International Journal of Heat and Mass Transfer 85 (2015) 473–487

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Impingement heat/mass transfer to hybrid synthetic jets and other reversible pulsating jets

Z. Trávníček [a,*], T. Vít [b]

[a] Institute of Thermomechanics v.v.i, Czech Academy of Sciences, Dolejškova 5, 182 00 Prague 8, Czech Republic
[b] Technical University of Liberec, Studentská 2, 461 17 Liberec, Czech Republic

ARTICLE INFO

Article history:
Received 3 October 2014
Received in revised form 25 January 2015
Accepted 25 January 2015

Keywords:
Impinging jet
Reversible pulsating jet
Synthetic jet
Mass transfer
Heat transfer
Naphthalene

ABSTRACT

This study focused on round, hybrid synthetic (non-zero-net-mass-flux) jets impinging on a wall. To complete this study, two additional variants of reversible pulsating jets were investigated, namely synthetic (zero-net-mass-flux) jets and mixed pulsed jets (pulsed jets containing an additional blowing component). For comparison purposes, the continuous jet was used. The working fluid was air. The Reynolds numbers ranged from 4000 to 6000, the dimensionless stroke lengths were 14–16, and the dimensionless orifice-to-wall distances were 2–16 (both related to the orifice exit diameter of 8 mm). The experiments used flow visualization, single-sensor hot-wire measurements, and mass transfer measurements on the wall using the naphthalene sublimation technique. The local heat transfer coefficient, expressed as a Nusselt number, was evaluated using the heat/mass transfer analogy.

All tested jets exhibited relatively flat, nearly top-hat velocity profiles. An increase of the Reynolds number by an additional blowing component resulted in a heat/mass transfer enhancement. The flow oscillations (for the present geometry and driven parameters) caused a heat/mass transfer enhancement of 12–40%.

The main outcome was that the 26% larger flow rate of the hybrid synthetic jet, versus the conventional synthetic jet, resulted in an 18% increase in the heat transfer rate. These gains were caused by a partial rectification effect of incorporated fluidic diodes, without consuming any additional energy and without introducing movable parts.

1. Introduction

Submerged *impinging jets* (IJs) and impingement heat and/or mass transfer on exposed walls have been widely studied in the past. Because of their high heat and mass transfer values in single-phase flows, there are large number of applications for IJs. This has resulted in significant research. The most important early results were collected in monographs, such as the outstanding book by Dyban and Mazur [1] and the distinguished work by Martin [2]. Since then, several comprehensive reviews have appeared, e.g. [3–7]. The majority of previous studies focused on continuous (steady-flow) IJs. Despite the ability of steady IJs to achieve very high heat fluxes, further intensification of the transport processes seems possible through an incorporation of unsteadiness effects. However, pulsations do not automatically lead to enhanced rates of heat transfer; the effect can sometimes be found to increase the transfer, sometimes to decrease it, or to have a negligible effect – see, e.g. Herman [8], Herwig et al. [9], and Persoons et al. [10].

There are many ways to generate a pulsatile character of IJs, which utilize mechanical vibration/motion, alternate blowing, and fluidic oscillators with no moving parts. For example, when Page et al. [11] used a straight circular pipe nozzle with a collar to generate a self-oscillating IJ, they concluded that its use resulted in a 45% enhancement of the impingement heat transfer at a rather high orifice velocity of 153 m/s. Camci and Herr [12] used a fluidic oscillating nozzle to generate a self-oscillating IJ with a periodic flapping motion, which, based on their conclusions, resulted in a 40–70% greater heat transfer rate than that from a continuous IJ.

Liu and Sullivan [13] investigated the heat transfer to excited round IJs at relatively small nozzle-to-wall spacings. They obtained either an enhancement or reduction of the local heat transfer by controlling the development of the vortex structure by forcing the excitation frequency to be near the natural frequency of the unexcited free jet or its subharmonic frequency, respectively.

Gau et al. [14] concluded that excitation at the natural frequencies of the unexcited free jet (at the first or second subharmonic

* Corresponding author.
E-mail addresses: tr@it.cas.cz (Z. Trávníček), tomas.vit@tul.cz (T. Vít).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.01.125
0017-9310/

