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COMPARISONS OF EXPERIMENTAL RESULTS AND PREDICTION METHODS OF SUPERCRITICAL CO_2 COOLING HEAT TRANSFER AND PRESSURE DROP IN MACRO- AND MICRO-SCALE CHANNELS

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ABSTRACT

Comparisons of heat transfer and pressure drop experimental data and correlations for supercritical CO_2 cooling are presented in this article. First, the physical and transport properties of CO_2 at supercritical conditions are discussed and then their influence on heat transfer and pressure drop. Then, comparison and analysis relative to the available heat transfer and pressure drop correlations for supercritical CO_2 cooling were done where possible. Noting the lack of all pertinent experimental details required to use the data published in many of the available studies, comments are given on how to reduce and present supercritical CO_2 experimental data properly in the future. Simulations by the available heat transfer correlations were performed and the predicted results were compared with each other. Based on the comparisons and analysis, it is recommended that further efforts be made to develop improved heat transfer methods for supercritical CO_2 cooling based on a more accurate database in the future. To achieve this, more careful experiments should be done in both macro- and micro-channels over a wide range of test parameters, including the effect of oil. In addition, several experimental studies show that the Blasius equation works well for pressure drop of CO_2 cooling in the supercritical region. More careful experimental data are still needed to further validate this conclusion.

INTRODUCTION

CO_2 is a potential alternative refrigerant for automotive air-conditioning whilst already employed in heat pump and low temperature refrigeration systems. CO_2 also has very positive attributes as a secondary refrigerant at low temperatures. The critical point of CO_2 corresponds to a pressure of 7.38 MPa (p_{cr}) and a temperature of 31.1°C (T_{cr}). Therefore, for usual ambient air temperatures, the heat transfer process on the high pressure side of a CO_2 cycle is not a condensation process as in conventional systems but a supercritical gas cooling process [1]. Furthermore, the physical and transport properties of CO_2 are quite different from those of conventional refrigerants and thus they have a great effect on both evaporation and gas cooling heat transfer characteristics [1-6]. Figure 1 shows the specific heat of CO_2 versus temperature at pressures of 7.5, 8, 9, 10 and 12 MPa, which were obtained from Refprop 7.0 [7]. For a constant pressure larger than the critical pressure, an important characteristic is that the specific heat reaches a sharp maximum as shown in Fig. 1. This point is called the pseudocritical point as indicated by the vertical dashed line in Fig. 1 for the pressure of 9 MPa and the corresponding pressure and temperature are the pseudocritical pressure (p_{pc}) and the pseudocritical temperature (T_{pc}). During a supercritical heat transfer process, the physical and transport properties of CO_2

change drastically with temperature around the critical point in an isobaric process, especially near the pseudocritical and critical points. In the vicinity of the pseudocritical points, with an increase in pressure, these changes become less pronounced.

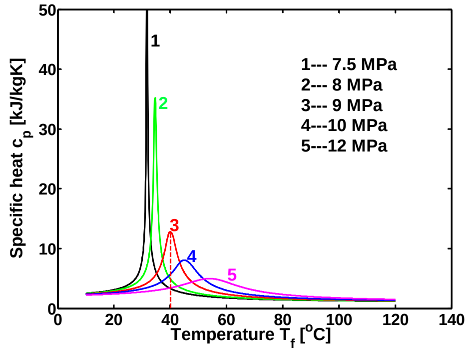


Figure 1 Specific heat vs. fluid temperature

The heat transfer coefficients and pressure drops of supercritical CO_2 are greatly dependent on both local mean temperature and local heat flux because of the strong physical property effects caused by the temperature gradients. The ε-NTU and LMTD methods used to extract data require that the specific heat and thermal conductivity be nearly constant over the design section or test section. Consequently, supercritical CO_2 heat transfer coefficients have to be calculated locally and heat exchangers with small increments. In addition, because of the large viscosity changes and gradients near the wall, pressure drop correlations need to be validated for supercritical CO_2.

