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# Investigation of a MEMS-based capillary heat exchanger for thermal harvesting

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ABSTRACT

This article describes theoretical and experimental studies of MEMS-based capillary heat exchangers, designed for use as the heat sink in a waste thermal energy harvesting system currently under development. Specific goals include the understanding of the impact of thermal conductivity and capillary dimensions. Experimental studies were done using silicon and SU-8 based heat exchangers each with rectangular capillaries having width of 100 μm. The depth of silicon capillaries was maintained at either 64 or 100 μm while that of SU-8 capillaries was varied from 48 to 134 μm to 160 to 375 μm. The overall footprint of each microdevice was 38 mm by 13 mm. The fluid used was 3M™ HFE 7200. Heat exchanger performance was characterized based on operating temperature, mass transfer rate, heat flux, and thermal resistance. Studies were done for two different operating temperatures, one below the boiling point and another at the boiling point of the working fluid. These two operating temperatures were referred to in this article as low-temperature and high-temperature operation mode. Based on the experimental study the fluid was found to wet both silicon and SU-8 with contact angle measured to be 6°. From the experimental studies conducted it was found that the pumping effect of the capillaries increased with increasing wall height. Based on the thermal tests it was observed that the highest mass transfer rate and heat flux under the low-temperature and high-temperature operation mode were obtained for an SU-8 heat exchanger with capillary height of 134 μm and silicon heat exchanger with capillary height of 100 μm, respectively. Based on this study it was found that under low-temperature operation mode the capillary dimension was more influential than thermal conductivity; however, under high-temperature operation mode the opposite was proved to be the case. The thermal resistances were found to vary from 0.011 to 0.09 $\frac{m^2\,C}{W}$ and from 0.0073 to 0.0096 $\frac{m^2 C}{W}$ for low-temperature and high-temperature operation mode respectively. Also it was found based on comparison that the conceptualized MEMS-based capillary heat exchanger was found to have lower thermal resistance than existing heat sinks. Using the experimentally validated theoretical model developed in this work it was found that the performance of the MEMS-based capillary heat exchangers improved with increasing thermal conductivity of the substrate as well as the capillary dimensions. The model has helped conclude that developing SU-8 capillaries on aluminum or copper substrates would optimize the influence of thermal conductivity and capillary dimensions on the performance of the MEMS-based heat exchanger.



## 1. Introduction

There is a growing need for research that emphasizes energy efficiency for many reasons. These include growing global sustainability concerns. This is especially true considering expected global population growth and the resultant increase in energy demand. The US Department of Energy predicted that compared to 2006 energy consumption levels, global demand will increase 44% by 2030 [1]. As a response, so-called "green" energy sources are being investigated aggressively. These include sources like solar and wind. This paper concentrates on enabling technology suitable for an alternative clean source: waste thermal energy. This "waste heat" is energy that has been discarded as part of a larger thermodynamic process. Through its effective capture and use, this wasted energy is converted to useful form. Due to the low efficiency (25–40%) of heat engines as well as the high energy consumption of the transportation sector, engines are a natural target for waste thermal energy scavenging [2,3]. There is further opportunity for scavenging via applications that include industrial heat sources [4]. Other potential sources beyond the scope of waste heat recovery include the harvesting and conversion of low temperature thermal energy that is available from environmental sources.

One approach to scavenge waste thermal energy is through the use of thermoelectric (TE) materials, specifically thermoelectric generators (TEGs). TEGs are coupled to thermal sources which are used to scavenge waste thermal energy as schematically represented in Fig. 1.

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**Nomenclature**

| | |
|---|---|
| $A$ | area between capillary channel walls ($m^2$) |
| $A_b$ | area of heat exchanger base including capillary channel walls ($m^2$) |
| $d$ | substrate thickness (m) |
| $h$ | heat transfer coefficient $\left(\frac{W}{m^2K}\right)$ |
| $h_{fg}$ | latent heat of vaporization $\left(\frac{J}{kg}\right)$ |
| $j$ | mass flux $\left(\frac{kg}{m^2}\right)$ |
| $k$ | thermal conductivity $\left(\frac{W}{mK}\right)$ |
| $M$ | molecular weight |
| $\dot{m}$ | mass flow rate $\left(\frac{kg}{sec}\right)$ |
| $R_u$ | universal gas constant |
| $R_{th}$ | thermal resistance $\left(\frac{C}{W}\right)$ |
| $P$ | heat flux $\left(\frac{kW}{m^2}\right)$ |
| $T$ | temperature (°C) |
| $\triangle T$ | temperature gradient (C) |
| T/C | thermocouple |
| $t$ | time (sec) |

