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Research paper

Effect of rib spacing on heat transfer and friction in a rotating two-pass square channel with asymmetrical 90-deg rib turbulators

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HIGHLIGHTS

- Six different p/e cases (3.8–14.4) with asymmetrical rib arrangement are studied.
- Rib spacing effects are discussed up to Ro = 0.8 for two rotation direction.
- Heat transfer affected by rib spacing at lower Ro rather than high Ro.
- High Ro cause much higher pressure drop for most rib spacing cases.
- Best thermal performances are observed at p/e = 3.8 and 10 for different cases.

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ABSTRACT

Effect of rib spacing on heat transfer and friction in a rotating two-pass square channel is experimentally investigated. The Reynolds numbers and rotation numbers vary from 20000 to 50000 and 0 to 0.8, respectively. The 90-deg ribs are arranged on leading and trailing surfaces asymmetrically with height-to-hydraulic diameter (e/D_h) ratio of 0.1. The rib pitch-to-height (p/e) ratio on the pressure side varies from 3.8 to 14.4 at positive rotational direction, while keeps the constant value of 10 on the suction side. The results indicate that the rib spacing effect is more pronounced in the first radially outward flow passage than the second passage. Rotation reduces rib spacing effect and p/e = 10 has the best surface average heat transfer enhancement except for the trailing wall of the first passage. As more ribs are added, the channel friction increases until p/e down to 5. But rotation cause lower pressure drop at low rotation number for most cases. The very close rib spacing of p/e = 3.8 has the best thermal performance for positive rotational direction. For negative direction, p/e = 10 turns to be the best rib spacing ratio.

1. Introduction

Due to the inlet temperature of gas turbine is increasing over the melting points of the turbine blade material, various cooling techniques have been invented to guarantee the engine safe operation. Researches on turbine blade internal cooling have been initiated and conducted by different organizations over the past several decades to improve the design of gas turbine with respect to heat transfer. Many of the works have been systematically reviewed by Han et al. [1-4].

In general, the researches of turbine blade internal cooling are divided into three parts due to the blades heat load distribution: the leading edge is cooled by jet impingement with film cooling, the middle portion is cooled by serpentine rib-roughened passages with local film cooling, and the trailing edge is cooled by pin fins with trailing edge ejection. The current study mainly focuses on the middle serpentine cooling channel. In this region, turbulators are widely used on the internal surfaces of both pressure side and suction side. The rib turbulators breaks the boundary layer and increasing turbulence, and thus heat transfer can be increased. Moreover, as the channel rotates, the rotation induced Coriolis force and buoyancy force also show influence on heat transfer distribution. Consequently, a considerable amount of literature works have been devoted to evaluating heat transfer performance of both stationary and rotating channels [5-34].

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1.1. Effect of rib enhancement

Fundamental studies began in non-rotating cooling channels with rib turbulators. For square channel, Han and Park (1985) [5] and Han et al. (1991) [6] found that the highest *Nu*, along with the highest pressure drop, occurred at a rib angle of attack between 60 deg and 70 deg. Later, they (1988, 1992) [7,8] investigated heat transfer in various aspect ratio channels with 30, 45, 60, and 90 deg angled ribs. Results showed that the 45/60 deg angled ribs provide better heat transfer performance for low aspect ratio channels, while 30/45 deg angled are better for high aspect ratio channels. Kukreja et al. (1993) [9] presented detailed local heat/mass transfer distributions for square channels with angled ribs, which showed remarkable spanwise variations of the average heat coefficients. Han and Zhang (1992) [10], Ekkad and Han (1996) [11] presented more detailed heat transfer distributions in a square channel with 90-deg ribs, 60-deg parallel or V ribs. On the other hand, Chandra et al. (1997, 2003) [12,13], Rau et al. (1998) [14], and Ahn et al. (2008) [15] focused the number of ribbed walls (one to four) on heat transfer. They found that both the heat transfer coefficient and the friction factor increase with an increasing number of ribbed walls, but the relative increase in heat transfer is lower than the increase in friction factor.

1.2. Effect of rotation

As the channel rotates, the internal coolant experiences Coriolis and centrifugal forces which significantly alter the flow field inside the channel. Wagner et al. (1991, 1992) [16-18] provide a set of data in a square multi-passage channel with smooth and 90-deg ribs. They concluded that the local heat transfer coefficients increase over 200% on the trailing surface and decrease up to 60% on the leading surface compared to non-rotating results in the first pass. And the overall heat transfer in the ribbed passage was almost doubled compared with the smooth case. Taslim et al. (1991) [19] performed experiment to study the rotation effects in a rotating ribbed channel. They also noted that heat transfer on the trailing surface increases with rotation number, but decreases with Ro on the leading surface. Such heat transfer trend was also observed in different types of ribs by Parsons at al. (1994) [20], Azad et al. (2002) [21] and Al-Hadhrami et al. (2003) [22].

