International Journal of Heat and Mass Transfer 93 (2016) 683–694

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Experimental and numerical investigation of impingement heat transfer on the surface with micro W-shaped ribs

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ARTICLE INFO

*Article history:*
Received 22 July 2015
Received in revised form 28 September 2015
Accepted 12 October 2015

*Keywords:*
Impingement cooling
W-shaped ribs
Heat transfer enhancement
Liquid crystal thermography
Numerical computation

ABSTRACT

The paper proposes a technique of using micro-W-shaped ribs on a test plate to improve the impingement heat transfer performance in a multiple-jet impingement cooling system. A combined experimental and numerical investigation has been conducted on the heat transfer characteristics of multiple jet impingement on a flat plate and a roughened plate with micro W-shaped ribs under maximum crossflow scheme. The jet-to-plate spacing of H/D = 1.5 was used in the impingement systems with both the flat plate and the micro-W-rib roughened plate. Transient liquid crystal thermography method has been used in the experiments to obtain detailed heat transfer distribution on the test plates for the Reynolds numbers ranging from 15,000 to 30,000. The experiments showed that the micro W ribs can improve the area-averaged impingement heat transfer on the test plate by about 9.6% at a Reynolds number of 30,000, and the pressure loss is negligibly increased compared to the impingement on the flat plate. In addition, numerical computations have further been done to examine more flow and heat transfer details in the impingement system with the micro-W-rib roughened plate. The comparisons between the experimental and numerical data showed that the numerical computations can well predict the impingement heat transfer patterns on the micro-W-rib roughened plate.



## 1. Introduction

To increase the thermal efficiency, gas turbines are designed to operate at increasingly higher temperature, which vitally requires the development of more effective internal cooling strategies for gas turbine blades and combustion chambers [1]. Jet impingement provides a very efficient cooling performance due to the ability of achieving very high heat transfer rates. It is therefore being used in the gas turbine blade internal cooling and low-NOx combustor wall cooling.

Numerous studies on the multiple jet impingement heat transfer have been done in order to achieve both sufficiently higher average heat transfer rates and better heat transfer uniformity to provide a better cooling for the gas turbine hot components. Martin [2], Han and Goldstein [3], and Weigand and Spring [4] made technical reviews and showed that the impingement cooling performance can be influenced by many different parameters, such as the jet Reynolds numbers, impingement plate to target plate spacing, jet hole diameter, and jet hole spacings. Metzger et al. [5] and Florschuetz et al. [6,7] investigated the effects of parameters of jet hole pattern, jet-to-plate spacing and jet hole spacing, and on the impingement heat transfer coefficient of circular jets. They showed that the mean heat transfer coefficients for the inline pattern are better than those for the corresponding staggered pattern. An optimum jet-to-plate spacing for impingement heat transfer occurs at the values between 1 and 3. Xing et al. [8] investigated detailed heat transfer characteristics within an impingement system with inline or staggered jets at different Reynolds numbers and different crossflow schemes, and they found that independent of crossflow scheme, the inline pattern always outperformed the staggered configuration in terms of achievable heat transfer rates.

Recently more research interests have been drawn to the impingement cooling on roughened plates, since the impingement heat transfer could be augmented by roughened elements on the test plate [9–20]. Trabold and Obot [9] obtained jet impingement heat transfer on roughened surfaces with micro square ribs (rib height was 0.813 mm (0.1D) and pitch-to-height ratio was 6–10). They found that the presence of roughness results in small upstream reductions in the heat transfer coefficient and marked improvement in downstream sections for the maximum crossflow scheme, indicating that roughness elements can be used to compensate for the degradation that is usually associated with impingement on smooth surfaces due to crossflow. Gau and Lee [10] experimentally studied a slot-air-jet impingement cooling

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.10.022
0017-9310/

**Nomenclature**

| | |
|---|---|
| $c$ | specific heat (J/(kg K)) |
| $C_L$ | pressure loss coefficient |
| $D$ | impingement jet diameter (m) |
| $G_j$ | flow rate through one jet hole in CFD model ($m^3$) |
| $\overline{G_j}$ | assumed mean flow rate through jet holes in CFD model ($m^3$) |
| $h$ | heat transfer coefficient (W/($m^2$ K)) |
| $H$ | jet-to-plate spacing (mm) |
| $k$ | thermal conductivity (W/(m K)) |
| $L$ | impingement plate length (m) |
| $Nu$ | local Nusselt number, based on jet diameter |
| $\overline{Nu}$ | area-averaged Nusselt number |
| Re | Reynolds number, based on jet diameter |
| $t$ | time (s) |
| $T_w$ | wall temperature (K) |
| $T_B$ | airflow bulk-temperature (K) |
| $T_0$ | initial wall temperature (K) |
| $\Delta p$ | pressure loss (pa) |
| $U$ | Streamwise velocity ($ms^{-1}$) |
| $X$ | spanwise jet-to-jet spacing (mm) |
| $Y$ | streamwise jet-to-jet spacing (mm) |
| $z$ | coordinate (m) |

