

Mechanisms of power dissipation in piezoelectric fans and their correlation with convective heat transfer performance

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ABSTRACT

Piezoelectric fans offer an intriguing alternative to conventional rotary fans for thermal management of portable and wearable electronics due to their scalability, low power consumption and simple mechanical construct. We report a combined experimental and modeling study to help elucidate power dissipation mechanisms in piezoelectric fans. To analyze contributions from these different mechanisms, mathematical models that account for mechanical hysteresis, dielectric loss and viscous damping from generated air flows are used in conjunction with vibration amplitudes and power consumption data obtained experimentally from piezoelectric fans of different blade lengths, thicknesses and mass distributions. In parallel, we perform experiments on convective heat transfer coefficients and aerodynamic forces acting on surfaces that are oriented perpendicular with respect to fan-induced air flows. These experiments establish that the portion of power dissipation ascribed to air flows correlates well with the heat transfer performance and aerodynamic force. A power ratio, defined as the fraction of the air flow power to the total power dissipation, is then proposed as a useful indicator of the power efficiency of the piezoelectric fans. We show that the power efficiency exhibits a peak at a particular bias voltage amplitude, and provide a guideline to determine this optimum voltage. Lastly, we relate the air flow power to the blade's geometrical parameters to facilitate systematic optimization of the blades for both cooling performance and power efficiency.

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1. Introduction

Recent development in portable and wearable electronics with limited access to power sources has led to challenges in their thermal management. Conventional rotary fans are difficult to scale down and are power inefficient when miniaturized. Piezoelectric fans are a promising alternative because of their simpler structures, less noise, and lower power consumption [1–3]. Piezoelectric fans typically consist of flexible blades attached to ceramic actuation beams. When operated near its resonance frequency, the blade undergoes large-amplitude vibrations, which in turn generate net airflows in the forward direction and induce convective heat transfer.

The fluid dynamics of vibrating beams has been widely investigated in the past. For example, Kim et al. [4] studied flow fields generated by vibrating beams using the particle image velocimetry and smoke visualization techniques. Eastman et al. [5] studied thrust forces generated by the motion of an oscillating cantilever

beam over a wide range of Reynolds numbers and proposed a correlation relating the thrust to the vibration amplitude and frequency. The effects of solid sidewalls on the amplitude and resonance frequency of a piezoelectric beam were examined by Eastman and Kimber [6]. Interactions among piezoelectric fans operating in the vicinity of each other was studied in [7].

Past studies [8–16] also examined the effects of various parameters on the heat transfer performance of piezoelectric fans. These parameters include the gaps between blade tips and surrounding surfaces; the relative thickness and mechanical modulus of piezoelectric and blade materials; the blade length and width; and the amplitude and frequency of vibration. Huang et al. [17] used 3D numerical simulation in conjunction with an inverse design technique to determine the optimum position of a fan blade for maximum heat transfer performance. A similar approach was used to find the optimal positions and phase angle of a dual piezoelectric fan assembly [18]. Petroski et al. [19] attempted to tailor air flows created by piezoelectric fans using complex geometric features to improve cooling performance. Local and average mass transfer coefficients were measured using the naphthalene sublimation technique in [20].

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Power consumption is an important aspect of piezoelectric fans. Liang et al. [21] reported an impedance method for calculating electrical power dissipation in piezoelectric beams. Cho et al. [22] extended this work and developed a five-port equivalent electric circuit model, where power dissipation in piezoelectric bimorphs was represented in terms of equivalent electric impedances. Wait et al. [23] experimentally studied the electromechanical coupling factors (EMCF) of piezoelectric fans and concluded that the highest EMCF could be achieved at the 1st resonant natural frequency as opposed to higher-order resonant frequencies. The EMCF is a measure of the efficiency of the fans in converting electrical energy to mechanical energy.

Electrical losses, however, represent only a portion of power dissipation in piezoelectric fans. Mechanical losses due to mechanical hysteresis in shims and interfacial bonding materials, for example, can be appreciable. In a related study, Sheu et al. [24] observed that the hardness and thickness of bonding materials can have significant effects on vibration amplitudes.

Despite many past studies on piezoelectric fans, detailed understanding of their power dissipation mechanisms and power efficiency has been rather lacking. In the present work, we aim to improve our understanding of the power efficiency of convective cooling by piezoelectric fans and provide a guideline for selecting optimal fan operating bias voltage for maximum power efficiency.

We examine three main sources of power dissipation: dielectric loss within a piezoelectric actuator; mechanical hysteresis loss; and viscous dissipation in induced airflows. We use independently validated mechanical models together with experimentally measured data to estimate the contribution from each source of power dissipation. Convective heat transfer coefficients and normal forces due to the fan's operation are then correlated with the component of power directly related to induced air flows, referred to as air flow power. An optimal bias voltage for maximum power efficiency, as characterized by the ratio of the air flow power to the total consumed power, is then determined using our model. Lastly, we relate the air flow power, and hence indirectly the heat transfer coefficient and normal force, to the blade's geometrical parameters to facilitate systematic optimization of the blades for both cooling performance and power efficiency.

