Applied Thermal Engineering 106 (2016) 881–889

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

An investigation into flow and heat transfer of an ultrasonic micro-blower device for electronics cooling applications

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HIGHLIGHTS

- We study the mechanical, thermal, and fluid response of an ultrasonic micro-blower.
- Optimal cooling occurs for jet-to-surface spacings of 15–30 jet diameters.
- The flow differs from a steady jet over the first 10 diameters past the exit.
- The best COP occurs at a frequency above the resonant condition.

ARTICLE INFO

Article history:
Received 1 March 2016
Revised 23 April 2016
Accepted 15 June 2016
Available online 16 June 2016

Keywords:
Ultrasonic blower
Impingement
Electronics cooling
Particle image velocimetry
Synthetic jet
Thermal management

ABSTRACT

As compact electronics increase in functionality, new electronics cooling approaches must be more effective, and they must be lower in form factor. In this paper, we investigated the cooling performance of a miniature ultrasonic micro-blower impinging upon a vertical heater. We studied the temperature response at different operating conditions, determining the optimal thermal conditions. We further examined the local flow field using the particle image velocimetry (PIV) technique at the same operating conditions, providing explanations for the heat transfer response in terms of the fluid dynamics. Heat transfer measurements show that the maximum cooling performance occurs at a jet-to-surface spacing ratio of $15 < H/D < 30$, and the performance slowly decays when the jet is located further away. The preferred operating frequency of the piezoelectric cooling device occurs at an ultrasonic frequency of over 20 kHz, meaning that this device can function outside the human hearing range. The PIV results demonstrate that the jet profile in the near field deviates significantly from a traditional turbulent free jet. In the far field, it nearly matches the self-similar, fully-developed jet profile. The jet cooling performance is sensitive to the frequency, with the thermal performance dropping by a factor of six when varying by less than 1 kHz from the peak. At the optimal heat transfer condition, the coefficient of performance is measured at approximately three, which is lower than that of some synthetic jets.

1. Introduction

Modern electronics have been decreasing in size for decades, so their cooling systems must continually improve in efficiency at reduced sizes too. In particular, compactness is vital, which is challenging, because typical thermal management uses relatively large fans and heat sinks. Powerful cooling techniques such as advanced liquid cooling, additional coolant and structures are required, somewhat counteracting the improvement with liquid heat transfer. Ideally, thermal management solution should be economical, low volume, and localized on the powered devices. Fortunately, some recent advances in synthetic jet devices [1,2] may provide a potential solution in both air and liquids cooling.

Synthetic jets use an oscillating structure near an orifice, which produces a periodic jet outflow and sink inflow. When averaging over time, this leads to an axial jet, which can be directed towards a powered device. Unlike traditional impingement cooling, the jet is supplied by ambient fluid, as opposed to an additional coolant. Newer actuators also have more compact structures [2], potentially reducing volume further.

Over the past 30 years, a number of researchers have examined the thermal performance of synthetic jet and similar micro-flow devices. Early studies with pulsating jets increased convection by a factor of four [3,4], while later piezoelectric devices produced similar performance in a smaller planform [5]. Improved actuator

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http://dx.doi.org/10.1016/j.applthermaleng.2016.06.094
1359-4311/

structures led to higher jet speeds, leading to heat transfer enhancement by 10–15 times [2,6,7]. Most synthetic jets have used circular exits, while a recent design by Ghaffari et al. [2] applied a slot jet with an aspect ratio of 8:1 and a rectangular cross section. In addition, the driving piezoelectric disk was aligned in-line with the jet axis, resulting in high speeds while remaining at a compact size.

One of the prime limitations of synthetic jets is their high noise output. Piezoelectric designs generate rapid diaphragm motion, producing a high velocity jet stream that mixes with the ambient air. Unfortunately, effective synthetic jets often require operation at the actuator resonant frequency to maximize jet exit velocity, coinciding with the highest noise output [8–10]. For example, Arik [11] observed that a synthetic jet with a 1-mm orifice achieved its peak jet velocity of 90 m/s at a resonant frequency of 3.6 kHz. However, the corresponding acoustic intensity was 73 dBA, comparable to loud appliances like vacuum cleaners and leaf blowers.

There are some existing methods that can decrease the noise level of synthetic jets. First, designers may use slightly off-resonant actuation conditions to produce a lower noise, but this also reduces the heat transfer [12]. Second, a new actuator topology can be developed to reduce noise generation without decreasing the peak jet velocity. Jabbal and Kykkotis [13] designed a synthetic jet with two chambers and a corrugated-lobed orifice, which had a 20 dB (or 32%) noise reduction compared to a single chamber, circular orifice device at the Helmholtz frequency. This new device only had a 7% reduction in peak jet velocity, while maintaining the same discharge area. However, it required a more complex structure that may be challenging to miniaturize further.

