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Research Paper

Heat transfer of impinging jet arrays onto half-smooth, half-rough target surfaces

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HIGHLIGHTS

- The flow exit orientation is a dominant factor for the impingement heat transfer.
- Partially roughened surfaces could achieve over 50% heat transfer enhancement.
- The concept may be applied to improve heat transfer on other roughened surfaces.

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ABSTRACT

Detailed heat transfer distributions from arrays of impinging jets on a half-smooth, half-rough target surface were experimentally investigated using a transient liquid crystal technique. The target surface was roughened through the creation of rectangular grooves aligned with the jet holes. The grooved regions were designed either parallel (longitudinal grooves) or orthogonal (transverse grooves) to the exit flow direction. Jet-to-jet spacing and jet-to-surface spacing (Z/d) were 4 and 3, respectively. In this experimental test, the effect of crossflow was investigated for three exit flow directions, each with a jet Reynolds number ranging from 2500 to 7700. Heat transfer was enhanced near the edge of grooves, whereas the heat transfer was degraded inside grooves. For the half-smooth, half-rough surface, the sudden change in surface geometry broke the flow development and caused intensified flow mixing in the impingement flow channel. Compared with traditional fully roughened surfaces, the half-rough surface is more effective for heat transfer, and an enhancement of more than 50% was achieved for the longitudinal grooves. The idea of partially roughened surfaces may be further extended to the other internal flow channels with different roughness elements.

1. Introduction

Utilizing impinging jets for heat transfer is useful for industrial applications such as heating, drying, cooling, and defrosting. Jet impingement provides high convective heat transfer by directing the coolant jets on the hot target surfaces. Multiple jets or jet arrays are implemented for large surface areas. In this scenario, a crossflow stream is developed by the spent jets that shift the impingement core. Thus, the effectiveness of the jet impingement is reduced. The effective location of the impingement jet was shifted by the crossflow [1]. Jet impingement arrays that used inline or staggered patterns were investigated and the influential parameters included jet hole spacing, hole diameter, and channel height [2]. Additionally, heat transfer through an array of impinging jets was studied for cases with and without a crossflow [3], an initial crossflow effect [4], and an exit flow direction [5]. A detailed description of impingement heat transfer for turbine blade cooling was provided by Han et al. [6]. Furthermore, the effect of jet-to-jet spacing and jet-to-plate spacing on impingement heat transfer has been investigated [7,8].

Further improvements to the impingement heat transfer process are possible using roughened target surfaces such as ribs, pins, or dimples. Ribs are a common turbulence promoter used in internal flow channels for heat transfer enhancement because they break the boundary layer and cause flow reattachment. When the jet impinged on the ribbed surface, the rib-induced flow cells between the ribs can prevent the impinging jet flow from touching the surface [9,10]. However, the turbulent jet can successfully impinge on some regions, which substantially enhanced heat transfer. An influential factor for multiple jet impingement on ribbed surfaces was the ratio between the jet and the rib sizes

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Nomenclature

A_j	area of the jet holes (m^2)	T_i	initial temperature of the test section (°C or K)
C_d	discharge coefficient	T_w	wall temperature (°C or K)
d	diameter of the jet hole (m)	T_m	mainstream temperature (°C or K)
e	depth of the groove (m)	t	transient testing time (s)
h	convective heat transfer coefficient (W·m^2/K)	V_j	jet velocity (m/s)
k	thermal conductivity of acrylic (W·m/K)	X	axial (streamwise) distance of the impingement surface (m)
k_a	thermal conductivity of air (W·m/K)	Y	spanwise distance of the impingement surface (m)
L	thickness of the target plate (m)	Z	distance between the jet hole and target plate (m)
$\dot{m}_j$	jet mass flow rate (kg/s)	α	thermal diffusivity of the acrylic test section (m^2/s)
Nu	Nusselt number (=hd/k_a)	ρ	density of fluid (kg/m^3)
ΔP_j	pressure drop across the orifice plate	μ	dynamic viscosity of fluid (kg/m·s)
Re	average jet Reynolds number (=ρV_jd/μ)	τ_j	time step (s)
S	distance between the jet holes (m)		

