International Journal of Heat and Mass Transfer 126 (2018) 256–280

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A comparative study of passive control on flow structure evolution and convective heat transfer enhancement for impinging jet

Xuzhi Du [a,b], Zhigang Yang [a,b,c,*], Zheyan Jin [a,d], Chao Xia [a,b], Di Bao [a,b]

[a] Shanghai Automotive Wind Tunnel Center, Tongji University, Shanghai 201804, China
[b] Shanghai Key Lab of Vehicle Aerodynamics and Vehicle Thermal Management Systems, Shanghai 201804, China
[c] Beijing Aeronautical Science & Technology Research Institute, Beijing 102211, China
[d] School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 200092, China

ARTICLE INFO

Article history:
Received 23 October 2017
Received in revised form 2 January 2018
Accepted 14 January 2018

Keywords:
Impinging jet
Passive control
Flow structure
Heat transfer
PIV
IR thermography
LES

ABSTRACT

The present study experimentally and numerically investigated the passive control on flow structure evolution and convective heat transfer enhancement for impinging jet. Four different impinging jets, including a baseline circular jet (CJ) and three passive controlled jets, i.e., an elliptic jet (EJ), a circular-chevron jet (CCJ) and an elliptic-chevron jet (ECJ), were comparatively analyzed by utilizing the Particle Image Velocimetry (PIV) technique, infrared (IR) thermography and large eddy simulation (LES) over a wide range of jet-to-wall distances (H/D) at the jet Reynolds number (Re) of 20,000. The results showed that, unlike CJ which presented a general shedding of axisymmetric toroidal vortices, EJ showed highly deformed toroidal structures accompanied with the axis switching effect, both CCJ and ECJ exhibited the well-organized counterrotating streamwise vortex pairs developing from the chevron notches. All the three passive controlled strategies were found to induce a stronger mixing and fluctuating activity near around the stagnation region, especially for ECJ (i.e., the passive–passive controlled device) which showed the highest turbulence level approaching the target wall due to the double-passive enhancement. Moreover, compared with the baseline jet CJ, all the passive controlled jets achieved a significant heat transfer improvement in the vicinity of the stagnation point, particularly for ECJ which presented the highest heat transfer enhancement of about 41% at $H/D = 5$. Whereas both CCJ and ECJ were found to exhibit a less-than-ideal heat transfer performance at a small H when the heat transfer uniformity was specifically considered, due to the anisotropic thermal imprint distributions.

1. Introduction

Impinging jets have received considerable attention due to their widespread industrial application, such as food processing [1], glass tempering [2], turbine blade cooling [3], cooling of electronic devices [4], deicing of aircraft [5] and defrosting of automobile windshield [6], etc. They are generally employed in massive cases where there is a great necessity to achieve an excellent convective heat transfer performance with respect to the uniform or high spotted scalar transfer. Thus, more efficient solutions are expected to be implemented based on a better understanding of the fundamental thermal-fluid dynamics of impinging jets.

Over the years, tremendous efforts have been made to investigate the factors that play a key role in the impinging jets with respect to flow structures, thermal imprint patterns and heat transfer enhancement, as reported by a series of pertinent reviews [7–10]. It was found that the thermal-fluid dynamics of impinging jet were largely influenced by various parameters, such as the jet Reynolds number (Re), the Prandtl number (Pr), the turbulence intensity at nozzle exit, the nozzle-to-plate distance (H), the impingement angle between the nozzle axis and the target plate, the confinement and nozzle geometry, etc. According to different characteristic behaviors, the impinging-jet flow field could be generally divided into three zones: the free jet, the stagnation and the wall jet regions.

A certain number of studies [11–14] have been carried out to investigate the dependence of the impinging jet heat transfer (i.e., the Nusselt number) on the jet Re and the H based on a fully developed circular pipe flow. The results indicated that the maximum Nusselt number (Nu) generally occurred at the stagnation point, and the optimal Nu could be achieved for $H/D = 6$ which appeared to coincide with the potential core length of the jet [7].

---

[*] Corresponding author at: Shanghai Automotive Wind Tunnel Center, Tongji University, Shanghai 201804, China.

E-mail address: zhigang.yang@sawtc.com (Z. Yang).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.01.061
0017-9310/© 2018 Published by Elsevier Ltd.

However, a few studies [15–17] revealed that a circular jet with convergent nozzle (i.e., the quasi-uniform velocity distribution at the nozzle exit) presented the maximum *Nu* about $0.6-0.7D$ away from the stagnation point for $H/D<4$, and it was also found that the optimal *Nu* corresponded to a larger H (i.e., larger than 6 D) with the increase of *Re*. For small H, the vortical structures of impinging jet were shown to play a key role in the radial heat transfer distribution where the distinct second *Nu* peak was found to form, which largely influenced the overall heat transfer performance [9,10].

Over the past few decades, A certain amount of works have been conducted to elucidate the underlying physics of the occurrence of the second peak, and the results varied quite a lot. Gardon and Akfirat [7,20] conducted early studies and they believed that the second peak was caused by a local thinning of the boundary layer within the wall jet due to a transition from the free jet into wall jet region, which was also confirmed by Hoogendoorn [21] about ten years later. About twenty years later, Goldstein at el. [18] thought such a second peak was mainly attributed to the energy separation in the shear layer vortices. Kataoka at el. [19] revealed that a surface renewal effect caused by the striking large-scale structures led to the occurrence of the second peak. In 1993, Fox at el. [22] concluded that it could be ascribed to the competition between the vortex rings and secondary vortices on the impinging wall. Both Lytle at el. [12] and Uddin at el. [23] summarized that the higher turbulence in the boundary layer due to flow acceleration and intense shear between the radially injected jet and the stagnant ambient triggered the formation of the second peak. In recent years, Hadziabdic and Hanjalic [24] found that the reattachment of the recirculation bubble and associated turbulence production due to the interaction of shear layer vortices with the impingement plate produced the second peak. Tummers at el. [25] stated that it was caused by the instantaneous flow reversals in the near wall region playing a key role in heat transfer augmentation. Benhacine at el. [26] believed that the merging and especially the breakdown of the organized vortices originating from the outer shear layer and the wash-up of the wall boundary layer contributed to the second peak. Dairay at el. [17] observed that the strong events related to the azimuthal distortion of the toroidal large-scale structures and the simultaneous development of radial vortices induced the formation of the second peak.

