International Journal of Heat and Mass Transfer 100 (2016) 634–645

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

An investigation into flow and heat transfer for a slot impinging synthetic jet

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ARTICLE INFO

Article history:
Received 14 December 2015
Received in revised form 29 April 2016
Accepted 30 April 2016

Keywords:
Synthetic jet
Impingement
Electronics cooling
Particle image velocimetry
Phase-locked transient flow

ABSTRACT

According to the latest trends in miniature consumer and military electronics, there is a need for compact cooling solutions to meet performance requirements at compact volumes. Successful technology must feature a thin profile and a small footprint area, while still removing a significant amount of heat dissipation. Impinging synthetic jets driven by a piezoelectric membrane are a promising method for cooling small-scale electronics. In this paper, we explore the thermal response of a miniature synthetic jet impinging upon a vertical heater. In addition, we study the local flow field using the particle image velocimetry (PIV) technique to couple heat transfer with fluid dynamics. Heat transfer results show that the maximum cooling performance occurs with a jet-to-surface spacing of $5 \leqslant H/D_h \leqslant 10$, which is associated with the flow consisting of coherent vortex structures. There is a degradation of heat transfer for closer jet-to-surface spacings, such as $H/D_h = 2$. This was due to the incomplete growth of the vortices, along with re-entrainment of warm air from the impinging plate back into the jet flow. There was also some warm air sucked back into the jet during the suction phase of the synthetic jet. For a fixed value of Reynolds number, cooling was improved at high Stokes numbers, but with a reduced coefficient of performance.

1. Introduction

Liquid cooling is typically applied for high-power electronics problems because of its high heat transfer coefficients. Even so, most designers would prefer to use air cooling, which has benefits such as availability, lower cost, reliability, and previous understanding in implementation. As electronic components continue to shrink over time, it is critical that thermal management methods be compact. Successful cooling technology must feature a low cost, very thin profile and a small footprint area. In this regard, synthetic jet actuators [1–4] may provide an effective solution.

Synthetic jets operate on the zero-net mass flow rate principle. Typically, they inhale and expel high speed working fluid through an orifice, producing a net positive momentum flow. Synthetic jets have been explored for flow control, low-speed maneuvering, and propulsion for traditional propeller-driven underwater vehicles [5–6]. In addition they have been used to enhance boundary layer turbulence [7]. Recently, these devices have been explored for heat transfer applications. Here, the cooling may be improved in multiple ways, such as impingement of ejected vortices onto hot surfaces [2,8–11] and enhancement of the primary cooling methodology [12,13].

Synthetic jets are mainly compatible with miniature devices, such as those on circuit boards. In these applications, free convection is insufficient, and traditional forced convection with fans is limited by volume and acoustic concerns. On the contrary, synthetic jets use the environmental fluid in their operation, eliminating the need for different or complex plumbing [14].

Recently, He et al. [4] compared the cooling effect of a mesoscale synthetic jet to a steady impinging jet. They found that synthetic jets can provide 20% enhancement over a steady jet for the same amount of ejected mass. There was also a significant benefit when comparing performance at the same exit speed and diameter. Different numerical studies on impinging synthetic jets also concluded that synthetic jets can lead to considerable improvement of the local heat transfer from heated surfaces, as strong mixing disturbs the surface thermal boundary layer [15–16].

Cooling performance of an impinging synthetic jet is highly sensitive to the distance between the nozzle exit and the wall [2,4,10,11,17]. In the case of impinging synthetic jets, the flow structure also depends on this distance. This variable determines the propagation distance of the vortices, the level of jet confinement, and the amount of recirculation. Typically, the vortex pairs

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.04.115
0017-9310/

remain coherent for some distance before decaying. This distance depends on how close the impingement surface is to the orifice, H, as well as the stroke length, L_0 [10,11], which is related to the amount of fluid ejected per stroke.

Gillepsie et al. [9] and Pavlova and Amitay [10] each experimentally studied the influence of jet-to-surface spacing on impinging synthetic jet heat transfer. In each study, the peak heat transfer occurs for a nondimensional spacing from $4 < H/D < 11$. However, relatively few studies have considered smaller distances, where $H/D < 4$ [2,11,16]. Here, the cooling performance degrades by approximately 40% [2], but the fundamental mechanism for this behavior is not well understood.

