Condensation heat transfer characteristic of R410A-oil mixture inside small diameter smooth copper tubes

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ABSTRACT

In order to promote the application of small diameter copper tubes in HVAC industry, condensation heat transfer characteristic of R410A-oil mixture inside small diameter smooth copper tubes is investigated experimentally. The experimental results indicate that the presence of oil always deteriorates the heat transfer, and the deterioration effect become obvious with the increasing oil concentration. At oil concentration of 5%, the heat transfer coefficient decreases by maximum 28.5% for small diameter smooth tubes. A new heat transfer correlation for R410A-oil mixture flow condensation inside smooth copper tubes is proposed, which agrees with all the experimental data within a deviation of -30% ~ +20%.

Keywords: Condensation; Correlation; Heat transfer; Oil; R410A; Small diameter copper tube;

Nomenclature

G	mass flux (kg m^{-2} s^{-1})	Φ	two-phase frictional multiplier
Ga	Galieo number	*Subscripts*	
m	mass flow rate (kg s^{-1})	B	free convection condensation
Nu	Nusselt number	bub	bubble
Ph	phase change number	F	forced convection condensation
Pr	Prandtl number	in	inlet
q	heat flux (W m^{-2})	L	liquid
Re	Reynolds number	local	local
T	temperature (^{o}C)	m	mixing chamber
x	vapor quality	no	nominal
X_{tt}	Martinelli parameter	o	oil
Greek symbols		out	outlet
α	heat transfer coefficient (W m^{-2} K^{-1})	r	refrigerant
ε	void fraction	sat	saturated
λ	thermal conductivity (W m^{-1} K^{-1})	tp	two-phase
μ	dynamic viscosity (Pa s)	V	vapor
ρ	density (kg m^{-3})	wi	inside tube wall
ω	oil concentration		

1. Introduction

Copper has been the material of choice for air conditioner tubes because of its inherent heat transfer properties, corrosion resistance and relative ease of manufacture. Although copper has meet the challenge of aluminum caused by the higher relative material cost of copper to aluminum in the recent years, the excellent antimicrobial benefit and less carbon footprint are the particular advantages of copper utilization.

In response to relative material costs, and in order to defend the global market for HVAC tubes, a new and more efficient copper tube technology, i.e., the small diameter copper tube technology has been applied in HVAC industry. HVAC manufacturers can use smaller diameter tube in products immediately on current production equipment, with a minimal change to their existing tube expansion process. Small diameter copper tubes are cost effectively in heat exchangers for residential air conditioners compared with aluminum alternatives, because it can maintain the familiar copper coil assembly processes, margins, and production control; avoid aluminum micro-channel investments and production challenges; and avoid the difficulties of joining dissimilar metals. Therefore, it is necessary to investigate the heat transfer characteristic of refrigerant inside small diameter copper tubes.

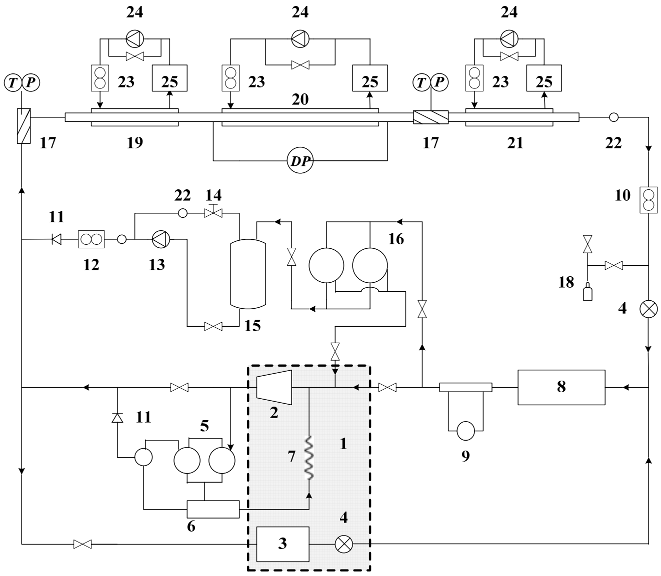
R22 will be phased out for its ozone depletion effect, and R410A is recognized as the main replacement to R22 because of free ozone depletion effect. The working pressure of a R410A air conditioner is higher than that of a R22 air conditioner, and then the influence of pressure drop on the performance of a R410A air conditioner is not as obvious as that of a R22 air conditioner, making it possible to employ smaller diameter copper tubes (e.g. 5 mm and 3 mm outer diameter tubes) in R410A air conditioners. In air-conditioning systems, a small amount of oil is needed for lubricating and sealing inside a compressor. Lubricating oil circulates with the refrigerant in refrigeration cycles, and affects the performance of refrigerant condensation. Then it is necessary to know the heat transfer characteristics of R410A-oil mixture flow condensation inside small diameter tubes.