*Greek Symbols*

| | |
|---|---|
| $\rho$ | density (kg/$m^3$) |

flow structure and heat transfer along rib-roughened walls. Due to the protrusion of the rib, the formation of an air bubble enclosing the cavity occurs which can prevent the jet from impinging on the wall and reduce the heat transfer. However, some portion of the jet flow in the downstream region, especially when it becomes turbulent, can penetrate the air bubble and impinge and recirculate inside the cavity, which significantly increases the heat transfer. Andrews et al. [12] used a high rib blockage of the impingement gap of 50% in the impingement cooling system. They concluded that the ribbed surfaces may not provide higher averaged heat transfer than for a smooth surface. The wall jet interaction on the smooth surface was significantly greater than that created by crossflow/rib interactions, and the presence of the ribs stopped the impingement wall jet flow interaction and the associated turbulence generation. Andrews et al. [13] further indicated that for an element blockage of 50%, the crossflow resulted in higher impingement heat transfer enhancement in the trailing-edge region of a test surface with interrupted rib obstacles. The total surface heat transfer enhancement (based on the target plate projected area) was small at 15%, and in the absence of crossflow in the leading-edge region, heat transfer deteriorated relative to a smooth surface. Son et al. [14] also investigated the use of roughness elements (cylindrical pimple, diamond pimple and hexagonal rim) to enhance impingement heat transfer. The results showed that the hexagonal rim roughness element can enhance the total performance of the impingement cooling system by up to 12% (based on the target plate projected area) with very low extra pressure loss of about 6.7%. Wan et al. [16] numerically investigated the impingement heat transfer on roughened plates with square pin fins. They found that the total heat transfer can be enhanced by about 60%, but the heat transfer on the flat portion of the roughened plate can eventually be reduced. Yan et al. [17] examined the detailed local heat transfer coefficient distributions over a rib roughened surface under a jet impingement array. They found that the surface with continuous ribs provides a better impingement heat transfer than that with broken ribs. Compared to the flat surface, the heat transfer over the roughened surface may be enhanced or decreased. Xing and Weigand [18] experimentally studied the impingement heat transfer on a dimpled surface. They found that the area averaged heat transfer can be increased by about 6.2% under maximum crossflow scheme, however under all crossflow schemes the heat transfer uniformity on the test plate was distinctively degraded.

More recently, El-Gabry and Kaminski [19] studied the impingement heat transfer on flat and micro-structure roughened surfaces (having uniform sandpaper roughness) under an array of orthogonal and angled impinging jets at Reynolds numbers from 15,000 to 35,000. They found that the rough surface shows higher (by about 33%) and more uniform heat transfer than the smooth surface, and angled impinging jets produce more uniform heat transfer. The additional pressure loss due to the surface roughness is negligible. Xing et al. [20] investigated the detailed impingement heat transfer distribution on a plate with micro transverse ribs. They found that the micro-rib roughened plate showed higher average heat transfer by up to 9.6% than the flat plate. However, their results still showed that the heat transfer non-uniformity on the micro-rib roughened plate becomes more distinctive, especially in the regions in-between streamwise pairs of jets.

Detailed examination of the literature shows that the choice and organization of roughening elements on the test plate are of significant importance for the improvement of the impingement cooling performance. Even though the plates with roughening elements can improve the total heat transfer performance mostly due to the enlarged heat transfer area, the roughening elements can change the flow characteristics and cause locally decreased heat transfer rates and bigger pressure loss [10–17], or degrade the heat transfer uniformity on the test plate when there are jet-generated crossflow effects as is shown in Refs. [18,20].

Unique from the previous geometric configurations for the impingement cooling with roughened test plates, the present paper explores the idea of using micro-sized W-shaped ribs, which are sparsely arranged midway between the jets in streamwise direction, to effectively interact with the wall jets and crossflow to improve the impingement heat transfer performance. The present study is different from previous studies on the impingement heat transfer on the plate with normal-sized roughening elements, and also different from the impingement on the plate with denser micro traverse straight ribs by Trabold and Obot [9] and Xing and Weigand [20], since the W shaped ribs should be more effective than the straight ribs in convective heat transfer enhancement by producing downwashing vortex flow [21–23]. On the other hand, sparsely arranged W ribs on the test plate do not stop the wall jet spreading. The paper conducted detailed experimental and numerical studies to examine the effects of micro W-shaped ribs on the plate on the heat transfer, pressure loss and flow structure characteristics in the impingement cooling system.

## 2. Experimental Setup

Transient heat transfer experiments based on thermochromic liquid crystal (TLC) thermography have been done to obtain the local heat transfer coefficient distributions over the flat plate and the micro-W-rib roughened plate in the impingement cooling system. The experimental system consists of a variable-speed blower, a vortex flowmeter, a differential pressure transducer, an inlet