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Comparison of Heat Transfer Coefficient of R-12, R-134a and R-409a for Condensation Based on Existing Correlations

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The heat transfer coefficient of refrigerants R-12 (dichlorodifluoromethane), R-134a (1, 1, 1, 2, tetrafluoroethane) and R-409a (60 % R22, 25 % R124 and 15 % R142b) are compared on the basis of six existing correlations at condensing temperature 45 ˚C. Heat transfer coefficients are measured for horizontal tube having internal diameter 8 mm, external diameter 9.52 mm and length of 5 m, mass flux varies from 25 to 450 kg/m^{2}sand quality (dryness fraction) varies from 0 to 1. In the comparison of three refrigerants, Bohdal correlation predict that heat transfer coefficient for R-409a is higher than R-134a and R-12 while according to Cavallini and Zecchin, Shah, Traviss, Huang and Park correlation heat transfer coefficient for R-134a is higher than R-409a and R-12.

1. Introduction

Heat transfer evaluation of R-134a and other refrigerants have become important for reducing the use of R-12. R-134a is a potential replacement for R-12 (Eckles and Pate, 1991). R-134a contributed to global warming. R-409a is another alternative of R-12 and R-134a (Akintunde, 2013). R-409a is a mixture of 60 % R-22, 25 % R-124 and 15 % R-142b (Havelsky, 2000). Traviss et al., (1972) correlation developed from R-12 and R-22. Correlation is valid for $Pr_l > 3$. Shah (1982) correlation is valid for velocity of saturated vapor $u_v > 3$ m/s and for $350 < Re_l < 35000$. Cavallini and Zecchin (1974) correlation for condensation was developed for halocarbon refrigerants R-11, R-12, R-21, R-22, R-113, R-114.

This correlation is valid for $7000 < Re_l < 53000$ and for liquid to vapor viscosity ratios (μ_l / μ_v) from 11 to 314. (Park et al., 2011) conduct the experiment of condensation heat transfer data for refrigerant R1234ze (E), trans-1,3,3,3-tetrafluoropropene, and compared with refrigerants R-134a and R-236fa. The heat transfer performance of R-1234ze (E) was similar to R-236fa and 15–25 % lesser than that of R-134a. Bohdal et al. (2011) developed experimental correlation by using mathematical statics principals and with a selection of the model's parameters with Quasi-Newton and simplex methods. Huang et al. (2010) studied the influence of oil on condensation heat transfer of R-410A inside 4.18 mm and 1.6 mm inner diameter horizontal smooth tubes.

Table 1: Comparison of different refrigerants for condensation (continue)

Author	Year	Type of work	Refrigerants	Input parameter	Worked on	Results
Eckles Pate	&1990	Analytical	R-134a, R-12	D = 8.26 mm, G = 25 - 450 kg/m^{2}s, l = 5 m, x = 0 – 1, T_c = 40 ˚C	Condensation	Heat transfer coefficient of R-134a is 33 % to 38 % higher than R-12.
Eckles Pate	&1991	Experimental	R-134a, R-12	D = 8 mm, l = 3.67 mm, G = 125 – 400 kg/m^{2}s, x = 0 – 1, T_c = 30 – 50 ˚C	Condensation	Heat transfer coefficient of R-134a is 25 % to 35 % higher than R-12.

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Table 1: Comparison of different refrigerants for condensation

