inlet velocity, m/s
V	volume of test channel, m^3
W	channel width, mm
X	streamwise coordinate, mm

Greek symbols

α	rib angle-of-attack, °
δ	channel wall thickness, mm
λ	thermal conductivity, W/m/°C
v	specific volume, m^3/kg
υ	kinematic viscosity, m^2/s
η	heat transfer enhancement ratio

methods: (1) applying new cooling medium to replace air; (2) optimizing the structural parameters of the cooling channel with parallel rectangular ribs.

Steam has a higher specific heat and a better heat transfer performance than air. Applying steam as the coolant in the internal cooling channel of the turbine blade would lead to high cooling efficiency with a relatively simple structure [10–12]. Several studies have been focused on the flow and heat transfer characteristics of steam-cooled channels with parallel rectangular ribs. Liu et al. [13] pointed out that the average heat transfer coefficient of 45° ribbed channel was 15–25% higher than that of 60° ribbed channel using steam as the coolant. Shi et al. [14] found that the steam-cooled ribbed channel with 60° angled ribs had the best heat transfer performance. Shui et al. [15] experimentally and numerically investigated the effects of W/H on heat transfer performance of steam-cooled channel with 60° angled ribs, and found that the highest heat transfer enhancement occurred at $W/H = 2$. Gong et al. [16] analyzed that the average heat transfer coefficient of steam was 30.2% higher than that of air in a rectangular channel with W/H of 0.5. However, the combined effects of channel aspect ratio and rib angle on the heat transfer performance of steam-cooled channels with parallel rectangular ribs remain unclear, and the structural parameters optimization for the steam-cooled ribbed channel needs to be further studied.

Recently, artificial neural network (ANN), genetic algorithm (GA) and other novel hybrid methods have been used for modeling and optimizing in the field of heat transfer due to their high prediction accuracy and strong optimization capability [17,18]. Starace and Fiorentino et al. [19] developed a powerful hybrid method that takes advantages of both numerical and analytical approaches for the design of cross-flow compact heat exchangers. In this hybrid method, the computational domain is divided into control volumes, and the predictor functions for heat transfer and fluid dynamic performance are obtained with the regression technique based on experimental data. The results show that the small-scale hybrid method leads to high accuracy without incurring excessive costs of numerical simulation and experiments. Then, they applied the hybrid method to the design of the plate-finned tube evaporator [20] and the counter-current evaporative condensers [21], and achieved good results. Wang et al. [22] utilized the GA optimized Back Propagation neural network (GA-BP method) to predict the film cooling effectiveness of a gas turbine guide vane. Seo et al. [23] conducted a numerical multi-objective optimization of a boot-shaped rib in a cooling channel by using GA and approximation models. Damavandi et al. [24] carried out a multi-objective optimization of asymmetric V-shaped ribs in a cooling channel using CFD (Computational Fluid Dynamics), ANN and GA. Haasenritter et al. [25] optimized the rib structure in turbine blade internal cooling channels with the genetic algorithm, and pointed out that GA was a good method for the optimization of rib structure in internal cooling channels. Yang [26] found that GA was suitable for optimization of two-dimensional ribbed channels. Therefore, the artificial neural network combined with the genetic algorithm is a suitable and reliable method that can be used to model, predict and optimize the heat transfer performance of cooling channels.

The purpose of this study is to develop a model that can accurately predict the heat transfer performance of steam-cooled channels with parallel rectangular ribs based on experimental data, and to obtain the optimal W/H and α with the best heat transfer performance. Ten steam-cooled ribbed channels made of 3 mm thick stainless steel (0Cr18Ni9) plates and having aspect ratios of 0.25–4, rib angles of 30–90° and inlet Reynolds numbers of 10,000–100,000 were used. This study mainly analyzed the combined effects of W/H, α and Re on the heat transfer performance of steam-cooled ribbed channels; developed the semi-empirical correlation of heat transfer related to W/H, α and Re based on the experimental data; used the GA-BP method to fit the experiment data; applied the genetic algorithm for optimization of the channel structure based on the obtained BP neural network model at various Reynolds numbers; explored the heat transfer enhancement mechanism of the optimized channels by numerical method. The work may provide a reference for the design of internal cooling channels in the advanced gas turbine vane/blade.

2. Experimental setup

2.1. Test system

The test was conducted on the multifunctional cooling test platform of high-temperature turbine vane/blade with two coolants in Xi'an Jiaotong University, Xi'an, China. The schematic diagram of experimental apparatus is presented in Fig. 1. The apparatus