COOLING PERFORMANCE OF MICROMACHINED SELF-OSCILLATING REED ACTUATORS IN HEAT TRANSFER CHANNELS WITH INTEGRATED DIAGNOSTICS

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ABSTRACT

This paper presents heat transfer (HT) performance of small-scale MEMS-enhanced self-powered oscillating actuators for applications in highly-compact high-power air-cooled heat exchangers. Commercial air-cooled heat sinks are typically much larger than the systems they must cool due to large air-side thermal resistance. Our work is applying MEMS technologies to reduce this thermal resistance via the integration of small-scale oscillating actuators into small heat exchangers. Improved HT performance either yields smaller heat sinks or higher heat fluxes. These mm-scale actuators were built using MEMS manufacturing technologies such as laser micromachining, lamination, and/or metal patterning and etching. Conceptually, oscillating reeds inserted into the channels of an air-cooled heat sink induce small-scale motions in low-Reynolds number flows, which increases HT efficacy. Using MEMS-enhanced reed actuators, we experimentally demonstrated local HT enhancement up to 250% in microfabricated channels monitored by integrated temperature sensors.

INTRODUCTION

Thermal management of micro- and macro-scale actuators is critical for high-performance and long-term operation of these systems. However, due to large air-side thermal resistance, commercially-available air-cooled heat sinks are typically much larger than the systems they must cool, limiting miniaturization. Using MEMS technologies, our work focused on reducing this thermal resistance by integrating small-scale MEMS-enhanced oscillating reed actuators into the channels of small heat exchangers. As shown in Figure 1, the vibration of the reed in the air flow (typically driven by the system fan) leads to the formation of small-scale flow motions that significantly enhance heat transfer on the heated surfaces and mixes the heated air with the cooler core flow. Improved heat transfer (HT) performance either yields smaller heat sinks or higher heat fluxes.

The effectiveness of active flow mixing by inducing small-scale motions for enhanced heat transfer in low Reynolds number flows, which are characteristic of air cooling applications, has been previously reported. Technologies using synthetic jet actuators implemented in heat sinks have been previously reported to improve heat transfer [1]. The use of piezoelectrically-driven vibrating reeds for external cooling of low-power electronic packages has also been investigated [2].

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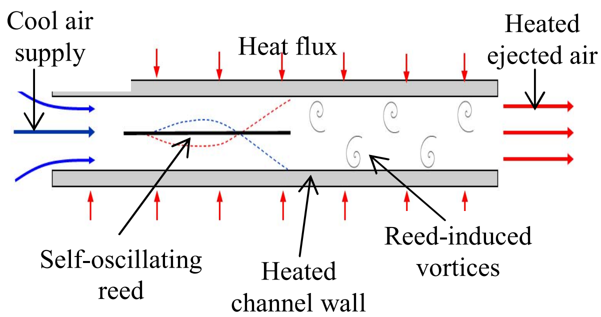

Figure 1: Rendering of the flow within a heated channel cooled by a vibrating reed (top view).

A piezo-fan on a heat sink demonstrated a 100% enhancement in heat transfer coefficient compared to natural convection in a cell phone application. Previously, we reported the fabrication and experimental validation of cm-scale piezoelectric vibrating resonant reeds [3]. These devices were tested in an air-cooled HT channel and heat transfer enhancement during reed actuation was demonstrated for a wide range of flow rate conditions. However, some technological drawbacks of a piezoelectric approach included device power consumption in order to actuate the piezoelectric driver, manufacturing, large increase in channel pressure drop due to the relatively wide reed profile, and device failure which was a result of material fatigue.

In this paper, we present the development of two key components for enhancing and measuring heat transfer enhancement in small-scale high-power heat sinks. First, we designed and fabricated a new generation of reed actuators. These MEMS-fabricated devices are flow-powered and self-oscillating, which results in improved heat transfer performance and system efficiency. Simplified fabrication processes and an improved and more reliable actuation mechanism are some of the main advantages of this new approach. Added microscale surface features also enabled better fluidic performance. Second, we developed a heat transfer test channel with integrated temperature diagnostics via conventional microfabrication technologies. Since small heat exchangers require micro-diagnostics to measure local HT coefficient and assess device performance, MEMS technologies are attractive and compatible with such requirements as they facilitate multi-sensor fabrication as well as controlled and in-situ sensor positioning. The self-oscillating reed actuators have been experimentally tested in both fluidic and heat transfer test channels.