Another intriguing solution is to operate the jet at a frequency higher than the audible level for humans, which is approximately 20 kHz. Fig. 1 shows an image of one such ultrasonic piezoelectric micro-blower, manufactured by Murata Manufacturing Co., Ltd. [14]. This device uses two cavities, which permits inlet and exhaust flows through orifices of differing sizes and locations.

Fig. 2 shows how the jet flow is generated. As with many synthetic jets, the primary driver is a piezoelectric disk, which is located on one surface of the inner cavity. An alternating current is applied in a sinusoidal waveform to the disk, which expands and contracts in turn. During the motion, this disk pushes an attached diaphragm, changing the volume of the inner cavity. This pulls fluid into and out of an orifice along the centerline of this cavity. Unlike with most synthetic jets, the inflow to the jet is primarily from the back of the device, where it enters the outer cavity along its circumferential perimeter. In the disk contraction phase, shown in Fig. 2a, the diaphragm is pulled back, expanding the inner cavity and sucking air into it through its orifice. In the expansion phase, shown in Fig. 2b, the diaphragm moves to contract the inner cavity, ejecting air through the orifice and the exhaust nozzle along its centerline. This process continuously repeats at the frequency of the piezoelectric vibration. The combination of alternating jet exhaust and sink inflow generates an axially-outward flow. Additional information about the device design is provided by the manufacturer [14]. The dual-cavity design is unique, allowing air inflow from a different location than the exhaust nozzle. In contrast, most traditional synthetic jets use the same orifice for inflow and outflow.

Fukue et al. [1,15] investigated the cooling performance of this miniature piezoelectric ultrasonic micro-blower. They reported that this device can generate airflow at speeds of about 20 m/s, and it can be used for cooling electronics in narrow passages. They also performed CFD modeling of the response, assuming the micro-blower works like a continuous jet. However, this assumption was not verified directly.

In a number of earlier studies of this device, the primary focus was its bulk 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 time-averaged flow analysis in order to better understand the driving mechanisms that affect the heat transfer of free and impinging jets. We summarize the goals of the current study:

- Find the best operating conditions of the ultrasound micro-blower by measuring the diaphragm deflection.
- Examine the flow mechanisms of both a free and an impinging blower jet, particularly at the best operating frequency.
- Examine the heat transfer performance of the impinging micro-blower jet and compare to other synthetic jets and continuous jets.
- Calculate the coefficient of performance (COP) to find the best operating condition for this micro-blower.

First, we present experimental measurements of actuator deflection, which helps in the selection of the optimal frequency. Second, we present PIV measurements of the flow dynamics for free and impinging jets. Third, we present the corresponding heat

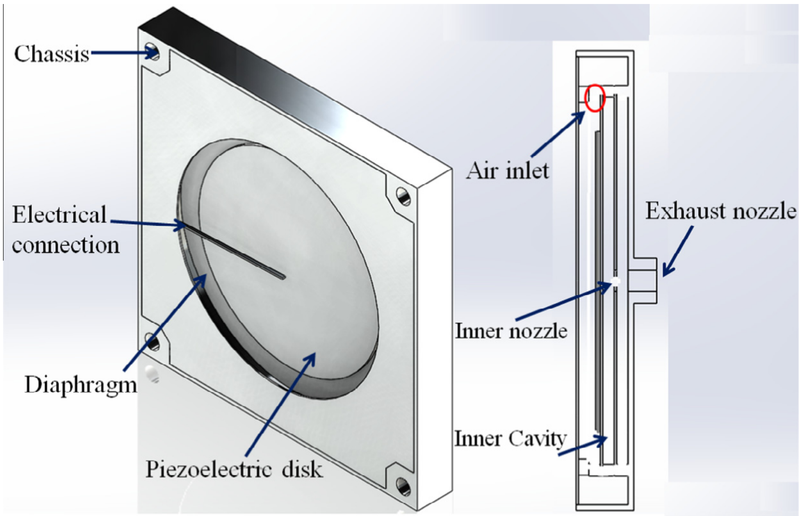

Fig. 1. Schematic of the piezoelectric ultrasonic micro-blower (footprint area of 20 mm × 20 mm; thickness of 2 mm; two millimeter-scale ports to the inner cavity for inflow and exhaust).