Heat transfer characteristics of pure R410A (containing no oil) flow condensation inside smooth tubes have been reported by many researchers, such as Cavallini et al. [1], Dobson and Chato [2], Eckels and Tesene [3], Jung et al. [4], Kim and Shin [5] and Wijaya and Spatz [6]. However, there is no research on the heat transfer characteristics of R410A-oil mixture flow condensation inside small diameter smooth copper tubes. The researches on heat transfer characteristics of other refrigerant-oil mixtures flow condensation inside smooth tubes show that flow condensation heat transfer characteristics of refrigerant-oil mixtures are affected by tube diameters and the properties of refrigerant-oil mixtures.

The purpose of this study is to investigate the flow condensation heat transfer characteristics of R410A-oil mixture inside small diameter smooth copper tubes experimentally, and to propose a correlation for predicting the local heat transfer coefficient of R410A-oil mixture flow condensation inside small diameter smooth tubes.

2. Experimental apparatus and test conditions

The experimental rig consists of a refrigerant loop, a lubricating oil loop and a cooling water loop, as shown in Fig. 1. The refrigerant loop is designed to measure the heat transfer characteristics of refrigerant-oil mixture; the lubricating oil loop is designed to provide the required oil concentration of test section for investigating the influence of oil on condensation heat transfer and pressure drop performance; the cooling water loop is designed to achieve the condensation of refrigerant.



1-Outdoor unit, 2-Compressor, 3-Condenser, 4-Electronic expansion valve, 5-Oil separator for compressor, 6-Oil container, 7-Capilary, 8-Indoor unit, 9-After-heater, 10-Refrigerant mass flowmeter, 11-Check valve, 12-Oil mass flowmeter, 13-Oil pump, 14-Regulating valve, 15-Oil tank, 16-Oil separator for test section, 17-Mixing chamber, 18-Sampling cylinder, 19-Pre-condenser, 20-Test section, 21-After-condenser, 22-Sight glass, 23-Water volume flowmeter, 24-Water pump, 25-Thermostat

Fig. 1. Schematic diagram of experimental rig

The test tubes used in this study are small diameter smooth copper tubes with outside diameter of 5 mm and 3 mm (inside diameter of 4.18 mm and 1.6 mm). The test fluids are R410A and ester oil RB68EP. The ester oil has good miscibility with R410A and it is one of the most common ester oils for R410A air conditioner. The thermodynamic properties of oil and R410A-oil mixture can be seen in Hu et al. [7]. All test conditions are tabulated in Table 1. The maximum uncertainty of heat transfer coefficient is ±12.5% at typical test conditions without oil, which is estimated based on the analysis of error propagation reported by Moffat [8].

Table 1. Test conditions

Tube diameter, mm	Mass flux, kg $m^{-2} s^{-1}$	Heat flux, kW m^{-2}	Inlet quality	Condensing temperature, ^{o}C	Oil concentration, wt. %
5 (O.D.)	200	4.23	0.3 ~ 0.9	40	0, 1, 3, 5
	300	6.35			
	400	8.46			
4 (O.D.)	500	15.89			
	600	19.07			

3. Data reduction

3.1 Heat transfer coefficient

The local flow condensation heat transfer coefficients for pure refrigerants and refrigerant-oil mixtures are defined by the following equations [9]:

$$\alpha_{tp,r} = q/(T_{sat} - T_{wi}) \quad (1)$$

$$\alpha_{tp,r,o} = q/(T_{bub} - T_{wi}) \quad (2)$$

where

q – heat flux, W m^{-2}

T_{wi} – inside tube wall temperature, ^{o}C

T_{sat} – saturation temperature of the refrigerant, ^{o}C

T_{bub} – bubble point temperature of the refrigerant-oil mixture, ^{o}C

The bubble point temperature of the refrigerant-oil mixture, T_{bub}, is determined using the vapor-liquid equilibrium prediction method [9]. For a pure refrigerant, T_{bub} equals to T_{sat}, i.e. the definition in Eq. (2) is consistent thermodynamically with that in Eq. (1).