DESIGN AND FABRICATION

Self-Oscillating Reeds

Unlike the previous generation of small-scale piezoelectrically-driven reed actuators [3], this new generation of low-profile fluidic-to-mechanical reed actuators are self-powered. The devices extract their mechanical energy from the air flow coming from the system fan and flowing through the heat sink channels. As a result, the reed vibration is forced by air motion on both sides of the reed, and a flag-like motion has been observed experimentally under specific flow rate conditions. When the interaction between the reed motion and the flow, which is accompanied by regular shedding of vortices, exceeds a certain threshold, large reed displacements can be attained which in turn intensifies the strength of the shed vortices. These vortices lead to significant enhancement of the heat transfer in the channel by disrupting the thermal boundary layers and enhancing mixing with the cooler core flow.

MEMS-enhanced reed actuators with various designs have been designed and fabricated as shown in Figure 2. The reeds were approximately 50 to 100-µm-thick and 8 to 15-mm-long. The active reed area was inserted vertically within the heat transfer channel for testing. The supporting fixtures allowed for reed clamping. Length and thickness design optimization were performed experimentally by measuring the reed vibration in a air flow channel as a function of flow rates. Parameters of interest were 1) required threshold flow rate to observe large-displacement reed oscillations, 2) total pressure drop across the test channel, and 3) amplitude and frequency of the oscillations.

Mass-production-compatible techniques were utilized for the fabrication of these reed actuators such as laser machining, polymer molding, metal patterning and etching. Such fabrication techniques enabled the implementation of additional surface features (e.g., corrugated ridges as shown in Figure 2b), and/or honeycomb metal patterns to alter the reed stiffness to weight ratio, which modifies the reed mechanical and fluidic characteristics and improve device performance as demonstrated by fluidic measurements in the following section.

The reed technology directly benefited from alleviating the need for brittle PZT materials previously used for reed oscillation generation [3]. As a result, reduced reliability issues and material fatigue were observed. Furthermore, arrays of self-oscillating reeds in multi-channel heat sinks will not require any control circuitry or external power unlike the PZT reeds; two major advantages for system integration.

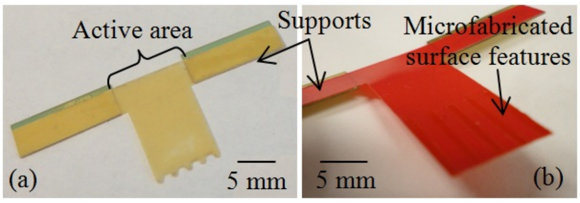

Figure 2: Photographs of laser-machined reeds with mirofabricated surface features: (a) Laser-machined polymer reed, and (b) with microfabricated surface features (strips with darker shade).

MEMS-Fabricated Heat Transfer Channel with Integrated Diagnostics

Small high-performance heat exchangers require micro-diagnostic capabilities in order to measure local HT coefficient and assess device performance. MEMS technologies are compatible with such requirements as they facilitate multi-sensor fabrication as well as controlled and *in-situ* sensor positioning. As a result, both the heating element and the temperature sensors were microfabricated. The heaters consisted of high-density titanium-coated copper windings on glass substrates. For sensing, these same windings integrated temperature-dependent resistive sensors. A photograph of the device is shown in Figure 3. Glass substrates were used in this experiment because of their low thermal conductivity. This is unlike a typical heat sink configuration that uses high-thermal conductivity materials such as aluminum to maximize cooling through conduction. However, this experimental setup intended to decouple conductive and convective cooling in order to isolate the reed performance through convective cooling. As a result, any temperature effect observed downstream of the reed location could be attributed to the propagation of reed-induced vortices within the core flow.

