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# An experimental study on the effects of agitation on convective heat transfer

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ABSTRACT

In this study, agitation is produced inside a channel by a plate that is periodically oscillating normal to the channel side walls. The test channel simulates a deep-finned rectangular channel open on one end to a plenum and with a gap to allow flow over the tip of the agitator plate. The purpose of agitation is to strongly mix the near-wall flow, to thin the thermal boundary layer and to increase the convective heat transfer coefficient. Heat transfer and velocity measurements are made within different regions of the channel to study the effectiveness of such agitation. The entry region which is closest to the open end (plenum) is characterized by unsteadily driven periodic flow. The base region close to the channel base and agitator tip gap has high vortical activity and turbulent flow. The central region between the two has an unsteadily driven channel flow in one direction of oscillation and is rich in advected turbulence in the other direction. A parametric study is done to identify parameters that are critical to enhancing heat transfer. The amount of agitation produced in the channel directly scales with increasing frequency. Agitation is found to scale almost entirely with agitation velocity, the product of amplitude and frequency, with amplitude being only slightly more important than frequency in a few cases. Though this study finds application in electronics cooling where agitation can be used inside finned, air-cooled heat sinks to enhance heat transfer with walls, the results could be applied to any similar situation with such enhancement of heat or mass transfer with active surfaces. Very few experimental studies can be found in the literature on flow agitation effects on wall transport.

## 1. Introduction

Agitation as a mixing mechanism is used in a wide variety of applications such as in the food industry for improved heat and mass transport in stirred mixtures [1,2]. In industrial mixing, agitation is used in stirred tanks to mix fluid and solid phases. The chemical engineering industries employ numerous agitation techniques in their reactors [3–6]. Unsteadiness and turbulence generated by agitation can be used in single phase flows for improved transport from walls to fluids, e.g. in electronics cooling.

Electronics cooling technology demands rapid development to accommodate the ever-increasing heat dissipation rates of modern devices. Though phase change and liquid cooling are options, new methods of cooling with air are continually being explored. To address this, the present paper discusses a mini-channel heat sink with agitated flow for improved mixing and advanced cooling that does not resort to phase change or liquid cooling.

According to Moore, the number of transistors on a chip doubles every 1.5 or 2 years [7]. As the speed of operation and density of transistors increase, dissipation of heat from the chip rises, demanding continued attention. Without continued advancements in accommodating thermal dissipation and without a breakthrough in electronics technology, processing speed and reliability will be jeopardized. Thermal designers have traditionally used conventional fans to cool heat sink fin arrays that dissipate heat from chips in electronic devices and would like to advance air cooling technology.

The present technique employs piezoelectrically driven agitators. Many researchers have used piezoelectric actuators for cooling of electronic devices. Liu et al. [8] experimentally studied heat transfer performance of horizontal and vertical arrangements of piezoelectric fans. They concluded that heat transfer augmentation by a piezofan was due to entrained air flow during each oscillation cycle and the jet-like air stream at the fan tip. Acikalin et al. [9] characterized and optimized the performance of miniature piezoelectric fans. They evaluated changes with fan amplitude, distance to the heat source, fan length, and frequency relative to

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**Nomenclature**

| | |
|---|---|
| $U_{peak}$ | agitator maximum tip speed (m/s) |
| $A_a$ | amplitude of agitation, mean to peak (mm) |
| $f$ | frequency of agitation (Hz) |
| $Re$ | agitator tip speed Reynolds number |
| $\nu$ | kinematic viscosity of air ($m^2$/s) |
| $L$ | agitator to fin maximum distance when the agitator is in the mean position (mm) |
| $H$ | fin length (mm) |
| $w$ | agitator cavity width (mm) |
| $\pi_a$ | agitator thickness (mm) |
| $\delta_{tip}$ | tip gap (mm) |
| $h$ | heat transfer coefficient (W/$m^2$ K) |
| $V$ | voltage(V) |
| $I$ | current (A) |
| $A$ | area of plate ($m^2$) |
| $\theta_s$ | temperature of plate (K) |
| $P$ | power supplied to copper plate (W) |
| $Q_{net,in}$ | heat flows from neighboring copper plates (W) |
| $\theta_{sink}$ | sink temperature (K) |
| $U_{mean}$ | ensemble averaged mean velocity (m/s) |
| $Ui(t)$ | velocity measurement at time $t$ within the cycle number $i$ (m/s) |
| $U'_{RMS}$ | ensemble averaged RMS velocity (m/s) |
| $t$ | time instant within the cycle (s) |
| $T$ | oscillation cycle time (s) |
| $a_{peak}$ | peak acceleration (m/$s^2$) |

resonance. Kimber et al. [10] developed correlations that could predict thermal performance of the fan over ranges of amplitude, frequency and fan dimensions. Kimber et al. [11] studied the heat transfer performance of arrays of piezoelectric fans in their first resonant mode and noted strong dependence of heat transfer coefficient on fan pitch.

