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 3.44W, 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

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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.

Keywords: Waste heat, Lattice Boltzmann, Heat exchanger, Capillary channels, Electroplating, Copper

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

14 existing physical effects to power additional systems, such as MEMS devices
15 [2]. One such device, the micro-channel heat exchanger (MHE), uses multi-
16 ple fluid-filled channels which, at reduced scales, produce effective heat and
17 mass transfer due to dynamic boundary layers [3, 4]. Maximizing efficiency
18 of MHEs necessitates optimizing channel fluid dynamics while minimizing
19 thermal resistance [3, 5]. Thermal resistance is reduced using two-phase
20 flows and materials with high thermal conductivities [3, 5].

21 Beginning with the seminal publication by Tuckerman and Pease, micro-
22 channels have been extensively studied for their transport phenomena char-
23 acteristics [6]. A decade after Tuckerman and Pease, researchers began to
24 focus on two-phase flow initially studying heat transfer flow models, channel
25 pressure drop, and critical heat flux [7]. Though flow regimes were varied
26 in systematic flow reviews, fluid was pumped through the channels in forced
27 convection flow [8, 9, 10, 11, 12, 13]. Forced flow in the micro-channels in-
28 creases the heat transfer potential; however, for low-power environments,
29 methods must be used which maximize the capability of the solitary device
30 [11, 14, 15].

31 Applications for MHEs have ranged from electronics cooling to harnessing
32 waste energy [6, 16]. Recent research has explored system level waste heat en-
33 ergy harvesting solutions by characterizing heat transfer devices coupled with
34 thermoelectric generators [17, 18, 19, 20, 21, 22]. However, researchers have
35 noted that in addition to improving the conversion efficiency of thermoelec-
36 tric material itself, there is a parallel need to research and develop advanced

associated heat exchangers [23, 24, 25, 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, 28, 29, 30, 31, 32, 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, 35, 36, 37, 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

60 the autonomous channel horizontal capillary flow provides fluid motion in
61 the MHE [40, 41, 42]. In addition to fluid flow economy, the heat transfer
62 requirements of the MHE demands choosing a substrate which meets the
63 desired thermal conductivity.

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

78 Closed system devices can be notoriously difficult to characterize *in situ*
79 without compromising the nature of the device. However, using theoretical
80 formulas and experimental data, a simulation can be prepared which can ver-
81 ify system operation and provide useful insight into device operation. It is in
82 this vein that a modified lattice Boltzmann model is presented to establish

83 interior operation of the experimental MHE. The lattice Boltzmann method
84 (LBM) performs particularly well for systems with dynamic surface inter-
85 actions, including multi-phase systems, which are fundamentally difficult to
86 model and computationally costly. The LBM provides an improved model on
87 these constraints due to removing the explicit tracking of the moving phase
88 interfaces [47].

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

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

Figure 1: Components of MHE.

106 working fluid travels to the MHE copper lid where heat transfer to the heat
 107 sink allows condensation to occur and the working fluid returns to either
 108 the micro-channels or the reservoirs on the ends. The boiling and condensing
 109 process within the MHE is shown in Figure 2. While the MHE described
 110 is designed for multiple applications in multiple environments, the working
 111 fluid tested and modeled is specified as 3M[®] HFE-7200. Copper was selected
 112 for the MHE due to thermal properties; however, any metal which can be
 113 electrodeposited can be used as an alternative.

114 Once experimentally characterized and boundary conditions known, the
 115 LBM for a single micro-channel is developed and simulated for the working
 116 fluid phase change. Implementing the LBM scheme requires a thorough un-
 117 derstanding of the system in question as well as the properties of the working

Figure 2: Fluid Cycle Interaction in the MHE, where each Channel is Simultaneously Boiling and Condensing due to the Constant Heat Source and Heat Sink.

fluid. In order to simulate the system properly, the physical system must be numerically modeled equivalently and the lattice network must be of sufficient resolution with an appropriate time step [48]. These constraints assist in representing the correct physics for the system. While in many cases the physical system units are non-dimensionalized prior to discretizing the lattice, it is not absolutely necessary [48]. The model presented in this work maintained all units which allowed for better comparison with parameter calculations and experimental data.

2. Experimental Method

2.1. Fabrication

Prior to the production of a working MHE, fabrication methods were determined. There are five broad fabrication classifications for processing micro-channels: photolithography, expansion, solidification, subtractive, and

additive [49, 50, 51]. All five methods potentially include expensive equipment or clean-room laboratory conditions that are capable of producing high-quality micro-channel devices. There are, however, low-cost options which allow for ease of manufacture and a more widespread use of metal-based MHEs. A general laboratory method that did not require expansive clean-room facilities was pursued for these devices for this reason. One important photolithography technique for metallic micro-structures is LIGA (German for lithography, galvanoformung (electroplating), and abformung (molding)) where thick photoresists are applied to substrates as molds and filled with electroplated metals [52]. An adaptation of LIGA involved using polyimide as the applied mold which is a low-cost alternative to traditional LIGA photoresists [53]. As an alternative to the polyimide, some researchers have used dry film photoresists as the mold due to numerous advantages [54, 55]. This adapted technique produces an efficient, high-precision, low-cost method when combined with a COTS mask process.