Author	Year	Type of work	Refrigerants	Input parameter	Worked on	Results
Suhayla Younis Hussain	2011	Experimental	R-134a, R-12	D = 8 mm	Condensation	Heat transfer coefficient obtained from experiment is 5 % to 12 % different than computed from Shah correlation.
Akintunde	2013	Experimental	R-12, Blend of R-134a, R-406a & R-600a	-	Domestic refrigerator	COP of R-12 is 2.08, COP of blend of R-134a / R-600a is 2.30.
Kim & Mudawar	2013	Analytical	R-12, R-1234ze(E), R-134a, R-404a, R-410a, R-600a	D = 0.424 – 6.22 mm, G = 53 – 1403 kg/m^{2}s, Re_l = 276 – 89798, x = 0 – 1, P_R = 0.04 to 0.91	Condensation	Two new correlations developed, one for annular flow & other for slug flow. New correlation gives better result.
Mustafa Ahmed Abdel Hussain	2013	Experimental	R-134a, R409a	-	Domestic refrigerator	R-409a has better COP and less power consumption than R-134a.
N. Austin	2016	Experimental	R-134a, R-600a	-	Domestic Refrigerator	R-600a performs better than R-134a.
Kukulka et al	2017	Experimental	R-410a	Inner and outer diameter of tube = 11.5 mm to 12.7 mm, x = 0.2 – 0.9	Condensation	Heat transfer coefficient of 2EHT-2 tube is higher than 2EHT-1 tube.
Zhao et al	2017	Experimental	R-134a, R-404a	Four test tubes of iron cupronickel and aluminium brass of length 1500 mm, 1464 mm, 1450 mm and 1471 mm	Condensation in single horizontal enhance tube	Condensation heat transfer of R-404a is more sensitive to surface structure and thermal conductivity than R-134a.
Kukulka et al	2018	Experimental	R-410a	Inner and outer diameter of tube = 8.32 mm to 9.52 mm, x = 0.2 – 0.8, G = 150 - 460 kg/m^{2}s	Condensation	Heat transfer performance and pressure drop is highest for 1EHT-1 tube.
Rahman et al	2018	Experimental	R-134a	D = 0.64 to 0.81 mm, l = 852 mm, T_s = 30 to 35 ˚C, G = 50 – 200 kg/m^{2}s	Condensation in multiport mini channel with and without fin	Heat transfer of rectangular multiport mini channel with fin is 10 – 39 % higher than without fin.
Evim et al	2018	Experimental	R-134a	Inclination angle of tube = -90˚ to +90˚, G = 50, 75 & 100 kg/m^{2}s	Condensation in inclined smooth tube	Downward flow gives maximum heat transfer coefficient at inclination of -15˚ to -30˚.
Medina et al	2018	Analytical	Water, air	D = 20 – 50mm, G = 2 – 75 kg/m^{2}s, P_R = 0.0008 to 0.11	Condensation	New Model valid for large range of Reynolds number unlike Chato equation.
Medina et al	2018	Analytical	Air	Air velocity = 0.1 – 20 m/s, Ambient temperature = 15 – 43 ˚C, D = 0.019 - 0.035 mm , Wind speed = 0 – 45 km / h	Condensation	Mean deviation found was 6.5% in 84.8% of the correlated experimental data.

2. Methodology

2.1 Average heat transfer coefficient correlations for condensation

Table 2: Local heat transfer coefficients correlations for condensation

References	Correlations
Traviss et al. (1972)	$h_{TP} = \left(\frac{Pr_l Re_l^{0.9}}{F_2}\right)F_t$, For $0.15 < F_{tt} < 15$, Where, $F_{tt} = 0.015\,(X_{tt}^{-1} + 2.85\,X_{tt}^{-0.467})$ F_2 can be determine as follows If $Re_l < 50$, then $F_2 = 0.707\,Pr_l\,Re_l^{0.5}$, If $50 < Re_l < 1125$, then $F_2 = 5\,Pr_l + 5\,\ln(1 + Pr_l(0.09636\,Re_l^{0.585} - 1))$, If $Re_l > 1125$, then $F_2 = 5\,Pr_l + 5\,\ln(1 + 5\,Pr_l) + 2.5\,\ln(0.00313\,Re_l^{0.812})$
Cavallini & Zecchin (1974)	$h_{TP} = 0.05\,Re_{eq}^{0.8}\,Pr_l^{0.33}\left(\frac{k_l}{D}\right)$, Where, $Re_{eq} = Re_l + \left(\frac{\mu_v}{\mu_l}\right)\left(\frac{\rho_l}{\rho_v}\right)^{0.5} Re_v$
Shah (1981) (1981)	$\Psi = \frac{h_{TP}}{h_l} = 1 + \frac{3.8}{Z^{0.95}}$, Where, $Z = \left(\frac{1}{x} - 1\right)^{0.8} P_R^{0.4}$, $h_1 = h_l\,(1 - x)^{0.8}$, $h_l = 0.023\left(\frac{GD}{\mu_l}\right)^{0.8} Pr_l^{0.4}\left(\frac{k_l}{D}\right)$
Huang et al. (2010)	$h_{TP} = 0.0152\,(-0.33 + 0.83\,Pr_l^{0.8})\frac{\phi_v}{X_{tt}} Re_l^{0.77}\left(\frac{k_l}{D}\right)$, Where, $\phi_v = 1 + 0.5\left(\frac{G}{\sqrt{g\rho_v(\rho_l-\rho_v)D}}\right)^{0.75} X_{tt}^{0.35}$
Bohdal et al. (2011)	$h_{TP} = 25.084\,Re_l^{0.258}\,Pr_l^{-0.495}\,P_R^{-0.288}\left(\frac{x}{1-x}\right)^{0.266}\left(\frac{k_l}{D}\right)$
Park et al. (2011)	$h_{TP} = 0.0055\,Pr_l^{1.37}\frac{\phi_v}{X_{tt}} Re_l^{0.7}\left(\frac{k_l}{D}\right)$ Where, $\phi_v = 1 + 13.17\left(\frac{\rho_v}{\rho_l}\right)^{0.17}\left[1 - \exp\left(-0.6\sqrt{\frac{g(\rho_l-\rho_v)D^2}{\sigma}}\right)\right] X_{tt} + X_{tt}^2$