The microfabrication process started with the deposition of a titanium/copper/titanium layer on top of glass substrates. The first titanium layer acted as an adhesion layer between the glass and the micron-thick copper layer, while the second titanium layer was used to prevent copper oxidation. In order to pattern the serpentine microstructure, a photoresist layer was patterned and used as an etching mask. Diluted hydrofluoric acid and ferric chloride were used to etch titanium and copper, respectively. After etching, the photoresist was dissolved in solvent. The resulting structure exhibited a 1-µm-thick and 500-µm-wide copper trace with 50 µm gap between windings. The high-density design was critical in achieving uniform and realistic temperature distribution. To ensure heater/sensor stability in the 25-80°C temperature range, the devices were annealed at 125°C for 24 hours.

The integrated temperature sensors operate using a four-probe measurement technique. The current flowing through the sensors corresponds to the heater current, and voltages are measured across the sensor windings. Since the sensor resistance is temperature dependent, one can measure local temperatures with this approach. The sensors, which were first calibrated in a heated environment for maximum accuracy, exhibited a temperature resolution of 0.1°C.

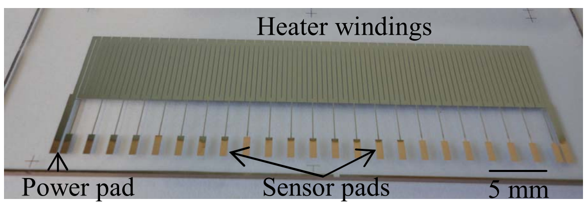

Figure 3: Microfabricated titanium-coated serpentine copper heater with integrated temperature sensors on low thermal conductivity glass substrate.

EXPERIMENTS

The cooling enhancement factor, which measures the efficacy of the self-oscillating reed technology, includes local heat transfer improvement as well as detrimental factors such as reed power consumption (null for self-oscillating actuators but non-negligible for previously-reported piezoelectrically-driven reeds) and increase in pressure drop due to the presence of the vibrating reed in the channel. As a result, both pressure drop and heat transfer experiments were conducted.

Experimental Setup

The HT test channel consisted of a miniature wind tunnel and a settling section designed to ensure fully-developed uniform flow (not shown in Figure 4), and a 2.5-mm-wide, 10-mm-tall and 30-mm-long HT channel that included two microfabricated heated sidewalls with *in-situ* temperature diagnostics. The channel high aspect ratio further validates the need for microfabricated temperature sensors as conventional thermocouple would be challenging to assemble. Further, the MEMS sensors are surface features which did not affect flow uniformity. Figure 4 shows the fully-assembled heat transfer channel as well as the wiring for powering the heaters and for sensing local temperatures in the streamwise direction. The reed actuator was vertically inserted at approximately 5 mm from the channel entrance, and located at the center of the channel width. As indicated in Figure 2, only the active area of the reed interacted with the air flow, while the supporting tabs allowed for reed assembly within the test channel.

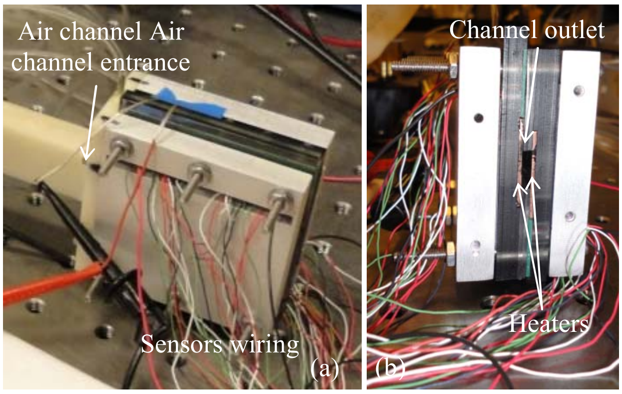

Figure 4: Heat transfer (HT) channel experimental setup: (a) General view, and (b) view from outlet side. The active test section is 2.5-mm wide, 10-mm tall and 30-mm long.

