International Journal of Heat and Mass Transfer 125 (2018) 153–170

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effect of surface tension, gravity and turbulence on condensation patterns of R1234ze(E) in horizontal mini/macro-channels

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ARTICLE INFO

Article history:
Received 31 January 2018
Received in revised form 2 April 2018
Accepted 8 April 2018

Keywords:
Condensation
Mini/macro-channels
Surface tension
Gravity
Shear stress
Turbulence

ABSTRACT

The condensation patterns of R1234ze(E) in circular mini/macro-channels with diameters ranged from 0.493 to 4.57 mm was numerically investigated. The effects of mass flux, vapor quality and tube diameter on heat transfer coefficients were analyzed. The relative role of surface tension, gravity and shear stress in mini/macro-channels was explored and the turbulence effect of liquid phase was discussed. The heat transfer coefficients increased with the mass flux, vapor quality and the decrease of tube diameter. The liquid film thickness decreased significantly when reducing the tube dimension for the increased shear stress. The surface tension was found to play a role to increase the heat performance by enhancing the heat convection between liquid film and wall surface, which was only obvious in mini-channels. Contrary to the effect of surface tension, the gravity effect was negligible in mini-channels with a diameter less than 1 mm, while had an important effect on heat transfer coefficients for macro-channels. The gravity affected both liquid film distribution and velocity field, which can either enhance or weaken the heat transfer coefficient during condensation flow. The turbulence in liquid film played an important role in reducing the local thermal resistance and was more important in tubes with larger diameter. The onset of turbulence inside the liquid film may occur at much lower liquid Reynolds numbers for mini-channels.

1. Introduction

Condensation flow inside mini-channels has been recognized as the promising way to deal with the large heat dissipation in a limited space by utilizing the latent heat of the coolant. Except the high heat removal capacity, the usage of mini-channel heat exchangers also reduces the refrigerant charge and decreases cooling system volume and weight, which has been widely applied in water cooling of turbine Blades, rocket engine nozzle cooling, avionics cooling, satellite electronics and so on [1]. With the pipe diameter decrease, the shear stress and surface tension tended to dominate the gravity during the condensation process, which significantly influences the final heat transfer and pressure drop characteristic. Therefore, knowledge of detailed information about the behavior of the vapor and liquid phase under the role of shear force, surface tension and gravity in varying diameter tubes was necessary to either the design or optimization of heat exchangers.

A lot of analytical and experimental condensation work has been conducted for the shear-controlled annular flow which persisted over most of the length of the passages in condensers. Coleman and Garimella [2] pointed out that when decreasing the tube diameter, the range of annular flow would increase, while the gravity-dominated wavy flow would decrease or even disappeared as the tube diameter decreased to 1 mm. Thus, reliable predictive models for the shear-dominated annular flow regimes are of great importance for condenser designs. A comprehensive review of the literature concerning condensation flows inside mini-channels can be found in Awad et al. [3,4]. Considerable heat transfer models have been proposed so far, while most of them were just based on their own experimental data, the available empirical or semi-empirical correlations with general applicability were limited. Shah [5–7] did a great job of developing a general correlation for heat transfer during condensation flow in tubes. In 1979, he proposed a simple dimensionless correlation expressed as a product of the single-phase heat transfer model of the liquid (Dittus-Boelter equation) and a two-phase multiplier. This correlation was validated by comparison with a wide variety of experimental data including 474 data points. However, the author also pointed out that this model may be not applicable at low Reynolds numbers or near the critical pressure. In 2009, a modified correlation including two heat transfer equations developed for different flow regimes was proposed and the range of applicability was widened. The new model was applicable for 22 fluids including

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.039
0017-9310/

Nomenclature

B	damping factor
C_p	isobaric specific heat (J kg^{-1} K^{-1})
D_h	hydraulic diameter (m)
D	internal diameter (m)
E	specific sensible enthalpy (J kg^{-1})
g	gravitational acceleration (m s^{-2})
G	mass flux (kg m^{-2} s^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
h_{lv}	latent heat of vaporization (J kg^{-1})
k	turbulent kinetic energy (m^2 s^{-2})
$\dot{m}$	mass source due to phase change (kg m^{-3} s^{-1})
p	pressure (Pa)
Pr_t	turbulent prandtl number
r	empirical coefficient (s^{-1})
Re_G	vapor Reynolds number
Re_L	liquid Reynolds number
Re_t	turbulent Reynolds number
S	modulus of the mean rate-of-strain tensor
T	temperature (K)
v	velocity (m/s)
x	vapor quality

Greek symbols

α	volume fraction
σ	surface tension (N m^{-1})
σ_k	turbulent prandtl number for k
σ_ω	turbulent prandtl number for ω
κ_L	interface surface curvature (m^{-1})
μ	dynamic viscosity (Pa s)
μ_t	turbulent viscosity (Pa s)
ρ	density (kg m^{-3})
λ	thermal conductivity (W m^{-1} K^{-1})
θ	angular coordinate
δ	liquid film thickness (μm)
ω	specific dissipation rate of k (s^{-1})

