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Review

A review of heat transfer and pressure drop characteristics of single and two-phase microchannels

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ABSTRACT

An impressive amount of investigations has been devoted to enhancing thermal performance of microchannels. The small size of microchannels and their ability to dissipate heat makes them as one of the best choices for the electronic cooling systems. In this paper, a comprehensive review of available studies regarding single and two-phase microchannels is presented and analyzed. 219 articles are reviewed to identify the heat transfer mechanisms and pressure drops in microchannels. This review looks into the different methodologies and correlations used to predict the heat transfer and pressure drop characteristics of microchannels along the channel geometries and flow regimes. The review shows that earlier studies (from 1982 to 2002) were largely conducted using experimental approaches, and discrepancies between analytical and experimental results were large, while more recent studies (from 2003 to 2013) used numerical simulations, correlations for predicting pressure drop and heat transfer coefficients were considerably more accurate.

Contents

1. Introduction

In early 1981, Tuckerman and Pease [1] first explained the concept of microchannel heat sinks and predicted that single-phase forced convective cooling in microchannels could potentially remove heat at a rate of the order $1000\,\frac{\mathrm{W}}{\mathrm{cm}^2}$. Forced convection in channels and liquid injection has been used for faster and larger scale cooling in industry for decades. Microchannel heat transfer, however, has become increasingly popular and interesting to researchers due to high heat transfer coefficients, with potential for record-high heat transfer coefficients and low to moderate pressure drops when compared to conventional air and liquid

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Nomenclature

a	channel height (m)
b	channel width (m)
BL	boiling number
Bo	Bond number
C	Lockhart–Martinelli parameter
C_P	specific heat (J/kg K)
Co	convective number
d_h	hydraulic diameter (m)
f	friction factor
Fr	Froude number
F_{fl}	fluid-surface parameter
G	mass velocity
h	heat transfer coefficient (W/m^2 K)
j	total mixture volumetric flux
k	thermal conductivity (W/m K)
Ma	Mach number
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
S	Chen’s suppression factor
T	temperature (K)
u	velocity (m/s)
Y	Chisholm parameter
We	Weber number

Greek symbols

τ	shear stress (Pa)
μ	dynamic viscosity(Pa s)
ρ	density (kg/m^3)
α	channel aspect ratio
κ	Hagenbach factor
Φ_{LO}	two-phase multiplier (for liquids only)
σ	surface tension

Subscripts

app	apparent
crit	critical
f	frictional, forced convection
FD	fully developed
Gn	Gnielinski’s method
L	liquid
m	momentum, mean
s	static
sat	saturation
TP	two-phase mixture
tot	total
V	vapor
W	wall

cooled systems [2–7]. For example, microchannel heat sinks have been demonstrated for high-power laser diode array cooling and have achieved a heat flux removal rate of 500 $\frac{\mathrm{W}}{\mathrm{cm}^2}$ [8–10].

In most cases when the cooling requirement is over 100 $\frac{\mathrm{W}}{\mathrm{cm}^2}$ the cooling cannot be easily met either by simple air-cooling or water-cooling systems. In many applications, where high heat flux of the components has to be dissipated, the required heat sinks must be larger than the components themselves. Nevertheless, hot spots usually appear, and non-uniform heat flux levels are observed at the heat sink level. This has motivated researchers to develop new heat sinks that can be directly embedded on the back of the heat source for uniform heat flux removal. Such a heat sink is usually made of silicon, with a silicon oxide layer to keep the component electrically insulated. Very narrow rectangular channels are formed with fins in the micrometer range that ensure uniform heat flux removal by circulating cold fluid through the rectangular microchannels.

Several investigators have proposed different criteria for minichannels. Serizawa et al. [11] described one criterion for classification of microchannels as follows:

$\lambda \geqslant d_h$ where λ and d_h are the Laplace constant and channel diameter, respectively.

Mehendale et al. [12] classified micro heat exchangers based on the hydraulic diameter as:

$$\begin{cases} \text{Micro heat exchangers} & : 1\ \mu\text{m} \leqslant d_h \leqslant 100\ \mu\text{m} \\ \text{Macro} - \text{heat exchangers} & : 100\ \mu\text{m} \leqslant d_h \leqslant 1\ \text{mm} \\ \text{Compact heat exchangers} & : 1mm \leqslant d_h \leqslant 6\ \text{mm} \\ \text{Conventional heat exchangers} & : d_h \geqslant 6\ \text{mm} \end{cases} \tag{1}$$

Kandlikar and Grande [13] used the hydraulic diameter for classification of single-phase and two-phase heat exchangers as,

$$\begin{cases} \text{Microchannels} & : 10\ \mu\text{m} \leqslant d_h \leqslant 200\ \mu\text{m} \\ \text{Minichannels} & : 200\ \mu\text{m} \leqslant d_h \leqslant 3\ \text{mm} \\ \text{Conventional channels} & : d_h \geqslant 6\ \text{mm} \end{cases} \tag{2}$$

Also, Palm [14] described the microchannels as heat transfer elements where the classical theories cannot correctly predict the friction factor and heat transfer characteristics. Stefan [15] used a microscale system as one whose typical phenomena are absent in a macro system. Therefore, it is not always suitable to differentiate mini- and microchannels by a specific diameter like other researchers, although this definition is often used nevertheless.

Halelfadl et al. [16] focused on analytical optimization of a rectangular microchannel heat sink using aqueous carbon nanotubes based nanofluids as coolant. The optimized results showed that the use of the nanofluid as a working fluid reduces the total thermal resistance and can enhance significantly the thermal performances of the working fluid at high temperatures. Warrier et al. [17] proposed and analyzed a novel two-phase microchannel cooling device that incorporates perforated side walls for potential use as an embedded thermal management solution for high heat flux semiconductor devices. Yu and Zhang [18] focused on the hydraulic and thermal characteristics of fractal tree-like microchannels with different aspect ratios for Reynolds numbers ranging from 150 to 1200. The experimental results showed that the fractal tree-like microchannels had a much higher heat transfer coefficient than the straight microchannels. Wang and Wu [19], Wang et al. [20], Revellin et al. [21], and Senn and Poulikakos [22] performed similar studies on the thermal performance of tree-like microchannels.

The impacts of periodic reversed flow and induced boiling fluctuations on the performance of a microchannel evaporator used in air-conditioning system can cause some problems [23–30]. Tuo and Hrnjak [23] proposed a novel solution to reduce these effects by venting and bypassing back flow vapor accumulated in the inlet header. Frost formation on a louvered fin microchannel heat exchanger was experimentally investigated by Moallem et al. [31]. They developed a novel methodology to measure frost thickness and frost weight at intervals during the frosting period. The experimental data showed that at a given air dry bulb temperature, the fin surface temperature and air humidity are the primary