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Experimental study on convective heat transfer from a rectangular flat plate by multiple impinging jets in laminar cross flows

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ABSTRACT

Convective heat transfer from a flat plate impinged by a row of air jets in laminar cross flows was studied experimentally. Several parameters, including the jet-to-cross-flow velocity ratio ($1 \le r \le 30$), Reynolds number ($Re = 250$–1750), and relative jet height ($10 \le L/d \le 80$), were explored. Results show that convective heat transfer can be enhanced significantly by a row of circular impinging jets. A critical jet-to-cross-flow velocity ratio exists for each experimental profile. Above this critical ratio, the relative Nusselt number, Nu_r, increases linearly with the jet-to-cross-flow velocity ratio. A large Reynolds number results in good convective heat transfer under the condition that the other parameters are unchanged. Furthermore, the relative Nusselt number decreases with the relative jet height when the jet-to-cross-flow velocity ratio and Reynolds number are small; meanwhile, it increases with the relative jet height initially and decreases afterward when both the jet-to-cross-flow velocity ratio and Reynolds number are sufficiently large. An empirical correlation, Nu_r (r, Re, L/d), with an uncertainty of 17.2% was developed.

1. Introduction

The impinging jet is adopted in many engineering applications, such as blade cooling in gas turbines, orientation manipulation in short/vertical take-off aircrafts, anti-sediment jets in power plants, annealing in steel/glass manufacture, and electronic cooling in the chip industry. Many studies have been conducted on the physics of flow and heat transfer for an impinging jet [1,2]. These areas have also been reviewed recently [3]. Comparisons and discussions of previous related studies show that an impinging jet can enhance convective heat transfer by a notable amplitude. Its potential has been highlighted in recent studies. For example, the effect of nozzle shape [4–6], jet inclination [7,8], jet confinement [9,10], jet fluid [11,12], fluid pulsation [13–15], fluid swirling [16–18], and target surface [19] on the performance of an impinging jet has been explored. These structural or non-structural parameters can be optimized to obtain improved heat transfer. Multiple impinging jets have elicited much research interest in recent years [20–24].

Multiple impinging jets with a high density of jets do not always improve heat transfer [20]. Further studies have shown that heat transfer is strongly related to the flow field near the impingement surface, which is mainly controlled by the dynamics of the vortex rings formed in each impinging jet according to the jet-to-jet spacing [21]. For the composite arrangement of pulsed and steady flows in multiple impinging jets, significantly high heat transfer can be obtained by the combinations of intermittent–steady jets rather than sinusoidal–steady ones [22]. The target surface of a multiple impinging jet system may also be a concave surface. Experiments [23] and numerical investigations [24] have shown that the advantage of the multiple impinging jets remains, and new aspects, such as Görtler vortices [23] and structural parameters [24], are closely related to heat transfer performance. The studies shown above focused on multiple impinging jets, and only a few of them considered a secondary flow, i.e., a cross flow perpendicular to the impinging jet flow. This phenomenon can be observed in many industrial scenarios, such as the anti-sediment jets in power plants, the impinging jets in the selective non-catalytic reduction (SNCR) method in reducing NO_X emissions, and the separated over fire–air (SOFA) jets in the furnace of a large-capacity utility boiler. In one of our studies, a high-momentum impinging jet was used to improve combustion efficiency and limit combustion instability [25]. Therefore, studying the heat transfer of an impinging jet/multiple impinging jets with cross flows is worthwhile.

Several previous studies have reported the effects of cross flows

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on impinging jet heat transfer [26–31]. Wang et al. [26] conducted a comprehensive literature survey in this field and showed that the existence of cross flows degrades the heat transfer performance of the impinging jet. Their work [26] also revealed that the relative Nusselt number increases with the Reynolds number. This phenomenon was confirmed by Wae-Hayee's work [27]. A similar study found that the size of the re-circulation region upstream of the impinging jet and the length of the potential core of the impinging jet are closely related to heat transfer performance [28]. Wang et al. [29] focused on the potential core shifting of an impinging jet on the concave surface in cross flows and indicated that the boundary layer thickens with the appearance of cross flows, which degrade heat transfer. A similar study [30] by this team on an impinging jet in a circular cylinder revealed that the cylinder-to-jet diameter ratio is the main parameter that controls the potential core characteristics and the corresponding heat transfer performance. Yasaswy et al. [31] measured the local heat transfer distribution of an impinging air jet through a cross flow and showed that the stagnation point shifts according the jet-to-cross-flow velocity ratio.

Only a few of the studies stated above focused on multiple impinging jets in cross flows. In addition, they were limited to several parameters, e.g., the jet-to-cross-flow velocity ratio and the relative jet height were limited to 12.0 or less, and the Reynolds number was larger than 5000. In the current work, the heat transfer from a heated rectangular flat plate subjected to a row of impinging jets in laminar cross flows was studied carefully under different jet-to-cross-flow velocity ratios ($1 \leq r \leq 30$), cross flow Reynolds numbers ($Re = 250-1750$), and relative jet heights ($10 \leq L/d \leq 80$). Detailed results were presented, and careful discussions were performed. Useful conclusions were obtained from the discussions. The results can be specifically applied to a row of anti-sediment impinging jets in power plants.