The fabrication of MHEs from the modified LIGA technique concentrated on electroplating copper onto copper substrates. To create the device shown in Figure 1, a 100-200 μ m layer of copper was electrodeposited onto the copper substrate to produce the reservoirs and micro-channels. This basic design was consistent with prior exchangers fabricated by our lab using nickel as the deposited material and a similar fabrication process to the one described here [5]. Overall dimensions of the exchangers were 22mm in width and 44mm in length. After the MHE bottom plate with channels was fabricated,

154 another copper plate was polished for smoothness and used as the MHE
155 lid. Since the system was designed for closed system operation, an access
156 port was installed on the lid to allow addition of working fluid. The specific
157 fabrication steps are discussed in the following paragraphs.

158 A rigid substrate was necessary to limit plating delamination and plat-
159 ing cracking due to device handling and operation. Copper 110 sheeting
160 of 0.6mm thickness was purchased (McMaster-Carr[®]) for the substrate and
161 lid construction. In order to create a process which minimized equipment
162 and fabrication time, dry film (Elga Europe[®] Ordyl[©]) was purchased for
163 the MHE mask patterning. Electroplating and polishing was performed with
164 solutions of copper sulfate/sulfuric acid and phosphoric acid (Alfa Aesar[®]).

165 The copper substrate was initially cleaned with acetic acid solution to
166 remove any residual contamination and rinsed with DI water. A flat iron
167 was then heated on a hot plate to approximately 80°C in order to laminate
168 the dry film onto the substrate. Once the dry film adhered to the substrate,
169 the 300 μ m width channel mask was secured to the dry film. In traditional
170 micro-fabrication processes, a mask aligner is used to expose the film. In
171 this work however, a mercury light source was used for exposure which fell
172 within the recommended wavelength for the dry film. This enabled future
173 ability to manufacture the MHE outside of laboratory environments and in
174 lower cost processes. After an exposure time of 15 seconds, the undeveloped
175 dry film was removed from the substrate using the recommended potassium
176 carbonate solution. Figure 3 depicts a sample with a developed dry film and

Figure 3: Copper Substrate with Developed Photoresist prior to Electroplating.

177 substrate prepared for electroplating.

178 Prior work indicated that electropolishing the copper substrate would
 179 provide an improved and cleaner surface for electroplating. Polishing the
 180 substrate creates a surface with enhanced uniformity, prevents delamination
 181 of plating, and allows for repeatability of fabricating MHEs. A phosphoric
 182 acid based solution was selected for the polishing step. Table 1 shows the
 183 final solution composition and conditions. The established mixture of copper
 184 sulfate and sulfuric acid was chosen for electroplating due to ease of prepa-
 185 ration and accounting for chemical safety. Table 2 shows the final solution
 186 composition and conditions for electroplating.

187 The initial plating current density found in industry literature was $3 \frac{A}{dm^2}$
 188 [57]. The plating area of the MHE, including outside boundary edges was

Table 1: Copper Electropolishing Bath[56]

H_3PO_4	157mL
H_2O	75mL
<i>Current</i>	0.045A
<i>Temperature</i>	55 °C

Table 2: Copper Electroplating Bath[57]

$CuSO_4 \cdot 5H_2O$	188 $\frac{g}{L}$
H_2SO_4	74 $\frac{g}{L}$
<i>Current Density</i>	3 $\frac{A}{dm^2}$
<i>Temperature</i>	37 °C

189 200mm². This corresponded to a current of 0.61A. Unfortunately, the sample
190 plated uncontrollably in the narrow channel areas. In order to produce evenly
191 plated equivalent channels, the current was lowered to 0.4A which produced
192 optimal channel geometries given economical plating time. Deposition rate
193 of copper was also a required parameter for MHE repeatability. The aspect
194 ratio of channel width to channel wall height has important effects on fluid
195 flow through the MHE. As the aspect ratio approaches rises from 0 to 1, the
196 friction coefficient decreases, allowing fluid to minimize microscale surface
197 effects [58]. Since the channel width was 300μm , it was desired to have
198 a channel height of at least 100μm giving a minimum aspect ratio of 0.3.
199 Given MHE geometry and a desired channel height of 100μm , the minimum
200 quantity of copper to electroplate was 0.003 moles. Several samples were
201 plated for varying times, giving sample channel wall heights between 60μm
202 and 200μm , and a Dektak 150 Surface Profiler was used to measure the
203 deposited channel wall heights. Using the fabrication method presented,
204 the deposition rate of copper plating was determined to be approximately

Figure 4: Copper MHE Base Substrate with Plated Micro-channels.