3.2 Oil concentration

Nominal oil concentration and local oil concentration are defined by Eqs. (3) and (4), respectively [9]:

$$\omega_{no} = m_o/(m_o + m_r) \quad (3)$$

$$\omega_{local} = \frac{m_o}{m_o + m_{r,L}} = \frac{\omega_{no}}{1 - x_{r,o}} \quad (4)$$

where

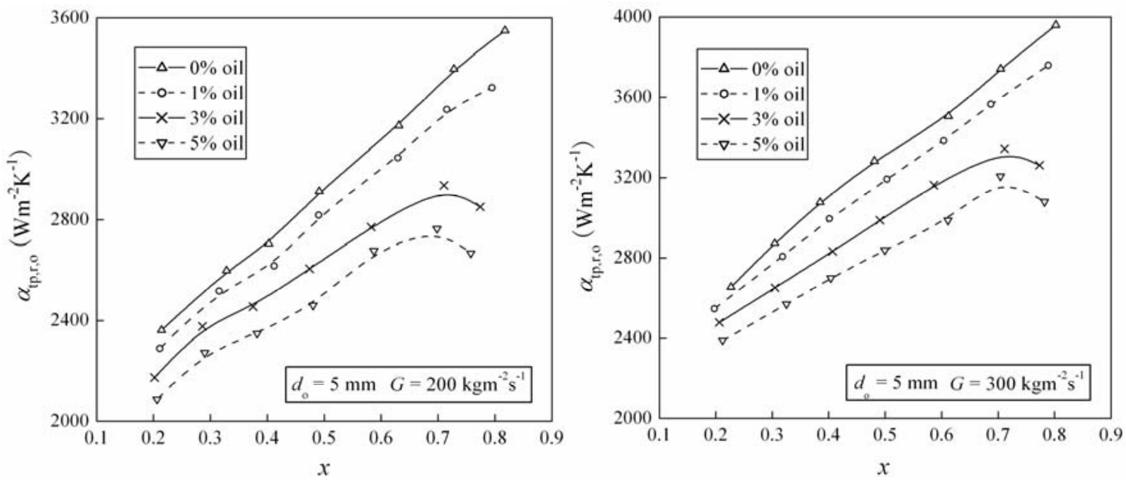
ω_{no} – oil mass fraction in subcooled liquid before evaporation begins

ω_{local} – oil mass fraction in liquid phase of refrigerant-oil mixture

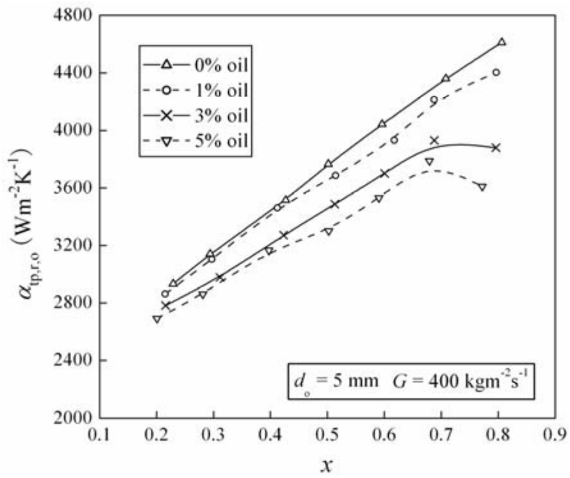
$x_{r,o}$ – local vapor quality of refrigerant-oil

4 Experimental results and analysis

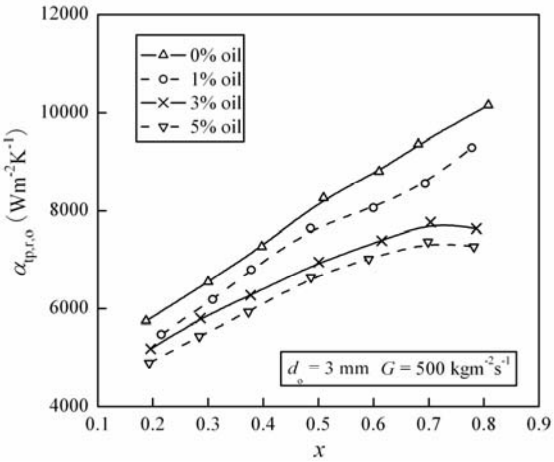
Figure 2 shows the local heat transfer coefficients of R410A-oil mixture flow condensation inside 5 mm and 3 mm O.D. smooth tubes as a function of vapor quality at different mass fluxes.