Table 3: Average heat transfer coefficients correlations for condensation

References	Correlations
Traviss et al. (1972)	$h_{TPavg} = 0.15\,\frac{Pr_l\,Re_{lavg}^{0.9}}{F_2}\left(\frac{k_l}{D}\right)\left[0.8367\left(\frac{\mu_v}{\mu_l}\right)^{0.1}\left(\frac{\rho_l}{\rho_v}\right)^{0.5} + 2.498\left(\frac{\mu_v}{\mu_l}\right)^{0.0476}\left(\frac{\rho_l}{\rho_v}\right)^{0.238}\right]$ Where, $Re_{lavg} = \frac{GD}{2\mu_l}$ F_2 can be determine as follows If $Re_{lavg} < 50$, then $F_2 = 0.707\,Pr_l\,Re_{lavg}^{0.5}$, If $50 < Re_{lavg} < 1125$, then $F_2 = 5\,Pr_l + 5\,\ln(1 + Pr_l(0.09636\,Re_{lavg}^{0.585} - 1))$, If $Re_{lavg} > 1125$, then $F_2 = 5\,Pr_l + 5\,\ln(1 + 5\,Pr_l) + 2.5\,\ln(0.00313\,Re_{lavg}^{0.812})$
Cavallini and Zecchin (1974)	$h_{TPavg} = \frac{0.05}{1.8} Pr_l^{0.33}\left(\frac{k_l}{D}\right)\left(\frac{b^{1.8}-a^{1.8}}{b-a}\right)$, Where, $a = \frac{GD}{\mu_l}$, $b = \left(\frac{GD}{\mu_l}\right)\left(\frac{\mu_v}{\mu_l}\right)\left(\frac{\rho_l}{\rho_v}\right)^{0.5}$
Shah (1981)	$h_{TPavg} = hl\left(0.55 + \frac{2.09}{P_R^{0.38}}\right)$, Where, $h_l = 0.023\left(\frac{GD}{\mu_l}\right)^{0.8} Pr_l^{0.4}\left(\frac{k_l}{D}\right)$
Huang et al. (2010)	$h_{TPavg} = a\left[0.5711\left(\frac{\mu_v}{\mu_l}\right)^{0.1}\left(\frac{\rho_l}{\rho_v}\right)^{0.5} + 0.5593b\left(\frac{\mu_v}{\mu_l}\right)^{0.065}\left(\frac{\rho_l}{\rho_v}\right)^{0.325}\right]$ Where, $a = 0.0152\,(-0.33 + 0.83\,Pr_l^{0.8})\left(\frac{GD}{\mu_l}\right)^{0.77}\left(\frac{k_l}{D}\right)$, $b = 0.5\left[\frac{G}{\sqrt{g\rho_v(\rho_l-\rho_v)D}}\right]^{0.75}$
Bohdal et al. (2011)	$h_{TPavg} = 19.902\left(\frac{GD}{\mu_l}\right)^{0.258} Pr_l^{-0.495} P_R^{-0.288}\left(\frac{k_l}{D}\right)$
Park et al. (2011)	Average heat transfer coefficient from Park et al formula is obtained by Trapezoidal rule, as follows $h_{TPavg} = \frac{L}{2}\left[(h_{TP1} + h_{TPn}) + 2(h_{TP2} + h_{TP3} + \ldots + h_{TP(n-1)})\right]$ L = interval h_{TP1}, h_{TP2}, …, $hTP_{(n-1)}$, $h_{TP(n)}$ = values of h_{TP} for a range of x from 0 to1 with interval of 0.01.

Average heat transfer coefficient correlations are shown in Table 3. Which are developed by integrating the local heat transfer coefficient (given in Table 2) over a quality range from 0 to 1 by using Eq (1)

$$h_{TPavg} = \frac{1}{X-X_0}\int_{X_0}^{X} h_{TP}\,dx \tag{1}$$

2.1.1 Dimensionless term

$Re_l = \frac{GD(1-x)}{\mu_l}$, $Re_v = \frac{GDx}{\mu_v}$, $Pr_l = \frac{\mu_l C_{Pl}}{k_l}$, $P_R = \frac{P}{P_{crit}}$, $X_{tt} = \left(\frac{\mu_l}{\mu_v}\right)^{0.1}\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}$

3. Results and evaluation

Local and average heat transfer coefficient for R-12, R-134a and R-409a at 45˚C condensing temperature is calculated from correlations given in Table 2 and Table 3. The calculated heat transfer coefficients of three refrigerants are compared with each other. Comparison is presented as a ratio of heat transfer coefficient. Thermodynamic properties of R-12 and R-134a are taken from International Institute of Refrigeration and ASHRAE Fundamental Handbook. Thermodynamic properties of R-409a are taken from www.ethermo.us.