Nomenclature

CJ	continuous (steady) jet
D	orifice exit diameter, see Fig. 1
D_n	mass diffusion coefficient of naphthalene vapor in air
f	actuating frequency
h	local heat transfer coefficient
h_m	local mass transfer coefficient
H	orifice-to-wall distance, see Fig. 1
HSJ	hybrid synthetic (non-zero-net-mass-flux) jet
IJ	impinging jet
k	thermal conductivity of air
L_0 and L_{0A}	extruded fluid column length, defined as $U_0\,T$ and $U_{0A}\,T$, respectively
MPJ	mixed pulsed jet
Nu	Nusselt number, hD/k
r	radial coordinate, see Fig. 1
Pr	Prandtl number
Re_{SJ}, Re_{HSJ}, and Re_{MPJ}	Reynolds numbers of SJ, HSJ, and MPJ, respectively; $U_{0A}\,D/\nu$
Re_{CJ}	Reynolds number of the continuous jet, $U_{CJ}D/\nu$
Sc	Schmidt number
Sh	Sherwood number, $h_m\,D/D_n$
SJ	synthetic (zero-net-mass-flux) jet
t	time
T	time period, $1/f$
T_E	extrusion stroke duration
u_0	orifice velocity
U	velocity averaged over time
U_A	average orifice velocity defined by the integration over the entire cycle, see Eq. (3)
U_{CJ}	time- and spatial-averaged orifice velocity of the continuous jet
U_f	periodic component of the velocity related to the actuating frequency f
U_0	orifice velocity averaged over time, see Eq. (1)
U_{0A}	time- and spatial-averaged orifice velocity, see Eq. (2)
u	velocity
u'	RMS value of fluctuating velocity component
V_P	fluid volume pumped (extruded) from the actuator through its orifice during the pump stroke
V_S	fluid volume sucked back into the actuator through its orifice during the suction stroke
x	axial coordinate, see Fig. 1
ε_N	volumetric efficiency, see Eq. (4)
τ	time
ν	kinematic viscosity of air

frequency) can enhance impingement heat transfer by increasing turbulence intensity, while other frequencies can reduce turbulent intensity and decrease heat transfer.

Hwang et al. [15] investigated the flow characteristics and heat transfer to an actively controlled axisymmetric IJ. The frequency of the excitation was chosen to correspond with the natural frequency of the unexcited free jet. The harmonic or double harmonic excitation caused the promotion or suppression of vortex pairing, and measurable enhancement or reduction in heat transfer, respectively. Correspondingly, a region of maximum heat transfer moved further or closer to the orifice.

The properties of a round IJ with the target placed relatively close to the nozzle and under simultaneous excitations at two frequencies was investigated by Vejražka et al. [16]. The sensitivity of vortex roll-up processes to excitations was found to occur at Strouhal numbers ranging from 0.56 to 2.4.

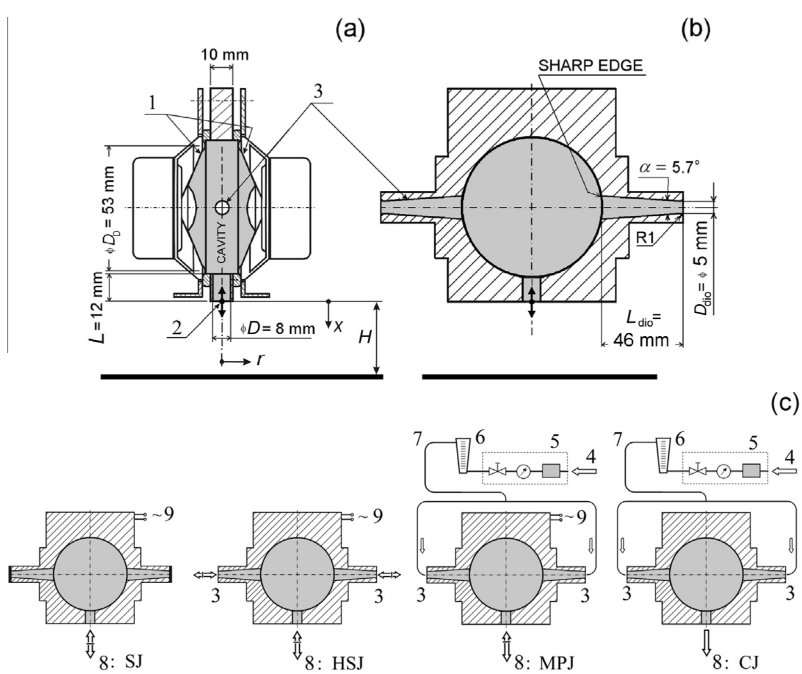

Fig. 1. Investigated actuator and configurations, (a) cross-section, (b) side view, (c) setup of four investigated variants: SJ, HSJ, MPJ, and CJ. 1: actuating diaphragms, 2: orifice, 3: fluidic diodes shaped as the conical ducts, 4: air flow supply, 5: filter and pressure regulator, 6: rotameter, 7: flexible tubing and T-shaped connecting tube, 8: generated jet, 9: sinusoidal AC supply.