Fig. 1 depicts a slot synthetic jet impinging on a flat vertical heater, which has been utilized in this work. The synthetic jet used in the present study consists of a piezoelectric actuator and a circular plate, which are attached along most of their perimeter using an elastomeric material. In one small section of the perimeter, there is a rectangular opening, which has an aspect ratio of 8. This rectangular orifice is the sole location where internal fluid may interact with the outside environment. In operation, the piezoelectric material is actuated by an AC power source at specific frequency, which inhales and exhales air at the opening. Through appropriate selection of the actuator frequency and geometry, a specific jet flow rate can be obtained. In application, the lower frequency limit usually relates to the lowest operating frequency where the jets produce heat transfer exceeding natural convection. The upper frequency limit corresponds to a fundamental frequency for the actuator, usually a structural resonance for the piezoelectric diaphragm or the Helmholtz frequency for the cavity. At one of these conditions, the exit velocity reaches its peak value.

Earlier studies of this actuator primarily focused on the heat transfer response, leaving the underlying mechanisms behind its performance unclear. Thus, we have examined the flow physics for this device using particle image velocimetry (PIV). We have conducted both time-averaged and phase-locked flow analysis in order to understand the driving mechanisms that affect the heat transfer of free and impinging slot synthetic jets. Here, we summarize the goals of this study:

- Find the fundamental frequency and best operating conditions of the synthetic jet by measuring the diaphragm deflection.
- Examine the flow mechanisms of both the free and impinging slot synthetic jet, particularly at the fundamental frequency.
- Determine the reason for the significant degradation of heat transfer at small orifice-to-plate ratios, specifically by investigating the effect of jet-to-surface distance on the flow field at $H/D_h = 2$, 5 and 10.
- Investigate the wall jet profile of the synthetic jet, comparing it with laminar and fully turbulent profiles.
- Calculate the coefficient of performance (COP) to find the best operating condition for this slot synthetic jet.

First, we present experimental measurements of actuator deflection, which helps in selection of the optimal frequency. Second, we present PIV measurements of the flow dynamics for free and impinging synthetic jets. We consider a range of different orifice-to-impingement surface distances, as well as two different operational frequencies. Third, we present the corresponding heat transfer and coefficients of performance, and we discuss their implications.

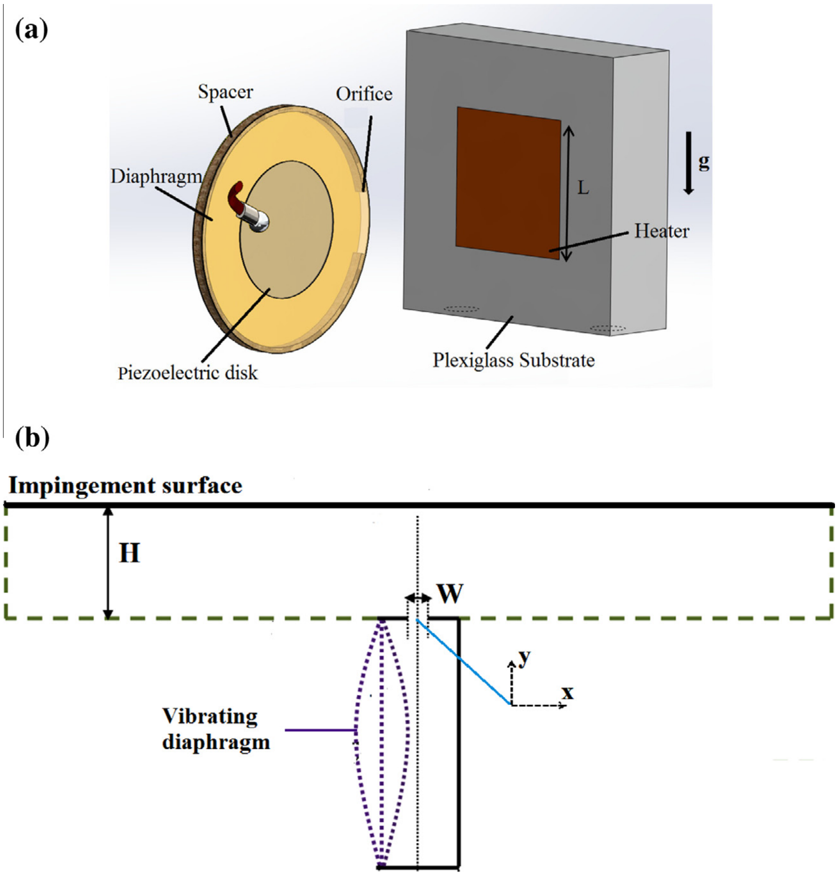

Fig. 1. (a) Isometric view of an impinging slot jet and (b) Schematic of a slot impinging jet.