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Experimental and numerical investigation of a shaped microchannel evaporator for a micro Rankine cycle application

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A B S T R A C T

In the present study, numerical analysis and experimental observations have been conducted to investigate the heat and mass transfer behavior in a shaped microchannel evaporator and to determine its ability to provide high quality steam for micro Rankine cycle application. The micro evaporator is designed to prevent the presence of liquid droplets at the exit by incorporating re-entrant wall angles for capillary flow stabilization and a stream wise temperature gradient to allow a range of wall temperatures along its length. Meniscus evaporation, periodic bubbly evaporation and boiling regimes were observed based on experiments at different mass flow rates and working temperatures. Experimental results show that the meniscus evaporation and periodic bubbly evaporation regimes provide fully evaporated steam without droplets at the exit. Thus they are successful operating regimes for the micro evaporator in micro Rankine cycle application. One dimensional conjugate heat transfer was considered along the microchannel evaporator with thin film theory used to model the evaporation rate. The numerical results are in good agreement with experimental observation for the meniscus evaporation regime. This kind of micro evaporator achieves the objective of providing a constant flow of fully evaporated steam without the presence of mixed flow at the exit, but only up to a limit flow rate.

1. Introduction

The idea of acquiring energy from micro power generation systems was introduced by Epstein and Senturia [1] in the mid-1990's. They proposed a micro gas turbine engine to convert chemical energy of fuel to mechanical or electrical energy at small scales [2]. This approach was based on the air breathing Brayton cycle and needed fuel as the energy source. Frechette et al. [3] introduced a closed micro Rankine steam cycle that used waste heat as the energy source. It consists of a millimeter-scale turbine microfabricated in silicon using microelectromechanical system (MEMS) technologies that would incorporate a micro-pump, an electromagnetic micro-generator as well as two-phase flow heat exchanger. Applications include waste heat recovery to increase the efficiency of automobile engines or thermal energy harvesting to power wireless sensors. Some parts of this microsystem, such as the micro turbine and the micropump, have been demonstrated, showing the potential for this approach [4–6]. A key component of a steam power-plant-on-a-chip is a micro evaporator that can provide the micro turbine with a flow of superheated vapor. Thus the ability to provide a flow of superheated steam without any pulsation or liquid droplets is very important for this application. Microscale two-phase flow is an active research area driven mainly by the high heat rates that can be achieved by boiling or evaporation to meet the increasing cooling needs of microelectronics [7–10]. Bubbly, slug flow, annular flow, and mist flow were observed during flow boiling in microchannels. Thus, unsteady flow and pressure variations, and alternating liquid and vapor slugs exiting the microchannel are achieved [11,12] and so it is not

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Nomenclature

A	dispersion constant (J)
h_{fg}	latent heat of vaporization (J/kg)
K	thermal conductivity (W/m K)
M	molecular weight (kg/mol)
m''	interface net mass flux (kg/m^{2}s)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
P	pressure (Pa)
$\overline{R}$	universal gas constant (J/mol K)
T	temperature (K)
V	molar volume (m^3/mol)
x	coordinate along thin film (m)

Greek symbols

α	channel aspect ratio
δ	film thickness (m)
ν	kinetic viscosity (m^2/s)
ξ	coordinate along micro evaporator (m)
ρ	density (kg/m^3)
σ	surface tension (N/m)
$\hat{\sigma}$	accommodation coefficient

Subscripts

c	capillary
d	disjoining
l	liquid
lv	liquid–vapor interface
sat	saturation
v	vapor
w	wall

acceptable for micro Rankine cycle application. Thin film evaporation is the liquid–vapor phase change mechanism that takes placed in microchannels and porous media without vapor bubble formation. It has been studied extensively in the past few decades to increase the evaporation rate [13–17]. However, more efforts are needed to provide a vapor flow without any pulsation or liquid droplets. Azarkish et al. [18] investigated the water evaporation phenomena on the different micro and nanostructured surfaces to provide a vapor flow without any pulsation or liquid droplets. They introduced a novel silicon bi-textured micropillar array to provide fully evaporated steam for a micro-Rankine cycle application [19]. High quality vapor flow with appropriate mass flow rate was achieved by using bi-textured micropillar array. However, superheating the vapor flow is difficult in this approach. It seems that using the parallel microchannels are more appropriate for superheating. Hardt et al. [20] analyzed flow patterns during the evaporation process in parallel microchannels. A stationary meniscus is seen at low mass flow rate. In this situation, water is completely vaporized from a meniscus in microchannel. However, it is very sensitive to variation of mass flow rate. Parallel and chaotic oscillations of meniscus were observed by increasing the mass flow rate.

Fully evaporated steam flow in a microchannel was achieved by Arslan et al. [21,22] using a thermal gradient along shaped channels with multiple expansions and contractions. The schematic of a shaped microchannel evaporator is shown in Fig. 1. Water enters from one side of micro evaporator and heat is applied on the other side (exit). There is a temperature gradient along the microchannel due to thermal resistance of narrow empty channels in the silicon wall that located between each cell.

Silicon is a slightly hydrophilic material, so in the straight part of the shaped channel (zones 1 on Fig. 1), the capillary forces are in the flow direction helping to pump water through channel. However, the meniscus changes curvature in the expansion area due to the shaped walls (zone 2 on Fig. 1). Here, the capillary forces are acting against the external pumping force, which tends to stop the water flow. If the wall temperature is appropriate at this location, the water will vaporize at the incoming flow rate and the meniscus will be stable. Evaporation will occur along thin films that wicked on the expansion walls. Otherwise, the cell fills with water and it flows to the next cell with higher potential of evaporation because of its higher wall temperature. Arslan et al. [21,22] showed that a stable evaporating meniscus can be observed at different locations along the shaped channel, depending on the water mass flow rate and the temperature gradient along the channel. Boiling and the formation of detrimental vapor bubbles within the microchannel were prevented and a fully evaporated flow of superheated steam was provided at the exit. The operating

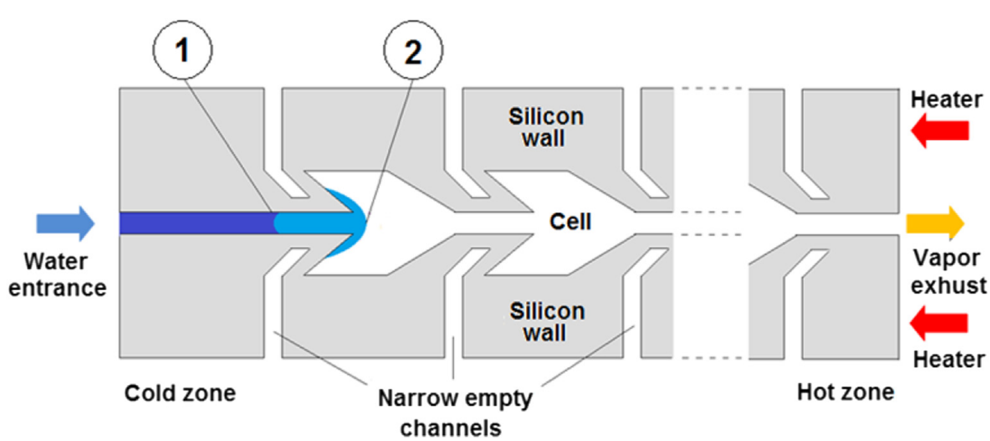

Fig. 1. The schematic of shaped microchannel as a micro evaporator.