Pressure Drop Measurements

The pressure drop measurements were performed in a similar test channel measuring 2.5-mm wide, 10-mm high, and 186-mm long. The on-glass microfabricated heaters were replaced by glass sidewalls. Static pressure measurements within the test and flow settling sections were obtained using a pressure transducer with a resolution of 0.25% of the full scale coupled with a 48-port pressure switch to monitor pressure along the channel length. The baseline pressure drop of the channel without reeds is plotted in Figure 5. Data are expressed as a function of Reynolds number. As expected, the presence of the reeds in the channel increases pressure drop. It was observed that self-oscillating reeds exhibited larger displacements than the channel width, causing the flapping element to be pushed against the channel sidewalls, potentially causing additional flow blockage and thus increased pressure drop. This was particularly visible at higher flow rates. As a result, stiffer reeds were utilized at high flow rate operations.

In addition, the micro-patterned corrugated reed exhibited lower pressure drop compared to a non-corrugated reed of the same dimensions, indicating that micro-structuring improves the performance of these self-oscillating actuators. The authors believe that the lower pressure drop observed with the micro-structured reeds was a result of minimized reed-to-wall interactions, which in turn reduced air flow blockage across the reed element. Furthermore, the pressure drop increase due to the actuator presence in the channel was approximately two times lower than PZT reeds [3].

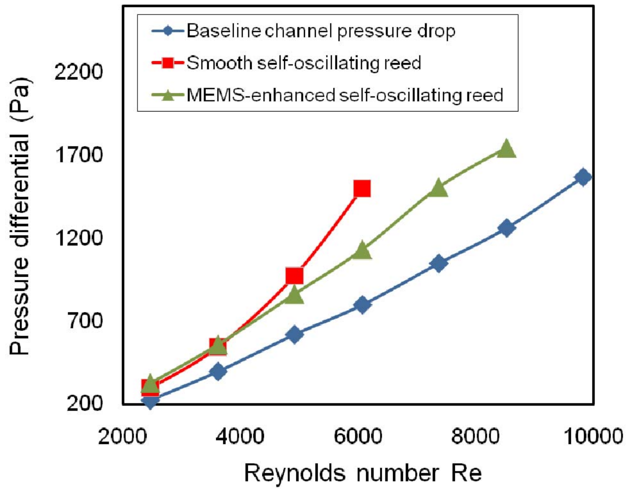

Figure 5: Pressure drop across the entire channel as a function of Reynolds number for various reeds.

Heat Transfer Measurements

In operation, constant heat flux conditions were set by controlling heater input power and air flow rate. The reed performance was measured by local temperature measurements and by comparing data from the baseline case (i.e., no reed inserted in the channel) against data measured with a vibrating self-oscillating reed. Figure 6 plots the results of a HT experiment at a flow rate of 15 liters/min and dissipated power of 12 Watts, which are relevant operating conditions for high-power small-scale heat sinks. The baseline experiment exhibited a linear increase in temperature along the channel length. This result is characteristic of the low-thermal conductivity sidewalls. Under similar testing conditions, the presence of the self-oscillating reed led to a significant improvement in HT coefficient and a decrease in wall temperature over 10°C across the channel, confirming the effect of the self-oscillating reed technology. The temperature decrease past the reed location was also very significant and was solely attributed to the reed motion since the thermal conductivity of the glass sidewalls was low. This result indicated that the vortices generated by the vibrating reed propagated downstream.

