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Twisted symmetry in multiple impingement jets at low Reynolds number

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In this study, the cooling effect of nine confined jets arranged in square in-line array is investigated experimentally. The individual jet diameter is 3 mm, the jet-to-jet spacing ratio is two times as much as the jet diameter and the jet-to-plate spacing varies from 1 to 4 times as much as the jet diameter. The jet Reynolds number varies up to 880. An infrared camera is used for quantitative temperature measurement on the rear face of the impingement plate and a PIV system is installed to obtain the velocity field on different planes. The results show a twisted symmetry pattern of the flow field and heat transfer on the impingement plate when the confined ratio equals to jet-to-jet spacing ratio. This condition is produced only for the square in line array configuration and is due to the different interactions of central jet with lateral and corner jets.

1. Introduction

Impinging jets are used in many industrial applications because they produce high local heat transfer with relatively low pressure drop. They are often used in arrays to benefit the high heat transfer coefficient of the stagnation zone. In such cases the interaction between the jets in the array plays an important role in the heat transfer rates distribution on the impingement plate.

There are two different approaches of research on multiple jets impingement. Several works are carried out for a practical case with a large number of jets to make a parametric study of the jet array on average heat transfer coefficient. In these cases, the results are presented globally emphasizing the overall heat transfer cooling with little explanation on the underlying physics describing the interactions between neighbouring jets [1–5]. On the other hand, there are a number of researches using a limited number of jets where the objective is more fundamental and the results interpretations are made with consideration of direct interaction effects between adjacent jets. Examples are the work of Baydar [6] on two jets, or the paper of Oyakawa et al. [7] on four jets and also the researches of Arjocu and Liburdy [8] on nine elliptical jets. San and Lai [9] also studied five circular air jets in equilaterally staggered arrays with different confined ratios and several jet-to-jet spacing ratios. They investigated the optimum spacing ratio for a range of turbulent Reynolds numbers. They explained the appearance of high or low heat transfer rate by taking into account the jet interference before impingement and the jet fountain effect. Aldabbagh and Sezai [10] simulated numerically the flow and heat transfer characteristics of impinging multiple laminar square jets. They changed the jet-to-jet spacing and confined ratio. They found that the flow structure depended strongly on the jet-to-surface spacing, but the jet-to-jet spacing did not affect Nusselt number at the stagnation point. None of these works obtained any symmetry breaking. The first paper which represented a symmetry breaking was that of Thielen et al. [11]. They studied the flow field and heat transfer of multiple impinging jets for two different configurations, a square set-up and a circular set-up. They simulated a quarter of the domain and finally all the domain with different turbulence models and found an unforeseen breakup of symmetry for the square set-up geometry which is similar to the present work. Geers et al. [12] continued the research of Thielen [11] experimentally in the same laboratory. They applied several methods to identify coherent structures of multiple impingement jets and especially for the square set-up. For example, in PIV snapshots, they recognized the asymmetrical behaviour of the flow field, but the physical reasons of the symmetry breaking have not been cleared yet completely. In another work Geers et al. [13] applied liquid crystal method to obtain the temperature

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Nomenclature

d	jet diameter (mm)
e	stainless steel foil thickness (μm)
g	heat generation in the foil (W/m^3)
H	jet-to-plate spacing (mm)
h	heat transfer coefficient (W/m^2 K)
k	foil thermal conductivity (W/m K)
Nu	Nusselt number
P	pressure
q	heat flux (W/m^3)
s	jet-to-jet spacing (mm)
T	temperature (K)
t	time (s)
V	velocity
x,y	horizontal dimensions on the foil (mm)
z	vertical dimension (mm)
Greek symbols	
ρ	density(kg/m^3)
λ	air thermal conductivity at jet temperature
δ	vortex radius
Subscripts	
ad	adiabatic temperature
j	jet
f	stainless steel foil
nc	natural convection
r	radiation
θ	tangential direction

distribution produced by the previous in-line arrangement of nine jets. They observed an elliptical form of the temperature contour of the lateral jets for $H/d = 4$ and $S/d = 4$ configuration. In addition, an asymmetric velocity flow field was observed on the horizontal plane near the impingement plate. They detected a weak vortex in this plane. The vortex moves and causes an asymmetric flow with an elliptical form of the central jet impingement zone. They also detected a horse-shoe vortex around the peripheral jets and an instantaneous deformation of these jets which diminishes the Nusselt number in the impingement zone. They concluded that the asymmetric flow field obtained numerically by Thielen et al. [11] was a physical phenomenon and not due to a numerical artefact. In another work Kharoua et al. [14,15] studied numerically flow field and heat transfer of nine round turbulent jets in an in-line array. They also obtained a flow asymmetry using Large Eddy Simulation.

