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Jet impingement on a rib-roughened wall inside semi-confined channel

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ABSTRACT

Convective heat transfer on the rib-roughened wall impinged by a row of air jets inside semi-confined channel was experimentally investigated. Four rows of transverse ribs were arranged in the wall-jet zone downstream from the impinging jet stagnation to enhance heat transfer. Three typical rib configurations, including orthogonal ribs, V-shaped ribs and inverted V-shaped ribs, were considered under different non-dimensional jet-to-target distances ranging from 1 to 3 diameters and impinging jet Reynolds numbers ranging from 6000 to 30,000. The results show that the rib-roughened wall enhances the convective heat transfer up to 30% in the ribbed region by comparison with the smooth wall under the same jet Reynolds number. Among three rib configurations, the inverted V-shaped rib seems to be advantageous on the convective heat transfer enhancement, especially at lower jet-to-target spacing. The ribs on the impinging target do provide stronger convective heat transfer in the wall-jet region, but at greater expense of pressure drop inside the channel. At the jet-to-target spacing ratio of 1, the flow coefficient of the rib-roughened channel is decreased 5%–10% in related to the smooth channel.

1. Introduction

Impingement heat transfer is considered as a promising heat transfer enhancement scheme. It provides significantly high local heat transfer coefficient around the impinging jet stagnation region for the main reason is that the jet impingement forms a very thin stagnant boundary layer. Due to its simple design and low cost, jet impingement has been applied in a wide variety of practical applications that aim to achieve intense heating, cooling or drying rates. Typical applications of jet impingement include the tempering and shaping of glass, the annealing of plastic and metal sheets, the drying of textile and paper products, the anti-icing of aircraft wings and the cooling of turbine blades, combustor liners and electronic equipments.

The heat and mass transfer produced by the turbulent impinging jets had been characterized in a number of investigations reviewed by Viskanta [1], Weigand and Spring [2]. Basic investigations on single impinging jet with and without cross-flow were conducted for example by Goldstein and Behbahani [3], Baughn and Shimizu [4], and Lee et al. [5]. These investigations have shown that the heat transfer produced by an impinging jet depends mainly on a number of parameters, including the Reynolds number of the jet, the jet-to-target spacing, the presence of a confining wall, and the Prandtl number, etc. Convective heat transfer enhancement, increase in the heat transfer rate uniformity, improvement in the coverage of the impingement surface, and decrease in the coolant mass flow rate are some of the concerns of jet impingement [6–13].

Significantly high local heat transfer coefficient is achieved on the stagnation zone by the jet impingement, but the local heat transfer degrades rapidly away from the jet stagnation for a single jet or a row of jets. Although multiple jets or array jets could be used to obtain high averaged heat transfer coefficient, the coolant used to generating multiple jets is monotonically increased with the jet number. Therefore, the subject of heat transfer enhancement of jet impingement by introduction of ribs on the wall-jet zone has been extensively studied. Gau and Lee [14] made an investigation on the impingement cooling flow structure and heat transfer along

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Nomenclature

Bi	Biot number
c_d	flow coefficient
d_j	diameter of jet hole (m)
e	rib height (m)
h	convective heat transfer coefficient (W/m^2 K)
H	jet-to-target spacing (m)
$\dot{m}$	total mass flow rate of jets (kg/s)
N	number of jet holes
Nu	Nusselt number
p	rib-pitch (mm), pressure (Pa)
q	heat flux (W/m^2)
Re_j	jet Reynolds number
T	temperature (K)
u_j	jet velocity (m/s)
w	rib width (m)
x	x-direction, streamwise distance
y	y-direction
y_n	jet spanwise pitch (m)
z	z-direction

Greek letters

δ	thickness (m)
ε	emissivity
ρ	density (kg/m^3)
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (Ns/m^2)
ν	kinematic viscosity (m^2/s)
σ	Stefan–Boltzmann constant

Subscripts

a	relative to ambient
av	laterally-averaged
b	relative to back
c	relative to convection
inj	jet at inlet
r	relative to radiation
w	wall

