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Effects of vortex generators on the jet impingement heat transfer at different cross-flow Reynolds numbers

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ABSTRACT

Experiments are carried out to investigate the effects of vortex generators on the jet impingement heat transfer in cross-flow. This study is a continuation of our previous research (Wang et al., 2015). In the present paper, the jet Reynolds number is fixed at 15,000 and the cross-flow Reynolds number varies from 40,000 to 64,000. The nozzle-to-surface distance to jet diameter ratio is 4.0. A vortex generator pair (VGP), placed in the cross-flow channel and upstream of the jet exit, is to enhance the impingement heat transfer. Both delta winglet (DW) and rectangular winglet (RW) are applied with different heights. Measurements of detailed heat transfer distributions on the impingement wall are conducted. Results show that the presence of VGP substantially augments the impingement heat transfer in cross-flow for all the cases, and its effect depends on the shape of the VGP, the height of the VGP, and also the cross-flow Reynolds number. The RW provides better heat transfer enhancement than the DW due to stronger vortical flow. The enhancement also increases monotonically with the height of the VGP. In addition, the averaged Nusselt number and pressure drop of the jet and cross-flow at different cross-flow Reynolds numbers are included. It is found that the favorable effects of the VGP are more significant as the cross-flow Reynolds number increases. Some PIV measurements were carried out. The flow structures and heat transfer mechanisms are discussed.

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1. Introduction

Jet impingement provides an effective and flexible means of high heat/mass transfer, and it has been widely applied in various industrial processes, which include cooling of gas turbines and electronic components, processing of food, drying of textile and paper, annealing of metals, and so on. There are numerous studies on the jet impingement heat transfer and they are summarized in some recent books/reviews [1–4].

However, it is usually encountered that the presence of initial cross-flow or that developed from the spent jets upstream tends to deflect the impinging jet and degrade its favorable thermal performance [5,6]. To account for the impact of cross-flow on the impingement heat transfer, correlations have been developed based on the experimental data [7,8]. The most important parameters determining the impingement heat transfer include the jet Reynolds number, the jet to cross-flow velocity ratio, and the nozzle-to-surface distance to jet diameter ratio [9]. The exit orientation of cross-flow also plays an important role and the minimum cross-flow scheme shows the optimal thermal performance among all the jet arrays [10]. Compared to the staggered jet array, the in-line arrangement is shown to have a better performance by reducing the adverse effect of cross-flow [11,12]. The negative effect of cross-flow is found to be further reduced with film cooling holes on the impinging surface, which leads to an increase of the overall heat transfer [13]. Detailed measurements and simulations of locally resolved jet impingement heat transfer in cross-flow can be found [14–16]. In addition, the unsteady vortex structures of the jet and cross-flow are shown to have significant influence on the instantaneous heat transfer on the target wall [17].

Extensive studies have been carried out concerning the heat transfer enhancements of the jet impingement in cross-flow. Generally, this can be achieved by applying ribbed surfaces [18,19], pinned surfaces [20], dimpled surfaces [21,22], and bumps [23] on the target wall. Near the jet nozzle exit, introducing swirling strips [24], triangular tabs [25], acoustic excitations [26], and pulsations [27], or changing the jet nozzle geometries and configurations [28] could effectively improve the heat transfer characteristics as well. Investigations have also shown that significant heat transfer improvements were found in the swirl chambers with jet impingement [29]. It is worth mentioning that these methods lead to additional pressure drop penalty simultaneously.