The merits of agitation as a mixing technology are known [1–6]. As a step towards improving air cooling technology, our research group employed piezoelectric technology in a different way, using piezostacks to translationally oscillate blades that agitate the flow inside heat sink channels to thoroughly mix the flow, thus improving convective heat transfer. The idea is to thin the thermal boundary layer by generating flow unsteadiness and turbulence.

Yeom et al. [12] experimentally explored agitation for an actual-scale, single channel of the heat sink. They designed an oval loop shell with a piezo actuator to drive the agitator plates for translational oscillatory motion. The channel was cooled both by agitation and throughflow. Frequencies of around 1000 Hz and 1–2 mm amplitude range were achieved. They were able to observe an improvement in heat transfer rate of around 55% due to agitation. Yu et al. [13] numerically studied factors influencing heat transfer in channels cooled by translationally oscillating agitator plates. Enhancements as high as 61% were observed. Heat transfer enhancement was found to increase with increases in amplitude and frequency. When cases of various amplitude and frequency were run, they found that agitation velocity, which is proportional to the product of amplitude and frequency, primarily effected heat transfer enhancement with amplitude being only slightly more important than frequency. Turbulence was generated in the narrow gap between the channel base and the agitator plate. This turbulence was found to play a key role in flow mixing and increasing heat transfer. Yu et al. [14] numerically studied heat transfer enhancement obtained when fan-cooled heat sinks were assisted by active devices like agitators and synthetic jets. This study was done for a single channel of the heat sink. Enhancement of around 80% was found when the performance was compared with a case of channel flow only. In another study, Yeom et al. [15] found a 91% enhancement when the throughflow-cooled channel was assisted by agitation at a frequency of 1140 Hz.

Careful agitator or heat sink design can increase the benefits that one can reap from this technology. Design studies have been done to find directions toward getting maximum heat transfer benefits with minimum agitator driving input power. Yu et al. [16] carried out a numerical study to compare the coefficient of performance when the channel is cooled by long-blade or short-blade agitators. It was found that the short blade had a better coefficient of performance compared to the long blade due to the additional vorticity generated at the edges. Significantly less power was consumed in driving a short blade. Agrawal et al. [17] numerically optimized a heat sink design. They explored the effects of the number of channels in the heat sink on heat transfer performance and agitator driving power consumption. They found that having more, narrower channels gave the best performance.

To study the agitator phenomena in detail, the effects of agitation in a single channel of a heat sink were experimentally documented by Agrawal et al. [18,19] in a Large Scale Mock Up unit that is dynamically similar to a single channel of an actual-size heat sink. They measured time-averaged heat transfer coefficients and unsteady velocities over a representative agitation cycle in various flow regions of the channel. Their study identified mechanisms of mixing within the different regions.

The aim of the present study is to explore agitation as a mixing mechanism with application to enhancing heat transfer. Aside from the study from which the present paper originates [18,19], little has been done to provide heat transfer and flow measurements with active agitation of this type. For this, experiments were done in a Large Scale Mock Up unit (described below) and parameters critical to enhanced heat transfer were identified. The results add to our understanding of the fundamentals of agitation on heat transfer.

## 2. Experimental setup

Fig. 1 shows the actual heat sink with agitators, an oval loop shell bow and a piezostack. As the piezostack contracts and expands, it drives the agitator assembly inside the heat sink channel via the bow motion [12,20].

A single channel of the actual heat sink might be as wide as 3–4 mm. A channel as small as this does not allow space for detailed heat transfer and velocity measurements. Since a detailed understanding of the mixing generated by agitator motion is essential for efficient design, a dynamically-similar, large-scale mock-up test facility was constructed to simulate an electronics cooling heat exchanger. The test described herein focuses on agitation, so no throughflow is present. The large scale test facility allows high resolution, both in time and space. The test channel is a rectangular channel open on one end to allow inflow and outflow of air to a plenum, as driven by agitator movement. *Thus, the facility allows the study of agitation alone, with all flow driven by the agitator itself.* Both heat transfer and velocity measurements are made in the channel cavity. Time-averaged heat transfer is measured over