Superscripts

*	total

rib-roughened surface which was made from parallel rectangular ribs attached to a heated wall. It was found that in some situations the heat transfer along the roughened wall was indeed significantly enhanced. Miyake et al. [15] investigated the impinging jet heat transfer from rib-roughened flat surfaces and presented some optimum conditions (i.e. rib height, shape, pitch, jet-to-plate distance, etc.) for the maximum heat transfer. Detailed heat transfer measurements in the form of local distributions were also presented by Son et al. [16,17] for different element types. The results showed that the elements enhance total heat transfer performance of the impingement cooling system at low pressure penalty. The effect of fillet radii was evaluated but only little difference was reported between rounded and sharp-edged elements. Yan et al. [18] and Yan and Mei [19] also presented locally resolved heat transfer contours for rectangular ribs at 45, 60, and 90° ribs. For their configuration, 45° ribs were found to increase average Nusselt numbers and continuous ribs gave better results than broken ribs. Katti and Prabhu [20] reported an experimental investigation of heat transfer enhancement in turbulent jet impingement with axisymmetric detached ribs. It is found that contrary to a smooth surface, there is a continuous increase in Nusselt number from a stagnation point. They investigated the effect of rib width, rib height, pitch between ribs, clearance under the ribs, jet-to-plate spacing, and location of first rib from a stagnation point. Gau and Lee [21] reported that the presence of triangular surface corrugations permitted a significant increase of the local heat transfer coefficient. However, their study was limited to the analysis of the Nusselt number at the stagnation point. These results were confirmed by Hsieh et al. [22] in the case of rectangular and ellipsoidal corrugations, which allowed an increase of 20–30% of the local Nusselt number. Sagot et al. [23] made a study on the enhancement of jet-to-wall heat transfer using axisymmetric grooved impinging plates, for two types of axisymmetric grooves (square or triangular). Square grooves were found to be more efficient, for heat transfer intensification, than those with a triangular profile. The intensification was found to be effective only for r/d_j values lower than approximately 6. Azad et al. [24] studied the impingement effect on dimpled and pinned surfaces. Because the dimples and pins were circular depressions and protrusions, respectively, these two target surfaces offered an interesting comparison of the heat transfer enhancement. At lower Reynolds number the pinned surface performed better than the dimpled surface. However at higher Reynolds numbers, the dimpled surface performed better than the pinned surface for a certain flow orientation. The detailed heat transfer measurements of three impinging jet arrays issued from grooved orifice plates were performed by Su and Chang [25] to study the combined effects of groove and nozzle-size distribution on the heat transfer with various jet-to-target distances and Reynolds number values. The heat transfer characteristics of an in-line impingement on a flat and micro-rib roughened plate with different crossflow schemes were investigated by Xing et al. [26] using both experimental techniques and numerical methods. From the investigated configurations, the jet-to-target spacing of 3 resulted in the highest heat transfer coefficients for both the flat and the micro-rib-roughened plate. Overall heat transfer performance on the micro-rib roughened plate was always best for the minimum crossflow case. The heat transfer enhancement ratio was increased with increasing Reynolds number. The highest enhancement caused by the presence of micro-ribs was 9.6% for the maximum crossflow. Caliskan and Baskaya [27,28] made detailed heat transfer measurements over a surface with V-shaped ribs (V-SR) and convergent–divergent shaped ribs (CD-SR) by a circular impinging jet array using thermal infrared camera. It was found that the best heat transfer performance was obtained with the V-SR arrangements. The average Nusselt number values for the V-SR plate showed an increase ranging from 4% to 26.6% over those for the smooth plate.

The results in literature mentioned above provide many insights into the jet impingement heat transfer performance on the smooth and rib-roughened plates. A lot of studies have shown marked effect of surface roughness on the heat transfer enhancement impinged by the jets. These investigations mainly focused on the heat transfer over the rib-roughened surfaces impinged directly by the jets, especially on the relative position of the jet holes to the ribs. To our knowledge, little attention has been paid on the heat transfer produced by single row of impinging jets inside a confined channel where the ribs are only mounted in the wall-jet zone. This situation can be regarded as a combination of impingement jet cooling in the stagnation zone and rib-roughened convective cooling in the wall-jet zone. Such heat transfer processes are widely occurred in combustor wall cooling schemes in the gas turbine [29].