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IMPINGEMENT HEAT TRANSFER FROM RIB ROUGHENED SURFACE WITHIN ARRAYS OF CIRCULAR JET : The Effect of the Relative Position of the Jet Hole to the Ribs

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BREAK

ABSTRACT

Impingement heat transfer from rib roughened surface within two-dimensional arrays of circular jet has been investigated experimentally. After the jet impinges on the rib roughened surface parallel to the jet plate, it is constrained to exit in a single direction along the channel formed by the jet plate and the rib roughened surface. An initial crossflow is present which approaches the arrays through an upstream extension of the channel. The configurations considered are intended to simulate the impingement cooling midchord region of the gas turbine aerofoils in case where an initial crossflow is also present. The study covered four different relative positions of the jet hole to the ribs: jet hole before the rib (-p/4), jet hole on the rib, jet hole behind the rib (+p/4) and jet hole between the ribs(midst,+p/2). The tests were performed for Reynolds number Re=8000 and 15000, and the nondimensional jet-to-surface spacing z/d=1.4, 2.0 and 3.0. The test results show that the impingement heat transfer from the rib roughened surface can be considerably improved by adequately arranging the relative position of the jet hole to the ribs.

NOMENCLATURE

A_i	Heat transfer area
d	Jet hole diameter
e	Rib height
G_c	Crossflow mass flux average over channel cross-sectional area at entrance to individual spanwise row domain
G_j	Jet mass flux at individual spanwise row based on jet hole area
k	Thermal conductivity of fluid
Nu_i	Individual segment Nusselt number
$\overline{Nu}$	Average Nusselt number
p	Rib pitch
Q_{ci}	Convective heat transfer
Re_j	Individual spanwise row jet Reynolds number
T_{awi}	Individual spanwise row adiabatic wall temperature
T_{Ri}	Fluid reference temperature
T_{wi}	Average temperature of segment
x	Streamwise coordinate
x_n	Jet hole spacing in x direction
z	Jet-to-surface spacing

INTRODUCTION

The impingement heat transfer from the rib roughened surface is an effective approach for heat exchanging . This is of interest in numerous industrial applications such as the cooling of the gas turbine and electronic components as well as some aspects of drying and evaporation etc. because many surfaces which must be cooled or heated are not smooth. Especially , in the current and high performance turboengines , the internal cooling for the gas turbine aerofoils is very important because the gas temperature is too high for the materials of guide vane and blade to withstand without proper cooling. This investigation is intended here to include the flow and the heat transfer characteristics of the jet impinging on the rib roughened surface with initial crossflow for simulating the impingement cooling midchord region of the gas turbine aerofoils in case where an initial crossflow is present . This paper is the second part of the reports of the extensive research program dealing with impingement heat transfer from complicatedly geometric surface.

The impingement heat transfer and augmented heat transfer by roughened elements have been investigated by lots of researchers. Kercher and Tabakoff (1970) researched the heat transfer within an array of impinging jets with small spacing-to-diameter ratio. Hollworth and Berry (1978) studied the heat transfer within an array of impinging jets with large spacing-to-diameter ratio without initial crossflow. Florschuetz et al (1981) and Florschuetz et al (1984) researched the heat transfer within arrays of impinging jets with the initial crossflow . Obot and Trabold (1987) researched the effect of the nondimensional jet-to-surface spacing z/d on the heat transfer. The augmented heat transfer by complex geometric surface has also been investigated by many researchers. Hong and Hsieh (1993) studied the effect of the staggered and inline ribs on the flow and the heat transfer characteristics. Han and Park (1988), Han et al (1989) and Han et al (1991) researched the augmented heat transfer in rectangular channel of narrow aspect ratio with rib turbulators and in square channel with parallel, crossed and V -shaped ribs.

Koyelev (1978) stated that the combination of the impingement heat transfer and augmentation of the roughened surface will enhance the heat transfer efficiency and reduce the coolant consumption. But, so far

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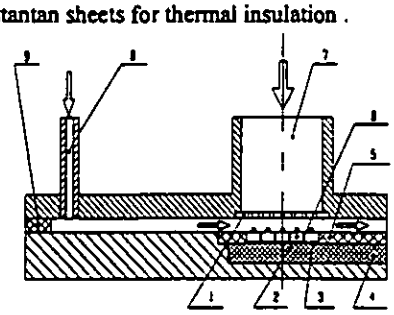
the publishing materials are only a few concerned in the impingement heat transfer from the rib roughened surface. Obot and Trabold (1987) and Jiang (1990) researched the impingement heat transfer within arrays of circular jets and stated that the heat transfer characteristics for the jet impinging on the rib roughened surfaces is different from that on the smooth surface, and it is considerably affected by the jet-to-surface spacing. Chang et al (1996a) researched the effect of the initial crossflow on the impingement heat transfer from rib roughened surface within arrays of circular jet. The effect of the relative position of the jet hole to the ribs on the flow and heat transfer characteristics of the jet impinging on the rib roughened surface had not been concerned so far. Chang et al (1996b) studied the flow behavior by flow visualization and shown that the relative position of the jet hole to the ribs has a considerable effect on the flow behavior, and it certainly will effect the heat transfer characteristics.