205 $1 \frac{\mu m}{min}$. Several examples of plated MHE channels of wall height $120 \mu m$ were
 206 prepared, two of which are presented in Figures 4 and 5.

207 Once the MHE bottom was electroplated for 2 hours with a channel wall
 208 height of $120 \mu m$, a second copper substrate was polished which served as the
 209 MHE lid. Before securing the lid to the plated substrate, an access port with
 210 diameter 3mm was drilled into the center of the lid. Centering the access
 211 port provided equal dispersion of the working fluid, via the micro-channels,
 212 to the two reservoirs. The bottom plate and lid were then contacted with a
 213 press and bonded with epoxy on the vertical sides. The relative smoothness
 214 of the plating enhanced thermal contact between the plates; the external
 215 seal covered the entire vertical sides of both plates to ensure working fluid
 216 did not escape during operation due to the porosity of the electroplating
 217 process. The epoxy used for sealing the MHE side walls had a low thermal

Figure 5: Copper Plated MHE Capillary Micro-channels.

conductivity which was beneficial for limiting side wall thermal losses. Facilitating device re-use in testing due to closed system operation, the MHE lid access port was sealed with Kapton tape and thermal paste after filling with working fluid. Figure 6 shows a completed MHE, ready for fluid fill and testing.

2.2. Test Setup

Prior to testing with working fluid, the MHEs were baselined in a dry condition. Devices were tested with no fluid first and then working fluid was added to the MHEs. The baseline measurement was performed to determine the energy lost to surroundings. The amount of fluid necessary to fill the MHE reservoirs and channels was $150\mu\text{L}$ based on the device geometry. This value was used to determine an appropriate volume of working fluid for test-

Figure 6: Completed MHE Sample with Lid and Access Port. Note the visibility of the channels through the Access Port.

ing. A vapor-liquid interface was desired so the MHE was not filled entirely
 with working fluid and forced into a pressurized pool boiling operating mode.
 In this operating mode, the capillary channels would be ineffective. Based
 on the necessity to have the vapor-liquid interface and condensation at the
 MHE lid, the volume of working fluid added to the MHE was $120\mu\text{L}$, or 80%
 of total MHE volume. The MHE was designed to have multiple applica-
 tions in multiple environments. In this work, a low-temperature waste heat
 environment was targeted with temperatures below 150°C . Therefore, 3M[®]
 HFE-7200 engineered fluid was selected as the working fluid. The low liquid
 viscosity increased capillary flow through the channels and the boiling point
 of 76°C was low enough to provide a testing platform for low-power input

241 applications. Loading of the MHE fluid was performed by manually filling
242 the MHE using a Gilson[®] Pipetman[™] pipette. Following filling of the MHE,
243 the devices were ready for testing.

244 Tests were conducted to characterize energy absorption and transfer of
245 the MHE and temperature profiles of MHE bottom and lid. The fabricated
246 MHEs were tested in a setup depicted in Figure 7. To minimize energy
247 losses to surroundings, the testing was performed on a piece of balsa wood,
248 which has a thermal conductivity twice that of air. Omega[®] k-type bare wire
249 thermocouples (TC) were used to measure temperature at discrete points on
250 the heater, heat sink, heat flux sensors, and the MHE. Omega[®] listed the
251 error of each TC as $\pm 0.5^{\circ}\text{C}$. The heat source of the test device was provided
252 by an Omega[®] KHLV-101/10-P resistance heater. The heater was connected
253 to a power supply with a measured 3.6W input power maintained for every
254 test. This power was selected to ensure the bottom of the MHE reached
255 temperatures above the working fluid boiling point in order to cause the
256 required and desired phase change.

257 To quantify the thermal energy transfer through the setup, an Omega[®]
258 HFS-4 thin film heat flux sensor (HFS) was placed between each layer as
259 noted in Figure 7. Worth noting was a method used to minimize energy loss
260 through the test setup under Heater #2. Heater #1 and HFS #1, from Figure
261 7, were included in order to offset heat output from Heater #2 towards the
262 setup base. The additional HFS underneath Heater #2 was used to minimize
263 energy loss through the balsa base by tracking HFS #1 from Figure 7 and

Figure 7: Test Setup with Thermocouples Shown as Yellow Circles.

maintaining a heat flux measurement of zero, such that Heater #1 acted as a guard heater. This ensured that the majority of output from Heater #2 was directed towards the MHE. The nominal sensitivity of each HFS-4 has an error of $\pm 10\%$, according to Omega[®].

The heat sink used in the test setup was a Xigmatek A10 S80DP, typically used for cooling PC processors. The heat sink had enough thermal mass to hold constant temperature during device testing. A lab jack was used to ensure good thermal contact between the MHE, all sensors and heaters, and the heat sink. As shown in Figure 7, this setup was maintained for all tests. Care was taken to maximize thermal contact between setup layers by using Omega[®] Omegatherm[©]201 thermal paste. Data was recorded and analyzed via a Lab-View program on a connected PC. The two heat flux sensors (HFS #2 and HFS #3) provided heat flux data which was used to calculate energy transference and losses. Each HFS was calibrated and verified by Omega[®]. The heat flux transfer through the MHE and temperature data allowed char-

acterization of the MHE as described in the Experimental Results section.

