Heat Transfer and Pressure Loss Simulations of Matrix Cooling Channels for Gas Turbine Airfoils

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Abstract. The paper selected 10 geometrical parameter combinations to numerically investigate the dependencies of heat transfer enhancement, flow resistances and overall thermal performance on three geometrical factors including rib inclination angle, channel blockage ratio and subchannel number. The investigated Reynolds number starts at 5,000 and can be as high as 90,000. The turbulence model selected was Transition SST model. The results show that the matrix cooling channels of 30deg rib angle have greater heat transfer enhancement and much higher pressure loss than that of 60deg rib angle. Moreover, matrix cooling channels of higher channel blockage ratio have greater heat transfer enhancement and higher flow friction, while the relationship between the overall thermal performance and the channel blockage ratio depends on the Reynolds number. It was also concluded that the heat transfer performance factor of matrix cooling channel does not change linearly with the subchannel number and the effect of subchannel number on heat transfer performance is less significant than the other two factors. Besides, matrix cooling channels of higher subchannel number have higher pressure loss and poorer overall thermal performance.

1. Introduction
The matrix cooling channels is firstly applied by former Soviet design bureau engineering system in turbine blades [1]. It is equipped with two layers of interweaved ribs that splits the fluid path into several zigzag subchannels. The matrix cooling channel has significantly large effective heat transfer area and complex inner fluid dynamics but its pressure loss can also be quite high. Hence it is a priority for gas turbine cooling system designers to figure out the impact of multiple geometrical parameters on the heat transfer and pressure loss characteristics to obtain better overall thermal performance.

Bunker [2] used transient liquid method to acquire the primary surface heat transfer coefficients of matrix cooling channels with 45deg ribs. The averaged heat transfer coefficient of the primary surface is approximately 1.5 times of the smooth passage level. Su et al. [3] conducted numerical simulations on a turbine rotor blade internally cooled by serpentine cooling channels, matrix cooling channels and trailing edge slots. The results show that the matrix cooling channels in the blade mid portion contribute a uniform heat transfer distribution. Deng et al. [4] experimentally studied the heat transfer and flow friction of matrix cooling channels with two lateral slots using the vapor condensation heat transfer method. The authors found that introducing the slots significantly reduce the flow resistances, and the wider slots bring about more overall thermal performance enhancement. Hagari and Ishida [1]
numerically studied the impact of rib inclination angle on heat transfer and flow friction. The authors observed that the channel-averaged Nusselt number increases with the rib inclination angle when the angle falls within 41–68 deg. Carcasci et al. [5] experimentally investigated the effect of rib height, rib width, and subchannel number on the heat transfer and pressure loss of matrix cooling channels whose rib angle is 45 deg using thermocouples. The results show that the heat transfer improvement is mostly affected by the rib height. Ramireddy et al. [6] numerically studied the dependences of flow friction and heat transfer of matrix cooling channels on subchannel sectional shape and aspect ratio. It was found that the U-shaped subchannel configuration has the highest overall thermal performance and the pressure loss reduces with the increase of subchannel aspect ratio. Bu et al. [7] conducted a large amount of numerical simulations to figure out the effect of rib-to-subchannel width ratio and the density of ribs on matrix cooling channel thermal performance. The results showed that both heat transfer and pressure loss grow with the rib-to-subchannel width ratio rising, and the heat transfer enhancement factor firstly decreases with the rib density to the trough when the subchannel number equals to 5 and then increases.

In this study, the matrix cooling channels applied in gas turbine blades are simplified to rectangular channels with extended inlet and outlet sections. 10 geometrical configurations were numerically simulated to figure out the influence of rib inclination angle, channel blockage ratio and subchannel number on the heat transfer and pressure loss characteristics with the Reynolds number ranges from 5,000 to 90,000.

2. Computational Setup

2.1. Geometries

Figure 1 displays the dimensions of the extended inlet and outlet sections as well as the core heat transfer section, which remain unchanged in the study of effects of rib and subchannel parameters. The sizes of the overall channel are 144mm (length) × 34mm (width) × 6mm (height), and the sizes of the core heat transfer section are 64mm (length) × 34mm (width) × 6mm (height). There are two layers of interweaved ribs that are closely connected to each other and have the same height (3mm) in the core heat transfer sections. The geometrical parameters of rib and subchannel are shown in figure 2 including rib inclination angle α, rib width r as well as the width of subchannel s. Moreover, the channel blockage ratio (r/s) is defined as the ratio of rib width and subchannel width. And the subchannel number (n) is defined as the number of inflow subchannels in both layers.

