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Experimental study on the heat transfer of heat sink with bio-mimetic oscillating foil ☆

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ABSTRACT

This paper experimentally investigates the heat transfer performance and characteristics of a heat sink with bio-mimetic oscillating foil. The oscillating foil is driven by a novel mechanism of grooved cam with linkage. The air flow is drawn into a rectangular duct through the motion of the bio-mimetic oscillating foil. Various heat sinks were set at the outlet of the duct to study the thermal performance. Two types of grooved cams were designed to obtain different angular velocity profiles for the oscillating foils. The angular velocity was specified as fast forward/slow backward and sinusoidal patterns. Foils with three flexural stiffness values were utilized in the study. The averaged velocity at the inlet was measured to estimate the Reynolds number and Strouhal number. The effects of configuration of heat sink design with oscillating foil were also under investigation. The junction temperature of the heat sink was measured to obtain the effective thermal resistance. Results show that the angular velocity profile and flexural stiffness of the oscillating foil have a significant effect on the thermal performance of the heat sink.

1. Introduction

Due to the development of electronic technology, a continuing need for handling cooling systems for electronic devices has driven various novel designs. For example, LED uses cooling modules with natural convection systems, and high heat flux devices employ phase change liquid cooling systems. However, most electronic devices use electric fan cooling of forced convection because of cost issues. Piezoelectric materials have been discovered for years, and are widely used for actuator and sensor components because they possess both electrical and mechanical characteristics. Piezoelectric fans are a relatively new application for cooling, Toda [1,2] first proposed the concept of PZT fans for a cooling system because of their small size, low power consumption, and long lifetime. Piezoelectric fans can be fabricated in small sizes to fit applications that require cooling. In cases where rotary fans are ineffective for dissipating heat or where local cooling is required, the piezoelectric fan provides an effective and reliable alternative approach to heat transfer.

In most studies, piezoelectric fan is usually made by bonding a PZT plate to a plastic sheet or metal sheet. As the operating voltage to the PZT plate is alternating, the PZT fan is excited to flap backward and forward. Acikalin et al. [3] reported that piezoelectric fans are a feasible technology for cooling electronic devices because of their small size, low noise, and low energy consumption. Acikailn et al. [4] developed a single PZT fan cooling system that can be used to cool a heated surface. Their system showed that the enhancement in the heat transfer coefficient can reach up to 375% compared with natural convection. Recently, a number of studies on PZT fans used for cooling applications have been presented for both liquid cooling [5,6] and air cooling [7,8]. Kimber and Garimella [9] proposed a measurement method to investigate a piezoelectric fan mounted perpendicular to a constant heat flux surface and predicted the thermal performance across the entire range of fan dimensions, vibration frequency, and amplitude. The resonance frequencies of the six piezoelectric fans range from 60 Hz to 250 Hz. The experimental results show that the influence of vibration frequency on the heat transfer rate is larger than that of the vibration amplitude. Wait et al. [10] simulated and measured the flows of piezoelectric fans with three different blade lengths to compare the effects of different resonance frequencies on flow field and energy consumption. Yoo et al. [11] researched the influences of the dimension and the material on a PZT fan, finding that phosphor bronze and aluminum are also good choices for a PZT fan. However, it is difficult to implement piezoelectric fans in electronic cooling applications because piezoelectric fans are only suitable for small power components and is used only for small expanded areas with a single piezoelectric fan. Buermann et al. [12] investigated optimal designs of two symmetric piezoelectric fans for driving fluid through an analytical Bernoulli-Euler model as well as a finite element (FE) model of the composite piezo-beam. They found that the optimal values of patch-to-beam ratio, patch location, and patch-to-beam thickness are different depending on whether the optimization criterion is posed in terms of maximal electromechanical coupling factor and the maximal tip deflection and rotation at

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Nomenclature

b	thickness of the foil (m)
D_h	hydrodynamic diameter of the duct (m)
E	Young's modulus of foil (GPa)
e	porosity of fin array
f	oscillating frequency (Hz)
h	height of foil (m)
I	inertia moment of cross-section of foil (m^4)
l	total excursion of the trailing edge of a rigid foil during oscillation (m)
$\dot{Q}$	heating power (W)
Re	time-averaged Reynolds number
R_{th}	effective thermal resistance of heat sink (°C/W)
St	Strouhal number
T_a	ambient temperature (°C)
T_j	junction temperature of the heat sink (°C)
U_{avg}	the averaged velocity along the duct (m/s)
ρ	density of air (kg/m^3)
μ	viscosity of air (Pa.s)
Δ	difference

resonance. Ma et al. [13] designed an innovative multiple vibrating-fan cooling system actuated by both piezoelectric force and magnetic force. In the cooling system, four magnetic fans and one PZT fan were vibrated simultaneously by the two forces. The effects of configuration, location, and heat sink design were also under investigation by Abdulah [14,15], and by Li et al. [8]. The angular velocity profile is not under control during the flapping of piezoelectric fan while the angular velocity is important in driving air flow. This has been verified in bio-mimetic oscillatory foils.