Cheng et al. [1] have recently conducted a comprehensive review of heat transfer and pressure drops of supercritical CO_2 with and without lubricating oil under cooling conditions and concluded: (i) although there are a number of heat transfer correlations for cooling of supercritical CO_2, it is not possible at this point to provide a documented recommendation of which one(s) is (are) best since few data are presented in a usable format for such comparisons, (ii) several studies have shown that the Blasius correlation works well for the frictional pressure drop of supercritical CO_2 in both macro- and micro-scale channels. More careful experimental friction pressure drop data are still needed to further validate this conclusion because some experimental data are much different from others, (iii) lubricating oil has a very adverse effect on heat transfer and pressure drops. Generally heat transfer coefficients decrease and pressure drops increase with increasing oil concentration, by as much as 50% or more. So far, apparently there are no heat transfer or pressure drop correlations accounting for the effect of oil. Furthermore, Cheng et al. [1] have presented comparisons of experimental heat transfer data to the predicted results by several supercritical CO_2 cooling correlations. However, most studies are published without wall temperature data and it is impossible to use these incomplete experimental data to verify these heat transfer correlations. In the present paper, simulations by the available supercritical cooling heat transfer correlations were performed for two conditions and the results were compared. Based on the comparisons and analysis, comments on the future research are given.

NOMENCLATURE

A	[-]	Cofficient
c_p	[kJ/kgK]	Specific heat
$\overline{c}_p$	[kJ/kgK]	Average specific heat
D	[m]	Tube diameter
f	[-]	Friction factor
G	[kg/m^{2}s]	Mass flux
Gr	[-]	Grashof number
g	[m/s^2]	Gravitational constant
h	[W/m^{2}K]	Heat transfer coefficient
i	[J/kg]	Ethalpy
K	[-]	Constant
k	[W/mK]	Thermal conductivity
L	[m]	Tube length
m	[kg/s]	Mass velocity
Nu	[-]	Nusselt number
n	[-]	Index
Pr	[-]	Prandtl number
p	[Pa]	Pressure
q	[W/m^2]	Heat flux
Re	[-]	Reynolds number
T	[K]	Temperature

Special characters

ε	[m]	Surface roughness
μ	[Pa.s]	Dynamic viscosity
ρ	[kg/m^3]	Density

Subscripts

cr	critical
f	fluid
in	inner
p	Pressure
pc	Pseudocritical
W	Wall

SUPERCRTICAL CO_2 HEAT TRANSFER AND PRESSURE DROP CORRELATIONS UNDER COOLING CONDITION

Heat transfer correlations

Most supercritical heat transfer correlations are based on a conventional single-phase in-tube forced convective heat transfer correlation by modifying the effect of variable physical properties near the critical point. The empirical heat transfer correlations typically used are summarized as follows:

(1) Dittus-Boelter correlation [8]:

$$Nu_f = 0.023 Re_f^{0.8} Pr_f^{n} \quad (1)$$

where $n = 0.4$ for heating and $n = 0.3$ for cooling. The equation is applicable to the conditions: $10^4 \le Re_f \le 1.2\times10^5$, $0.7 \le Pr_f \le 120$, $L/D \ge 10$.

(2) Gnielinski correlation [9]:

$$Nu_f = \frac{\frac{f}{8}(Re_f - 1000)\Pr_f}{1 + 12.7\sqrt{\frac{f}{8}}\left(Pr_f^{2/3} - 1\right)}\left[1 + \left(\frac{D}{L}\right)^{2/3}\right]K \quad (2)$$

where f is calculated by the Filonenko correlation as

$$f = (1.82\log_{10} Re_f - 1.64)^{-2} \quad (3)$$

where $K = (Pr_f/Pr_W)^{0.11}$ for liquids ($0.05 < Pr_f/Pr_W < 20$) and $K = (T_f/T_W)^{0.45}$ for gases ($0.5 < T_f/T_W < 1.5$). Re_f is calculated according to bulk fluid temperature T_f. Pr_f and Pr_W are calculated according to bulk fluid temperature T_f and wall temperature T_W, respectively. The dependence of the properties on the temperature is taken into account. The correlation is applicable to: $2300 < Re_f < 10^6$, $0.05 < Pr_f/Pr_W < 20$.