Furthermore, heat transfer in high aspect ratios channels (2:1, 4:1) with ribs are investigated by Fu et al. (2004) [23], Griffith et al. (2002) [24] and Wright et al. (2004) [25]. They reported significant spanwise variation in the heat transfer coefficients on both leading and trailing surfaces. Also, the high aspect ratio shows weaker rotation effect compared results in low aspect ratios studied by Fu et al. (2005) [26].

1.3. Effect of rib spacing

The rib spacing has a profound impact on the heat transfer enhancement in rib-roughened channel. The space between the ribs will change the flow reattachment pattern and create different heat transfer results. Too large spacing can result in the reduction of the heat transfer enhancement brought by ribs, but too small spacing can induce large pressure drop. Han et al. (1978) [27] studied the effect of pitch-to-height ratio (p/e) on heat transfer and friction coefficient in a wide channel (12:1) at stationary. They reported that as p/e varies from 5 to 20, both friction factor and Stanton number increase at first and then decrease with the maximum value at p/e = 10. And then the rib spacing effect in square channel with p/e = 10, 20 and 40 was studied by Han (1984) [28], which showed that the average friction factor and Stanton number decreases with increasing p/e.

Liu et al. (2006) [29] investigated the effect of angled rib spacing in a rotating channel in AR = 1:2 channel. Results showed that the p/e = 3 case has the best heat transfer performance and the rotation effect increases with decreasing rib spacing. Rib spacing effect in a more narrow channel with AR = 1:4 studied Huh et al. (2009) [30]. They reported that the p/e = 2.5 case has the highest heat transfer enhancement. Giovanni Tanda (2010) [31] reported heat transfer performance and friction in a rectangular channel with p/e = 6.66-20. They concluded that superior heat transfer performance was found at the optimal p/e of 13.3 for one-ribbed wall channel and at p/e = 6.66-10 for two-ribbed wall channel. Lei et al. (2012) [32] focused on rib spacing effect in AR = 2:1 channel at high rotation numbers. They found that the effect of rotation on heat transfer enhancement remains about the same for varying p/e from 10 to 5.

1.4. Objective

Although many groups have focused their researches to rib-enhanced effects, most of the ribs are symmetrically arranged on both leading and trailing walls. However, rotation causes different heat transfer level between leading and trailing walls. Thus, it is necessary to determine the rib spacing that yields the best thermal performance in rotating square cooling channels with asymmetrical rib arrangement.

The current study extends our previous works (2013) [33] by considering the effect of asymmetrical 90-deg rib arrangement on heat transfer performance in a rotating two-pass square channel. And we aim to provide additional information for the square channel in terms of heat transfer with asymmetrical ribs at large rotation numbers. The objectives of the current study are:

1. Investigate the effects of asymmetrical rib pitch-to-height ratio (p/e) on heat transfer coefficient in a two-pass square channel for both stationary and rotating cases. In current study, six p/e ratio cases were considered: p/e = 3.8, 5, 6.4, 8, 10 and 14.4.
2. Compare the rib spacing effect on surface average heat transfer for both positive direction rotation (varying p/e from 3.8 to 14.4 on pressure side, keeping p/e of 10 on suction side) and negative direction rotation (varying p/e from 3.8 to 14.4 on suction side, keeping p/e of 10 on pressure side).
3. Investigate the friction factors and thermal performance with different p/e ratios for both stationary and rotating cases, and further determine p/e ratio for the best thermal performance.

2. Experimental setup

The experimental investigations with actual turbine blade and actual operational states are achieved by similarity theory using the scale-up model in the laboratory. But the typical rotation numbers for aircraft engines turbine blades are near 0.25 with Reynolds number of 50000, which is difficult to achieve with larger hydraulic diameter. One common method to achieve similar condition is to increase the inlet coolant air pressure. Actually, at the given Reynolds number and hydraulic diameter, an increase in density will cause a decrease in velocity, which in turn increase the rotation number. In order to obtain larger rotation number at high Reynolds numbers, the experiments are operated at the air pressure of about 5 atm. And thus, the maximum rotation number in current study can be reached up to 0.8 (800 rpm) at Reynolds numbers of 20000.

2.1. Rotating facility

As is shown in Fig. 1, the rotating rig, consists of six main parts: electric motor, support module, rotating module, temperature measurement module, slip rings module and pressure