International Journal of Heat and Mass Transfer 126 (2018) 591–617

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Review

Review on flow boiling of refrigerants R236fa and R245fa in mini and micro channels

Stanislawa Sandler *, Bartosz Zajaczkowski, Zbigniew Krolicki

Wroclaw University of Science and Technology, Faculty of Mechanical and Power Engineering, Wyb. Wyspianskiego 27, 50-370 Wroclaw, Poland

ARTICLE INFO

Article history:
Received 27 April 2018
Received in revised form 9 May 2018
Accepted 9 May 2018

Keywords:
Small-scale flow boiling
Mini channels
Micro channels
Thermal modeling

ABSTRACT

Flow boiling in mini and micro channels is considered to be one of the most efficient cooling solutions for mobile devices and electronic components. Cooling systems relying on flow boiling should be able to work efficiently in a wide range of operating conditions including saturation temperature. Employing refrigerants characterized by low saturation pressures assure lightweight structure of the cooling system even at high operating temperatures. Therefore, this article focuses on two low-pressure refrigerants R236fa and R245fa (refrigerants which are characterized by low saturation pressures corresponding to high saturation temperatures) with special emphasis on the influence of saturation temperature on flow boiling characteristics. It presents a detailed review on the most recognized heat transfer models during flow boiling and an experimental database on R236fa and R245fa covering channel hydraulic diameters ranging from 0.1 to 3 mm, mass fluxes from 42 to 2500 $kg/m^2/s$, and wall heat fluxes varying between 6.5 and 422.7 kW/m^2. The covered vapor qualities range from −0.09 to 1.14 (which translates into subcooled, saturated and superheated flows) and reference saturation temperatures vary between 14 and 120 °C. Subcooling at the heat exchanger inlet changes from 0 to 19 K. The amassed experimental data are compared with the results obtained from 24 theoretical models on flow boiling. The models follow additive, asymptotic, Nusselt-type and phenomenological approaches. The accuracy of the models is assessed on the basis of Mean Absolute Percentage Error *MAPE* and standard deviation σ_{SD}. The additive models of Saitoh et al. with $MAPE = 27.4\%$ and $\sigma_{SD} = 43.8\%$, Chen with $MAPE = 28.6\%$ and $\sigma_{SD} = 35.8\%$ and an Nusselt-type correlation of Sun and Mishima with $MAPE = 28.4\%$ and $\sigma_{SD} = 43.4\%$ exhibit the best accuracy. The amassed database allowed determination of the range of experimental conditions that need further scientific investigation. Review on heat transfer models together with results of comparison between the models and experimental data allowed identification of the most problematic aspects of modeling flow boiling in mini and micro channels.

Contents

* Corresponding author.
E-mail address: stanislawa.sandler@pwr.edu.pl (S. Sandler).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.048
0017-9310/

Nomenclature

A	channel flow area, m^2
A_D	ratio of the dryout perimeter to the entire tube perimeter, –
AR	aspect ratio, $AR = MIN(H, W)/MAX(H, W)$, –
C	chisholm parameter, –
Co	confinement number, $Co = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)D_h^2}}$, –
Con	convection number, $Con = \left(\frac{1-x}{x}\right)^{0.8}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}$, –
c_P	specific heat capacity, J/kg K
B	base width of the heat sink, m
Bd	Bond number, $Bd = \frac{(\rho_l - \rho_v)D_h^2 g}{\sigma}$, –
Bo	Boiling number, $Bo = \frac{q_w}{rG}$, –
D	channel diameter, m
e	entrained liquid fraction, –
f	fanning friction factor, –
F	enhancement factor, –
Fr	Froude number, $Fr = \frac{G^2}{\rho_l^2 \cdot g \cdot D_h}$, –
Fr_m	mixture Froude number, $Fr_m = \frac{G^2}{(\rho_l - \rho_v)^2 \cdot g \cdot D_h}$, –
g	gravitational acceleration, $g = 9.81\ m^2/s$, m^2/s
G	mass flux in a single channel, $kg/m^2/s$
h	heat transfer coefficient, $W/m^2\ K$
H	single channel height, m
i	enthalpy, J/kg
k	thermal conductivity, W/m K
L	channel length, m
m	proportionality ratio in the buffer zone, –
M	molar mass, kg/kmol
$MAPE$	Mean Absolute Percentage Error, %
N	number of channels, –
Nu	Nusselt number, –
n	exponent used in Eq. (53), –
q	heat flux, W/m^2
p	pressure, Pa
p_r	reduced pressure, $p_r = p/p_{crit}$, –
HP	heated perimeter, $HP = \pi D_h$ for circular ducts, $HP = 2H + W$ for rectangular ducts, m
Pr	Prandtl number, $Pr = c_P \cdot \mu/k$, –
r	latent heat of evaporation, J/kg
Re	Reynolds number, –
Re_l	liquid Reynolds number, $Re_l = \frac{(1-x)G \cdot D_h}{\mu_l}$, –
Re_{lo}	liquid-only Reynolds number, $Re_{lo} = \frac{G \cdot D_h}{\mu_l}$,
Re_v	vapor Reynolds number, $Re_v = \frac{xG \cdot D_h}{\mu_v}$, –
s	slip ratio, –
S	suppression factor, –
T/t	temperature, K/°C
U	velocity, m/s
W	single channel width, m
We_{lo}	liquid-only Weber number, $We_{lo} = \frac{G^2 D_h}{\sigma \rho_l}$, –
We_v	vapor-phase Weber number, $We_v = \frac{(xG)^2 D_h}{\sigma \rho_v}$, –
WP	wetted perimeter, $WP = \pi D_h$ for circular ducts, $WP = 2H + 2W$ for rectangular ducts, m
x	vapor quality, $x = \frac{i - i_{l,sat}}{i_{v,sat} - i_{l,sat}}$, –
X	Martinelli parameter, –

Greek letters

α	void fraction, –
β	aspect ratio, $\beta = \frac{H}{W}$, –
δ	thickness, m
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
σ	surface tension, N/m
σ_{SD}	standard deviation, –
τ	time, s
$\tau\tau$	shear stress, Pa
υ	specific volume, m^3/kg
ϕ_f	two-phase multiplier, –

Subscripts

b	bubble departure
base	base
conv	convective
crit	critical
dry	dryout
equiv	equivalent
exp	experimental
f	fluid
film	liquid film
fin	fin
h	hydraulic
inl	inlet
l	liquid
nb	nucleate boiling
out	channel outlet
sat	saturated conditions
sp	single phase
sub	subcooled conditions
theor	theoretical
tp	liquid-vapor mixture
v	vapor
w	wall