(3) Gnielinski correlation [9]:

$$Nu_f = \frac{\frac{f}{8}(Re_f - 1000)Pr_f}{1 + 12.7\sqrt{\frac{f}{8}}\left(Pr_f^{2/3} - 1\right)} \tag{4}$$

where the friction factor is obtained using Eq. (3). The correlation is applicable to: $2300 < Re_f < 10^6$, $0.5 < Pr_f < 2000$.

Most CO_2 gas cooling heat transfer correlations are modifications of one of these methods above. The supercritical nature of CO_2 requires heat transfer correlations that are specifically developed at supercritical operating conditions.

(4) Pitla et al. correlation [10]:

$$Nu = \left(\frac{Nu_W + Nu_f}{2}\right)\frac{k_W}{k_f} \tag{5}$$

$$h = \frac{Nu}{D} k_f \tag{6}$$

where thermal conductivities k_W and k_f are based on wall temperature T_W and bulk fluid temperature T_f, respectively, Nu_W and Nu_f are calculated by the Gnielinski equation (Eq. (4)) at T_W and T_f, respectively.

(5) Fang et al. correlation [11]:

$$Nu_W = \frac{\frac{f_W}{8}(Re_W - 1000)Pr_W}{A + 12.7\sqrt{\frac{f_W}{8}}\left(Pr_W^{2/3} - 1\right)}\left(1 - 0.001\frac{q_W}{G}\right)\left(\frac{\overline{c_p}}{c_{p,W}}\right) \tag{7}$$

where $A = 1+7\times10^{-8}Re_W$ for $Re_W < 10^6$ and $A = 1.07$ for $Re_W \geq 10^6$. f_W is the friction factor evaluated at T_W either by the Blasius equation for $Re_W \leq 10^4$ or by the Filonenko equation (Eq. (3)) for $10^4 < Re_W \leq 5\times10^6$ according to the value of Re_W. Average specific $\overline{c_p}$ is defined as

$$\overline{c_p} = \frac{i_f - i_W}{T_f - T_W} \tag{8}$$

Nusselt number Nu_W and specific heat $c_{p,W}$ are based on wall temperature T_W. The correlation is applicable to the conditions: $3500 \leq Re_W \leq 2.5\times10^4$ and $-115 \leq q/G \leq -3\ Jkg^{-1}$. Fang et al. [11] suggested that their equation could be used in the range of $3000 \leq Re_W \leq 10^6$ and $-350 \leq q/G \leq 0\ Jkg^{-1}$.

(6) Yoon et al. correlation [12]:

$$Nu_f = 0.14 Re_f^{0.69} Pr_f^{0.66} \quad \text{for } T_f/T_{pc} > 1 \tag{9}$$

$$Nu_f = 0.013 Re_f Pr_f^{-0.05}\left(\frac{\rho_{pc}}{\rho_f}\right)^{1.6} \quad \text{for } T_f/T_{pc} \leq 1 \tag{10}$$

where physical properties in Nu, Re and Pr are evaluated at bulk fluid temperature T_f, densities ρ_f and ρ_{pc} are based on bulk fluid temperature T_f and pseudocritical temperature T_{pc}.

(7) Son-Park correlation [13]:

$$Nu_f = Re_f^{0.55} Pr_f^{0.23}\left(\frac{c_{p,f}}{c_{p,W}}\right)^{0.15} \quad \text{for } T_f/T_{pc} > 1 \tag{11}$$

$$Nu_f = Re_f^{0.35} Pr_f^{1.9}\left(\frac{\rho_f}{\rho_W}\right)^{-1.6}\left(\frac{c_{p,f}}{c_{p,W}}\right)^{-3.4} \quad \text{for } T_f/T_{pc} \leq 1 \tag{12}$$

where physical properties in Nu, Re and Pr are evaluated at bulk fluid temperature T_f, densities ρ_f and ρ_W are based on bulk fluid temperature T_f and wall temperature T_W, respectively, specific heats $c_{p,f}$ and $c_{p,W}$ are based on T_f and T_W, respectively.