because the rib-induced flow recirculation has a detrimental effect that hinders the impinging jets [11]. Rhee et al. [12] investigated initial crossflow effect in an impingement/effusion cooling system that included ribs. The ribs protected the impinging jet flow by partially blocking the upcoming crossflow, providing mass transfer enhancement of 4–11%. Yan et al. [13] investigated the effects of rib configuration on impingement heat transfer and concluded that 45° V-shaped ribs offer the highest heat-transfer capability. Wang et al. [14] used a rib to control the impingement heat transfer and found that the enhanced heat transfer region was expanded. Spring et al. [15] instrumented ribs between the impinging jets in inline and staggered jet arrays, and the staggered pattern resulted in less heat transfer because of the stronger influence of the crossflow. In addition, an investigation of jet-to-plate spacing on impingement heat transfer confirmed that smaller spacing amplified the crossflow effect [16]. The cited studies have suggested that impingement heat transfer can be enhanced or impeded on the ribbed surfaces, and minimizing the crossflow effect was beneficial for improving heat transfer performance.

In addition to ribs, protruded or recessed surface structures were also considered for enhancing impingement heat transfer. Pin-fins are commonly applied on heat-transfer surfaces because they induce a horseshoe vortex and enlarge the heat-transfer area. Azad et al. [17] studied impingement on a pinned surface and the results indicated that the heat transfer enhancement or degradation was dependent on the exit flow direction. Andrew et al. [18] investigated impingement heat transfer on surfaces with rectangular pin-fins. For the strong crossflow-dominated region, the presence of the pin-fins improved heat transfer. Hong et al. [19] measured heat/mass transfer in an impingement/effusion system with pin-fins and found that the pin-fins protected the wall jet from being swept away by the crossflow, increasing the local heat/-mass transfer in the injection region. Recently, two studies investigated impingement on microfinned surfaces and indicated an increase in heat transfer [20,21]. The enhancement of jet impingement heat transfer could be up to 200%, primarily because of the increased heat transfer area and enhanced flow mixing.

Regarding recessed surfaces, impingement heat transfer on a dimpled surface was found to be lower than that on a pinned surface at lower Reynolds numbers [22]. Subsequently, an investigation of jet impingements on a dimpled surface revealed that the degraded impingement heat transfer was attributable to the flow bursting phenomenon on the dimples, which broke up the impingement core [23]. However, the local turbulence, flow separation, and reattachment produced by the dimples were beneficial for heat transfer enhancement. The effect of the crossflow on the dimpled surface was investigated, and a small jet-to-plate spacing (Z/d = 2) aggravated heat transfer because of the effect of recirculation inside dimples [24]. However, the strong crossflow can enhance heat transfer on the dimpled surface, and the heat transfer results can be correlated using dimensionless parameters [25]. Another study of impingement on a dimpled surface concluded that the most effective heat transfer performance was obtained using the minimum crossflow and narrow jet-to-plate spacing [26]. For grooved surfaces, impingement heat transfer on target surfaces with inline or staggered grooves was investigated by Liu et al. [27] and the results indicated that the enhancement was within 15%. In summary, the effectiveness of jet impingement was reduced when the creation of additional secondary flow from the surface structure disrupted the jet flow. For the strong crossflow-dominated region, the presence of surface roughness benefited heat transfer.

However, every aforementioned study used uniformly distributed roughness over the entire surface. The improper arrangement of the roughness structure may hinder the jet flow and fully roughened surfaces may not be optimal for enhancing heat transfer. No attention has been paid to partially smooth, partially rough surfaces in the impingement channel. Therefore, if a roughness structure was only partially fabricated at discrete locations, distinct jet flow and crossflow schemes could possibly contribute to higher heat transfer. In the current study, the effects of jet impingement on surfaces with longitudinal and transverse grooves were investigated under three exit flow directions. The detailed heat transfer contours on the target surface were measured using the transient liquid crystal technique, which gave an insight into the impingement heat transfer phenomena on half-smooth, half-rough surfaces.

2. Experimental setup and procedure

Fig. 1 shows the experimental setup. The air flow from a blower was preheated using a pipe heater, and the air temperature was varied using a temperature controller. A three-way ball valve diverted the flow into the test section until the air temperature reached a preset value. The preset temperature was adjusted to ensure an acceptable transient testing time (30–80 s), and the initial mainstream temperature at the inlet was approximately 55–70 °C. The target plate was initially maintained at the ambient temperature, and four thermocouples were used for temperature measurement. This hot air was directly impinged on the target surface, causing a color change in a thermochromic liquid crystal coating (R30C5W, Hallcrest Inc). An airbrush was used to spray the liquid crystal and black paint on the target surface. A CCD camera (Prosilica GigE: GS1380) recorded color images of the liquid crystal coating on the test surface, and the measurement region on the tar-