2.3. Experimental Results

The results of prototype testing are included in this section. Tests were conducted to characterize the operation of the dry copper-based MHE versus a working fluid wetted MHE. The thermal testing reported how added thermal energy to the device altered heat flux and temperature measurements in order to characterize heat transfer and energy transference of the device. This was utilized in subsequent model evaluation and validation work.

Though the given energy input to the heater was 3.6W, resistive losses reduced energy input supplied to the MHE to 3.44W. This corresponded to a heat flux entering the MHE of $8.7 \frac{kW}{m^2}$. For the dry MHE, the output heat flux, measured at the interface between top MHE surface and heat sink, was $7.6 \frac{kW}{m^2}$ while the wetted MHE output was $8.3 \frac{kW}{m^2}$, depicted in Figure 8. The percentage of input flux which exited through the MHE was 87.5% for the dry MHE and 95.4% for the wetted MHE. Through the use of the working fluid, energy transfer through the device was increased by approximately 8%. Energy rejected from the sides of the MHE was assumed negligible versus the overall thermal energy passing from source to sink. This was based on the operating temperatures, heat flux, and side cooling that was restricted to radiation or free convection. Direct calculation of the side losses for both the dry and wetted MHE tests yielded less than 1% of the total input power to the device. Remaining input which was lost to the surrounding environment

Figure 8: Heat Flux Data from Dry and Wetted Tests.

301 was the result of energy absorbed by the copper MHE due to the increase in
 302 experimental temperature, energy lost through the MHE bottom plate into
 303 the balsa wood base, energy absorbed by the working fluid and vapor due
 304 to increases in temperature, and the energy absorbed by the working fluid
 305 during phase change.

306 The temperature profile of the dry and wetted MHE also yielded inter-
 307 esting results. The working fluid acted as a heat sink, which lowered the
 308 measured thermocouple temperatures an average of 9°C except for the ac-
 309 tual heat sink and heat source. Both the dry and wetted MHE testing yielded
 310 a heat sink temperature of 37°C while the heat source maintained a temper-

Figure 9: Dry MHE Temperature Data.

311 ature of 109°C. The temperature data for the dry and wetted MHE tests are
 312 shown in Figure 9.

313 The underlying key to these tests was the contribution to efficiency through
 314 the use of the working fluid within the MHE. In the dry tests, there was only
 315 air in addition to the copper channels between the top and bottom which
 316 reduced the thermal conductivity and the energy transference of the MHE.
 317 However, after adding working fluid, the pocket was filled 80% with work-
 318 ing fluid. The vapor-liquid interface allowed greater conductivity but also
 319 introduced phase change. The phase change within the channels was specif-
 320 ically examined in the complimentary modeling effort. The capillary action

321 of the micro-channels pulled liquid over the heat source. Vaporization of
322 fluid caused micro-channels to pull additional liquid and the temperature of
323 the MHE lid indicated condensation of working fluid back to the channels
324 and reservoirs to begin the cycle anew as shown in Figure 2. Subsequent
325 modeling work examined this behavior in greater detail.

326 The channels themselves represented unique structures unlike standard
327 micro-fabricated structures. SEM images of the plated copper are shown in
328 Figures 10 and 11. Estimation of porosity was performed both with a linear
329 bulk volume measurement and via the SEM software. Given the volume of
330 the designed MHE, the fabricated sample was massed and converted to vol-
331 ume using the density of copper. It was calculated that the samples' average
332 volume was 85% of the theoretical volume of the MHE, thus giving a porosity
333 of 15%. This agreed well with the SEM software which averaged porosity
334 calculations to 16%. The porous structure of the channels increased device
335 surface area and enhanced contact area for the working fluid. Capillary
336 and wicking action allowed working fluid to inundate the entire channel sys-
337 tem, not just the capillary micro-channels. Liquid distribution in the MHE
338 is primarily driven through the bi-directionality capillary flow in the main
339 channels; however, because the channel walls are porous, there is also liquid
340 distribution throughout the walls that act as a sponge. This behavior was
341 previously noted using nickel-based porous channels [5]. Though the system
342 is closed, this structure promoted a highly interactive vapor-liquid interface
343 which increased overall heat transfer of the device.

Figure 10: SEM Image of Plated Channels at 500 μ m Scale.

344 3. Model Description

345 Once the initial experimental boundary and initial conditions were tested
 346 and characterized, it was important to develop a model of the device interior
 347 to better characterize phase change activity and interior operation of the
 348 MHE. Due to symmetry, the simulation involved the momentum and energy
 349 transport along one channel length.

