International Journal of Heat and Mass Transfer 117 (2018) 1019–1031

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effects of the stroke length and nozzle-to-plate distance on synthetic jet impingement heat transfer

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ARTICLE INFO

Article history:
Received 13 September 2017
Accepted 28 September 2017

Keywords:
IR Thermography
Synthetic jets
Heat transfer
Vortex ring
Trailing jet

ABSTRACT

This study focuses on the combined effect of the nozzle-to-plate distance and of the stroke length on the cooling performances of impinging synthetic jets. Infrared thermography is used as temperature transducer in conjunction with the heated thin foil heat transfer sensor to measure time- and phase-averaged convective heat transfer. All the experiments have been performed at a fixed Reynolds number equal to 5250, while different values of the dimensionless stroke length (L_0/D equal to 5, 10 and 20) and nozzle-to-plate distance (H/D between 2 and 10) have been considered. At high L_0/D, the heat transfer behaviour resembles that of a continuous impinging jet. It is characterized by a time-averaged stagnation Nusselt number maximum between H/D equal to 4 and 6 and inner and outer ring-shaped regions of Nusselt number maximum at short H/D. These two regions are replaced by a bell-shaped distribution at higher nozzle-to-plate distances. The existence of these regions is clearly observed through the phase-averaged heat transfer measurements. At short H/D, the heat transfer evolution reveals the simultaneous presence of two outer ring-shaped regions. The external outer region is ascribed to the strong coherence of the primary vortex ring, while the internal one is mainly due to the vortex rings generated by the Kelvin–Helmholtz instability along the trailing jet shear layer. At high H/D, the internal outer-ring shaped region disappears because of the weakening of the trailing jet Kelvin–Helmholtz vortex rings. In opposition, at short L_0/D, the time-averaged stagnation point Nusselt number is found to have a maximum at lower values of H/D, and no inner ring-shaped region of heat transfer maximum is observed. This region is not present, at low dimensionless stroke lengths, because of the weakness and reduced extent of the trailing jet in the flow field. Indeed, the phase-averaged measurements mainly show the heat transfer caused by the impinging primary vortex ring. Despite the weakness of the trailing jet, the outer ring-shaped region of heat transfer maximum is observed at short H/D because of the presence of a strong primary vortex ring. In addition to that, the dimensionless stroke length and nozzle-to-plate distance also affect the heat transfer fluctuations, which decrease as L_0/D decreases and/or H/D increases.

1. Introduction

Impinging jets are widely recognized and quoted in the scientific literature [1–3] as one of the most effective techniques to achieve high convective heat transfer rates, thus they are one of the preferred choices for high performance heating/cooling applications. Recent literature is focusing on the design and optimization of advanced impinging jet devices in order to apply them in specific fields such as that of electronic cooling. In particular, several literature works [4–7] deal with the exploitation of impinging synthetic jets. Synthetic jets are jets with zero-net-mass-flux, directly “synthesized” from the fluid system in which the jet actuator is embedded. Such a feature obviates the need for an external input piping, making them ideal for low cost and reduced space applications.

A synthetic jet is generated by a membrane oscillating in a cavity, which produces a periodic volume change and therefore a periodic pressure variation. As the membrane oscillates, the fluid is periodically entrained into and expelled out of the cavity through an orifice. Such a behaviour is usually modelled by using a lumped element method [8–11]. During the suction portion of the cycle, the flow field could be considered as one induced by a sink, which coincides with the orifice. On the contrary, during the ejection portion of the cycle, a vortex ring is formed nearby the orifice. Under

