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Fluid-structure interaction study of natural convection heat transfer over a flexible oscillating fin in a square cavity

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ABSTRACT

The material of this study is a numerical formulation of a fluid-structure interaction represented by an oscillating elastic fin attached to a hot vertical wall of a square cavity. The cavity is filled with air, $Pr = 0.7$, and differentially heated while the horizontal walls are kept adiabatic. The finite element Galerkin method with the aid of the Arbitrary Lagrangian-Eulerian (ALE) procedure is used in the numerical analysis. The elastic fin undergoing an excitation and is subjected to buoyancy forces. The ranges of the studied parameters are the Rayleigh number $Ra = 10^4–10^7$, fin length $L = 0.1–0.4$, oscillating amplitude $A = 0.001–0.1$, oscillating period $\tau = 0.01–1$, thermal conductivity ratio (fin to fluid) $k_r = 1–1000$, and the non-dimensional Young's modulus $E = 10^8$-10^{13}. The results show that increasing the non-dimensional amplitude the oscillating fin can significantly enhance the Nusselt number. The non-dimensional periods about $\tau \approx 0.1$ and higher shows better enhancement compared to lower periods. A fin length of 0.2 can be considered as the best length for heat transfer enhancement and compatible with various oscillating amplitudes.

1. Introduction

The enormous development of electronic technology has become more pronounced in many engineering, industrial, and environmental applications. This development did not exist without an accompanied progress in heat rejection (cooling) methods. Enhancement of natural convection has been and will continue to be pivotal in improving the performance of the cooling mechanisms of electronics contained in enclosures. During the last two decades, there has been a developing efficient mechanism for enhancing the natural convection by exciting the entire enclosure or its boundaries using an external mechanical or an electrical force. Hence, this mechanism is unrestricted by the electrical or thermal properties of the fluid. The analysis of such problem is classified as a moving boundary problem, which is encountered in many engineering applications and in nature as well. Cooling fan induced vibration in electronic devices, biological micro-scale experiments, mixing and sterling devices, and heat exchangers are examples of these applications. These problems are classified as fluid-structure interaction (FSI) which is often used for unsteady flow interacting in two ways manner between the fluid and solid boundaries. The effects of vertical vibration and gravity on the induced convection inside enclosure were simulated by Fu and Sheih [1,2]. Kimoto and Ishidi [3] investigated the vibration effects on the natural convection heat transfer in a square enclosure. Fu et al. [4] reported a remarkable increase in heat transfer associated with laminar forced convection in a parallel-plate channel including an oscillating block. Florio and Harnoy [5] studied the enhancement of natural convection cooling of discrete heat source in a vertical channel using a vibrating plate. Convection in porous media undergoing mechanical vibration is reported by Razi et al. [6]. Chung and Vafai [7] investigated the vibrational and buoyancy induced convection in a vertical porous channel with an open-ended top and a vibrating left wall. Cheng et al. [8] proposed a novel approach to enhance the convective heat transfer in heat exchanger by using the flow induced vibration instead of strictly avoiding it.

However, in devices cooling strategy, imposing vibration to the

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Nomenclature

A	amplitude of the oscillating fin
b	fin thickness
$\boldsymbol{d}_s$	displacement vector
E	Young's modulus
$\boldsymbol{F}_v$	body force vector
$\boldsymbol{g}$	gravitational acceleration vector
H	cavity length
k	Thermal conductivity
L	Fin length
Nu	Nusselt Number
P	Pressure
Pr	Prandtl number
Ra	thermal Rayleigh number
Re	Reynolds number in Ref. [26]
t	time
T	temperature
TR	period of the fin's oscillation/convection time in Ref. [28]
$\boldsymbol{u}$	velocity vector
W	work
x,y	Cartesian coordinates

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
λ	Frequency of the oscillation
ν	kinematic viscosity
ρ	density
σ	stress tensor
τ	period of oscillation
υ	Poisson's ratio

Subscripts

c	cold
f	fluid
fixed	a *fixed fin without oscillation*
h	hot
local	local value
oscillating	an *oscillating fin*
P	partition
r	the property ratio of the solid to the fluid
s	solid