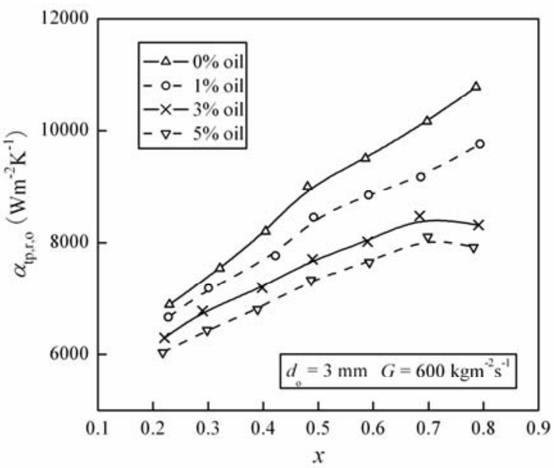
(a) d_o = 5 mm, G = 200 kg m^{-2} s^{-1} (b) d_o = 5 mm, G = 300 kg m^{-2} s^{-1}



(c) d_o = 5 mm, G = 400 kg m^{-2} s^{-1}



(d) d_o = 3 mm, G = 500 kg m^{-2} s^{-1}



(e) d_o = 3 mm, G = 600 kg m^{-2} s^{-1}

Fig. 2. Local heat transfer coefficient of R410A-oil mixture flow condensation inside 5 mm and 3 mm O.D. smooth tubes as a function of vapor quality at different mass fluxes

It can be seen from Fig. 2 that, the heat transfer coefficients of pure R410A decrease with the decrease of vapor quality, and the trend is the same as other pure refrigerants. The reason is that the increase of condensing liquid film thickness leads to the increase of thermal resistance.

A maximum of heat transfer coefficient appearing around the vapor quality of 0.7 for R410A-oil mixture of 3% and 5% oil concentrations can be found in Fig. 2. This phenomenon is resulted from two opposing factors in the liquid film: (1) at high vapor qualities, the condensing liquid film on the perimeter of inner tube wall is thin but oil-rich, resulting in a high viscosity and mass transfer resistance effect in the film, which deteriorates the heat transfer; (2) as the vapor quality decreases, the condensing liquid film becomes thicker and oil concentration in the oil-rich liquid film becomes smaller, resulting in the decrease of viscosity and mass transfer resistance effect in the film, which benefits the heat transfer. Thus, at high qualities, there is a trade-off of these two opposing factors, leading to a peak of the condensing heat transfer coefficient at 3% and 5% oil concentrations.

It can be concluded from Fig. 2 that the presence of oil deteriorates the flow condensation heat transfer, and the negative effects of the oil increase with the increase of oil concentration. The negative effects are distinct for different oil concentrations. At oil concentration of 1%, the heat transfer coefficients of R410A-oil mixture are lower than that of pure R410A with a reduction range of 0.7 ~ 6.4% for 5 mm O.D. tube, and 4.7 ~ 10.3% for 3 mm O.D. tube, meaning the oil influence is unobvious at small oil concentration. At oil concentrations of 3 and 5%, the presence of oil degrades the heat transfer seriously, and the deterioration effect is obvious especially at higher vapor qualities. At high vapor quality of about 0.8, condensation heat transfer coefficients at 5% oil concentration decrease by maximum 24.8% and 28.5% for 5 mm and 3 mm O.D. tube, respectively. The degradation of the condensation heat transfer coefficient owes to the higher viscosity of the R410A-oil liquid film as compared to the pure R410A, especially at higher oil concentrations and vapor qualities. The higher viscosity reduces the molecular and turbulent transport in the condensate film, thus deteriorates condensation heat transfer.

5 Development of heat transfer correlation for R410A-oil mixture flow condensation inside smooth tubes

Until now, there is no heat transfer correlation for R410A-oil mixture flow condensation inside small diameter smooth copper tubes, and then for the utilization of small diameter copper tube in HVAC industry, it is necessary to develop a new heat transfer correlation to predict the condensation heat transfer characteristic of R410A-oil mixture inside small diameter smooth copper tubes.

The new correlation is developed based on Haraguchi et al. [10] correlation expressed as the superposition of Nusselt number for forced convection condensation and that for free convection condensation:

$$\mathrm{Nu} = \alpha_{\mathrm{tp,r,o}} D / \lambda_{\mathrm{L}} = (\mathrm{Nu}_{\mathrm{F}}^2 + \mathrm{Nu}_{\mathrm{B}}^2)^{0.5} \tag{5}$$

$$\mathrm{Nu}_{\mathrm{F}} = 0.0152 (\Phi_{\mathrm{V}} / X_{\mathrm{tt}}) \mathrm{Re}_{\mathrm{L}}^{0.77} (-0.33 + 0.83\, \mathrm{Pr}_{\mathrm{L}}^{0.8}) \tag{6}$$

