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A novel control of jet impingement heat transfer in cross-flow by a vortex generator pair

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ABSTRACT

Jet impingement is an effective heat transfer method while the favorable performance is usually degraded by the cross-flow. In this article, a novel control of the impinging jet in cross-flow has been proposed. A delta winglet vortex generator pair (VGP) is installed in the cross-flow channel upstream of the jet nozzle. The jet and the cross-flow Reynolds numbers are 15,000 and 40,000, respectively. The ratio of nozzle-to-surface distance to jet diameter is 4.0. Experimental measurements are conducted to study the characteristics of heat transfer with liquid crystal thermography (LCT). Results indicate that the VGP with common-flow-up (CFU) configuration promotes the jet penetration in cross-flow and augments the impingement heat transfer greatly on the target wall compared to the baseline case without the VGP. In addition, the enhancement increases monotonically with the angle of attack of the VGP varying from $\alpha = 15°$ to 45°. The spacing between the VGP $l_1 = 1.2d$ is preferred with the highest heat transfer augmentation of jet impingement among $l_1 = 0.5–2.0d$. The optimal value of spacing between the VGP and the jet nozzle l_2 is suggested to be $4d$ in terms of enhancing the heat transfer, for the measurement range from $l_2 = 2d$ to $l_2 = 8d$. The VGP with common-flow-down (CFD) configuration is also tested, but it leads to slightly lower heat transfer than without the VGP. Pressure drop of the jet in cross-flow with VGP is measured and analyzed.

1. Introduction

As an effective and flexible means of high heat/mass transfer, jet impingement has been used in many industrial applications, which include cooling of gas turbines and electronic components, drying of textile and paper, processing of food, annealing of metals, and so on. A considerable amount of work has been carried out and several books/reviews have been published on the heat transfer of jet impingement [1–5].

However, in real applications, the impinging jet is usually deflected by the initial cross-flow or that developed from the spent jets upstream. Therefore the heat transfer characteristics of impinging jets are altered and its favorable thermal performance is degraded in the presence of cross-flow [6]. Based on the experimental data, correlations have been developed to account for the impact of cross-flow on the impingement heat transfer [7,8]. The jet Reynolds number, the ratio of nozzle-to-surface distance to jet diameter, and the mass velocity ratio of jet to cross-flow are among the leading parameters which determine the heat transfer of jet impingement [9]. It is also found that the in-line jet impingement array reduces the adverse effect of cross-flow and performs better than the staggered arrangement [10]. In addition, the exit orientations of cross-flow were reported to have significant influences over the thermal behavior of jet arrays, with the minimum cross-flow scheme showing the best heat transfer performance [11,12]. With film cooling holes on the impinging surface, the cross-flow effect is weakened and the overall heat transfer increases [13]. Detailed locally resolved heat transfer rates of jet impingement in cross-flow have been measured in more recent investigations [14,15].

To enhance the jet impingement heat transfer, many researchers have contributed significantly. Both active and passive control methods have been studied, and these are usually applied on the target wall. The heat transfer can be augmented by using dimpled surfaces [16,17], pinned surfaces [18], ribbed surfaces [19,20], and oscillating surfaces [21]. Another way to suppress the adverse effects of cross-flow is to promote the jet penetration and thus to improve the jet impingement capacity. Extensive studies have been done to modify the jet issuing behavior by introducing swirling strips [22], triangular tabs [23], pulsations [24], and acoustic excitations [25], or changing the jet nozzle configurations and geometries [26,27]. These measures can effectively affect the flow field and heat transfer characteristics. In addition, a combination of

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Nomenclature

A	total area for averaging Nusselt number (m^2)
d	diameter of the jet nozzle (m)
D_h	hydraulic diameter of the cross-flow channel (m)
h	convective heat transfer coefficient ($Wm^{-2}\,K^{-1}$)
H	height of the delta winglet (m)
k	thermal conductivity of air ($Wm^{-1}K^{-1}$)
L	chord of the delta winglet (m)
l_1	spacing between the two vortex generators (m)
l_2	spacing between VGP and the jet nozzle (m)
Nu	Nusselt number (hd/k)
$\overline{Nu}$	area-averaged Nusselt number
Nu_0	Nusselt number of the stagnation point
P_1	static pressure of tap 1 (Pa)
P_2	static pressure of tap 2 (Pa)
P_3	static pressure of tap 3 (Pa)
ΔP_c	pressure drop of the cross-flow (Pa)
ΔP_j	pressure drop of the jet (Pa)
Q_w	heat flux on the target wall (Wm^{-2})
Q_{loss}	heat loss on the target wall (Wm^{-2})
R	velocity ratio of jet to cross-flow (U_j/U_c)
Re_c	Reynolds number of the channel cross-flow (U_cD_h/ν)
Re_j	Reynolds number of the impinging jet (U_jd/ν)
T_w	wall temperature (°C)
T_0	inlet air temperature (°C)
U_c	bulk velocity of the channel cross-flow (ms^{-1})
U_j	exit velocity of the impinging jet (ms^{-1})
x_0	streamwise position of the stagnation point (m)
x	streamwise direction
y	wall-normal direction
z	spanwise direction
Greek symbols	
α	angle of attack of the vortex generator
ν	kinematic viscosity of air (m^2s^{-1})
Subscripts	
c	cross-flow
j	jet

jet impingement and swirl chambers has been investigated and significant improvements of heat transfer were shown [28].