350 Prior to examining specific performance of the proposed model, a general
 351 description of the LBM model construction is given along with all fundamen-
 352 tal equations. Since the MHE system includes multiple phases of working
 353 fluid, there is a need to establish both a density distribution function and a
 354 temperature distribution function in order to fully capture the particle evolu-

Figure 11: SEM Image of Plated Channels at 500nm Scale.

355 tion through lattice space and time. The LBM describes a single component
 356 or multi-component system by these evolutions of the particle distribution
 357 functions. The density distribution function evolves using the traditional
 358 BGK collision operator as given in Equation 1. A corresponding equilibrium
 359 distribution function relates the relaxation of the system, which is given in
 360 Equation 5. The last term in Equation 1 introduces a body force term as
 361 presented by Gong and Cheng [59]. This force term includes three forces
 362 which change associated velocity terms during collisions, the interparticle in-
 363 teraction force, the interaction force between surfaces and liquids, and the
 364 gravitational force [59].

$$f_i(\mathbf{x} + \mathbf{e}_i \delta_t, t + \delta_t) - f_i(\mathbf{x}, t) = -\frac{1}{\tau}(f_i(\mathbf{x}, t) - f_i^{eq}(\mathbf{x}, t)) + \Delta f_i(\mathbf{x}, t) \quad (1)$$

$$\Delta f_i(\mathbf{x}, t) = f_i^{eq}(\rho(\mathbf{x}, t), \mathbf{u} + \Delta \mathbf{u}) - f_i^{eq}(\rho(\mathbf{x}, t), \mathbf{u}) \quad (2)$$

365 where

$$\Delta \mathbf{u} = \mathbf{F} \cdot \delta t / \rho \quad (3)$$

366 is the velocity change due to body force during the time step. The force
367 term, $\mathbf{F}$, is given by

$$\mathbf{F} = \mathbf{F}_{int}(\mathbf{x}) + \mathbf{F}_s(\mathbf{x}) + \mathbf{F}_g(\mathbf{x}) \quad (4)$$

$$f_i^{eq} = \omega_i \rho \left[1 + \frac{\mathbf{e}_i \cdot \mathbf{u}}{c_s^2} + \frac{(\mathbf{e}_i \cdot \mathbf{u})^2}{c_s^2} - \frac{u^2}{2c_s^2} \right] \quad (5)$$

368

369

370 Analogous to the density distribution functions evolution equation, the
371 temperature distribution function has an evolution equation given by Equa-
372 tion 6. The equilibrium function, given by Equation 8, is very similar to the
373 density equilibrium function. The main difference between the two distribu-
374 tion functions is the last term of each equation. While the density evolution

375 incorporates a body force term, the temperature evolution uses an energy
 376 source term. Each distribution has with it an associated velocity, e_i , at
 377 position $\mathbf{x}$ and time t . The weighting coefficients, ω_i , for both equilibrium
 378 functions is based on statistical probability for particle movement.

$$g_i(\mathbf{x} + \mathbf{e}_i \delta_t, t + \delta_t) - g_i(\mathbf{x}, t) = -\frac{1}{\tau_T} (g_i(\mathbf{x}, t) - g_i^{eq}(\mathbf{x}, t)) + \delta_t \omega_i \phi \quad (6)$$

379 where

$$\phi = T \left[1 - \frac{1}{\rho c_v} \left(\frac{\partial P}{\partial T} \right)_{\rho} \right] \nabla \cdot \mathbf{U} \quad (7)$$

$$g_i^{eq} = \omega_i T \left[1 + \frac{\mathbf{e}_i \cdot \mathbf{U}}{c_s^2} + \frac{(\mathbf{e}_i \cdot \mathbf{U})^2}{c_s^2} - \frac{U^2}{2c_s^2} \right] \quad (8)$$

380

381

382 There are many different LBM schemes based on system dimensionality
 383 and potential locations for the particles to move. For the proposed model
 384 the D2Q9 lattice scheme was selected due to system symmetry. The D2Q9
 385 scheme is shorthand for two dimensional, nine discrete velocities within the
 386 momentum discretization [60]. Figure 12 depicts the velocities for the D2Q9
 387 scheme. There are nine potential velocities and each has an associated prob-
 388 ability, given in Equation 9.

Figure 12: Particle Progression for D2Q9 LBM Scheme.

$$\omega_i = \begin{cases} \frac{4}{9}, & i = 0 \\ \frac{1}{9}, & i = 1,2,3,4 \\ \frac{1}{36}, & i = 5,6,7,8 \end{cases} \quad (9)$$

389

390

391 Before initializing the model with the density and temperature distri-
392 bution functions, information given by 3M[®] was acquired concerning the
393 working fluid in question, HFE-7200. The large amount of 3M[®] published
394 data allowed for the use of two equations which correlate the density, tem-
395 perature, and partial pressure of HFE-7200 [61]. This information was used
396 to transform temperature data for boundary conditions into density data.

