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Research Paper

Evaluation of thermal-hydraulic performance of hydrocarbon refrigerants during flow boiling in a microchannels array heat sink

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HIGHLIGHTS

- Evaluation of refrigerants R600a, R290 and R1270 during flow boiling in a microchannels array.
- Comparison of data for hydrocarbons with previous data for R134a.
- Parametric analysis of heat transfer coefficient, pressure drop, ONB and exergy behaviors.
- Comparison of the experimental data and prediction methods from literature.
- In general, refrigerant R290 presents the best performance.

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ABSTRACT

The present study concerns an experimental evaluation of the performance of hydrocarbon refrigerants during flow boiling in a microchannels array heat sink. The heat sink is composed of fifty channels with cross sectional areas of $123 \times 494\ \mu m^2$ and length of 15 mm manufactured in a copper block. Heat transfer coefficient and pressure drop data were obtained for refrigerants R600a, R290 and R1270, mass velocities from 165 to 823 kg/m^2 s, heat fluxes up to 400 kW/m^2, liquid subcooling at the inlet of the test section of 5, 10 and 15 °C and saturation temperature of 25 °C. The data were compared with experimental results obtained in a previous study for R134a and predictions by methods from literature. In general, R290 presented the best performance, providing the highest average heat transfer coefficient and a pressure drop only slightly higher than R1270 that was the fluid presenting the lowest pressure drop. An exergy analysis also revealed the refrigerant R290 as the one presenting the best performance. However, R290 needed the highest excess of superheating to trigger the boiling process (ONB). The methods from literature evaluated in the present study poorly predicted the experimental data for two-phase pressure drop. On the other hand, the method of Kanizawa et al. (2016) was quite accurate in predicting the heat transfer results.

1. Introduction

In the pioneering work of Tuckerman and Pease [2], single-phase flow of water across microchannels was proposed as a solution to dissipate high heat fluxes. Since then, several authors have performed studies on single-phase flow and on convective boiling in microchannels aiming to achieve the dissipation of extremely high heat fluxes such as 3 MW/m^2 [3]. In the last years, emphasis was addressed into investigating convective boiling in multi-microchannels [4–17]. In general, these studies concern experimental evaluations of pressure drop, heat transfer coefficient, flow patterns, void fraction and thermal-hydraulic instabilities during flow boiling in microchannels array heat sinks (MAHS).

According to Ribatski [18], MAHS presents advantages over the competing technologies such as reduced refrigerant inventory, compactness, quasi-isotherm heat transfer process, heat transfer coefficient enhancement and, from a structural point of view, allows high operational pressures if necessary. These characteristics are responsible for the following benefits: (i) improvement of the thermal-hydraulic efficiency of the cooling system; (ii) suitability of the system to conditions characterized by restrictions to toxic and flammable fluids, allowing the use of refrigerants with low cost and negligible Global Warming Potential (GWP) and Ozone Depletion Potential (ODP); (iii) minimization of the environmental

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Nomenclature

A	area [m^2]
D_h	hydraulic diameter [m]
$\dot{E}$	exergy rate [W]
f	friction factor [dimensionless]
G	mass velocity [kg/m^2 s]
H	microchannel depth [m]
h	heat transfer coefficient [W/m^2 °C]
i	enthalpy [kJ/kg]
i_{lv}	enthalpy of vaporization [kJ/kg]
k	thermal conductivity [W/m K]
L	length [m]
MAE	mean absolute error [%]
$\dot{m}$	mass flux [kg/s]
p	absolute pressure [kPa]
$\dot{Q}$	heat [W]
q''	heat flux [W/m^2]
Ra	average roughness [μm]
Rq	quadratic mean roughness [μm]
Rt	maximum roughness height [μm]
$\dot{S}$	entropy rate [W/K]
s	entropy [kJ/kg K]
T	temperature [°C]
W	microchannel width [m]
x	vapor quality [dimensionless]
z	axial axis of the microchannel [m]

Greek symbols

α	void fraction [dimensionless]
Δp	differential pressure [kPa]
ΔT_{sub}	liquid subcooling at the inlet plenum [°C]
$\Delta\overline{T}$	average temperature difference [°C]
λ	data predicted within an error band of ± 30% [%]
ζ	ratio between microchannel and plenum areas [dimensionless]
η	second law efficiency [dimensionless]
ρ	density [kg/m^3]
σ	surface tension [N/m]

Subscripts

0	reference
1ϕ	apparent single-phase flow
2ϕ	flow boiling condition
a	air
accel	accelerational
ch	channel
cont	contraction
car	characteristic
eff	effective, effective heat applied
elec	electric
end	end
env	environment
exp	expansion
fluid	fluid
fp	footprint area
f	frictional
ger	generated
H	high
in or 2	heat sink inlet plenum
mo	momentum
l	liquid-phase
L	low
lv	latent vaporization
out or 3	heat sink outlet plenum
v	vapor-phase
plm	plenum
pred	predicted
sat	saturated state
rev	reversible
T	total
wall	wall
W	work

impact through the reduction of refrigerant contained in the system and the material used for its manufacture; (iv) possibility of high heat dissipation under extremely confined conditions. In this context, despite of the recognition of the advantages of implementing flow boiling in MAHS for thermal-management of electronic devices, the fluid refrigerant to be used in these systems is still an open issue.

Presently, most of studies available in literature about convective boiling in MAHS were performed for hydrofluorocarbons (HFCs) (mainly R134a) [8,19–22]. Experimental investigations concerning the hydro-fluoroolefins (HFOs) [13–15,23], HFE7100, FC77, FC72, methanol, acetone and water are also not rare in literature. However, most of these studies were performed for MAHSs with different geometries and configurations for the channels distributions, what makes difficult to compare data for different refrigerants obtained by independent laboratories. According to the knowledge of the present authors, a comparative and broad analysis of refrigerant performance for flow boiling in MAHS is still not available in the open literature.

Recently, as highlighted by Mota-Babiloni et al. [24], there is a tendency to replace the HFCs, due to their high GWP, by refrigerants less harmful to the environment. Currently, the search for these new refrigerants is based on the following main criteria: (i) null or low ODP; (ii) low GWP; (ii) to provide high efficient systems. In this context, natural refrigerants such as ammonia, CO_2 and hydrocarbons, although not being new, they emerge as a reasonable alternative by complying such criteria.

Table 1 compares the characteristics of three hydrocarbons (R600a, R290 and R1270) and the refrigerant R134a. According to this table, the hydrocarbons attend to the environmental requirements because they present null ODP and negligible GWP. Furthermore, their transport properties as higher thermal conductivities and lower viscosities favor high heat transfer coefficients under the predominance of convective effects. Moreover, the higher latent heat of vaporization of hydrocarbons than R134a implies on lower mass fluxes to dissipate the same amounts of heat. A negative aspect of hydrocarbons is their flammability that, however, is contra balanced by the reduced amount of refrigerant contained in the heat sink.

As far as the present authors know, despite the potential advantages of hydrocarbons, experimental data for flow boiling of these fluids in MAHSs are rare in the literature. Moreover, only two studies [27–28] are available concerning heat transfer data for flow boiling of hydrocarbons (R290) in single small diameter channels (less than 1 mm). As pointed out by Tibiriçá and Ribatski [29], it should be highlighted that under micro-scale conditions, different heat transfer behaviors are observed for flow boiling in single-channels and in MAHSs, even for parallel channels with constant cross-sectional area. Flow boiling in MAHS configurations is susceptible to back flow due to bubble growth under confined