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Numerical prediction of heat loss from a test ribbed rectangular channel using the conjugate calculations

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ABSTRACT

Conjugate heat transfer of air and steam in a rectangular channel with 90° ribs along two opposite walls was investigated experimentally and numerically. The stainless steel test section was 80 mm × 40 mm × 2.5 mm and the ribs were 80 mm × 2.5 mm × 2.5 mm with 25 mm between ribs. The tests investigated the effects of coolant mass flow rate (the corresponding Reynolds numbers in the range of 10,000-50,000) on the conjugate heat transfer enhancement with the ribs. Two conjugate heat transfer calculation methods with different models were developed. For the first model (CHT-Q model) solid domain was viewed as a uniform internal heat source with the adiabatic exterior surfaces, while for the second model (CHT-T model) the outwall temperature was specified by the fitting polynomials of measured data with the zero internal heat. Comparisons between the experimental and numerical results showed that the SST k–ω turbulence model was more suitable for the conjugate heat transfer in such channels. Regardless of numerical error, an approximation of heat loss was specified by the successive trial calculations of the CHT-Q model, while a relatively accurate heat loss was evaluated by the post-processing of the CHT-T calculation. Local heat transfer coefficient can be determined accurately by the quantified heat loss of test system. The critical impact of conjugate heat transfer was demonstrated. Furthermore, the steam coolant compared to air exhibited a higher heat transfer performance by 12–25% for both the ribbed and smooth walls at the same Reynolds number.

1. Introduction

Periodic ribs as turbulence promoters have been used in the current advanced turbine cooling vanes/blades to enhance internal heat transfer [1]. It is noted that periodic ribs can enhance the internal convective heat transfer at the cost of a pressure drop penalty. Internal cooling passages can be approximately modeled as rectangular channels with rib-roughened walls. Hence, there are numerous experimental and numerical investigations to determine the performances of the ribbed channels, which involve many factors such as rib height-to-passage hydraulic diameter or blockage ratio (e/D), channel aspect ratio (W/H), rib angle of attack (α), the array of periodic ribs (in-line, staggered, discontinuous, etc.), rib pitch-to-height ratio (P/e), rib shape, the state of reference frame (static/rotating), working fluid (air, steam, water, CO_2, et al.), entrance condition and Reynolds number (Re), and the number of ribbed walls [2, 3]. To achieve a better design with a higher heat transfer coefficient and reasonable flow characteristics, some of these factors have been studied. Han et al. [4–7] carried out a series of experimental investigations to measure the heat transfer and pressure drop characteristics in straight duct and U-duct with angled ribs and traverse ribs. Hwang and Liou [8] experimentally studied the combined effects of the rib open-area ratio, rib height-to-channel hydraulic diameter ratio, rib pitch-to-height ratio, and rib alignment on turbulent heat transfer and friction characteristics in a channel with perforated ribs mounted on two opposite walls. Taslim and Lengkong [9] tested heat transfer coefficient of three staggered 45°. rib geometries corresponding to blockage ratios of 0.133, 0.167, and 0.25 in a square channel for pitch-to-height ratios of 5, 8.5, and 10, respectively, at two distinct thermal boundary conditions of heated and unheated channel walls. Olssen and Sundén [10] presented smoke wire visualizations of secondary flow patterns, pressure drop and heat transfer coefficient for the ribbed channels with parallel, crossed, V-shaped, and multiple V-shaped ribs. Tsia and Hwang [11] experimentally examined the effects of composite, fully-attached and fully-detached ribs on friction factors and heat transfer coefficients in rectangular ducts. Maurer et al. [12] conducted an experimental and numerical study to determine the thermal performance of V-shaped ribs in a rectangular channel with an aspect ratio of 2:1 at Re = 95,000 to 50,000. It showed that small-scale ribs in a one-sided ribbed channel have the best thermal performance at high Re. Chang et al. [13]

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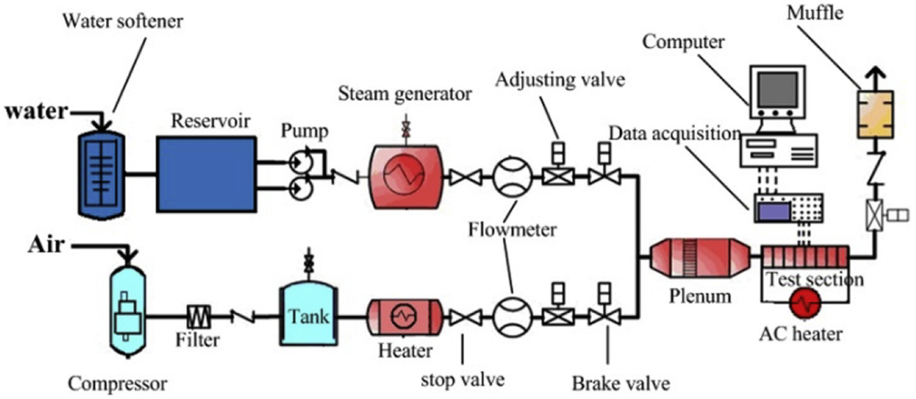

Fig. 1. Schematic layout of experimental apparatus.