In this paper, the heat transfer characteristics of jet impinging on the rib roughened and the smooth surface with initial crossflow have been experimentally investigated. The effect of the relative position of the jet hole to the ribs has been studied. The study covered four different relative positions of the jet hole to the ribs: jet hole before the rib (-p/4), on the rib, behind the rib (+p/4) and between the ribs (midst, +p/2). The experimental results show that the relative position of the jet hole to the ribs has the considerable effect on the impingement heat transfer from the rib roughened surface.

EXPERIMENTAL FACILITY

The experimental facility is consisted of three parts, the impingement jet system, the initial crossflow system and the geometrically changeable test section. the air of the impingement jet system comes from the air compressor and passes through a plate orifice meter and a valve for measuring and adjusting the flow rate. Then, the air flow passes through a settling chamber and the jet holes, and impinges on the rib roughened surface. The air of the initial crossflow system also comes from the air compressor and passes through a bypass pipe and a valve for adjusting the crossflow rate then through a rotary volume displacement for measuring the crossflow rate. Afterwards, the air flow passes through a stabilizer and channel with rectangular cross section for fully development then enters into the test section formed by the jet plate and the smooth or the rib roughened surface in the test section as initial crossflow.

The scheme of the test section is shown in Fig. 1. It includes the jet plate 1, rib roughened surface 2, electric heater 3 and thermal insulation layer 4. The rib roughened surface consists of 6 segments of copper plate with thickness 10 mm and there are 6 pieces of asbestos sheet between the copper segments for heat insulation. Under the copper plate, there are 6 pieces of constantan electric heater 3 for heating each copper segment independently. A layer of asbestos 4 covers the constantan sheets for thermal insulation.



1. jet plate, 2. rib roughened surface, 3. constantan heater, 4. insulation layer, 5. a board for fixing rib roughened surface 6. the asbestos sheets 7. the plenum 8. initial crossflow entrance 9. the spacer

Fig. 1 The scheme of the test section

The heat flux is controlled by a silicon-controlled rectifier and the total power input to the copper plate is obtained by the measured current and voltage. The temperature at the rib roughened surface is measured by 24 thermocouples. These thermocouples are fixed on the surface of each copper segment individually through the holes of 0.5 mm in the copper segments. Before the test, the thermocouples are calibrated.

The geometric parameters of the test models are intended to simulate the midchord region of the gas turbine aerofoils. The pitch-to-height ratio is p/e=10. The nondimensional jet-to-surface spacing is in the range of z/d= 1.5 - 3.0. The jet spacing-to-diameter ratio x/d=10. In this experiment, the ratio of the diameter of jet hole to the height of the rib is e/d=0.75. The relative position of jet hole to the ribs is changeable in four different cases as shown in Fig. 2, where in case (a) jet hole before the rib (-p/4), (b) jet hole on the rib, (c) jet hole behind the rib (+p/4) and (d) jet hole between the ribs (midst, +p/2).

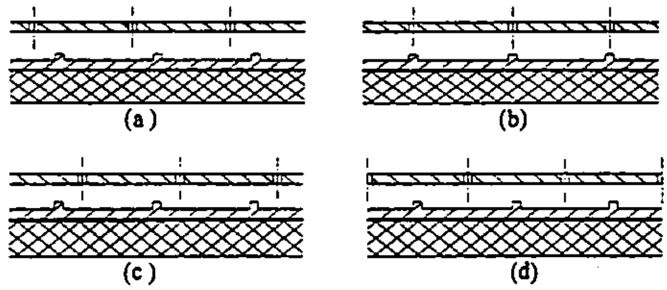


Fig. 2 The relative position of the jet hole to the rib

In this study, the temperature difference between the wall and the fluid is about 20 - 30 ℃. The uniform impingement surface temperature boundary condition and a regional average heat flux is considered. Expressed as the values of Nusselt number, the experimental data are reduced using the relation for a segment

$$Nu_i = (Q_{ci} \cdot d)/(k \cdot A_i) \cdot (T_{wi} - T_{Ri}) \qquad (1)$$

The convective contribution Q_{ci} is the difference between the total power input to a segment and the loss. The total power is determined in accordance with the input current and voltage. The power loss measured in this experiment does not exceed 5% of the total power.

