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Experimental and lattice Boltzmann simulated operation of a copper micro-channel heat exchanger

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ABSTRACT

The inherent inefficiency of many thermodynamic processes provide ample opportunity to harvest waste energy which would otherwise be released to the surrounding environment. A micro-channel heat exchanger (MHE) is presented that optimizes efficiency of energy transference by taking advantage of high thermal conductivity with copper fabrication and two-phase flow with a working fluid. Increasing the efficiency of the MHE, capillary channels allow fluid flow throughout the MHE, removing the necessity of an external work mechanism. For a power input of 3.44 W, the absorbed and transferred energy through the MHE was approximately 95% when working fluid was utilized, compared to 87% for the MHE with no working fluid. In addition to characterizing the MHE experimentally, internal operation was analyzed and reinforced through a lattice Boltzmann method simulation of a single micro-channel. The lattice Boltzmann method is a computationally efficient alternative for multi-phase systems, notoriously difficult systems to simulate. The overall objective was the development of a general laboratory fabrication technique that produced an effective two-phase MHE which was then experimentally characterized for device energy transference efficiency and computationally modeled, using experimental boundary conditions, for internal device operation. Using experimental and simulated methods, the copper MHE has proven a viable option for transferring low-temperature waste energy.

1. Introduction

Increasing annual consumption of energy has driven researchers to analyze possibilities of waste heat scavenging for greater energy efficiency and sustainability. While large scale heat integration has been studied for decades in industry, the increasing miniaturization of devices and processing over the past thirty years has opened new avenues for waste energy harvesting. Thermal scavenging can provide power for external sensors or provide a platform for structural health monitoring of systems on smaller scales. The key to taking advantage of these available harvesting possibilities explains the interest in sustainable alternatives: inefficiency of existing systems.

Many standard thermodynamic cycles have low efficiencies where much of the thermal energy generated is rejected to the surrounding environment [1]. Harnessing the rejected thermal energy via transduction mechanisms allows existing physical effects to power additional systems, such as MEMS devices [2]. One such device, the micro-channel heat exchanger (MHE), uses multiple fluid-filled channels which, at reduced scales, produce effective heat and mass transfer due to dynamic boundary layers [3,4]. Maximizing efficiency of MHEs necessitates optimizing channel fluid dynamics while minimizing thermal resistance [3,5]. Thermal resistance is reduced using two-phase flows and materials with high thermal conductivities [3,5].

Beginning with the seminal publication by Tuckerman and Pease, micro-channels have been extensively studied for their transport phenomena characteristics [6]. A decade after Tuckerman and Pease, researchers began to focus on two-phase flow initially studying heat transfer flow models, channel pressure drop, and critical heat flux [7]. Though flow regimes were varied in systematic flow reviews, fluid was pumped through the channels in forced convection flow [8–13]. Forced flow in the micro-channels increases the heat transfer potential; however, for low-power environments, methods must be used which maximize the capability of the solitary device [11,14,15].

Applications for MHEs have ranged from electronics cooling to harnessing waste energy [6,16]. Recent research has explored system level waste heat energy harvesting solutions by characterizing heat transfer devices coupled with thermoelectric generators [17–22]. However, researchers have noted that in addition to improving the conversion efficiency of thermoelectric material

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Nomenclature

$f_i(\mathbf{x},t)$	particle distribution function (–)	$g_i(\mathbf{x},t)$	temperature distribution function (–)
τ	relaxation time (s)	τ_T	temperature relaxation time (s)
$\Delta f_i(\mathbf{x},t)$	body force term (N)	ϕ	energy equation source term (–)
ρ	particle density (g/mL)	$f_i^{eq}(\mathbf{x},t)$	equilibrium distribution function (–)
$\mathbf{u}$	particle velocity (m/s)	T	temperature (K)
$\mathbf{F}_{int}$	interparticle interaction force (N)	$\mathbf{U}$	temperature velocity (m/s)
$\mathbf{F}_s$	solid surface/fluid interaction force (N)	P	pressure (bar)
$\mathbf{F}_g$	gravitational force (N)	R	gas constant (J/K mol)
$f_i^{eq}(\mathbf{x},t)$	equilibrium distribution function (–)	b	Peng–Robinson constant (m^3 mol)
ω_i	weighting coefficients (–)	a	Peng–Robinson constant ($kg/m^5\,s^2\,mol^2$)
$\mathbf{e}_i$	discrete velocity vector (–)	T_c	working fluid critical temperature (K)
c_s	lattice sound speed (m/s)		

itself, there is a parallel need to research and develop advanced associated heat exchangers [23–26]. In fact, researchers promote the optimization of TEG based systems rather than individual components in order to maximize the output power. The use of advanced heat transfer devices is critical to efficient TEG operation and future deployment [25]. Therefore, while researchers continue to investigate system level solutions for energy harvesting, the optimization of energy transfer via the MHE is the primary priority presented here.

