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Entropy generation analysis and dimensional optimization of an evaporator for use in a microscale refrigeration cycle

Göker Türkakar, Tuba Okutucu-Özyurt*

Department of Mechanical Engineering, Middle East Technical University, Üniversiteler Mahallesi, Dumlupınar Bulvarı, No: 1, ODTÜ, Çankaya, 06800 Ankara, Turkey

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A B S T R A C T

Entropy generation in the evaporator of a microscale vapor compression refrigeration cycle is investigated under the effects of vapor quality, mass and heat flux, saturation temperature, and channel dimensions. For a variety of channel heights and mass flow rates, the optimum vapor quality, and the channel and fin widths yielding minimum entropy generation are obtained. The variation of heat transfer coefficient with vapor quality, and pressure drop with heat flux compare very well with literature. The vapor quality yielding the minimum entropy generation is found as 0.846. The optimum channel and fin widths are 66 and 50 μm, respectively, for 700 μm channel height. Heat transfer is the major source of the total entropy production for 200–400 μm wide channels, while the contribution of pressure drop becomes comparable for narrower channels. The study is unique in the literature in pursuing an entropy generation minimization study for microscale two-phase flow.

Analyse de la production d'entropie et optimisation dimensionnelle d'un évaporateur utilisé dans un cycle frigorifique à micro échelle

Mots-clés : Micro-évaporateur ; Compresseur de vapeur à micro échelle ; Cycle frigorifique ; Ecoulement diphasique/multiphasique ; Refroidissement des équipements électroniques ; Optimisation dimensionnelle ; Minimisation de la production d'entropie

* *Corresponding author*. Tel.: +90 312 210 2575; fax: +90 312 210 2536.
E-mail addresses: turkakar@metu.edu.tr (G. Türkakar), okutucu@metu.edu.tr (T. Okutucu-Özyurt).
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Nomenclature

dz	unit length [m]
F	frictional
f	friction constant
G	mass velocity [kg m^{-2} s^{-1}]
i	enthalpy [kJ kg^{-1}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
H_c	channel height [μm]
k	thermal conductivity [W m^{-1} K^{-1}]
L	total channel length [cm]
$\dot{m}$	mass flow rate [kg s^{-1}]
q''	heat flux [W m^{-2}]
p	pressure [Pa]
P	perimeter [m]
$\dot{Q}$	heat transferred [W]
Re	Reynolds number
$\dot{S}_{gen}$	entropy generation [W K^{-1}]
s	specific entropy [kJ kg^{-1} K^{-1}]
t	substrate thickness [μm]
T	temperature [K]
v	specific volume [m^3 kg^{-1}]
W	total channel width [cm]
w_c	channel width [μm]
w_w	channel wall thickness [μm]
x	vapor quality

Greek letters

η	fin efficiency
σ'	entropy gen. per length [W m^{-1} K^{-1}]
ρ	density [kg m^{-3}]

Subscripts

acc	acceleration
base	base
CBD	convective boiling dominant
F	frictional
ht	heat transfer
pd	pressure drop
sat	saturation
seg	segment
t	total
tp	two-phase
l, f, L	liquid
lv	liquid vapor
LO	entire flow as liquid
NBD	nucleate boiling dominant
v	vapor

1. Introduction

Due to their high efficiencies, high heat removal rates and ability to maintain a heat generating system under a certain temperature for long time durations, microscale vapor compression refrigeration cycles (MVCRC) are considered as promising cooling options. In recent applications, as the cycle is generally used where the space is limited, its compactness is critical. In addition, the energy consumption becomes a challenge when these systems are to be mounted on mobile electronic devices. An entropy generation analysis and dimensional optimization of the micro-evaporator is believed to be useful for designing such a compact and efficient device.

The entropy generation minimization method has always attracted researchers, especially when they are designing a heat exchanger. To some extent, the method is used for designing microchannel heat sinks. Almost all studies using entropy generation minimization method have focused on single phase, laminar and incompressible flow (Khan et al., 2009; Jafari et al., 2010). Khan et al. (2009) carried out an optimization study for the overall performance of microchannel heat sinks employing entropy generation minimization method. Both thermal and hydrodynamic performance of the system is examined by the help of this method. Some general expressions were derived using mass, energy and entropy balances. In slip flow regime, important parameters, such as channel aspect ratio, Knudsen number, accommodation coefficient were evaluated for incompressible fluids. The authors concluded that the optimum entropy generation rate decreased with the increase in Knudsen number in the slip flow region. Similarly, Abbassi (2007) inspected the entropy generation in a uniformly heated microchannel heat sink, and sought a solution for fluid flow with the porous medium model on extended Darcy equation. A 2-D model for the heat transfer was used in the study. The effects of the channel aspect ratio, thermal conductivity ratio and porosity on thermal and entropy generation characteristics of the flow are examined. Abbassi (2007) reported that the ratio of the channel height to the channel width should be kept at the maximum in order to maximize the thermal performance. Contrary to majority of the studies dealing with optimization of rectangular microchannel heat sinks, Jafari et al. (2010) optimized a circular microchannel geometry using entropy generation minimization method. Water was used as a coolant, and the effects of the channel diameter, number of channels, heat flux and pumping power on the entropy generation rate were investigated. They reported that the channel diameter has no significant effect for low heat flux values.

Although there is no dimensional optimization study in microchannels using entropy generation method for two-phase flow, there are some studies focusing on the entropy generation analysis in two-phase flow in mini or macro channels. Revellin and Bonjour (2011) examined the entropy generation during flow boiling of refrigerant alone and refrigerant-oil mixture in a 10 mm diameter tube. Entropy generation rates are evaluated for smooth or enhanced tubes with varying tube diameters and mass flux (ratio of the mass flow rate to the flow cross sectional area) values for pure refrigerants or refrigerant-oil mixtures. The results indicated that the enhanced tube performed better in low mass velocities; on the other hand, smooth tubes are advised for higher mass velocities under uniform heat flux boundary condition at the tube wall. Sarkar et al. (2005) carried out a study minimizing the irreversibility of heat exchangers for transcritical CO_2 systems for macro scale systems. They have conducted a second law analysis for both the evaporator and the gas cooler. The analysis comprised both operational and material