Superscripts

*	dimensional parameters

heated surface/enclosure can seriously reduce the reliability and stability of the electronic device. Therefore, the increasing demands of heat removing have resulted in very effective mechanisms using passive or active enhancing techniques represented by thin fins attached to heat generating surfaces. The passive technique can be referred to flexible thin fin(s) placed in a flow undergoing a convective heat transfer. Ben-Nakhi and Chamkha [9,10] investigated the effect of the presence of a fixed thin fin on the heat transfer in a cavity. They [10] analyzed the effect of fin lengths equal to 20, 35 and 50% of the hot wall. They found that the effect of the fin length on the heat transfer rate in the cavity acted in an unordered way. The authors discussed this unordered way as being due to fact that the addition of a fin to an enclosure simultaneously restrained natural convection flow in the cavity but increased the heat transfer from the surface due to the enhanced conduction mechanism in the fin.

Turek and Hron [11] developed a self-sustained oscillation in 2D laminar channel flow basing on an elastic plate attached to the lee side of a rigid cylinder. Another method namely, sharp-interface Cartesian grid, was proven capable of simulating thin flexible structures as documented by Vigmostad et al. [12]. Nevertheless, the later attentions were focused on the Turek and Horn simulation procedures [13–17] including adaptive finite element approximation [13], comparison of segregated versus monolithic solvers [14], dealing with large deformation effects [15,16], and induced movements due to oscillation of the flow [17].

Khanafer et al. [18] studied the effects of the flow conditions and the geometric variation of the microcantilever's bluff body on the microcantilever detection capabilities within a fluidic cell. Their main result was that the introduction of a random noise in the fluidic cell which caused the microcantilever to oscillate in a harmonic mode at low velocity. Soti et al. [19] demonstrated numerically a large-scale flow-induced deformation as an effective passive heat transfer enhancement technique. They investigated the thermal augmentation as well as quantified the flow-induced deformation of an elastic thin plate attached to lee side of a rigid cylinder in a heated channel laminar flow.

The active augmentation technique utilizes the reversed piezoelectric effect that is either gluing the base of the fin on an oscillating specific element or bonding a piezoelectric patch on the surface of a thin fin. This technique is known as piezoelectric fan. The low consumed power, less noise, compact with light weight, and significantly heat dissipative have led to important contribution of piezoelectric fan in the development of powerful electronic devices. Toda and Osaka [20] reported that the temperature of a TV receiver could be dropped from 66 to 49 °C by 14 mW only provided to fan actuated using piezoelectric polymer PVF2. Yoo et al. [21] investigated several vibrating metal plates forming piezoelectric cooling fans. They found that the phosphor bronze vibrating plate is the most effective design. They correlated the physical properties and the vibrating plate dimensions in a useful equation that determines the resonance frequency.

Aciklican et al. [22] proved experimentally that the piezoelectric fans can provide subsistence cooling in hot spots where the rotary fan is inactive such as in some situations in a laptop and a personal computer. While in smaller devices (cellular phones for example) the piezoelectric fan could be wholly relied on. They reported 100% enhancement in the local heat transfer coefficient. Liu et al. [23] found experimentally that the fin tip plays a major role in inducing a jet-like air stream which in turn can augment the heat transfer. Kimber et al. [24] developed correlations to predict the thermal performance of a piezoelectric fan. These correlations are based on dimensionless parameters including the piezoelectric fan dimensions and the dynamic characteristics namely, and frequency of fin vibration and the amplitude. Ma and Li [25] obviated the insufficient cooling ability of piezoelectric fan for LEDs by using a dual-sided multiple fans arrangement with piezoelectric actuator ("D-MEPA"). Their results presented that the dimensionless heat convection number could be enhanced from 2.82 with 0.22 Watts power input to 3.92 with 0.2 Watts power input for a single piezoelectric fan and dual-sided multi fans, respectively. Sheu et al. [26] manufactured and tested nine piezoelectric fins subjected to various bonding and piezoelectric patches. They reported that the heat transfer augmentation can be 64% at 5 Watt only. Their study