(8) Liao-Zhao correlation [14]:

$$Nu_W = 0.128 Re_W^{0.8} Pr_W^{0.3}\left(\frac{Gr}{Re_f^2}\right)^{0.205}\left(\frac{\rho_f}{\rho_W}\right)^{0.437}\left(\frac{\overline{c_p}}{c_{p,W}}\right)^{0.411} \tag{13}$$

where average specific heat $\overline{c_p}$ has the same definition as in Eq. (8) and the Grashof number Gr is defined as

$$Gr = \frac{\left(\rho_W - \rho_f\right)\rho_f g D}{\mu_f^2} \tag{14}$$

where physical properties in Nu, Re_W and Pr are evaluated at wall temperature T_W, and those in Re_f are evaluated at bulk fluid temperature T_f, density ρ_f and dynamic viscosity μ_f are based on T_f, density ρ_W and specific heat $c_{p,W}$ are based on T_W. The applicable ranges of the equation are: $7.4 \leq p \leq 120$ *Mpa*, $20 \leq T_f \leq 110$ ℃, $2 \leq T_f - T_W \leq 30$ ℃, $0.02 \leq m \leq 0.2\ kgmin^{-1}$, $10^{-5} \leq Gr/Re_f^2 \leq 10^{-2}$ and $0.5 \leq D \leq 2.16$ *mm* for horizontal channels.

(9) Huai et al. correlation [15, 16]:

$$Nu_W = 2.22\times10^{-2} Re_W^{0.8} Pr_W^{0.3}\left(\frac{\rho_f}{\rho_W}\right)^{-1.47}\left(\frac{\overline{c_p}}{c_{p,W}}\right)^{0.083} \tag{15}$$

where physical properties in Nu, Re, and Pr are evaluated at the wall temperature T_W, density ρ_f is based on bulk fluid temperature T_f, density ρ_W and specific heat $c_{p,W}$ are based on T_W. Average specific heat $\overline{c_p}$ has the same definition as in Eq. (8). The correlation is applicable to: $7.4 \leq p \leq 8.5$ *MPa*, $22 \leq T_f \leq 53$ ℃, $113.7 \leq G \leq 418.6\ kgm^{-2}s^{-1}$ and $0.8 \leq q \leq 9\ kWm^{-2}$ for horizontal channels of inner diameter of *1.31 mm*.

Pressure drop correlations

Single phase flow friction pressure drop is defined with the following equation:

$$\Delta p = f\frac{G^2}{2\rho}\frac{L}{D} \tag{16}$$

where f is the friction factor. Many correlations have been developed for the friction factor. The Filonenko correlation Eq. (3) (for $10^4 \le Re_f \le 5\times10^6$) and the Blasius equation:

$$f = \frac{0.316}{Re_f^{\ 1/4}} \tag{17}$$

which is widely used for turbulent flow in smooth tubes (for $Re_f \le 10^5$). The "smooth" means that the wall roughness is so small that its influence does not extend beyond the laminar sublayer.

Moody [17] introduced the Colebrook and White [18] equation in his diagram. Colebrook and White [18] developed an equation that agrees with two extremes of roughness in the transition zone:

$$\frac{1}{f^{1/2}} = -2\log\left(\frac{\varepsilon / D}{3.7} + \frac{2.51}{Re_f\sqrt{f}}\right) \tag{18}$$

Swamee and Jain [19] proposed an implicit Colebrook-White equation as follows:

$$f = \frac{0.25}{\left[\log\left(\frac{\varepsilon / D}{3.7} + \frac{5.74}{Re_f^{\ 0.9}}\right)\right]^2} \tag{19}$$

which matches the Colebrook-White equation within 1% for $10^{-6} < \varepsilon/D < 10^{-2}$ and $5000 < Re_f < 10^8$.