397 Since there was a direct linear equation associating temperatures with spe-
 398 cific densities, the difficulty in fusing two distribution functions was simplified
 399 to include only the density distribution function values. The two equations
 400 are given in Eq. 10 and 11 below [61].

$$\ln P = 22.289 - 3752.1(1/T) \quad (10)$$

$$\rho = 1.4811 - 0.0023026(T - 273.15) \quad (11)$$

402 Once the density distribution function was established and the tempera-
 403 ture array was also calculated for the model, the pressure field needed to be
 404 determined. Since the pressure gives the phase change interface tracking, it
 405 was the overall objective of the simulation. In order to determine the pres-
 406 sure, an equation of state was used to associate all three variables of density,
 407 temperature, and pressure. The Peng-Robinson equation of state was chosen
 408 due to stability and accuracy for most models [59, 62]. Equation 12 gives the
 409 Peng-Robinson equation of state. The next section describes how the system
 410 was tested and the lattice parameters for model simulation.

$$P = \frac{\rho RT}{1 - b\rho} - \frac{a\rho^2\varepsilon(T)}{1 + 2b\rho - b^2\rho^2} \quad (12)$$

411 such that

$$\varepsilon(T) = [1 + (0.37464 + 1.54226\omega - 0.26992\omega^2)(1 - \sqrt{\frac{T}{T_c}})]^2, \quad (13)$$

412 with ω being the acentric factor. From correspondence with 3M[®] engineers,
 413 the acentric factor was identified as 0.459 for HFE-7200.

414 3.0.1. **Nomenclature**

Symbol	Units	Description
$f_i(\mathbf{x}, t)$	—	Particle Distribution Function
τ	s	Relaxation Time
$\Delta f_i(\mathbf{x}, t)$	N	Body Force Term
ρ	g/mL	Particle Density
$\mathbf{u}$	m/s	Particle Velocity
$\mathbf{F}_{int}$	N	Interparticle Interaction Force
$\mathbf{F}_s$	N	Solid Surface/Fluid Interaction Force
$\mathbf{F}_g$	N	Gravitational Force
$f_i^{eq}(\mathbf{x}, t)$	—	Equilibrium Distribution Function
ω_i	—	Weighting Coefficients
$\mathbf{e}_i$	—	Discrete Velocity Vector
c_s	m/s	Lattice Sound Speed
$g_i(\mathbf{x}, t)$	—	Temperature Distribution Function
τ_T	s	Temperature Relaxation Time
ϕ	—	Energy Equation Source Term
$f_i^{eq}(\mathbf{x}, t)$	—	Equilibrium Distribution Function
T	K	Temperature
$\mathbf{U}$	m/s	Temperature Velocity

P	bar	Pressure
R	$\frac{J}{Kmol}$	Gas Constant
b	$\frac{m^3}{mol}$	Peng-Robinson Constant
a	$\frac{kg \cdot m^5}{s^2 \cdot mol^2}$	Peng-Robinson Constant
T_c	K	Working Fluid Critical Temperature

415 3.1. Performance Setup

416 The initial step in pursuing an LBM simulation is the selection of the
417 program which will solve the model. Given the objectives of observing the
418 density, temperature, and pressure fields and the arrays which will develop
419 during the LBM, MATLABTM was selected. From the experimental data
420 published previously, the first step for the program is to determine the bound-
421 ary conditions of the system as well as the initial conditions for the fluid in
422 channel. Symmetry of the channel and the bi-directionality of the fluid flow
423 suggest periodic horizontal boundary conditions. The fixed top and bottom
424 plating provides for the traditional LBM bounce back condition. While these
425 boundary conditions apply to the momentum equations, there are also two
426 additional boundary conditions which account for the heat sink and source.
427 Therefore, temperature boundary conditions must also be set. This presents
428 difficulty in programming where an additional temperature distribution func-
429 tion must be defined. However, one benefit of using a manufactured working
430 fluid is the OEM data sheets and information which potentially provide alter-
431 native avenues to establishing a second distribution function. The boundary

Figure 13: Boundary and Initial Conditions prior to Saturation.

432 conditions and initial conditions for the channel model are given in Figure
 433 13.

434 The physical micro-channel had dimensions of 20mm long, $300\mu\text{m}$ wide,
 435 and $120\mu\text{m}$ in height. Therefore, the ratio of length to height is approximately
 436 166. While this ratio would simulate conditions along the entire channel,
 437 symmetry and bi-directionality of fluid motion due to capillary action allowed
 438 the physical ratio of the program to run at half of the channel size. Thus,
 439 the ratio used in the program is approximately 80. The height of the simu-
 440 lation was halved such that LY was set to $60\mu\text{m}$ for scaling and reducing the
 441 computational power needed to perform the simulation, effectively producing
 442 a model having $2\mu\text{m}$ of actual dimension per μm of the simulation dimen-
 443 sion. Therefore, the horizontal lattice was set to $4800\mu\text{m}$ to give the proper

dimensionality of the simulated channel. However once again, due to symmetry and bi-directionality, the horizontal lattice was reduced to efficiently conduct the simulation without incurring too much computational power and memory. Temperature from the experimental testing fixed the bottom plate temperature at 85°C and the top plate temperature at 50°C for tests with working fluid. Time steps were tried to measure the steps necessary to ensure steady-state conditions. Following application of boundary and initial conditions along with channel dimensions for the simulation, working fluid properties were considered to provide the LBM-generated pressure field.