The average temperature of heated surface T_{wi} is the average temperature of the copper segment obtained by regional average method from the measuring data.

It is of considerable importance to the design engineer who deals with the choice of reference temperature T_R for use in Equation (1). In principle, T_R should be the average recovery temperature measured at the target surface at actual crossflow temperature, but it is difficult to measure in practical experiment. While Obot and Trabold (1987) discussed that the differences of the heat transfer coefficients do not exceed 10% with the adiabatic wall, plenum or bulk mean temperature to replace T_R in Equation (1). In the present paper, the average adiabatic wall temperature of each copper segment T_{awi} is used as the reference temperature. It is measured at the target surface under the condition without heating (under the condition of a zero regional average heat flux).

The average Nusselt number for the whole rib roughened surface will be

$$\overline{Nu} = \sum_{i=1}^{6} Nu_i / 6 \qquad (2)$$

EXPERIMENTAL RESULTS AND ANALYSIS

Fig. 3 shows the changes of the local Nusselt number Nu with the changes of the relative position of the jet hole to the ribs under the condition of Re_j=8000, 15000, z/d= 1.4, 2.0 and Gc/Gj=0., 0.1, 0.3, 0.5, 0.7 . It can be seen that the change of Nu along the streamwise is

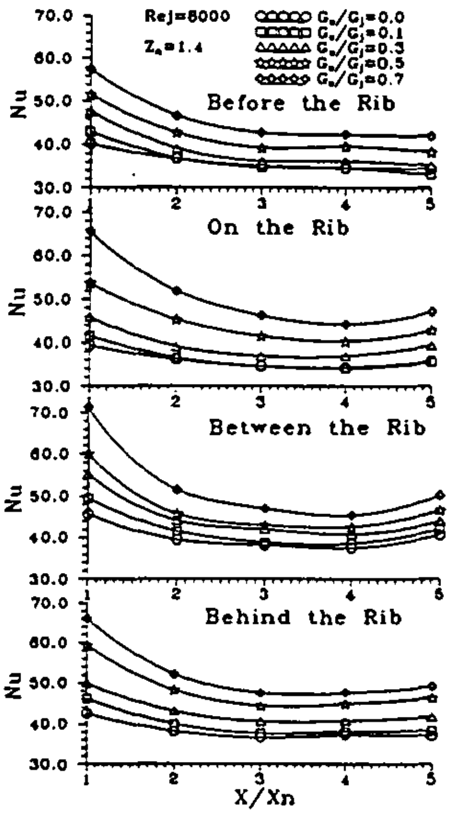


Fig 3 (a) The effect of the relative position and Gc/Gj on Nu

rather monotonous and smooth for a certain relative position of the jet hole to the ribs compared to that for hybrid relative position where the changes of Nu is irregular and somewhat undulant (Chang et al (1996a)). It can also be seen that the local Nusselt number Nu for the case of the jet hole between the ribs is higher than that for any other cases of relative position when the initial crossflow rate Gc/Gj is not too high .

Fig. 4 shows the changes of the average Nusselt number $\overline{Nu}$ with the initial crossflow rate for different cases of relative position of the jet hole to the ribs under the conditions of Re_j=8000 and z/d=1.4, 2.0 and 3.0 . It can be seen that the average Nusselt number $\overline{Nu}$ for the case of the jet hole between the ribs (d) is higher than that for any other cases of relative position under the conditions of z/d=1.4 and Gc/Gj=0-0.7 . The average Nusselt number $\overline{Nu}$ for the case of the jet hole behind the rib rises markedly with the increase of the initial crossflow rate. It closes to the value of that for the case of the jet hole between the ribs when the initial crossflow rate Gc/Gj approaches 0.7 . And , when

