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A Review of Recent Empirical Correlations for the Calculation of Determination of R134a's Convective Heat Transfer Coefficient in Vertical Condensers☆

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ABSTRACT

Condensation heat transfer of R134a which flowed in the inner tube and cooling water which flowed in the annulus were experimentally investigated inside a smooth tube-in-tube heat exchanger in author's previous studies. In this current work, the investigational setup consists of a 0.5 m long double tube and the inner tube is made up of smooth copper tubing of 9.52 mm outer diameter and 8.1 mm inner diameter. The experiments are carried out for the mass flux range of 260-515 kg $m^{-2}s^{-1}$ and the heat flux range of 11.3-55.3 kW m^{-2} and also at a mean saturation temperature interval of 40-50 °C. The mean heat transfer coefficient of R134a is found through executing an energy equivalence predicated on the energy flow from the test section. The predictability of actual correlations in open sources proposed for two-phase annular flow are tested by using authors' experimental database. Alterations of vapor quality and saturation temperature difference with calculated condensation heat transfer coefficients are also shown according to different condensing temperatures and mass fluxes. Moreover, the independency of annular flow heat transfer empirical equations from tube orientation and the overall practicality for a vertical tube is validated.

1. Introduction

Thermodynamic movement and behavior of refrigerants in heat exchangers such as evaporators or condensers are the most important issues with regard to the designing steps of refrigeration systems. The correct usage of the convective heat transfer coefficient of a flowing refrigerant in a condenser is an essential parameter for the cycle performance. In order to ascertain that a correlation is reliable, it is required to execute the correlation with different experimental data for many times and compare with the other expressions in the literature.

The study of Dalkilic et al. [1] include the impacts of heat and mass flux and also condensing temperature on the heat transfer coefficients. They tested numerous equations for annular flow and made comparison with each other utilizing their experimental database. They also proposed novel equations for the condensation heat transfer coefficient for engineering fields. The tested convective condensation heat transfer coefficients' studies, shown in Table 1, are summarized in the following paragraph.

One of the oldest and most acknowledged studies on the condensation is Soliman [2]'s study. The influence of the mist-annular transition on the heat transfer in condensation was investigated. The heat transfer correlation offered for the mist region was demonstrated that it was able to provide an acceptable agreement with different fluids independent of the tube shape. He developed the mist-flow-based correlation by using experimental data for N-shaped, triangular and W-insert tubes. Wang et al. [3] studied with R134a and investigated condensation heat transfer of the refrigerant inside a horizontal rectangular multi-port aluminum condenser tube of 1.46 mm hydraulic diameter. They developed a convenient correlation for millimeter-scale tubes by using their experimental data and expressions in the literature. Haraguchi et al. [4] analyzed the local condensation heat transfer coefficients of refrigerants R22, R134a and R123 inside a horizontal smooth tube for different mass flow rates. A novel correlation was developed by taking advantages of experimental results and it was in the form of the superposition of Nusselt number for forced convection during condensation. Bohdal et al. [5] performed an experimental research on heat transfer and pressure drop in the condensation process of the R134a and R404A refrigerants in minichannels that had an internal diameter range of 0.31-3.30 mm. An experimental correlation for the local condensation heat transfer coefficient was derived by modifying Haraguchi et al. [4]'s study and they demonstrated that the

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Nomenclature

A	surface area, m^2
c_p	specific heat, J $kg^{-1}K^{-1}$
D	diameter
d	internal tube diameter, m
Fr	Froude number
f	friction factor
G	mass flux, kg m^{-2} s^{-1}
Ga	Galileo number
g	gravitational constant, m s^{-2}
h	convective heat transfer coefficient, $Wm^{-2}K^{-1}$
i	enthalpy, J kg^{-1}
i_{fg}	latent heat of condensation, J kg^{-1}
k	thermal conductivity, W $m^{-1}K^{-1}$
L	length of test tube
m	mass flow rate, kg s^{-1}
Nu	Nusselt number
P	pressure
Ph	phase change number
Pr	Prandtl number
Re	Reynolds number
T	temperature
q	mean heat flux, kW m^{-2}
x	mean vapor quality
X_{tt}	Lockhart–Martinelli parameter
Greek symbols	
μ	dynamic viscosity, kg m^{-1} s^{-1}
α	void fraction
ΔP	pressure drop, Pa
ΔT	vapor side temperature, difference, T_{sat}–T_{wi}, °C
ρ	density, kg m^{-3}
θ	tube inclination angle, °
δ	film thickness, m
ν	kinematic viscosity, m^2 s^{-1}
ϕ	two-phase multiplier
Subscripts	
anul	annular
B	buoyancy convection
exp	experimental
F	forced convection
f	fluid
fg	fluid to gas, phase change
g	gas/vapor
h	hydraulic
l	liquid
lo	liquid only
m	mixture
Ph	preheater
red	reduced
sat	saturation
tp	two phase
w	wall