Though current publications have shown developed waste heat recovery processes and techniques from multiple energy sources and industries, including automotive, engines, oil and gas, steel, and steam, focus here is on maximizing energy transfer via the MHE for any low-temperature waste heat source [27–33]. Low-temperature heat sources allow the production of power from renewable energy sources, such as solar radiation. Much of the most recent research has been facilitated by developing mid- to large-scale Organic Rankine Cycle (ORC) systems; however, there is still continued interest in the possibilities of micro-scale energy harvesting [34–38].

While the characteristics of forced flow are important to the overall fundamental understanding of transport phenomena in micro-channels, the use of an external work mechanism reduces the overall efficiency of the device and increases overall expense due to additional equipment which is of vital concern for the MHE in question [39]. The incorporation of micro-channels and surface interactions promotes an economical path to fluid flow where the autonomous channel horizontal capillary flow provides fluid motion in the MHE [40–42]. In addition to fluid flow economy, the heat transfer requirements of the MHE demands choosing a substrate which meets the desired thermal conductivity.

Traditionally, the dominant platform for micro-fabrication and micro-scale devices has been silicon [43,44]. The reliance on silicon as the substrate or bulk material of fabrication is due to availability and established processing techniques [43–45]. Unfortunately, the low thermal conductivity of silicon, when compared to metals such as copper, and its fragility in wafer form demand viable alternatives for more effective and varied usage in dynamic environments [46]. Adoption of technologies on the global scale requires low-cost materials and processes which can be implemented with minimal equipment infrastructure. Mass-produced metal-based MHEs have the potential to yield mechanically robust systems, improved thermal conductivity, and allow varied usage around the world [5]. The exchanger proposed here has been designed to use micro-channels between two reservoirs, and was fabricated completely of copper via unique electrodeposition techniques.

Closed system devices can be notoriously difficult to characterize *in situ* without compromising the nature of the device. However, using theoretical formulas and experimental data, a simulation can be prepared which can verify system operation and provide useful insight into device operation. It is in this vein that a modified lattice Boltzmann model is presented to establish interior operation of the experimental MHE. The lattice Boltzmann method (LBM) performs particularly well for systems with dynamic surface interactions, including multi-phase systems, which are fundamentally difficult to model and computationally costly. The LBM provides an improved model on these constraints due to removing the explicit tracking of the moving phase interfaces [47].

Expanding on previous research and ongoing interest in small-scale heat exchangers in general, a copper-based, two-phase working fluid-filled MHE was constructed and tested. The overall device performance was analyzed via experimental characterization, however, there was parallel need to evaluate the internal operations of the device as well. Internal device performance was simulated using the LBM approach as detailed in this paper, relying heavily on the experimental boundary conditions and real device operating data. Through combination of the experimental and numerical research, the full operating characterization of the MHE was determined and the MHE suitability for waste heat recovery applications was confirmed.

As part of the experiment and fabrication effort, a method for the fabrication of the copper MHE is presented. The MHE has components as noted in Fig. 1. It is designed for closed system operation whereby no external work mechanism is needed for fluid movement. Thermal and momentum transport are driven by using phase change of a working fluid. The micro-channels drive capillary action of the fluid such that the working fluid is dispersed over the heat source area, improving heat transfer to the working fluid.

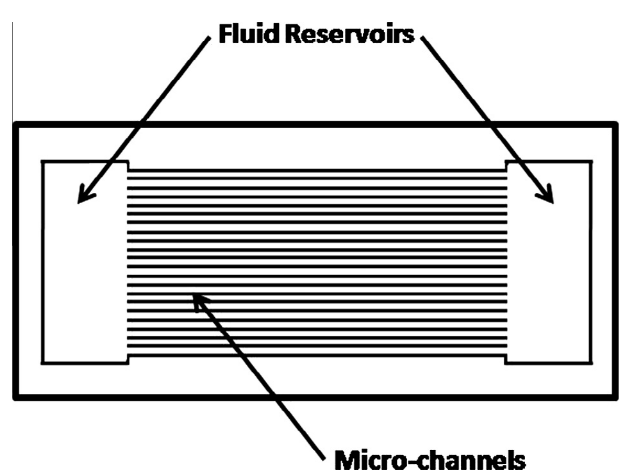

Fig. 1. Components of MHE.