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Numerical modelling of electrohydrodynamic airflow induced in a wire-to-grid channel

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A B S T R A C T

Electrohydrodynamic (EHD) airflows provide a means of generating air motion by a gas discharge across two electrodes without the need for moving parts. A two-dimensional numerical model for a wire-to-grid EHD air blower is developed, validated against previous data, and used to investigate the influence of key design parameters on blower efficiency, including the emitter wire diameter, the blower height, the locations of the collecting surfaces and grid wires, and the collecting grid density. The optimal locations of both collectors from the corona wire are determined based on blower efficiency at a fixed operating power, resulting in improvements in the average outlet velocity between 9% and 15%, depending on blower thickness. The presence of the grid has a strong influence on the electric field distribution and increases the blower performance, with higher flow, lower operating voltage and reduced blower size. An investigation into the effect of grid density reveals that using coarse collecting grids is generally beneficial, leading to higher efficiency with lower pressure losses.

1. Introduction

Due to its low cost and availability, air remains a widely used cooling medium in many important thermal management applications, including engine and turbine blades in the aerospace industry and a wide range of vehicle heat exchangers in the automotive industry [1]. The required cooling from a surface is usually achieved by convective heat transfer to air, whose motion is either generated passively (via thermal gradients) or through the continual input of energy to create a moving air stream. Despite a number of promising innovations using liquid on-chip cooling, Aquasar (IBM) [2], and dielectric liquid immersion technology [3], convective heat transfer to air as it flows over a heat sink is also still the most common cooling method for microelectronics. In such cases, the air is usually pumped over the hot electronic components by conventional rotary fans, where fan speeds are controlled to maintain appropriate CPU temperatures [4,5]. However, increased heat generation in microelectronic devices and the demand for ever smaller portable devices, where the performance of rotary fan-based cooling technology degrades as device dimensions reduce, has led to a critical need for efficient, compact thermal modules that provide acceptable acoustic levels, good reliability and high cooling density [6–8].

Wang et al. [7] recently compared the performance of a number of alternative air pumping methods for microelectronics cooling, including piezoelectric fans, synthetic jets and electrohydrodynamic (EHD) air pumps. They concluded that although piezoelectric fans and synthetic jets are potentially useful for cooling of localized hot-spots, they are generally unsuitable for consumer electronics due to their inability to generate sufficient air through the electronics they are cooling. In contrast, they found that EHD air movers offer important advantages over rotary fans due to their silent operation, reduced energy consumption, smaller volume requirements, and higher heat transfer performance on small form factor electronics.

EHD air pumps (also known as Electrostatic Fluid Accelerators) convert electrical energy into kinetic energy of the moving air stream by applying a high voltage electric field between a sharp electrode and a grounded surface in the air. This leads to ionization of air molecules, which are then accelerated by the electrostatic forces to create a moving air stream known as an ionic wind (also referred to as a corona or an electric wind). The ionic wind is not a new phenomenon and it was first reported by Francis Hauksbee in 1709 [9]. In the mid twentieth century, the basic theory of EHD

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pumps was developed, and the mechanism of gas movement under the ionic wind effect was investigated by Stuetzer [10] and Robinson [11]. The latter showed that the gas velocity depends linearly on the applied voltage and varies with the square root of the current. Although Marco and Velkoff [12] presented the first comprehensive investigation of the potential of EHD air pumps for convective heat transfer in 1963, and this has been extended by a number of studies subsequently [13–17], it is only in the last decade or so that it has received attention as a potential alternative to rotary fans in microelectronics cooling. EHD air pumps were also investigated as secondary flow generators in the presence of the bulk airflow to disrupt the thermal boundary layer for heat transfer enhancements [18–21].

A number of recent studies have investigated the effect of various design parameters affecting the emitter-to-electrode configuration on the efficiency of, and convective heat transfer generated by, EHD air pumps. Kalman and Sher [22] were the first to investigate the effectiveness of an optimized electrostatic blower, and explore its possibility to be used as a cooling system for electronic components in thermal management applications. The EHD blower consisted of a positively charged wire electrode, 0.5 mm in diameter, stretched between two grounded inclined wings located over a heated plate. They found that the optimized EHD blower can enhance the heat transfer by a factor of more than twofold compared with free convection mechanism. This study was later extended by Rashkovan et al. [23] with a wire electrode diameter reduced from 0.5 mm to 0.2 mm to increase the strength of the electric field and resulted in a 50% increase in the heat transfer rate over the previous EHD device. Moreau and Touchard [24] later presented a comprehensive investigation into the ionic wind speed induced by a needle emitter through a tube, considering the effect of voltage polarity and collecting electrode geometry (both grid and ring configurations) as well as electrode gap and tube diameter. They found that generally the ionic wind speeds produced by a positive corona are larger than with a negative one and that using a grid as a collecting electrode is more efficient than a ring; they also found that the grid density has an important influence on ionic wind generation.