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.09.118

Nomenclature

Bi	Biot number, dimensionless
c	constantan specific heat, J/(kg K)
D	nozzle diameter, m
f	actuation frequency, Hz
f_s	sampling frequency, Hz
Fo_f	modified Fourier number, dimensionless
H	nozzle-to-plate distance, m
h	instantaneous convective heat transfer coefficient, W/(m^2 K)
$\overline{h}$	time-averaged convective heat transfer coefficient, W/(m^2 K)
h_φ	phase-averaged convective heat transfer coefficient, W/(m^2 K)
i	current across the foil, A
k	air thermal conductivity, W/(m K)
L	nozzle length, m
L_0	stroke length, m
$L_0^{(f)}$	synthetic jet formation stroke length, m
$\overline{Nu}$	time-averaged Nusselt number, dimensionless
$\overline{Nu_0}$	time-averaged stagnation Nusselt number, dimensionless
Nu_φ	phase-averaged Nusselt number, dimensionless
Nu'	standard deviation of phase-averaged Nusselt number, dimensionless
p_a	jet centreline exit pressure, Pa
p_{amb}	ambient pressure, Pa
$\dot{q}_j$	Joule heat flux, W/m^2
$\overline{\dot{q}_j}$	time-averaged Joule heat flux, W/m^2
$\dot{q}_k$	tangential conduction heat flux, W/m^2
$\overline{\dot{q}_k}$	time-averaged tangential conduction heat flux, W/m^2
$\dot{q}_n$	natural convection heat flux, W/m^2
$\overline{\dot{q}_n}$	time-averaged natural convection heat flux, W/m^2
$\dot{q}_r$	radiation heat flux, W/m^2
$\overline{\dot{q}_r}$	time-averaged radiation heat flux, W/m^2
r	radial coordinate, m
Re	Reynolds number, dimensionless
Sr	Strouhal number, dimensionless
t	time, s
T_{amb}	ambient temperature, K
T_{aw}	adiabatic wall temperature, K
$\overline{T_{aw}}$	time-averaged adiabatic wall temperature, K
T_w	wall temperature, K
$\overline{T_w}$	time-averaged wall temperature, K
U_0	reference velocity, m/s
u_a	centreline exit velocity, m/s
V	cavity volume, m^3
v	voltage drop across the foil, V
x	spatial coordinate in the foil plane, m
y	spatial coordinate in the foil plane, m

Greek letters

α	foil thermal diffusivity, m^2/s
δ	foil thickness, m
ε	coating paint emissivity, dimensionless
λ_f	foil thermal conductivity, W/(m K)
μ	air dynamic viscosity, Pa s
ρ	air density, kg/m^3
ρ_{foil}	constantan density, kg/m^3
σ	Stefan–Boltzmann constant, W/(m^2 K^4)
τ	actuation period, s
φ	phase, degree

certain operating conditions [12], this vortex ring convects away from the orifice to form a time-averaged jet near the jet axis [13]. The velocity temporal variation at the orifice is used to define the parameters of the problem. In particular, the stroke length L_0 is defined as the integral of the axial velocity at the nozzle exit over the ejection part of the cycle, which correspond to half of the total actuation period τ:

$$L_0 = \int_0^{\tau/2} u_a(t)dt \tag{1}$$

where u_a is the exit velocity on the jet axis; accordingly, the reference velocity can be defined as:

$$U_0 = \frac{L_0}{\tau} \tag{2}$$

from which it is evident that U_0 is a characteristic velocity over the whole cycle of period τ. Following Smith and Glezer [13], the flow field of synthetic jets is characterized by a proper Reynolds number and a dimensionless stroke length, which is equal to the inverse of the Strouhal number [14] defined as:

$$Re = \frac{\rho U_0 D}{\mu} \tag{3}$$

$$\frac{1}{Sr} = \frac{L_0}{D} \tag{4}$$

where ρ is the air density, μ is the air dynamic viscosity and D is the nozzle diameter.

Research efforts on synthetic jets for cooling applications are quite recent and are limited mostly to the last decade, apart from the pioneering work of Gutmark et al. [15]. One of the first works is due to Mahalingam and Glezer [16], who studied the synthetic jet impingement for the enhancement of the thermal performances of heat sinks. The use of synthetic jets enabled to reduce the temperature of the cooled surface from 71.5 to 36 °C and to provide, at the same time, a power dissipation of 20–40% higher than that of the same heat sink coupled with a fan with similar power input. The promising performances of synthetic jets were later confirmed by the studies of Chaudhari et al. [4]. They showed that the Nusselt number of a synthetic jet, at a Reynolds number up to 4000, is comparable to that of a circular jet impinging on a plane surface. Furthermore, they argued that the performances of synthetic jets could overcome those of circular jets at higher Reynolds number [4].

Several researches focused on the quantitative characterization of the heat transfer performances in several operating conditions [5,17–19]. In particular, heat transfer correlations for impinging synthetic jets are reported by Arik and Icoz [20] and Persoons et al. [21]. Arik and Icoz [20] established a closed form correlation to predict the heat transfer coefficient as a function of the Reynolds number, the axial distance, the orifice size and the jet driving frequency. They observed that the cooling performances of synthetic jets peak at their resonance frequencies, and that the effect of the axial distance on the heat transfer becomes more important as the jet driving frequency increases. Persoons et al. [21] proposed a general correlation for the stagnation point Nusselt number including the effect of all appropriate scaling parameters: the Reynolds number ($500 \leqslant Re \leqslant 1500$), the jet-to-surface spacing ($2 \leqslant H/D \leqslant 16$) and the dimensionless stroke length ($2 \leqslant L_0/D \leqslant 40$).