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# New theoretical models of evaporation heat transfer in horizontal microfin tubes

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**Abstract**

A stratified flow model and an annular flow model of evaporation heat transfer in horizontal microfin tubes have been proposed. In the stratified flow model, the contributions of thin film evaporation and nucleate boiling in the groove above the stratified liquid level were predicted by a previously reported numerical analysis and a newly developed correlation, respectively. The contributions of nucleate boiling and forced convection in the stratified liquid region were predicted by the new correlation and the Carnavos correlation, respectively. In the annular flow model, the contributions of nucleate boiling and forced convection were predicted by the new correlation and the Carnavos correlation in which the equivalent Reynolds number was introduced, respectively. The flow pattern transition curve between the stratified-wavy flow and the annular flow proposed by Kattan et al. was introduced to predict the heat transfer coefficient in the intermediate region by use of the two theoretical models. The predictions of the heat transfer coefficient compared well with available experimental data for ten tubes and four refrigerants.


*Keywords:* Evaporation; Refrigerants; Microfin tubes; Stratified flow model; Annular flow model; Flow pattern transition

## 1. Introduction

Microfin tubes with spiral grooves are widely used for air conditioners and refrigerators as a high performance evaporator tube. A large number of researches have been made on the effects of fin dimensions and fin shape on the heat transfer performance and pressure drop during evaporation in horizontal microfin tubes. On the heat transfer performance, Miyara et al. [1], Murata and Hashizume [2], Kido et al. [3], Koyama et al. [4], Murata [5], Kandlikar and Raykoff [6], Thome et al. [7], Cavallini et al. [8], Yun et al. [9] and Mori et al. [10] have developed correlations of the heat transfer coefficient that are based on the correlations for smooth tubes. Honda and Wang [11] has developed a stratified flow model of evaporation heat transfer in which the effect of surface tension on the vapor–liquid interface profile was taken into account. For the region above the stratified liquid where thin film evaporation is dominant, a numerical analysis using exact boundary conditions was applied. For the stratified liquid region, the correlation proposed by Mori et al. [10] was applied. They compared the predictions of the heat transfer coefficient with available experimental data for four tubes and three refrigerants. The agreement was good in the low mass flux region where the heat flux was also low. In the medium-to-high mass flux region, however, the predictions underpredicted the measured values, with the difference increasing with the mass flux. This was mainly due to the increase in the effect of vapor shear, which resulted in the transition of flow pattern from the stratified flow to the annular flow. Another factor was that the contribution of nucleate boiling in the groove above the stratified liquid level was not taken into account.

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**Nomenclature**

| | |
|---|---|
| $A$ | cross-sectional area of tube, m$^2$ |
| $A_c$ | core flow area of tube, $\pi(d-2h)^2/4$, m$^2$ |
| $Bo$ | boiling number |
| $d$ | diameter at fin root, m |
| $d_o$ | outside diameter, m |
| $d_h$ | hydraulic diameter of tube, m |
| $Fr_0$ | dimensionless quantity, $G/\sqrt{dg\rho_v(\rho_l-\rho_v)}$ |
| $G$ | refrigerant mass velocity, kg/m$^2$ s |
| $g$ | gravitational acceleration, m/s$^2$ |
| $h$ | fin height, m |
| $h_{lv}$ | latent heat of vaporization, kJ/kg |
| $M$ | molar mass |
| $N$ | number of data |
| $n$ | number of fins |
| $p$ | fin pitch, m |
| $P$ | pressure, Pa |
| $P_c$ | critical pressure, Pa |
| $P_r$ | reduced pressure, $P/P_c$ |
| $Pr$ | Prandtl number |
| $q$ | heat flux, kW/m$^2$ |
| $r_b$ | radius of curvature of liquid meniscus, m |
| $r_t$ | radius of curvature at corner of fin tip, m |
| $Re_{l,h}$ | Reynolds number based on the hydraulic diameter, $Gd_h/\mu_l$ |
| $Re_{eq}$ | equivalent Reynolds number, $Re_{l,h}[1-\chi+(\rho_l/\rho_v)^{1/2}\chi]$ |
| $\Delta T$ | wall superheat, K |
| $x$, $y$ | curvilinear coordinates, Fig. 3 |
| $x_a$ | connecting point between non-evaporating and evaporating film regions, Fig. 3, m |
| $x_b$ | connecting point between thin film region and meniscus region, Fig. 3, m |
| $x_c$ | connecting point between fin flank and fin root tube surface, Fig. 3, m |
| $x_0$, $x_t$ | connecting points between straight and round portions of fin, Fig. 3, m |
| $X$, $Y$ | Cartesian coordinates, Fig. 3 |
| $z$ | vertical height measured from stratified liquid surface, m |
| $\alpha$ | heat transfer coefficient, kW/m$^2$ K |
| $\gamma$ | helix angle of groove, deg |
| $\delta$ | liquid film thickness, m |
| $\varepsilon_a$ | surface area enhancement compared to a smooth tube |
| $\theta$ | fin half tip angle, deg |
| $\lambda$ | thermal conductivity, kW/m K |
| $\mu$ | dynamic viscosity, Pa s |
| $\rho$ | density, kg/m$^3$ |
| $\sigma$ | surface tension, N/m |
| $\varphi$ | angle measured from tube top, rad |
| $\varphi_s$ | flooding angle, rad |
| $\chi$ | quality, – |
| $\omega$ | angle, Fig. 1, rad |

*Subscripts*

| | |
|---|---|
| an | annular model |
| db | dryout inception point |
| dc | dryout completion point |
| ev | evaporation component |
| fc | forced convection component |
| l | liquid |
| m | circumferential average |
| nb | nucleate boiling component |
| r | mid-point between adjacent fins at fin root |
| st | stratified model |
| v | vapor |
| 1 | region 1 |
| 2 | region 2 |

In this paper, new theoretical models (i.e., stratified flow model and annular flow model) of evaporation heat transfer in horizontal microfin tubes are proposed. On the basis of available experimental data for evaporation in horizontal microfin tubes, heat transfer correlations for the nucleate boiling component are developed. These correlations are incorporated into the stratified flow model of Honda and Wang [11] to take into account the effect of nucleate boiling explicitly. The annular flow model is based on the equivalent Reynolds number concept and takes into account the effect of nucleate boiling explicitly. The flow pattern transition curve between the stratified-wavy flow and the annular flow proposed by Kattan et al. [12] is introduced to predict the heat transfer coefficient in the intermediate region as a weighted mean of the predictions of the two theoretical models. The predictions of the new theoretical model and previously proposed empirical equations are compared with available experimental data for ten tubes and four refrigerants.

## 2. Expression for nucleate boiling component

Near the inception point of nucleate boiling, the circumferential average heat transfer coefficient $\alpha_m$ is determined by the contributions of the nucleate boiling component and the forced convection component. If the contributions of these components are assumed to be given by the expression of the form

$$\alpha_m = (\alpha_{nb}^3 + \alpha_{fc}^3)^{1/3} \tag{1}$$

then the heat flux $q$ is given by

$$q = (q_{nb}^3 + q_{fc}^3)^{1/3} \tag{2}$$