Tsubone et al. [25] and Fylladitakis et al. [26] presented experimental and numerical studies to explore the benefits of design optimization of EHD air pumps. The former used a design based on a partially covered wire to parallel plates channel and explored the effect of channel width, the number of emitter wire electrodes and the distance between the emitter wires on both the ionic wind velocity and corona current. Their results demonstrated ample scope for design optimization in order to maximize air speed, flow rate and mechanical power per corona input power. Fylladitakis et al. [26] considered the optimization of an EHD air pump for cooling high-power electronics by varying electrode gap and collecting grid density parameters for two EHD air pump prototypes of multi needle-to-grid and multi wire-to-grid configurations. Experimental results of the final optimal configuration demonstrated that the fabricated EHD air pump offered promising performance for practical applications. The first practical and successful integration of an EHD air pump into a real-world electronic application has been performed by Jewell-Larsen et al., in 2009 [6], with replacing the conventional fan of a high performance laptop by a retrofitted EHD cooling system. The EHD air pump exhibited a promising cooling performance with lower installation size and acoustic level, compared to the traditional fan.

The numerical modelling of the corona discharge and the resulting ionic wind has been performed by many studies and successfully validated against experimental findings [18, 19, 27–29]. Due to the wide range of the geometrical parameters that strongly affect the discharge process and the performance of the EHD airflow devices, numerical studies offer a great potential to explore various design parameters and save cost and time. The motivation of this work is based on the ongoing attention to improve the EHD flow technology to be an applicable cooling solution for advanced microelectronics. Design optimization is one of the critical factors that determine the performance of the EHD systems to be adopted for thermal management of real world applications. In this paper, a two-dimensional numerical model of a wire-to-grid EHD channel configuration is developed and validated using a finite element based method (employing COMSOL Multiphysics) against a range of experimental and numerical data. Based on thermal management requirements and from a design perspective, a comprehensive investigation and analysis into the influence of several geometrical parameters on the EHD blower efficiency is performed and an optimal configuration is proposed. These parameters are studied for different blower heights and include the emitter wire diameter, the electrode gap between the emitter and the grid, the collector location at the blower walls, and the collecting grid density.

2. Numerical modelling

2.1. EHD governing equations

The electric field intensity, $\vec{E}$, and the electric potential, V, are defined by Poisson's equation as,

$$\vec{\nabla}.\vec{E} = \nabla^2 V = -\frac{q}{\varepsilon_0} \tag{1}$$

where q is the space charge density (C/m^3) and ε_0 is permittivity of free space ($= 8.854 \times 10^{-12}$ C/V.m).

The charge transport equation that couples the electrostatic and Navier-Stokes equations for the airflow is derived by combining the following three equations:

i. The electric current density equation,

$$\vec{J} = \mu_p \vec{E} q + \vec{U} q - D\, \vec{\nabla} q \tag{2}$$

where μ_p is the air ion mobility in the electric field (m^2/V.s), $\vec{U}$ is the velocity vector of airflow, and D is the diffusivity coefficient of ions (m^2/s).

The three terms on the right side of Eq (2). represent the charge conduction (the ion movement due to the electric field), charge convection (transport of charges by the airflow), and charge diffusion, respectively [30].

ii. The continuity equation for electric current,

$$\vec{\nabla}.\vec{J} = 0 \tag{3}$$

iii. The conservation of mass equation,

$$\vec{\nabla}.\vec{U} = 0 \tag{4}$$

Combining equations (2) and (3) and using the continuity equation (4) gives the charge transport equation,

$$\vec{\nabla}.\left(\mu_p \vec{E} q - D\, \vec{\nabla} q\right) + \vec{U}.\vec{\nabla} q = 0 \tag{5}$$

Since the value of the air velocity ($\vec{U}$), which represents the charge convection term in Eq. (5), is very small compared with the drift velocity of ions ($\mu_p \vec{E}$) in the charge conduction term, it can be