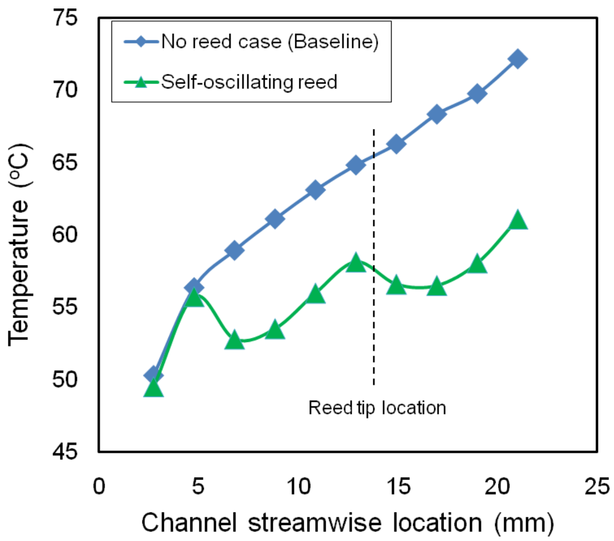

Figure 6: Channel sidewall temperature distribution measured with integrated sensors. Cases without and with the self-oscillating reed (flow rate = 15 Lpm; dissipated power =12 W).

Heat Transfer Enhancement

The streamwise variation of HT enhancement is plotted in Figure 7 and represented by a local enhancement factor η, a ratio of the calculated Nusselt numbers with and without the self-oscillating reed actuator. In effect, it represents the ratio of convective heat transfer coefficients with and without the reed actuator.

A local enhancement up to 2.5 times was calculated at the channel exit, as plotted in Figure 7. The overall improvement provided by this cooling technology is calculated by integrating the local enhancement over the channel length. Accordingly, the self-oscillating actuator exhibited a 60% HT enhancement, demonstrating the potential of this technology for high-performance heat exchangers. Moreover, because the local temperature measured at the channel exit was lower when the reed was operating than the temperature measured in the no reed case, longer channels would also exhibit a larger overall heat transfer improvement.

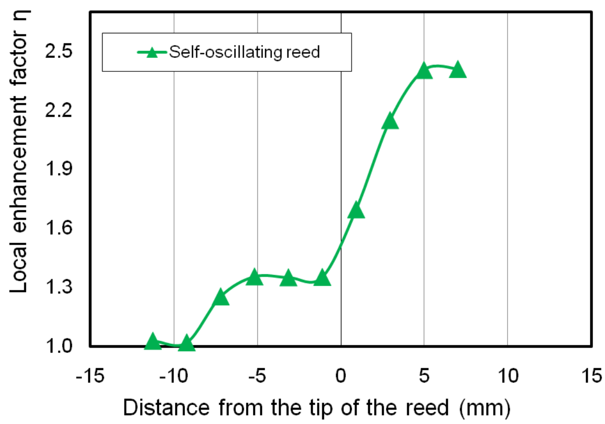

Figure 7: Local enhancement factor with self-oscillating reed (flow rate = 15 Lpm; dissipated power =12 W).

Heat Sink Integration

Figure 8 shows photographs of an example array of ten self-oscillating polymer reeds with single-ended supports assembled onto a cover plate. Unlike the reed actuators tested in the HT channel that were clamped on both sides, these reeds are only supported on one side. Using this support configuration, it was experimentally confirmed that pressure drop did not increase significantly and that displacement and operating modes were similar in both cases. Figure 8(b) shows the array inserted in a 10-channel aluminum heat sink. Integration was performed from the top, making this assembly/insertion process compatible with any existing heat sinks.

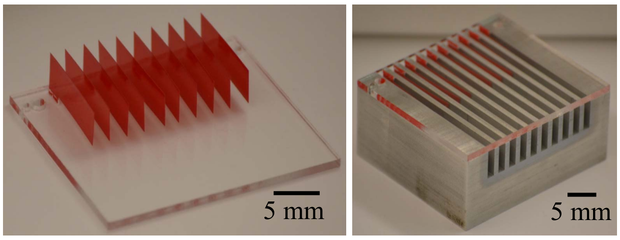

Figure 8: (a) Array of 10 self-oscillating reeds: (a) Before insertion, and (b) Integrated in a high-power heat sink.

CONCLUSIONS

We demonstrated an active cooling technology enhanced by MEMS technologies for modern compact air-cooled heat exchangers. Powered by the air flow generated from the system fan, self-oscillating actuators produced vortices which improved air mixing and increased heat transfer. Experimentally, these devices were characterized in a heat transfer test channel that featured MEMS-fabricated heaters and integrated temperature-sensitive micro-diagnostic sensors.

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