Consequently, according to the above description, an effective passive control on flow structures and turbulence level of impinging jets can be expected to yield a certain heat transfer improvement, which could be generally realized by the modification of the nozzle geometry, such as the use of lobed [27–29] or elliptic [6,30–36] nozzle, chevron [37–40] or tabbed nozzle [41–44], and swirling jets [45,46] etc. Meanwhile, elliptic and chevron or tabbed jets are usually treated as the promising passive devices owing to excellent heat transfer enhancement and high feasibility of parameterization design, research and fabrication.

So far, a series of classical works [47–50] have been carried out to study flow structures of the elliptic free jet. They found that the entrainment ratio of an elliptic jet was several times greater than that of a circular jet due to the different flow behaviors in the major and minor axis planes. Meanwhile, several studies have been performed on the heat transfer characteristics of elliptic impinging jets. Lee et al. [30,31] found that the maximum stagnation *Nu* of elliptic jet, with aspect ratio (*AR*) of 4 and *Re* of 10,000, was 15% larger than that of circular jet due to the different spreading rates along the minor and major axis plane. Zhao et al. [32] concluded that the highest *Nu* of elliptic jet occurred at a lower H (i.e., $H/D\approx4$) compared to that of circular jet which presented the highest *Nu* at $H/D\approx6$. Besides, the elliptic jet also provided higher average heat transfer rates than the corresponding circular jet under certain H and size of the averaging area. Yan et al. [33] stated that the axis switchover phenomenon with cross flow effect could be found for *AR* greater than 1.0 for multiple elliptic jets. Koseoglu and Baskaya [34] showed that much higher spreading rates could be achieved in the minor axis direction of the elliptic jet, and an increase in H would contribute to a reduction of flow field difference between the circular and elliptic jet. More recently, Koseoglu and Baskaya [35,36] revealed that the elliptic jets could increase the average heat transfer coefficient by about 6.01–16.8% depending on the *AR*, H and *Re*. Du et al. [6] investigated the geometry effects on flow, heat transfer and defrosting characteristics of a simplified windshield with inclined impinging jet arrays. They concluded that the elliptic jets enabled the average *Nu* to be increased by about 8–10% as compared to the circular jets, which led to a substantial improvement of the defrosting performance with the melted fraction being increased by about 40%.

In addition, a certain number of investigations have been performed to study the flow structure behaviors of the tabbed or chevron free jets [51–56]. Most of the results suggested that the mixing properties of a circular jet could be enhanced by placing delta or chevron tabs (i.e. the vortex generators) at the nozzle exit which, inducing low-speed region behind the tab (i.e., the chevron apex) and high-speed region on each side of the tab (i.e., the chevron notched), triggered the formation of counter-rotating pairs of streamwise vortices and shortened the potential core length of jet. However, just a few studies focus on the combined flow and heat transfer characteristics of the tabbed or chevron impinging jet. Gao et al. [41] summarized that the local heat transfer could be increased more than 25% in a series of distinct regions surrounding the impingement region with the use of tabbed jets as compared to that of circular jets. Violato et al. [37] showed that the chevron configuration led to an enhanced heat transfer performance with the improvement up to 44% at the stagnation point for $H/D=4$ compared to that of the circular jet. Yu et al. [42,43] revealed that the presence of tabs increased the jet core velocity and induced array pairs of vortices under single row of impinging jets, which substantially enhanced the heat transfer in the impingement region over the no-tab case. Iwana et al. [44] studied the fluid flow and heat transfer characteristics of an impinging jet with a combined active–passive device (i.e., the jet with triangular tabs and synthetic jets). Their results indicated that the combined device operation led to increased velocity magnitude and periodic disturbance of the primary jet, and thus augmented local *Nu* by about 35% near the stagnation point compared with cases where the device was not used. Vinze et al. [38] demonstrated that the chevron jet with chevron tips of 8 and tip angle of 10° provided the best heat transfer performance, which increased the local *Nu* by 26–38% as compared to the circular pipe jet. Guan et al. [39,40] found that the presence of chevrons increased the jet core velocity and produced more intensive jet fluctuation, thereby improved the heat transfer, particularly under a small *Re* or H.

Even though extensive researches [27–46] have been performed on the passive enhancement of the impinging jet heat transfer, to the authors' best knowledge, a combined jet with both elliptic nozzle shape and chevron-type vortex generators (i.e., the passive–passive device), namely elliptic-chevron jet (ECJ), has not yet been studied. Moreover, both elliptic and chevron jets are found to possibly present a nonuniform heat transfer pattern and few works have been conducted on a comparative analysis for various passive controlled impinging jets with respect to the flow behaviors, local and overall heat transfer evaluation based on different averaging areas. Therefore, in order to get a better insight into the underlying physics and generalize the design and use of passive controlled jets, it is of particular interest to know more details and differences between the baseline and different passive controlled jets in terms of the thermal-fluid behaviors.