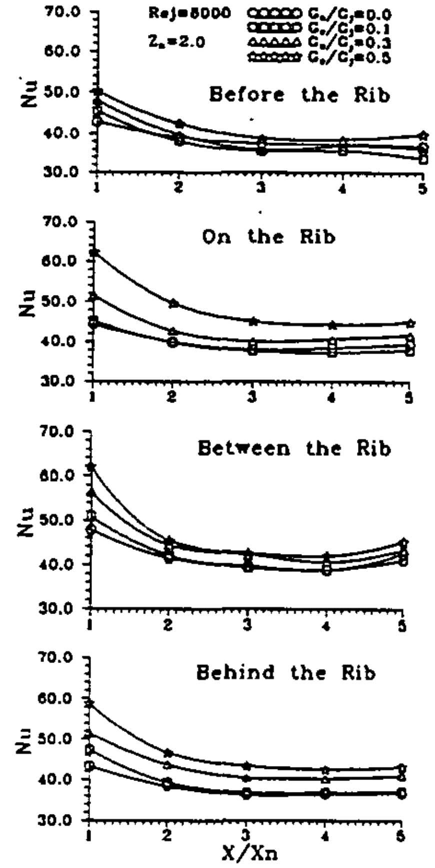


Fig 3 (b) The effect of the relative position and Gc/Gj on Nu

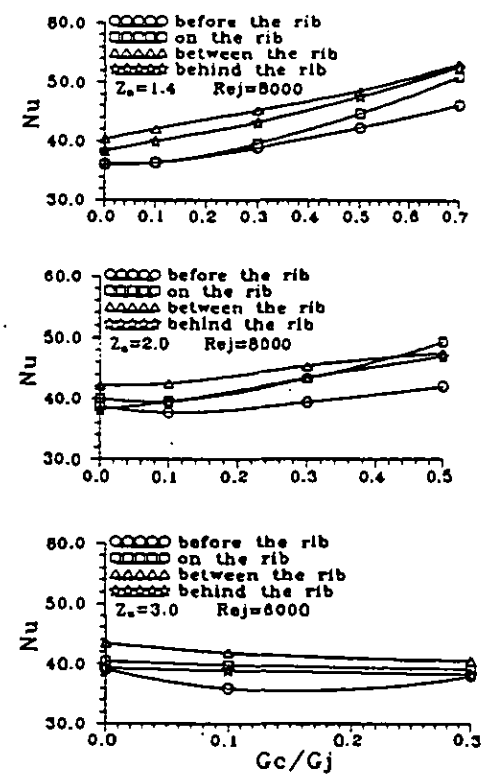


Fig. 4(a) The effect of the relative position of jet hole to the ribs

Gc/Gj > 0.3 ,the average Nusselt number $\overline{Nu}$ for the case of the jet hole on the rib rises promptly . It also closes to the value of that for the jet hole between the ribs when Gc/Gj = 0.7 . The average Nusselt number $\overline{Nu}$ increases with the increase of the initial crossflow rate Gc/Gj for all cases of the relative positions , nevertheless for the case of the jet hole before the rib rises slowly. Under the condition of

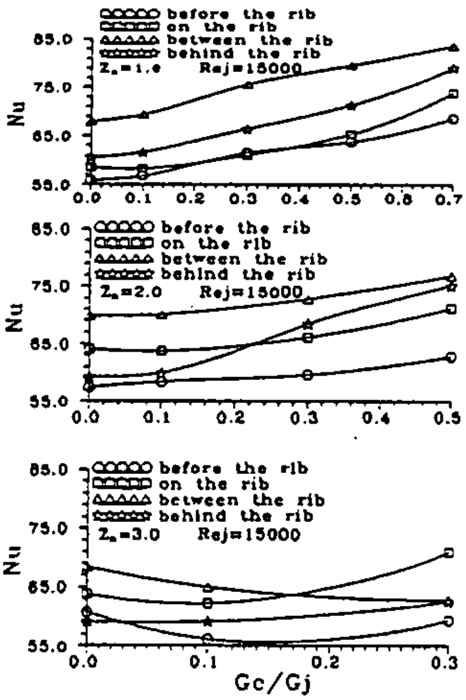


Fig.4(b) The effect of the relative position of jet hole to the ribs

z/d=2.0 , the changes of the average Nusselt number $\overline{Nu}$ keeps the same as z/d=1.4 when the initial crossflow rate Gc/Gj is low . When the initial crossflow rate Gc/Gj is high, say 0.4-0.5, the average Nusselt number $\overline{Nu}$ for the case of the jet hole on the ribs (b) is higher than that for other cases of relative position . The average Nusselt numbers still increase as the initial crossflow rate Gc/Gj increases , but somewhat smooth compared to that of z/d=1.4. Under the condition of z/d=3.0 , when the initial crossflow rate Gc/Gj is low, the average Nusselt number $\overline{Nu}$ almost keep even or a little decrease as the initial crossflow rate Gc/Gj increases . The value of $\overline{Nu}$ for the case of the jet hole between the ribs is still higher than that for any other cases of relative position of the jet hole to the ribs . Under any conditions , the value of $\overline{Nu}$ for the case of the jet hole before the rib is lower than that for any other cases of the relative position of the jet hole to the ribs.