![Figure 1](image1.png)

(a) Dimensions of the core heat transfer section   (b) Dimensions of the overall channel

Figure 1. Channel dimensions that is unchanged in the numerical simulations.
2.2. Solving Methods and Boundary Conditions

The computational domains were discretized by structural grids and the wall y+ values were kept near or below one. Figure 3 shows the computational grids for a typically-structured matrix cooling channel. The connected turning region of different layers of ribs is loaded with Y-blocks. The fractional error of the heat transfer and pressure loss computational results between the eight-million-node mesh and ten-million-node mesh or twelve-million-node mesh is below 2%, hence the eight-million-node mesh is employed in the following numerical investigations.

\[ Re = \frac{V \cdot D_m}{\nu} \]  
\[ Nu = \frac{hD_m}{\lambda}, \quad h = \frac{q}{T_w - T_m} \]  

Figure 2. Definitions of the rib and subchannel parameters.

Figure 3. Computational grids for a typically-structured channel.
\[ f = \frac{\Delta P \cdot D_m}{2\rho \nu^2 L} \]  \tag{3}

\[ Nu_0 = 0.023Re^{0.8} Pr^{0.4} \]  \tag{4}

\[ f_0 = 2(2.236\ln Re - 4.639)^{-2} \]  \tag{5}

\[ TPF = \frac{Nu}{Nu_0} \left( \frac{f}{f_0} \right)^{1/3} \]  \tag{6}

3. Results and discussion

3.1. Effect of Rib Inclination Angle

To investigate the impact of rib inclination angle on the heat transfer and pressure loss of matrix cooling channel, 4 kinds of geometrical parameter assembly are arranged and investigated as listed in table 1.

| Case No. | \( \alpha (^\circ) \) | \( r/s \) | \( n \) |
|---------|----------------|-------|-----|
| 1       | 60            | 0.5   | 8   |
| 2       | 30            | 0.5   | 8   |
| 3       | 60            | 1     | 12  |
| 4       | 30            | 1     | 12  |

Table 1. Geometrical parameter arrangement for numerical investigations of effect of \( \alpha \).

Figure 4 presents the comparison of dimensionless Nusselt number, dimensionless friction factor and overall thermal efficiency between 2 cases with rib angle of 30deg and another 2 cases with rib angle of 60 deg. The heat transfer level of the current 4 geometries is 3-6 times of the smooth channel. Under the same channel blockage ratio and subchannel number, matrix cooling channels of 30deg rib angle have greater heat transfer improvement and much higher friction loss than that of 60deg rib angle. This is because the decrease of rib inclination will increase the lateral turning regions, which is the main generator of the highly-turbulent longitudinal vortex in the downstream subchannel. However, the overall thermal efficiency of 60deg rib matrix cooling channel is higher than the 30deg rib matrix cooling channel since the pressure loss induced by the 30deg ribs is too high.

3.2. Effect of Channel Blockage Ratio

To investigate the impact of channel blockage ratio on the heat transfer and pressure loss of matrix cooling channel, 4 kinds of geometrical parameter assembly are arranged and investigated as listed in table 2.
Table 2. Geometrical parameter arrangement for numerical investigations of effect of r/s.

| Case No. | α (°) | r/s | n  |
|----------|-------|-----|----|
| 1        | 60    | 0.5 | 8  |
| 5        | 60    | 1.5 | 8  |
| 6        | 45    | 0.5 | 4  |
| 7        | 45    | 1.5 | 4  |

Figure 5 presents the comparison of dimensionless Nusselt number, dimensionless friction factor and overall thermal efficiency between 2 cases with channel blockage ratio of 0.5 and another 2 cases with channel blockage ratio of 1.5. Under the same rib inclination angle and subchannel number, matrix cooling channels of higher channel blockage ratio have greater heat transfer enhancement and higher friction loss. Although the heat transfer area between the passage and the fluid decreases as the channel blockage ratio increasing, the fluid velocity in the subchannels improves a lot, which bring about greater heat transfer benefit but higher energy loss at the turning regions, impingement regions and the intersections. Under the Reynolds number of 5,000, Case 6 has better overall thermal performance than Case 7. However, under the engine representative working conditions, where the Reynolds numbers are typically high, the overall thermal efficiency of Case 7 is much higher than Case 6. When the Reynolds number is lower than 30,000, the overall thermal efficiency of Case 5 is larger than Case 1, but the situation will be totally different if the Reynolds number is higher than 30,000.