correlation developed was compatible with annular refrigerant flows. Koyama et al. [6] examined the local characteristics of pressure drop and heat transfer of R134a on the condensation in multiport extruded tubes with experimental methods. Finally, they found a new equation benefitting from the correlations of Haraguchi et al. [4] and Mishima-Hibiki [7]. They experimentally investigated the condensation heat transfer of R134a in tubes having 8 channels in 1.11 mm hydraulic diameter and 19 channels in 0.80 mm hydraulic diameter. The condensation heat transfer coefficient has been derived as a unification of forced convection condensation and gravity controlled convection condensation. Park et al. [8] experimentally concentrated on the condensation heat transfer of the new refrigerant R1234ze(E) by comparing with R134a and R236fa. The correlation developed by Koyama et al. [5] was revised and modified according to the experimental data in this study. Akhavan-Behabadi et al. [9] researched condensation of R134a vapor inside a single microfin tube with different tube inclination angles of the direction of fluid annular counter-flow. A correlation suggested for prediction of condensation heat transfer coefficient at various vapor qualities, mass velocities and tube inclinations was developed. Khoeini et al. [10] conducted an experimental work over condensing heat transfer coefficient of R134a that was flowing in a corrugated tube with various inclination angles. They reported that the flow regime would keep on its annular status in the downward vertical flow. Huang et al. [11] experimentally considered the influence of oil on condensation of R410a inside horizontal smooth tubes. They studied the impact of oil on condensation heat transfer of R410a inside 4.18 mm and 1.6 mm inner diameter horizontal smooth pipes with an experimental setup. As a result, a novel equation for heat transfer coefficient has been explored for the condensation flow of R410A-oil mixture flow inside plain pipes.

In the present study, nine recent correlations compatible with two-phase annular flow in literature are compared with the experimental data derived through the study of Dalkilic et al. [1] over the calculation of the condensation heat transfer coefficient. The tested empirical correlations' predictability and accuracy are also examined by means of their alteration with vapor quality and temperature difference between saturation and inner wall. As a result, the primary purpose of this study is to increase the reliability of heat transfer data of the authors with actual correlations to the high mass flux region of the refrigerant during condensation in a smooth tube-in-tube heat exchanger. It should be noted that this paper should be considered as a continuation of authors' previous study [1] and the tested correlations' number has been increased from 11 researchers [12–22], as shown in Table 2, to 20 researchers with this study by the authors in this paper.

2. Experimental Method and Data Reduction

A detailed view of the experimental setup including test section and its explanation, calculation of experimental heat transfer coefficient, and uncertainties can be seen from authors' previous publications in the literature.

3. Results and Discussion

Condensing heat transfer coefficients have been determined by benefitting from the nine empirical horizontal annular flow condensation correlations mentioned in the previous section. Experimental procedure was accomplished with the use of various condensation temperatures, vapor qualities and the other experimental values obtained from Dalkilic et al. [1]. In the current study, these correlations are tested to illustrate the resemblance of annular flow correlations which are independent of tube orientation (horizontal or vertical) and also show the authors' experimental database's compatibility with recent studies having different operating conditions. Chen et al. [23] declared the resemblance in their study. They correlated an equation by creating a connection between the interfacial shear stress and flow conditions for annular film condensation inside tubes.

Predicated on Hewitt and Robertson's [24] flow regime map, the data points depicted in all figures were existed in an annular flow