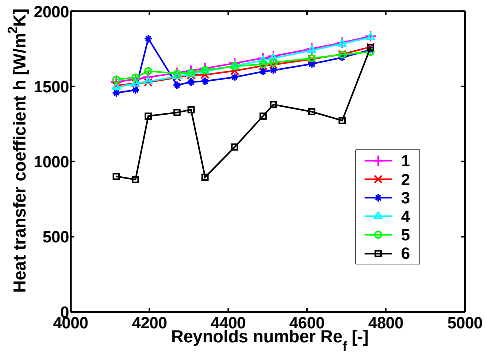
Churchill [20] proposed a more complicated expression for all flow regimes and all relative roughnesses which agrees well with the Moody diagram [17].

Fang et al. [21] made a comparison of the Blasius equation, the Filonenko equation, an explicit equation of Colebrook and White and the Churchill equation for CO_2 gas coolers. They recommended that the Churchill equation be used for fluid flow for transition and fully developed regimes or tubes whose relative roughness cannot be neglected.

Pitla et al. [22] presented a review of friction factor correlations especially developed for in-tube flow of supercritical fluids. They mentioned that some researchers used the Filonenko correlation for fluids in the supercritical region.

COMPARISONS OF HEAT TRANSFER AND PRESSURE DROP CORRELATIONS

Figure 2 shows the comparison of the experimental data of Huai et al. [15, 16] to the selected correlations [1]. The comparison made here only presents preliminary comparable results but not necessarily reveal the real situation as these data ($Re_f < 10^4$) were mostly out of the applicable range of these methods which were extrapolated [1]. Few studies present their data together with the corresponding wall temperatures. Thus, it is impossible to implement the correlations to compare to their data or to form a general database from all the published results. Here, simulations by the available supercritical cooling heat transfer correlations were performed for the indicated two conditions using the experimental conditions and simulated local fluid temperatures by Pitla et al. [10] as shown in Figs. 4 and 5. The maximum values are near the pseudocritical points. Big disagreement has been found among these correlations.



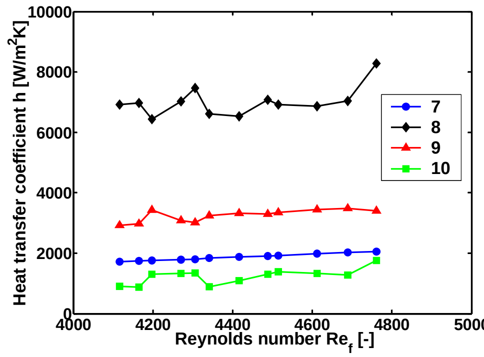


Figure 2 Comparison of experimental data to correlations 1- Eq.(4), 2-Eq. (5), 3-Eq. (7), 4-Eqs. (9) and (10), 5-Eq. (15), 6- experimental data [15], 7-Eqs. (2), 8-Eqs. (11) and (12) and 9-Eq. (13) and 10- experimental data [15].

Dang and Hihara [23] and Son and Park [13] presented a comparison of their macro-scale channel pressure drop data to the Blasius equation and found that the Blasius correlation worked well. Here, as an example, only the comparison by Son and Park [13] is shown in Fig. 3. Pettersen et al. [24] compared their micro-scale pressure drops to the Blasius, the Colebrook and White and the Swamee and Jain equations. All three equations predicted their data to within ±15%. Huai et al. [15] also compared their pressure drop data to the Blasius equation and it predicted their data to within ±25%. According to these studies, it seems that the Blasius equation can be used for the prediction of pressure drops for CO_2 cooling in both macro- and micro-scale channels. More careful experimental data are still needed to further validate this conclusion.