In this research nine jets in square in-line arrays are considered. The individual jet diameter is 3 mm and the jet-to-jet spacing ratio is two times as much as the jet diameter. The confined ratio is changed from 1 to 4 and the jet Reynolds number, based on jet average velocity and nozzle diameter, varies in the laminar region up to 880. The laminar jet was used in order to be able to explain clearly the phenomena produced due to different effects of jets interaction by removing turbulence effects. In this paper, the different factors affecting the flow structure and cooling effects will be discussed and the conditions for the symmetry breaking will be presented.

2. Measurement system

2.1. Apparatus

The configuration of confined air jets was obtained by an aluminium jet injection plate and an impingement stainless steel foil of 50 μm thickness. The central zone of the aluminium plate had a thickness of 6 mm where it was perforated by holes of 3 mm in diameter. As it is shown in Fig. 1, a complex and precise form for the impingement set-up plate was designed in order to be able to use an infrared camera in the back of the heated foil and a PIV camera with the laser sheet perpendicular to the plates (Fig. 2).

For multiple purposes the stainless steel foil was embedded in a plate of nylon. At first, the large dimensions of the heated foil in comparison with the jet diameter should be avoided, because the forced convection of the impinging jets converted to natural convection far from the stagnation zone which can disturb the flow field between the plates. In addition, in order to obtain the flow field velocity on vertical planes passing the jets centre, any obstacle between the internal confined region and the camera and laser should be avoided.

The foil has an effective surface of 5 * 5 cm^2 visualized by the infrared camera and a folded part for passing through the gap between the nylon plate and frame. Each edge of the foil is tightened by two cooper bars connected to a DC electric source to heat the foil by Joule effect.

The required air flow is supplied by a line connected to the laboratory compressed air and is controlled by two valves; one in the main line and the other attached to flow meter. A Glass tube flow meter of Brooks Instrument Company (model 1357) with ±3% accuracy was used on the air feeding pipe to the still tank. The jet Reynolds number is calculated based on the one ninth of the

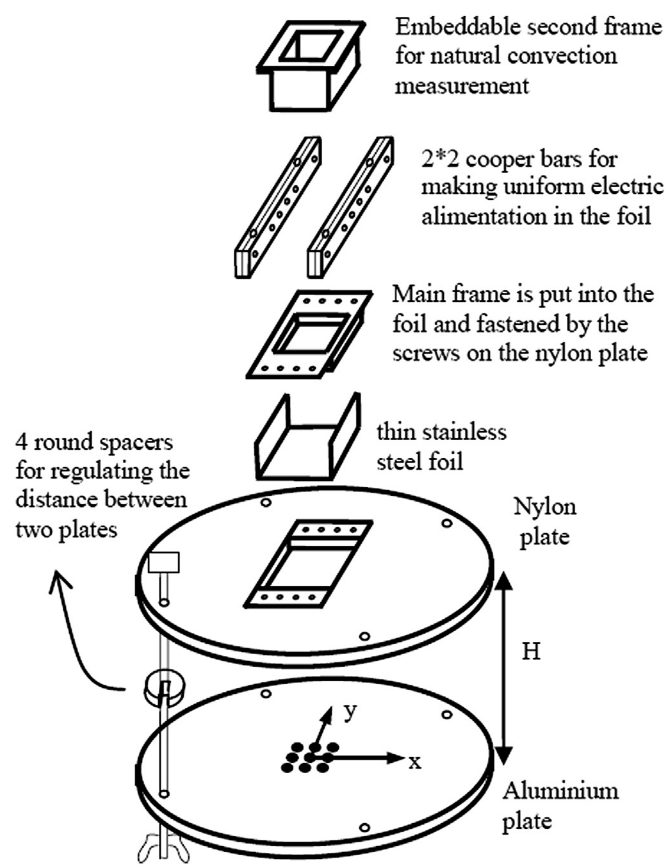

Fig. 1. Impingement and jet plates.