3.3. Effect of Subchannel number

To discover the influence of subchannel number on the heat transfer and friction loss of matrix cooling channel, 6 kinds of geometrical parameter assembly are arranged and investigated as listed in table 3.

Table 3. Geometrical parameter arrangement for numerical investigations of effect of n.

| Case No. | α (°) | r/s | n  |
|----------|-------|-----|----|
| 6        | 45    | 0.5 | 4  |
| 8        | 45    | 0.5 | 12 |
| 7        | 45    | 1.5 | 4  |
| 10       | 45    | 1.5 | 12 |
| 9        | 60    | 1   | 8  |
| 3        | 60    | 1   | 12 |

Figure 6 presents the comparison of dimensionless Nusselt number, dimensionless friction factor and overall thermal efficiency between 2 cases with subchannel number of 4, 1 case with subchannel number of 8 and other 3 cases with subchannel number of 12. The heat transfer enhancement of Case 8 is moderately higher than Case 6 at relatively high Reynolds number since the increase of
subchannel number will significantly increase the lateral turning regions as well as the heat transfer area between the passage and the fluid. In contrast, the heat transfer enhancement of Case 7 with lower subchannel number is higher than Case 10, since the increased subchannel turnings induce large area of fluid blockage and weak heat transfer. The Case 9 and Case 3 has totally different variation trend of heat transfer enhancement with Reynolds number. It can be found from the above analysis that the heat transfer enhancement of matrix cooling channel does not change linearly with the subchannel number and the effect of subchannel number on heat transfer performance is less significant than the other two factors. Under the same rib inclination angle and subchannel number, matrix cooling channels of higher subchannel number have higher pressure loss since the fluid has to travel through much longer distance and suffer from more energy loss due to the increased turning and impingement regions. The overall thermal performance of matrix cooling channels that have less subchannel is better as the other two factors keep identical.

![Figure 6. The variation of heat transfer and friction loss characteristics against Re.](image)

4. Conclusions
The paper selected 10 geometrical parameter combinations to numerically investigate the dependencies of heat transfer enhancement, flow resistances as well as overall thermal efficiency on three geometrical factors within the Reynolds number limits of 5,000 to 90,000. It is indicated by the results that the matrix cooling channels of 30deg rib angle have greater heat transfer enhancement and much higher friction loss than that of 60deg rib angle. The overall thermal performance of 60deg rib matrix cooling channel is better than the 30deg rib matrix cooling channel. Moreover, under the same rib inclination angle and subchannel number, matrix cooling channels that have higher blockage ratio can attain greater heat transfer improvement but higher flow resistance. However, the relationship between the overall thermal performance and the channel blockage ratio depends on the Reynolds number. The result also indicate that the heat transfer enhancement of matrix cooling channel does not change linearly with the subchannel number and the dependency of heat transfer performance on subchannel number is less significant than the other two factors. Besides, matrix cooling channels of higher subchannel number have higher pressure loss and poorer overall thermal performance.

References
[1] Hagari T and Ishida K 2013 Numerical Investigation on Flow and Heat Transfer in a Lattice (Matrix) Cooling Channel *ASME Turbo Expo 2013: Turbine Technical Conference and Exposition* vol 3A
[2] Bunker S 2004 *ASME Turbo Expo 2004: Power for Land, Sea, and Air* vol 3 pp 909-918
[3] Su S, Liu J, Fu L, Hu J, and An T 2008 *ASME Turbo Expo 2008: Power for Land, Sea, and Air* vol 4 pp 383-391
[4] Deng H, Wang K, Zhu J and Pan W 2013 *Journal of Thermal Science* 22(3) 250-256
[5] Carcasci C, Facchini B, Pievaroli M, Tarchi L, Ceccherini A and Innocenti L 2014 *Journal of Turbomachinery* 136(12) 121005
[6] Ramireddy R, Gurusiddappa P, Kesavan V and Kumar K 2014 Computational Study of Flow and Heat Transfer in Matrix Cooling Channels ASME 2014 Gas Turbine India Conference

[7] Bu S, Yang Z, Zhang W, Liu H and Sun H 2016 Applied Thermal Engineering 109 75-86