2. Experimental apparatus and procedure

The experimental setup is shown in Fig. 1. The target surface is a high-temperature co-fired ceramic (HTCC) rectangular flat plate heater, inside which an exothermic electric circuit was printed using slurry composed of wolframium, molybdenum, and manganese. This design ensures that the HTCC heater has a uniform heat flux on the external surface. The HTCC heater has the dimensions of 70 mm × 20 mm × 1.5 mm, and it was placed in a slot carved properly on the bottom wall of a square channel. A square Plexiglas channel with cross-section dimensions of 80 mm × 80 mm ($D \times D$) and a length of 500 mm was utilized as the flow tunnel of the cross flow, and the slot was located in the central part of the channel's bottom wall. The 70 mm side of the HTCC heater was aligned with the channel axis. A transition channel, a 20 mm thick perforated honeycomb, and a stainless gauze were installed ahead of the square channel to ensure the uniformity of the cross flow. The cross flow velocity was measured with a Testo 405 thermo-anemometer, whose uncertainty was 5%. A single row of aluminous jets was installed above the HTCC heater, and the distance between the jet nozzle and HTCC heater (L) could be modified. The jet nozzle and its 3D structure of the inner surface are shown in Fig. 2. A total of 13 circular jets existed, and each jet had a diameter (d) of 1.0 mm. The jet-to-jet distance was 1.8 mm, and the inner surface roughness (R_z) of the circular jet was 3.15 μm. Thirteen circular orifices were created with a mold through the extrusion forming method, which means the row of jets was embedded on a single plate with cross-section dimensions of 20 mm × 2 mm. The length of the plate was 100 mm, and a settling chamber was connected to the upper part of the orifice plate. This design helps reduce the blockage effect of the orifice plate on the cross flows. The blockage effect on heat transfer was disregarded. From the view of impinging direction, the central point of the cross section of the orifice plate coincides with that of the HTCC heater.

The cross and impinging jet flows were provided by a 1 m^3 air tank. The air flow rates were set by two Alicat mass flow controllers. The accuracy of the mass flow controller was ±0.8% of the reading plus 0.1% of the full scale, and the stocking pressure of the air tank was maintained by an automatic air compressor. The HTCC heater was powered by a DC power supply (Keithley 2268-60-14). The voltage drop in the connecting wires was not considered, and measurements showed that the voltage drop can be disregarded. The electric resistance of the HTCC heater changed linearly with temperature, and this preeminent feature was utilized to measure the averaged surface temperature because the Biot number is low [32,33]. The calibrated correlation between the electric resistance of the HTCC heater and the averaged surface temperature is shown in Fig. 3. Three Omega type-T thermocouples were used. One was installed in the transition channel to measure the inlet air temperature. The other two thermocouples were installed at a certain distance ($\Delta x = 4$ mm) on the edge of the heater and on the bottom wall of the cross flow channel, respectively, to measure the heat conduction loss from the HTCC heater. The measuring range and uncertainty of the thermocouples were −200 °C to 250 °C and 0.75% of the reading, respectively. The temperature signals were collected with an Agilent-34970A data acquisition instrument combined with the Benchlink Data Logger program. A sampling rate of 1 Hz was set for the temperature signals.

The experiment was initiated by closing the impinging jets. The relative jet height (L/d) was fixed while air was supplied to the square channel at a certain Reynolds number. The HTCC heater was heated to a thermally steady state, which is defined as when the

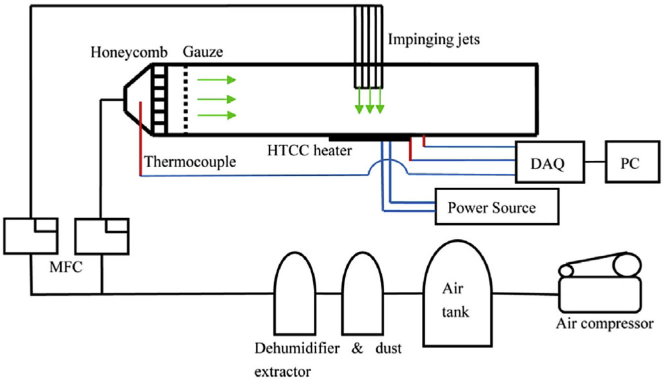

Fig. 1. Sketch of the experimental setup.

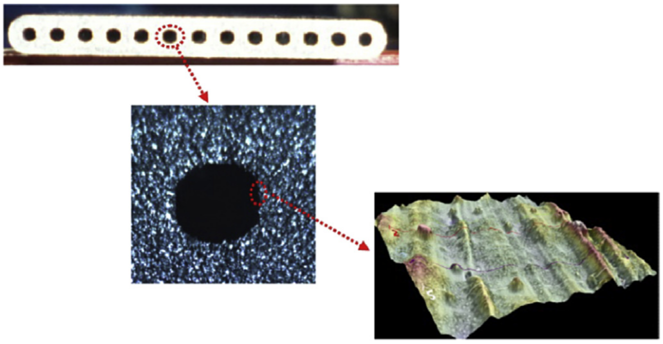

Fig. 2. Aluminous multiple jets and 3D structure of the inner surface.