$$\mathrm{Nu}_{\mathrm{B}} = 0.725 H(\varepsilon) (\mathrm{Ga}_{\mathrm{L}}\, \mathrm{Pr}_{\mathrm{L}} / \mathrm{Ph}_{\mathrm{L}})^{0.25} \tag{7}$$

where

$$\Phi_{\mathrm{V}} = 1 + 0.5 \left\{ G / [g D \rho_{\mathrm{V}} (\rho_{\mathrm{L}} - \rho_{\mathrm{V}})]^{0.5} \right\}^{0.75} X_{\mathrm{tt}}^{0.35} \tag{8}$$

$$H(\varepsilon) = \varepsilon + \left\{ 10[(1-\varepsilon)^{0.1} - 1] + 1.7 \times 10^{-4}\, \mathrm{Re}_{\mathrm{LO}} \right\} \varepsilon^{0.5} (1 - \varepsilon^{0.5}) \tag{9}$$

Φ_{V} is two phase frictional multiplier, $H(\varepsilon)$ is a function of void fraction ε. Void fraction ε is calculated based on Smith [11] correlation.

The comparison of experimental data with the predicted heat transfer coefficients calculated by new correlation is shown in Fig. 3. The new correlation agrees with all the experimental data within a deviation of -30% ~ +20%.

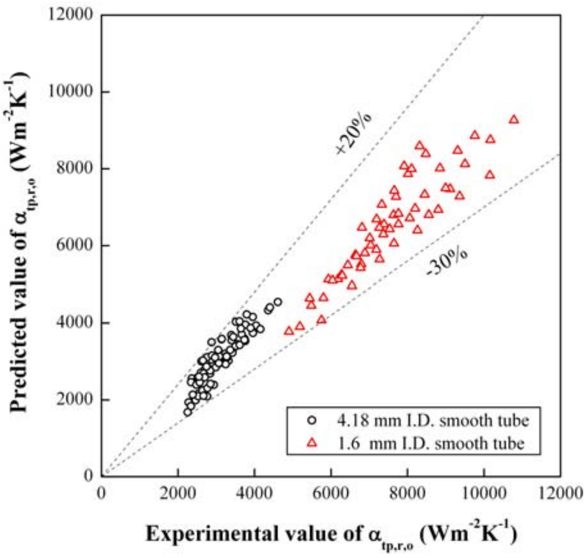


Fig. 3 - Comparison of experimental condensation heat transfer coefficient of R410A-oil mixture with new correlation

The applicable ranges of this correlation are as follows: mass fluxes from 200 to 600 kg m^{-2} s^{-1}, heat fluxes from 4.23 to 19.07 kW m^{-2}, vapor qualities from 0.3 to 0.9, and nominal oil concentrations from 0% to 5%.

6 Conclusion

Small diameter copper tubes are cost effectively in heat exchangers for residential air conditioners compared with aluminum alternatives, and it can reduce 20~30% refrigerant charge and also 20~30% heat exchanger cost, respectively. Then small diameter copper tube technology is a competitive and economic technology for HVAC industry.

In order to promote the application of small diameter copper tube, heat transfer characteristics of R410A and ester oil RB68EP mixture flow condensation inside small diameter copper smooth tubes are investigated experimentally, and the following conclusions are obtained:

(1) The presence of oil deteriorates the flow condensation heat transfer of R410A. At oil concentration of 1%, the negative effect is unobvious; while at oil concentrations of 3% and 5%, the presence of oil degrades the heat transfer seriously. At oil concentration of 5%, the heat transfer coefficient decreases by maximum 24.9% and 28.5% for 5 mm and 3 mm O.D. smooth tubes during the high vapor qualities.

(2) For R410A-oil mixture of 3% and 5% oil concentrations, a maximum of heat transfer coefficient appears around the vapor quality of 0.7; while for pure R410A and R410A-oil mixture of 1% oil concentration, this phenomenon is not observed.

(3) A new heat transfer correlation for R410A-oil mixture flow condensation inside smooth tubes is developed based on the refrigerant-oil mixture properties, and can agree with all the experimental data within a deviation of -30% ~ +20%.

Acknowledgements

The authors gratefully acknowledge the support from the National Natural Science Foundation of China (Grant No. 50906048) and the National Science Foundation for Post-doctoral Scientists of China (Grant No. 20090460618). The authors also gratefully acknowledge the supply of the lubricating oil and the oil property data from Nippon Oil Corporation and the supply of R410A from Honeywell Corporation for this study.

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