*Subscript*

| | |
|---|---|
| a | ambient |
| c | temperature of cold side of TEG |
| h | temperature of hot side of TEG |
| hs | heat sink |
| l | liquid |
| sat | saturated |
| Si | silicon |
| SU-8 | SU-8 |
| so | source |
| v | vapor |

Fig. 1 illustrates the scavenging process where TEGs convert wasted energy from the heat source to electrical output. The remaining waste energy is rejected to the ambient. TEGs are directly coupled to the heat source in order to maintain the temperature of its hot side at the maximum possible level. By contrast, the cold side of a TEG is thermally coupled to the ambient through a heat exchanger, specifically a heat sink, in order to maintain the temperature of the cold side as low as possible. Maintaining a maximum temperature gradient across the TEG is necessary to maximize electrical power output [5]. This implies that the cold side temperature as well as the energy conversion are dependent on the performance of the heat sink.

TEGs can perform thermal-to-electrical power conversion for temperature differences as small as 5–10 K [6,7]. There are significant advantages to their use including a solid-state construction with no moving parts [8]. However, a key technical challenge relates to their overall operating efficiency. Current efficiencies typically range from 5–10% depending on the material of construction [3,9], to increase these efficiencies, current research is focused on nano-scale materials enhancements [9,10]. Currently researchers have noted that in addition to improving the conversion efficiency of thermoelectric material itself, there is a parallel need to research and develop the associated heat exchangers [11]. In fact, researchers promote the optimization of TEG based systems rather than individual components in order to maximize the output power [11]. The use of advanced heat transfer devices is critical to efficient TEG operation and future deployment [4,12,13].

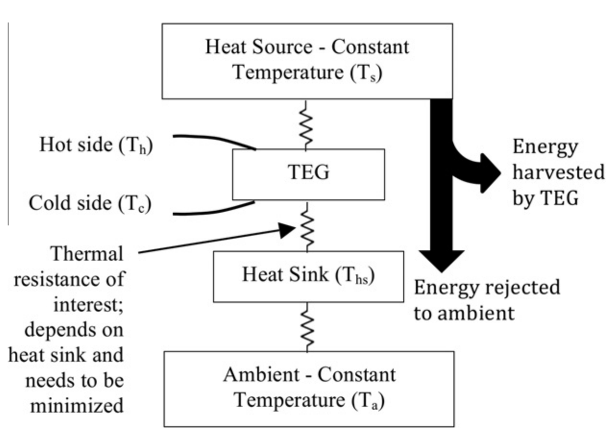


**Fig. 1.** Schematic of operation of TEG based energy harvesting system (arrows represent the direction of heat flow).

Advancements in microfabrication have enabled the development of MEMS-based heat exchangers for use in conjunction with TEGs as heat sinks. MEMS-based heat exchangers have advantages with respect to transport phenomena, size and manufacturing. The primary advantage of MEMS-based heat exchangers is their low conduction and convection thermal resistance. With respect to power output of TEGs, it increases with reduction in thermal resistance of the associated heat sink and thus microscale heat transfer devices offer unique advantages over macroscale heat transfer devices [14]. In addition, due to the small foot print of MEMS-based heat exchangers, a single microdevice may be used to scavenge thermal power from a small source. Through scaling and the high volume manufacturing, associated with microfabrication, multiple devices may be employed on larger thermal sources [15]. To the authors knowledge there is no record in literature of the use of two-phase heat sinks with TEGs. Two-phase heat sinks have lower thermal resistance than single phase heat sinks and can enhance the thermal-to-electric power conversion of a specific heat source. In addition, currently available single phase heat sinks utilize active mechanisms for transport of working fluid. This reduces the net useful power that can be made available from energy harvesting systems. The use of passive mechanisms for pumping coolant through the heat transfer device reduces the power requirements for operating the TEG based energy harvesting systems and in turn increases its overall energy conversion efficiency. Moreover, for phase change devices the temperature of the coolant is constant over the entire length of the device, unlike in single phase heat transfer devices. This implies that the temperature of the cold side of the TEG can be maintained constant over its entire length [16]. These advantages increase the potential final impact of thermal energy harvesting using TEGs [11]. This paper specifically introduces an advanced heat transfer device based on MEMS capillary heat exchange that incorporates the benefits of phase change as well as a passive pumping mechanism. The device is highly suitable for use as a heat sink in conjunction with TEGs and thermal scavenging. This article is dedicated to the theoretical and experimental analysis with specific reference to understanding the influence of thermal conductivity and capillary dimensions on the performance of MEMS-based capillary heat exchangers.

As previously noted, the development of heat sink technology is as significant as the development of thermoelectric materials. To this extent, researchers have analyzed several types of heat sinks for use in conjunction with TEGs. Heymann et al. [14] theoretically