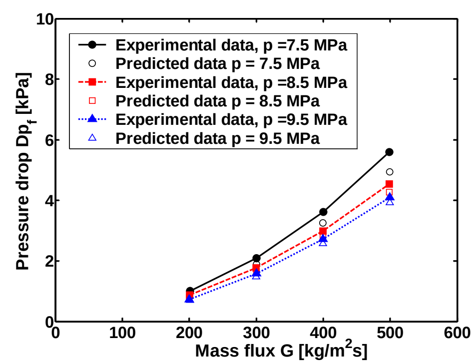
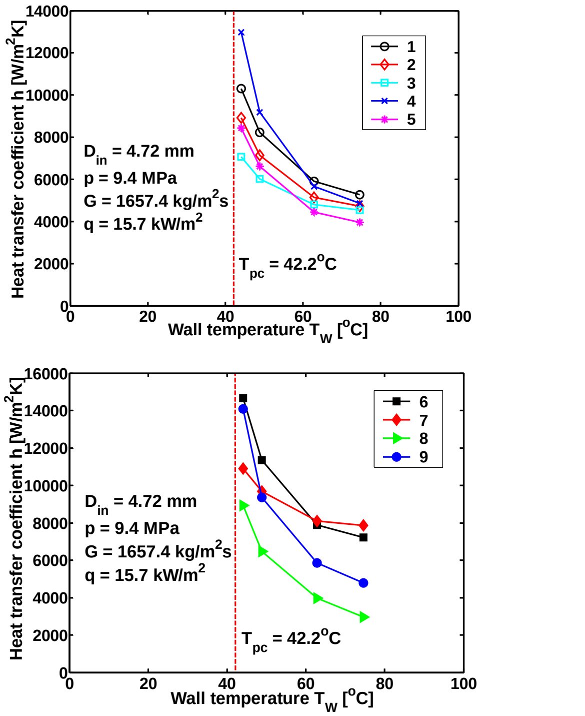
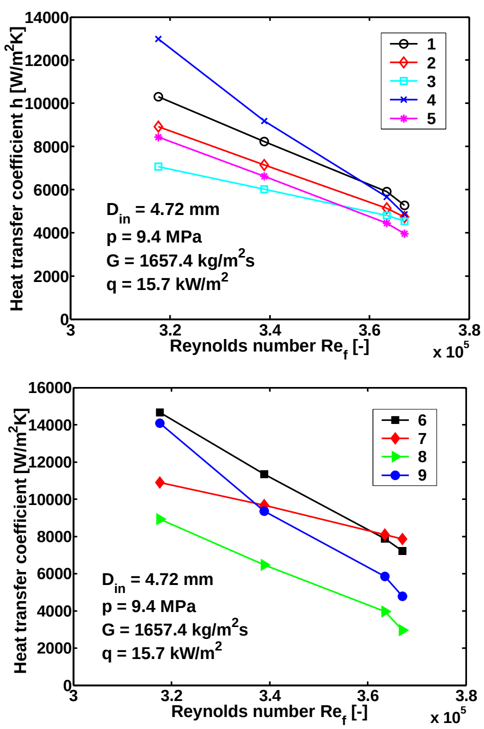


Figure 3 Comparison of the experimental data to the Blasius equation by Son and Park [13]