2. Experimental setup

We use commercial piezoelectric fans (Steminc, Inc.) modified in-house for the present study. The piezoelectric actuator in each of the fans consists of two 185 μm -thick piezoelectric ceramic film ($\text{Pb}(\text{Zr}_{0.53}\text{Ti}_{0.47})\text{O}_3$; PZT - 4) with a 142 μm -thick copper shim sandwiched in between. The other geometric parameters of the piezoelectric fans (Fig. 1) and their natural resonant frequencies are listed in Table 1. The blades of different thicknesses are made by bonding different numbers of Kapton sheets, each with a thickness of 0.127 mm. The blade width w_b is kept 12 mm. The actuators are clamped at the base to realize a cantilever configuration, as confirmed optically from the negligible slope of the actuator base during operation.

We use a high-speed camera with a maximum frame rate of 16,000 fps and a video zoom lens to measure the amplitude of both blade and actuator vibrations. The uncertainty in the measured vibration amplitudes is estimated to be approximately 7 μm , repre-

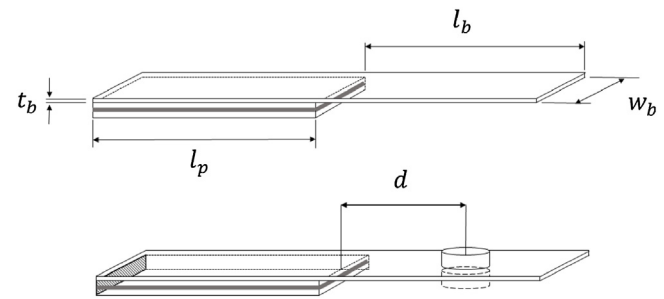


Fig. 1. The length (l_b), the thickness (t_b) and the location of the center of mass (d) of the blades are varied in different sets of experiments. The width of the blade is fixed.

senting less than 5% of the typical values of the measured vibration amplitudes of the actuator. The mechanical hysteresis and structural damping in piezoelectric fans is characterized in a vacuum chamber at a pressure of approximately 1 cm Hg where the effects of aerodynamic damping can be neglected [25].

A function generator (Model 33220A, Agilent) is used to generate small amplitude (0.4 V–2 V) pure sinusoidal voltage waves, which are then amplified using a high-voltage amplifier with a current monitor output (Model PZD700A, TREK). The uncertainty due to voltage and current measurements are estimated to be 2 V and 0.041 A, or approximately 2% and 7% in typical measurements. The total power dissipation in a piezoelectric fan is obtained by numerically integrating the product of the measured voltage and current profiles (sampling rate 5000 Hz), with an estimated uncertainty of 0.5 mW, approximately 8% of typical measured powers.

Fig. 2a schematically shows our experimental setups to characterize the heat transfer coefficient and normal aerodynamic force on flat surfaces. Convective heat transfer coefficients over a flat surface are measured using an aluminum block (5 cm \times 5 cm \times 0.48 cm) that has a thin-film electric heater of the same lateral dimensions attached to its back. The aluminum block-heat assembly is enclosed in a Styrofoam insulation to minimize parasitic heat loss through the side and back surfaces. The front surface of the aluminum block is coated with a black paint (Kylon Colormaster No.1602) to achieve uniform controlled emissivity. Five type k thermocouples are attached to the aluminum block at four corners and in the middle to monitor its temperature (Fig. 2b). The spatial variations in the measured temperature rises, relative to the ambient temperature, are less than 5%. For all the experiments reported in the present manuscript, we keep the distance of the fan blade tip to the heated surface constant at 20 mm. The major paths of heat loss are conduction through the insulation layer on the back and side surfaces and radiation from the heated front surface. Heat loss is thus estimated by knowing the emissivity of the coating on the front surface and measuring the temperature profile of the back and side surfaces, using $Q_{\text{loss}} = \int k_{\text{ins}} (T_1 - T_0(x,y)) l \, dS + [\epsilon \sigma S (T_s^4 - T_\infty^4)]$, where ϵ , σ , k_{ins} , l , S , T_0 , T_s and T_∞ are the emissivity of the coating on the aluminum surface (0.95), the Stephan-Boltzmann constant, the thermal conductivity of insulation, the length of heat transfer (insulation thickness), the area of the heated surface, the insulation temperature, front surface temperature and the room temperature respectively. The estimated total heat loss rate through the insulation is approximately 13%

Table 1
Experiment variables.

Control variable	l_b (mm)	t_b (mm)	d (mm)	Frequency (Hz)	Voltage amplitude (V)
blade length	63–20	0.26	–	30–188	70–140
blade thickness	32	0.13–0.5	–	35–119	70–140
location of mass	32	0.26	0 (no extra mass) - 17	62–20.7	50–190

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