Bio-mimetic oscillatory foils have been studied for its high propulsive efficiency and its potential applications in fluid-driven machines. The research of oscillating foils, involving the flow field structure, velocity, propulsive efficiency, and interaction between fluid and foil has attracted extensive research for the past decades. Koochesfahani [16] and Fremuth [17,18] conducted early flow field observations behind oscillating foils undergoing uniform stream. Heo et al. [19] studied the effect of stiffness on propulsion with an artificial caudal fin with a piezoelectric actuator. It was found that an appropriate stiffness of the foil caused a propulsion increase by about 20% and reduced Strouhal number by about 15% compared with rigid plates. Heathcote et al. [20] studied propulsion generated by flexible flapping foils and found that appropriate flexural stiffness improved thrust. It was also found that flexural stiffness affected the spacing of vortex rows. Chiu and his colleagues [21–23] developed a novel mechanism of grooved cam with linkage to simulate the movement of a fish's caudal fin for improving thrust. The feature of the novel mechanism produces an arbitrary motion for the flapping foil during oscillation. They found that the induced air flow with non-harmonic rotational oscillating foil is better than that with harmonic rotational oscillating foil.

In most previous researches, angular velocity profiles were considered symmetric to the central axis of the oscillation. However, the optimal angular velocity profile may not be in the sinusoidal form or a harmonic function. From the aspect of fluid dynamics, the angular velocity should be higher when the foil is sweeping in the direction of the flow. In other words, the rotation of the foil from one end to the central line should be faster than that from the central line to the other end. Fig. 1 shows the schematics of an angular velocity variation with a specified angular span. The sinusoidal pattern shown in Fig. 1(a) depicts slow motion at the two ends and fast motion in the range near the center line. The fast forward/slow backward (F/S) pattern shown in Fig. 1(b) presents faster motion when the foil rotates from one end toward the center line and slower motion from the center line toward the other end. The flow structures and the air flow rate will not be the same due to different relations of angular velocity and foil orientation.

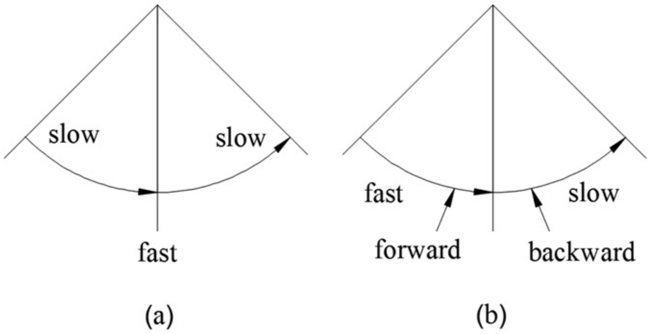

Fig. 1. Schematics of angular velocity for half a flapping cycle in (a) sinusoidal and (b) fast forward/slow backward patterns.

The main purpose of this research is to experimentally explore the air flow characteristics in a horizontal rectangular duct with various oscillating patterns and the heat transfer performance of heat sink with different configurations under these operating conditions of oscillating foil. The porosity of fin array for heat sinks and foil flexural stiffness were specified to understand the effects on the flow and thermal performance of heat sinks.

2. Design and fabrication of the mechanism

The rotational velocity profile of oscillating foil can be depicted in Fig. 2(a). In the diagram, only the first half of a flapping cycle is shown, with the total flapping range of 120°. The value of 0° means that the foil is aligned along the center line of duct. For F/S pattern, the averaged angular velocity from the forward end (same direction as air stream) to the center line is about twice of that from center line to the backward end (opposite direction to air stream). The angular velocity pattern is modified from a step function with smooth ramping. As for the sinusoidal velocity profile, it has the maximum angular velocity when the foil reaches the center line. The profile of the groove on the cam is then determined by different foil positions with computer-aided design software. The cam prototypes are shown in Fig. 2(b).

The components of this novel mechanism include a motor, a grooved cam, an oscillating foil, and a connecting rod as schematically shown in Fig. 3(a). The grooved cam is mounted on the motor. The connecting rod contains a shaft and a linkage. The linkage is inserted into the groove on the cam and the shaft links the pivot of the foil. The motor spins the cam and by turn drives the connecting rod through the linkage inserted in the groove on the cam. The shaft rotates to and fro and the foil oscillates with the designed angular velocity profile.

The foil has a dimension of 43 mm in length and 33 mm in height, with an aspect ratio of 0.70. Three types of foils were used in the research, mild steel, #304 steel, and PET, respectively. The flexural stiffness is defined as

$$\text{Flexural stiffness} = EI = \frac{Ebh^3}{12} \tag{1}$$

where E is Young's modulus, I is the inertia moment of cross-section, h is the height of the foil, and b is the thickness of the foil. The values of flexural stiffness for the foils are shown in Table 1.

3. Experimental apparatus and measurements

Fig. 3(b) describes the experimental apparatus which consists of a duct, the oscillating bio-mimetic structure, a heat sink, a heat source, and a measuring unit. The duct was built with acrylic. It has a dimension of 300 mm in length and 90 mm × 35 mm in cross-section, leaving allowances of 1.5 mm between the foil and the top/bottom walls of the