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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	length of the jet nozzle (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 ($m^2\,s^{-1}$)

Subscripts

c	cross-flow
j	jet

Effects of the cross-flow wall boundary layer on the dynamics of the impinging jet have been investigated in [30]. It is found that at the same velocity ratio, the momentum of the approaching cross-flow upstream of the nozzle exit tends to decrease as the boundary layer becomes thicker. This could result in less deflection and deeper penetration of the transverse jets [31]. The progress in understanding the flow physics of a jet in cross-flow provides new insights into the manner to control the heat transfer behavior. In our recent paper [32], a delta winglet vortex generator pair (VGP) with common-flow-up (CFU) configuration was placed upstream of the jet nozzle in cross-flow. By controlling the interaction between the counter-rotating vortices and the issuing jet, the jet penetration is significantly promoted and the impingement heat transfer is thus remarkably enhanced when compared to the baseline case without the presence of the VGP. Effects of the angle of attack, the spacing between the VGP and the spacing between the VGP and jet nozzle are thoroughly examined and the optimal arrangements are suggested.

This paper is a continuation of our previous study [32] to investigate the effects of vortex generators on the jet impingement heat transfer in cross-flow. Both the delta winglet (DW) and rectangular winglet (RW) vortex generators are installed in the cross-flow upstream of the jet nozzle to enhance the heat transfer at different Reynolds numbers. The DW and RW have widespread applications in the flow separation control [33,34] and heat transfer enhancement [35,36]. In addition, effects of the height of the vortex generators are also studied. Detailed heat transfer data are measured using liquid crystal thermography. The objective of this research is to offer more possibilities to control the jet impingement in cross-flow and provide an insight into the mechanism of heat transfer enhancement. The presented heat transfer and pressure drop results might be useful in validation of the CFD approaches and turbulence models. The flow mechanisms of the interaction between the vortex generators and the jet in cross-flow are conjectured and discussed based on the PIV results.

2. Experimental setup and procedures

The experimental setup is illustrated in Fig. 1. The jet flow is introduced by the air compressor system. The compressed air is filtered and then enters a big container to eliminate the compressibility. A rotameter manufactured by KROHNE is used to measure the volume flow rate of the jet flow, with maximum permissible error of less than 2%. The length of the jet pipe l is 1030 mm and the inner diameter d is 20 mm. The cross-flow is supplied by the channel flow, which is driven by the centrifugal fan downstream. The channel has a bell mouth at the inlet to provide a smooth entrance flow with turbulence intensities of less than 3.5%. The channel flow bulk velocity is measured by a Prandtl tube [14]. The length of the channel is 5,000 mm, with a 320 mm wide and 80 mm high rectangular cross section. This results in the ratio of the nozzle-to-surface distance to jet diameter to be 4.0, and the hydraulic diameter of the channel becomes 128 mm. The heat transfer plate for measurement is about 500 mm long and located 3,200 mm downstream of the inlet. The origin of the Cartesian coordinate system is placed on the heat transfer plate, at the position corresponding to the geometrical center of the jet nozzle. It is defined in such a way that the x-axis is along the channel flow direction, the y-axis is perpendicular to the heat transfer wall, and the z-axis is along the spanwise direction.

As seen in Fig. 1, a vortex generator pair (VGP) is placed on the top wall of the channel to enhance the jet impingement heat transfer. The VGP generates longitudinal vortices and these alter the upcoming cross-flow upstream of the jet. Two different vortex generators are studied and compared with each other, i.e., the delta winglet (DW) and rectangular winglet (RW) as shown in Fig. 2. The common-flow-up (CFU) configuration is selected here because it provides significant heat transfer augmentation compared with common-flow-down (CFD) configuration, as shown in our previous paper [32]. The VGP is made of aluminum with a thickness of 0.7 mm. Table 1 lists the tested parameters in the present study.

In the measurements, the jet exit velocity is fixed at U_j = 12 m/s. This gives the jet Reynolds number Re_j = 15,000, based on the nozzle diameter d. The cross-flow bulk velocity is varied from U_c = 5 m/s to 6 m/s and 8 m/s. This results in the cross-flow Reynolds number Re_c = 40,000, 48,000, and 64,000, respectively, based on the channel hydraulic diameter D_h. The jet to cross-flow velocity ratios are R = 2.4, 2.0, and 1.5. Both the jet and the cross-flow are kept at ambient temperature T_0.

A steady-state liquid crystal technique (LCT) is employed to measure the heat transfer on the impinging wall. A uniform heat

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