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Effects of jet-to-jet spacing and jet height on heat transfer characteristics of an impinging jet array

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ABSTRACT

The Nusselt number distributions for five confined circular air jets vertically impinging on a flat surface were measured. The jets were arranged as an equilaterally staggered array (a middle jet and four neighboring jets). The jet-to-jet spacing to jet diameter ratio (s/d) and the jet height to jet diameter ratio (H/d) were in the range of 2.0–8.0 and 0.5–3.0 respectively. The jet Reynolds number was 20,000. At small s/d and H/d values ($s/d = 2.0$ and $H/d = 0.5$), a maximum Nu, attributed to a strong flow impact (jet interaction) on the impingement plate, was clearly observed between the middle jet and every neighboring jet. The jet interaction decreases with an increase of the s/d and H/d. At small s/d and large H/d values ($s/d = 2.0$ and $H/d \geqslant 2.0$), jet interference before impingement causes a decrease in heat transfer. However, it achieves a uniform Nusselt number distribution in the region directly covered by the jet array. At intermediate s/d and large H/d values ($s/d = 4.0$ and $H/d \geqslant 2.0$), both the jet interaction and jet interference are weak, but the expelled air of the middle jet (cross flow) reduces the heat transfer of the neighboring jets. At large s/d values ($s/d \geqslant 6.0$), regardless of the H/d value (in the range of 0.5–3.0), every jet possesses an independent cooling area on the impingement plate. The result also shows that the maximum Nu variation in the region under the jet array almost linearly increases with the s/d.

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1. Introduction

Jet impingement is quite effective for achieving a high heat/mass transfer rate on a surface. In the past few decades, a tremendous amount of research has been done on this subject. Much of this work has focused on determining heat transfer data, while the rest aimed at exploring fluid flow and heat transfer characteristics. In designing jet impingement systems, this research provides much valuable information. Yet to fully understand the physical phenomena and improve heat transfer, continuous research is required.

Garimella and Rice [1], Fitzgerald and Garimella [2] and San et al. [3] elaborated earlier work on single-jet impingement heat transfer. Some of this work showed that, for a jet emanating from a nozzle, a so called "entrainment effect" (Fig. 1(a)) would cause the surrounding fluid to be sucked into the jet. Garimella and Rice [1] also found that, for a confined impinging jet, the entrainment effect induces a recirculation flow between the jet and a location extending to a distance of several jet diameters from the jet centerline. More recently, San and Shiao [4] and San et al. [5] proposed correlations between stagnation point Nusselt number and relevant parameters for a confined circular air jet impinging on a smooth surface. Choo et al. [6] investigated the effect of an inclination angle on the heat transfer characteristics of a slot jet. Chaudhari et al. [7–8] and Persoons et al. [9] examined the heat transfer characteristics of a synthetic impinging jet. Eastman et al. [10] measured heat transfer data for impinging jets generated by a piezoelectric air pump. In addition, many numerical simulations relevant to single-jet impingement can also be found in the literature [11–13].

Much work on multiple-jet impingement heat transfer [14–27] had also been done by different researchers. The result of this work shows that the heat transfer of a jet array is significantly reduced by arranging a cross flow passing through the jet array. In practical applications, the cross flow results from the expelled fluid of the upstream jets. As it passes through the downstream jets, the flow of these jets is disturbed. In addition, through the entrainment effect, a part of the cross flow mixes with these jets. Both cause a decrease of local heat transfer.

Jet interaction on impingement plate (Fig. 1(b)) is another factor that affects the fluid flow and heat transfer in multiple-jet impingement. Saripalli [28] conducted flow visualization for water jets impinging on a flat plate. A fountain resulting from flow impact on the plate (jet interaction) was clearly observed between two adjacent jets. Behbahani and Goldstein [29] and Slayzak et al. [30] found local maximum Nusselt numbers between jets in jet arrays. The local maximum Nusselt numbers were attributed

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Nomenclature

d	jet hole diameter (mm)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
H	distance from jet exit to impingement plate (mm)
k	thermal conductivity of air (W m^{-1} K^{-1})
Nu	local Nusselt number, hd/k
q	surface heat flux (W m^{-2})
Q	volumetric flowrate (m^3 s^{-1})
Re	Reynolds number, 4Q/πνd
s	jet-to-jet spacing (mm)
T_{aw}	adiabatic wall temperature (°C)
T_w	heated wall temperature (°C)
w	heating foil width (mm)
x	streamwise coordinate (mm)
y	spanwise coordinate (mm)

Greek symbol

ν	kinematic viscosity (m^2 s^{-1})

Subscripts

max	maximum value
min	minimum value

to jet interaction. In addition to cross flow and jet interaction, jet interference before impingement (Fig. 1(c)) could also affect the heat transfer of a jet array [31–32]. The jet interference disturbs the fluid motion of the jets in the jet array, thus the heat transfer is affected.