The effect of relative position of the jet hole to the rib can be explained by the flow pattern as shown in Fig.5 . It can be seen that in case (d) the impingement jet can develop in all around closed to the surface until the near wall stream meets the rib and separates from the surface . This is the best situation for heat transfer . In case (b) , two vortices occurred at two sides of the rib . These increase the pressure drop and decrease heat transfer efficiency in the stagnation region . Thus , the heat transfer will be affected . In the cases of (a) and (c) , the impingement jet can develop closed to the surface only at one side of the jet and the stream separates from the surface on the other side because of the obstruction of the rib . Thus the heat transfer is worse.

For the midchord region of gas turbine aerofoils , it is evident

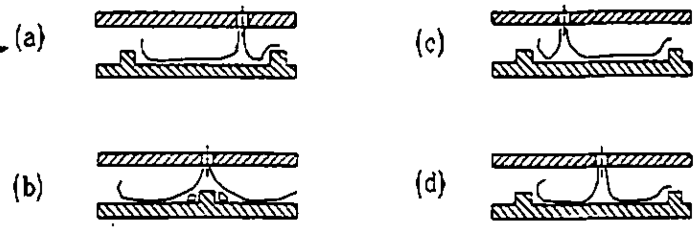


Fig. 5 The effect of the relative position of the jet hole to the ribs on the flow pattern

that the initial crossflow is present because of the cooling air of the leading edge and the upstream jets . The real position where the jet impinges on the rib roughened surface will shift downstream because of the blowing of the initial crossflow . The changes of $\overline{Nu}$ due to the initial crossflow have been analyzed in part one of this extending research report, (Chang et al (1996a)) . Here in this paper , the changes of the effect of relative position of the jet hole to the ribs on $\overline{Nu}$ due to the initial crossflow are concerned . When the value of Gc/Gj is low , the real position where the jet impinges on the rib roughened surface slightly shift downstream . So that , the effect of the relative position of the jet hole to the rib does not essentially change . When the value of Gc/Gj is high , the real position where jet impinges on the rib roughened surface greatly shift downstream due to the blowing of the crossflow . Therefore , the heat transfer characteristics for the case (b) and (c) will considerably improved when Gc/Gj increases. For the large z/d , the effect of the relative position on the heat transfer characteristics weaken as Gc/Gj increases.

It can be seen evidently from Fig.6 , that Reynolds number Rej considerably affects not only the heat transfer efficiency, but also the effect of the relative position on the heat transfer. The higher the Reynolds number , the stronger is the effect.

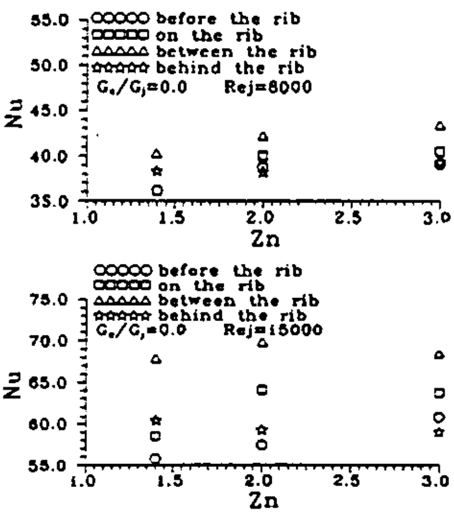


Fig. 6 The effect of z/d and the relative position on Nu .

CONCLUSIONS

In accordance with the experimental research covered the ranges of Rej=8000 and 15000 , z/d= 1.4 , 2.0 and 3.0 , as well as Gc/Gj=0 -

0.3 for the four relative positions of the jet hole to the ribs, the following conclusions can be summarized.

The relative position of the jet hole to the ribs has a great effect on the impingement heat transfer.

In the absence of the initial crossflow, the relative position of jet hole to the ribs of case (d), the jet hole between the ribs (midst, +p/2), is the best arrangement from the standpoint of flow and heat transfer characteristics.

In the presence of the initial crossflow, the real position where the jet impinges on the surface will shift downstream by the blowing of the crossflow. The heat transfer characteristics will change correspondingly. When Gc/Gj is low (0 ~ 0.3), the relative position of jet hole to the ribs of case (d), the jet hole between the ribs (midst, p/2), still the best arrangement from the standpoint of flow and heat transfer characteristics.

The high and well-distributed heat transfer characteristics can be obtained by the suitable arrangement of the structural and geometrical parameters.

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