presented two sets of average Nusselt number (*Nu*) and pressure drop coefficients (*f*) for a square spiral channel with two opposite endwalls roughened by in-line 45°ribs. Recently, Salameh et al. [14] found that the pressure drop was approximately the same for four studied shapes of the ribs while the dimpled rib case gave the highest heat transfer coefficient and the grooved rib presented the highest performance index for a solar air heater at the turning portion of a U-channel. Liou et al. [15] carried out infrared thermography and pressure measurements to obtain the detailed local *Nu* distributions over top-endwall and the pressure drop of a stationary two-pass 90°ribbed parallelogram channel. Seo et al. [16] performed a multi-objective optimization of a boot-shaped rib to simultaneously maximize the heat transfer performance and minimize the friction factor in a cooling channel. Chang and Jian [17] found that angled ribs combined with auxiliary fins can further promote the thermal performances of ribbed channel turbulent flows. Singh and Ekkad [18] showed that the combination of ribs and dimples resulted in higher heat transfer augmentation as well as higher thermal hydraulic performance when compared with ribs alone and dimples alone configurations for *Re* = 19,500-69,000. Liu et al. [19] pointed out that the truncated ribs can reduce the pressure loss penalty without decreasing the heat transfer enhancement of the ribbed channel, and a staggered arrangement can further enhance the heat transfer performance. However, the majority of these studies only investigated the pure convective process, as the test channel wall and the ribs in the experimental measurements are generally made of the very thin metallic-foil with the thickness of < 1 mm, and a uniform wall convective heat flux or temperature boundary condition is usually applied in numerical calculations.

To accurately investigate an internal cooling channel, the reproduced model with the imposed boundary conditions is needed to resemble the actual application environment. It is well known that heat transfer in cooling channel in engine environment is a coupled problem, involving convection at wall/fluid interface and conduction in the solid of channel walls and ribs. Therefore, the contribution of the solid conduction to the heat transfer enhancement should attract attention. However, only few studies deal with the conjugate investigation of rib-roughened internal cooling channels. Webb and Ramadhyani [20] found that conduction in channel walls plays a highly beneficial role in enhancing heat transfer. Davalath and Bayazitoglu [21], and Young and Vafai [22] studied a two-dimensional problem of conjugate heat transfer about laminar incompressible flow over an array of ribs in the rectangular channels. Their solid domains were volumetrically heated, accounting for a volumetric source term in the energy equation. Hung and Lin [23] studied experimentally the effect of the promoter on flow and thermal characteristics in the vertical rib-heated channel. It is noticed that the internal-energy change of the stainless steel sheet and the balsa was added to evaluate heat loss during the experimental period. To examine the heat transfer and friction characteristics in rectangular ducts with one wall roughened by slit or solid ribs, one side of the test channel and the mounted ribs used by Hwang and Liou [8] was made of copper with thickness of 3 mm and 13.3 mm, respectively. Iaccarino et al. [24] showed that conduction plays a major role in the downstream area of the rib and some discrepancies between experimental and numerical data can be eliminated if conduction heat transfer in the rib is taken into account. Hsieh and Lien [25] also adopted the conjugate heat transfer approach to solve conduction and convection equations simultaneously. Cukurel et al. [26, 27] stated that the thermal boundary conditions in purely convective studies are not realistic and the conjugate heat transfer analysis presents an opportunity to accurately model real engine conditions.

In the previous work, we studied the ribbed channels using the coolants of air and steam [28–32]· However, the convective heat flux in the data reduction process was treated to be evenly-distributed in all the walls of the test channel. Moreover, the results of Nusselt number in those papers may be a bit of question based on an estimated heat loss by simple assessment. The objective of this investigation is to determine the heat loss of test system using two conjugate modeling methods, and to conduct the experimental and numerical study of the conjugate heat transfer in a rectangular channel with two opposite ribbed walls for Reynolds number from 10,000 to 50,000. In this study, two conjugate calculation methods were established to accurately obtain the heat transfer coefficient by the quantified heat loss of test system. As the scarcity of conjugate heat transfer data, this study may provide a reference and basis for the design of internal cooling channels in gas turbines.

2. Experimental program and conditions

2.1. Experimental apparatus

Fig. 1 presents the schematic of the experimental apparatus, consisting of a steam generator and conditioning subsystem, a compressor and conditioning subsystem, plenum, the heating arrangement for the test channels, a test section with the instrumentation, a data acquisition system and exhaust system. The steam temperature varied from 100 °C to 230 °C, and the steam pressure ranged from 0.1 Mpa to 0.8 Mpa. The mass flow rate of steam was measured by a 60–600 kg/h range vortex shedding flow meter with an uncertainty of 1%. The air pressure from the compressor varied from 0.1 Mpa to 0.7 Mpa, the air temperature could be heated to 550 °C and the maximum air mass flow rate was 3 kg/s at room temperature and pressure. The mass flow rate of air was measured using a 0.2–3 kg/s range vortex shedding flow meter with an uncertainty of 1%. In order to simulate the actual entrance developing flow condition of turbine blade cooling channel, a stainless steel plenum was connected to the inlet of the test section to provide a sudden entrance condition. The wire grid of 100 mesh size was set to