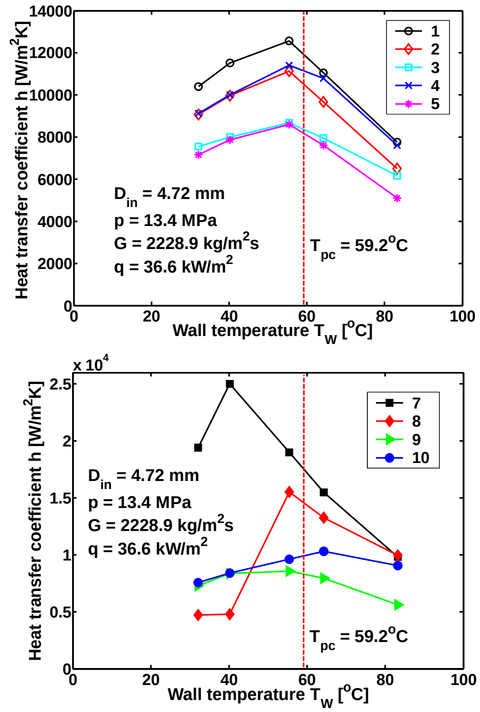


(a) Heat transfer coefficient vs. wall temperature (dashed lines are the pseudocritical points)



(b) Heat transfer coefficient vs. Reynolds number

Figure 4 Comparison of predicted results by correlations 1- Eq.(2), 2-Eq. (4), 3-Eq. (1), 4-Eq. (5), 5-Eq. (7), 6-Eqs. (9) and (10), 7-Eqs. (11) and (12), 8-Eq. (13) and 9-Eq. (15).



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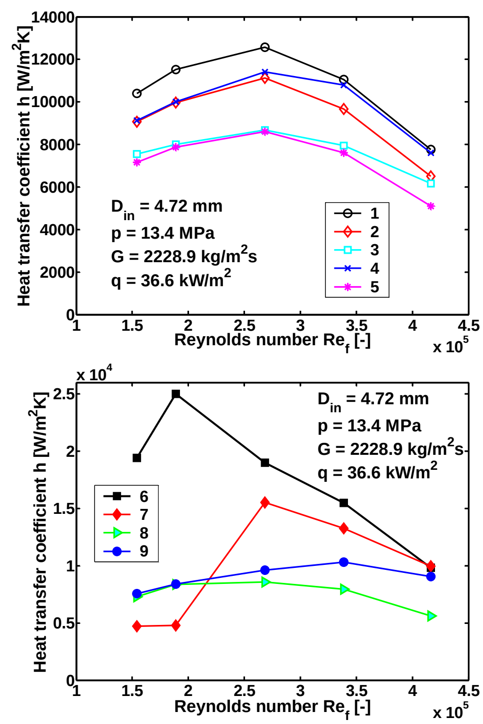

(b) Heat transfer coefficient vs. Reynolds number

Figure 5 Comparison of predicted results by correlations 1- Eq.(2), 2-Eq. (4), 3-Eq. (1), 4-Eq. (5), 5-Eq. (7), 6-Eqs. (9) and (10), 7-Eqs. (11) and (12), 8-Eq. (13) and 9-Eq. (15).

It should be mentioned that both macro- and microchannel heat transfer correlations were extrapolated. The Yoon et al. correlation gives extremely high values. Most correlations do not agree with each other. Thus, it is difficult to say at present which correlation gives the best prediction due to the lack of experimental data. Therefore, more accurate experimental data are needed to verify the available correlations or to develop a new one, including the measured wall temperatures as part of the database. It is very important to measure and deduce experimental data in a proper way because a little variation of temperature will cause significant change in heat transfer [1].

Furthermore, lubricating oil has a great effect on heat transfer and pressure drops [1, 25]. No heat transfer and pressure drop correlations are available at present. Therefore, experimental data considering the oil effect are also needed to develop new correlations. In addition, the physical mechanisms should be studies through flow visualisation to observe the oil-gas flow patterns (oil-gas) [26].

CONCLUSION

Simulations by the available supercritical cooling heat transfer correlations were performed for two conditions and the predicted results were compared with each other. These correlations do not agree with each other. It is difficult to say which correlation gives satisfactory prediction due to the lack of useful experimental data (most studies do not provide the corresponding wall temperature measurements and hence are incomplete publications and thus it is impossible to use those experimental data to verify these correlations). Therefore, it is recommended that further careful experiments should be done over a wide range of test parameters and proper measurement and data reduction methods be used. In addition, experiments with the oil effect should be performed and the physical mechanisms of the oil effect should be investigated as well.

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