Product information for 3M[®] Novec[™] HFE-7200 fluid included Equations 10 and 11 which provided correlation between vapor pressure, density, and temperature [61]. Given these equations, the temperature boundary conditions were transformed into part of the density array for the lid and bottom boundary conditions. With the boundaries established for the density array, the channel initial conditions were fixed. Since 80% of the channel is filled with working fluid and 20% is air at room temperature, the inner array has initial densities of $1.43 \frac{g}{mL}$ for the working fluid and $0.0012 \frac{g}{mL}$ for dry air. Immediately after inserting working fluid into the MHE, the working fluid began evaporating until the dry air was saturated.

In order to fully understand the system equilibrium initial conditions with saturated vapor and bulk working fluid, Raoult's Law for a single condensable species was used which is given by Equation 14.

$$p_i = y_i P = p_i(T) \quad (14)$$

Therefore, for the HFE-7200/air system at ambient conditions, the molar composition calculation used the 3M[®] partial pressure equation.

$$\ln P = 22.289 - \frac{3752.1}{298} = 9.6981 \implies P = 0.163 \quad (15)$$

Therefore,

$$y_{7200} = \frac{0.163}{1.01325} = 0.1607 \frac{\text{mol}_{7200}}{\text{mol}_{\text{mixture}}} \quad (16)$$

$$y_{\text{air}} = 1 - y_{7200} = 0.8393 \frac{\text{mol}_{\text{air}}}{\text{mol}_{\text{mixture}}} \quad (17)$$

Using density properties and channel geometry measurements, the calculation of the initial density condition gave the saturated vapor density as less than the bulk working fluid density, at ambient temperature, by approximately 0.002%. Thus, upon saturating the dry air of the channel, the system was assumed to have relatively uniform initial density. The dry air/working fluid interface tracked downward to provide the initial conditions of the simulation, shown in Figure 14.

In the two-dimensional system, the horizontal velocity component can be found by measurement of the physical device. Testing provided a flow velocity along the channel length of $20 \frac{\text{mm}}{\text{s}}$. At ambient temperature, 3M[®] published viscosity allows calculation of the Reynolds number to initially

Figure 14: Boundary and Initial Conditions after Saturation.

481 be 975.6, giving laminar micro-channel fluid flow. Gravity and buoyancy
 482 effects were also accounted for in the flow profile. However, Cheng and Wu
 483 published a correlation shown in Equation 18 [63]. For the system in question,
 484 channel diameter was much less than the equation requires, revealing that
 485 gravity effects on the symmetry flow was negligible. Establishing the physical
 486 system, boundary and initial conditions, and fluid momentum within the
 487 model allowed solutions of LBM collisions. This was coupled with the two
 488 OEM equations and the equation of state to determine phase transitions
 489 within the channel.

$$d_c = 0.224l_c \quad (18)$$

Table 4: Peng-Robinson EOS parameters [61]

a	$3.6705 \frac{kgm^5}{s^2mol^2}$
b	$0.00016 \frac{m^3}{mol}$
R	$8.314 \frac{m^2Pa}{Kmol}$
T_c	$483.15 K$
P_c	$2.01 MPa$

490 In order to develop the pressure field, the parameters of the Peng-Robinson
 491 equation of state needed to be determined. Table 4 was generated from cal-
 492 culation and working fluid information from 3M[®]. Note that all units were
 493 maintained due to the requirement that all model results be comparable to
 494 the experiment and experimental units. Taking all conditions and the phys-
 495 ical system parameters into account, simulations were performed to solve
 496 for the phase change interface transitions. The results suggested promising
 497 simulations of the phase change regimes which occurred within the micro-
 498 channel, reinforcing the fundamental MHE design and initial considerations
 499 of internal fluid flows.

500 3.2. Simulation Results

501 The initial simulations were plotted in intervals of 40 time steps for the
 502 density, temperature, and pressure arrays. The density array at the initial
 503 time step showed the dry air and bulk working fluid density difference. As
 504 time steps progressed, three interfaces began to form, one at the lid, one
 505 at the bulk vapor-liquid interface, and one at the bottom plate. The time-
 506 based progression of the central vapor-liquid interface moved $12\mu m$ from the
 507 lid down to approximately $23\mu m$ from the lid in the density array, shown in

Figure 15: Time Progression for Density Array.

Figure 15. After 360 time steps, there was less than 1% change between the densities at time step 320 and step 360, suggesting that the density array had reached steady-state conditions. Time progression of the density as a function of position from the lid is given in Figure 15 while the percent change from each time step to the next is given in Figure 16.