Subscripts

eff	effective
G	vapor phase
L	liquid phase
sat	saturation

halocarbon refrigerants, hydrocarbon refrigerants, water and various organics with mass flux ranged from 4 to 820 kg m^{-2} s^{-1}, tube diameters from 2 to 49 mm and reduced pressure from 0.0008 to 0.9. Dobson-Chato [8] experimentally investigated the condensation heat transfer and flow regimes of refrigerants R-12, R-22, R-134a and R-32/R-125 in horizontal round smooth tubes with tube diameters varied from 3.14 to 7.04 mm and mass flux varied from 25 to 800 kg m^{-2} s^{-1}. They proposed two correlations for the annular and wavy flow regimes based on their own experimental data. The two-phase multiplier method was chose for correlating the heat transfer data in the annular flow. While the wavy flow correlation was composed of two parts including the film condensation at the top of the tube and the forced-convective condensation at the bottom of the tube. The developed correlation predicted both their own data and that from other studies very well. Thome et al. [9] proposed a new heat transfer model for condensation in horizontal plain tubes based on the two-phase flow pattern map developed by Hajal et al. [10]. They assumed three simplified geometries for describing stratified, stratified-wavy and annular flow. The correlation developed for annular flow neglected the gravity effect. Thus the liquid film was considered to be uniformly distributed along the circumference. The film thickness and mean velocity were calculated based on a void fraction equation proposed in Hajal et al. [10]. Therefore, the prediction effect of this correlation was dependent on the accuracy of the applied void fraction equation to some extent. The model was considered to be applicable for 15 fluids with mass flux ranged from 24 to 1022 kg m^{-2} s^{-1}, vapor quality from 0.03 to 0.97, tube diameter from 3.1 to 21.4 mm and reduced pressure from 0.2 to 0.8. Cavallini et al. [11] proposed a new heat transfer model for condensation flow inside horizontal smooth tubes with internal diameters larger than 3 mm. They split the two-phase flow regime into two parts including the ΔT-independent flow regime and ΔT-dependent flow regime. Then two separate correlations employing the two-phase multiplier approach were developed based on the HFCs data of Cavallini et al. [12]. The new developed model predicted the experimental data including 4471 data points from several independent laboratories very well with the mean absolute deviation of 15% and standard deviation of 18%. Kim and Mudawar [13] developed a universal approach to predict the condensation heat transfer coefficients inside mini/micro-channels through amassing the consolidated database of 4045 heat transfer coefficients data points. Two correlations were separately proposed for annular flows and slug and bubbly flows. The annular flow model was based on the boundary-layer analyses with the assumption that the dimensionless temperature was a function of Re_f and Pr_f. The wall stress was calculated based on the pressure drop model proposed by the same authors [14]. The model for slug and bubbly flows was a superposition of their new annular flow model and a dimensionless function of the vapor-only Suratman number and superficial liquid Reynolds number. The correlations covered 17 different working fluids, vapor quality from 0 to 1, mass flux from 53 to 1403 kg m^{-2} s^{-1} and hydraulic diameter from 0.424 to 6.22 mm.

Although these correlations were considered to be applicable to estimate plenty of experimental data with reasonable accuracy, the range of best application was almost confined to conventional tubes according to the classification of Kandlikar and Grande [15]. There exist some deviations when extending the computing models for macro-channels to mini-channels. Koyama et al. [16] experimentally investigated the local heat transfer characteristics of R134a inside four kinds of multi-port extruded aluminum tubes with the hydraulic diameter around 1 mm. Correlations proposed for large diameter tubes including Moser et al. [17], Haraguchi et al. [18] and Dobson-Chato [8] correlation cannot satisfactorily predict their experimental data. The Moser et al. [17] significantly under estimated the Nusselt numbers, especially at low mass flux, while the Haraguchi et al. [18] and Dobson-Chato [8] correlation tended to over-estimate the experimental results in the case of high mass velocity. Park et al. [19] measured the heat transfer data of refrigerants R1234ze(E), R134a and R236fa in a vertically aligned aluminum multi-port tube with hydraulic diameter of 1.45 mm. The Thome et al. [9] correlation predicted only 40% of all data points within ±20% with the mean absolute error of 29.2%. The experimental data were under-estimated by the Thome et al. [9] correlation at low Nusselt numbers but over-estimated for the high Nusselt numbers. Even the prediction models developed for mini-channels including Bandhauer et al. [20], Cavallini et al. [21] and Koyama et al. [16] correlation failed to predict their experimental data. Liu et al. [22] measured the condensation heat