Recent studies identified the contributions of cross-flow wall boundary layer to the jet dynamics [29]. As stated by the authors [29], "Any mechanisms description lacking the influence of the wall boundary layer will miss many important physical phenomena in transverse jets". Muppidi and Mahesh [30] in their direct numerical simulations (DNS) demonstrated that at the same velocity ratio, the thicker boundary layer decreased the momentum of the cross-flow around the nozzle exit, which results in less deflection and deeper penetration of the transverse jets. The progress in understanding the flow physics of jet in cross-flow provides us new insights into the manner to control their heat transfer behavior.

In this article, a new method has been proposed to enhance the impingement heat transfer by controlling the cross-flow using a vortex generator pair (VGP) upstream of the jet nozzle. The VGP, which has been commonly used for flow separation control [31,32] and heat transfer enhancement [33,34], can effectively alter the upcoming boundary layer by generating two longitudinal counter-rotating vortices. This could promote the penetration of the impinging jet in cross-flow, and also augment the heat transfer on the target wall. This paper contributes to gain knowledge of augmenting impingement heat transfer in cross-flow using a VGP and also provides detailed heat transfer data for validating and improving numerical investigations.

2. Experimental setup and procedures

As shown in Fig. 1, an air compressor system is used to provide the jet flow. The compressed and filtered air passes through the pressure regulator, and enters a big tank which maintains the stable pressure downstream. Air flow of the jet is regulated by the valve and measured by a rotameter. After that, it flows into a 1030 mm long straight pipe made of stainless steel, which has a 20 mm inner diameter d. The nozzle is flush with the top wall and the jet issues perpendicularly into the channel.

The cross-flow is introduced by the channel flow as shown in Fig. 1. The rectangular channel is 5000 mm long, with a cross section of 80 mm height and 320 mm width. This gives a hydraulic diameter of the channel $D_h = 128$ mm and the ratio of nozzle-to-surface distance to jet diameter 4.0. Air flow in the channel is driven by the centrifugal fan positioned at the outlet. The flow rates can be adjusted by controlling the operating frequency of the fan. In the inlet, a bell mouth with a smooth contraction is installed to guide the air flow and avoid any separation. Static pressure drop is measured along the channel to determine the cross-flow velocity, which is also examined by a flowmeter. The channel consists of an inlet section (25 D_h), a test section (4 D_h), and an outlet section (10 D_h). The bottom wall in the test section is regarded as the target plate surface. For the Cartesian coordinate system, the x-axis is along the streamwise direction, the y-axis is normal to the wall, z-axis is along the spanwise direction, and the origin is placed at the position corresponding to the geometrical center of the jet nozzle on the bottom wall.

During the experiments, the cross-flow and the jet are maintained at isothermal condition (ambient temperature T_0). The exit velocity of the jet U_j is kept at 12 m/s and the bulk velocity U_c of the channel flow is fixed at 5.0 m/s. This results in a velocity ratio of jet to cross-flow $R = U_j/U_c$ as 2.4. Based on the jet velocity U_j and nozzle diameter d, the jet Reynolds number Re_j is calculated to 15,000. By using the cross-flow bulk velocity U_c and channel hydraulic diameter D_h, the cross-flow Reynolds number Re_c is determined to 40,000.

To modify the cross-flow, a vortex generator pair (VGP) is mounted in the channel, upstream the jet nozzle exit on the top wall, as shown in Fig. 2. In this study, the delta winglet type of VGP is used and placed in the common-flow-up (CFU) configuration and common-flow-down (CFD) configuration, respectively. Two counter-rotating longitudinal vortices are generated by the VGP in cross-flow and they may interact with the jet. In the CFU configuration, the secondary flow in-between has the same direction as the jet, while for the CFD configuration, the secondary flow in-between is against the direction of the jet, as seen in Fig. 2. The VGP is made of aluminium with a thickness of 0.7 mm. The geometry and position of the VGP are illustrated in Fig. 3. The detailed parameters tested are listed in Table 1, as shown below.

In the test section, heat transfer measurement is performed on the bottom wall using a steady-state liquid crystal (LC) technique. A heating foil is placed on the target surface, providing a uniform heat flux. Above that, a LC sheet (R35C5 W, LCR Hallcrest Ltd) is applied, which measures the surface temperature. The back side of the target wall is coated with a Styrofoam sheet of 50 mm thick,