The temperature array was simulated using Equation 11 and the density array. Another note for the temperature array was that at time step one, the air was already saturated with HFE-7200 using the calculation from Raoult's Law. The temperature as a function of position from the lid is plotted in Figure 17 which shows the temperature trends in the time progression mimic an

Figure 16: Percent Change in Density Array Time Progression.

518 inverse relationship to the density trends in Figure 15. Initially, the bulk fluid
 519 is at room temperature with the vapor showing a warming trend due to the
 520 heat sink kept at a constant temperature and the bulk liquid absorbing ini-
 521 tial bottom plate heat source energy . The time progression shows bulk vapor
 522 increasing in temperature while the bulk liquid acts as an internal heat sink.
 523 While temperature increases at the lid, the density and temperature arrays
 524 indicate liquid conditions, indicating that condensation is occurring at the
 525 lid. The large increase in temperature at the bottom plate indicates boiling
 526 occurring, given density and temperature data. The pressure array is critical
 527 to the density and temperature arrays to confirm phase change. Similar to

Figure 17: Time Progression for Temperature Array.

the density array, the largest changes were found in the span between time step 1 and time step 40, as shown in Figure 18. After 360 time steps, the temperature array percent change was less than 1%, indicating steady-state conditions which agreed with the density array.

Both the density and temperature arrays were used to produce the pressure array from the Peng-Robinson equation of state, indicating where the phase change was occurring in the channel profile. Shown in Figure 19, the pressure array appears similar in pattern to the density array. The pressure array is the key to determining phase change within the micro-channel. Note in the plot that the low pressure in the $5\mu\text{m}$ to $20\mu\text{m}$ range indicates vapor

Figure 18: Percent Change in Temperature Array Time Progression.

538 phase in the channel. The bulk liquid phase is indicated by the leveling off of
 539 the pressure. Figure 20 reinforces Figures 16 and 18 suggesting the steadying
 540 of conditions after 360 time steps. Beyond the array plots, Figures 21 and
 541 22 depict the time step progression of the pressure array with color maps
 542 in MATLABTM. The phase interfaces at the MHE lid and bottom are small
 543 in comparison with the bulk vapor-liquid interface, shown in yellow. The
 544 white shade indicates conditions where there are vapor bubbles interacting
 545 with bulk liquid while the orange shade indicates conditions where liquid
 546 condensate is interacting with the bulk vapor.

547 The simulated cyclical operation of the MHE provides reinforcement that

Figure 19: Time Progression for Pressure Array.

the experimental device is operating effectively as designed. Given the conditions of phase change at the heat source and heat sink, indicating boiling and condensation, and the large tracking vapor-liquid interface, the model reassures the operation of the experimental MHE as having a real internal fluid-vapor-fluid loop.

4. Conclusion

Fabrication and operation of a MHE has been investigated. The MHE acted in a closed system with operation based on development of capillary micro-channels which provided pump-like working fluid motion across a

Figure 20: Percent Change in Pressure Array Time Progression.

557 heated surface, inducing phase change of the fluid. This operation provided
 558 a more efficient transfer of energy across the copper device when compared
 559 with dry operation.

560 Fabrication of the copper device was based on electroplating techniques
 561 that produced channel widths of $300\mu\text{m}$ with heights of $120\mu\text{m}$. The fabri-
 562 cation methodology proved that devices can be manufactured with minimal
 563 equipment and laboratory necessities. This added benefit was meant to po-
 564 tentially increase the global adoption and use of such devices.

565 The introduction of the working fluid improved the energy transfer of the
 566 device by approximately 8%. With an energy flux supply of $8.7\frac{kW}{m^2}$, a dry

Figure 21: Color Map of Pressure at Initial Model Conditions

41
Figure 22: Color Map of Pressure at Steady-State Conditions (ts = 360)

device showed output flux of $7.6 \frac{kW}{m^2}$ whereas the wetted device showed output flux of $8.3 \frac{kW}{m^2}$. These results demonstrated the effectiveness of using working fluid and phase change within the devices. Use of working fluid, coupled with the development of copper techniques allowed a device to be fabricated entirely of copper. This increased thermal conductivity of the device when compared to traditional materials such as silicon and aluminum.

The closed system operation of the MHE required internal operation analysis via a simulated model using the lattice Boltzmann method. While a dual distribution function was needed for the multi-phase system, an alternative solution for programming was used whereby equations from the manufacturer, relating the temperature, density, and pressure, provided the necessary correlations to produce the system properties. The simulated micro-channel indicated that three areas of phase interface developed which reinforced the initial MHE design and cyclical operation of the working fluid.

The MHE presented was designed to be an efficient transfer device for waste energy which was fabricated using basic equipment and concepts. After testing the device both experimentally and using a simulated model, the MHE did provide a platform that accomplished its design objectives.

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