In this work, Nusselt number distributions for five confined circular air jets impinging on a flat plate were measured (Fig. 2). The jets were arranged as an equilaterally staggered jet array (one middle jet and four neighboring jets). As indicated above, cross flow, jet interaction and jet interference are three major factors affecting the heat transfer characteristics of a jet array. Without doubt, a clear understanding of these three factors would be helpful for designers to inspire new ideas, such as changing the shape of jet/impingement plate etc., enhancing the impingement heat transfer or achieving a uniform heat transfer. Hence, in addition to acquiring the heat transfer data, another mission of this

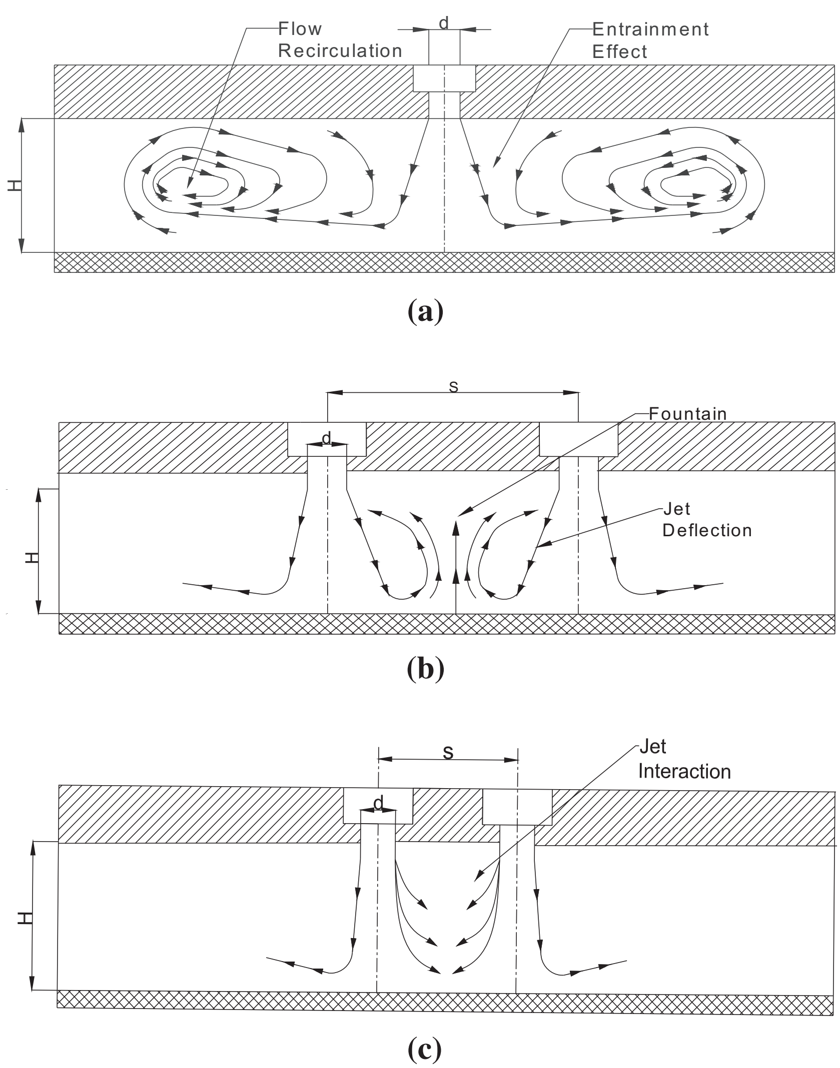

Fig. 1. (a) Entraintment effect of a confined impinging jet. (b) A strong jet interaction between wall jets. (c) Jet interference between two adjacent jets.

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