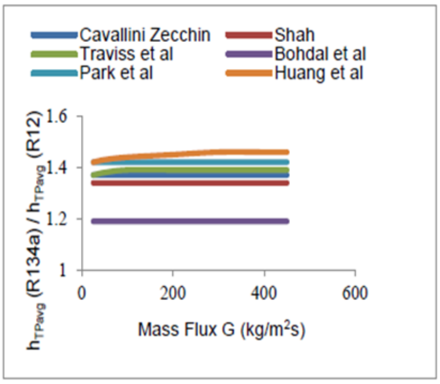

Figure 1: *Average heat transfer coefficient ratio of R-134a and R-12 at condensing temperature 45 ˚C*

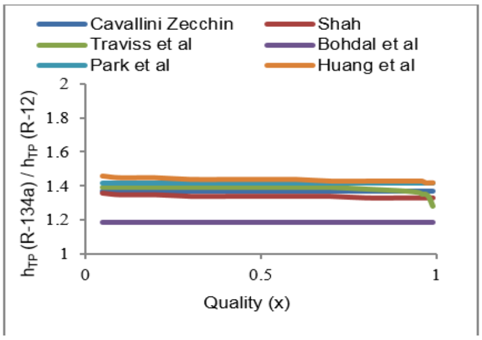

Figure 2: *Local heat transfer coefficient ratio of R-134a and R-12 at condensing temperature 45 ˚C*

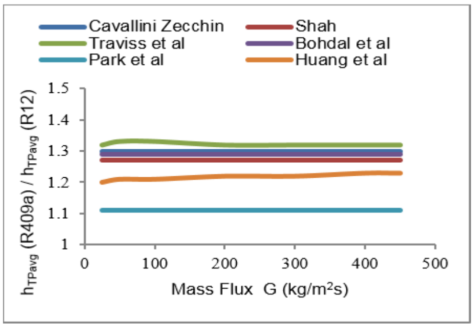

Figure 3: *Average heat transfer coefficient ratio of R-409a and R-12 at condensing temperature 45 ˚C*

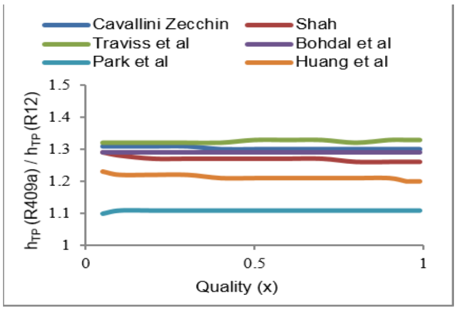

Figure 4: *Local heat transfer coefficient ratio of R-409a and R-12 at condensing temperature 45 ˚C*

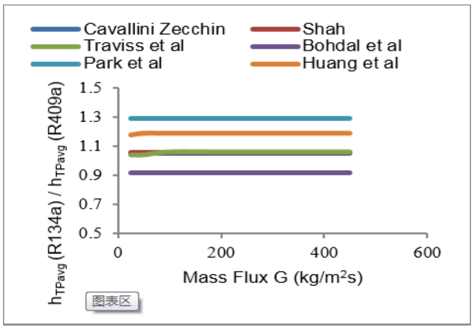

Figure 5: *Average heat transfer coefficient ratio of R-134a and R-409a at condensing temperature 45 ˚C*

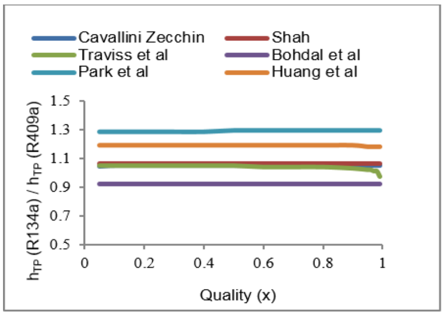

Figure 6: *Local heat transfer coefficient ratio of R-134aand R-409a at condensing temperature 45 ˚C*

3.1 Comparison of R134a and R12

Figure 1 shows average heat transfer coefficient ratio of R-134a and R-12 at condensing temperature 45 ˚C. The ratio is nearly constant over the whole range of mass flux for the six correlations, with values ranging from 1.19 to 1.46. Figure 2 shows local heat transfer coefficient ratio of R-134a and R-12 at condensing temperature 45 ˚C and mass flux of 100 kg/m^{2}s. The ratio varies from 1.19 to 1.46 for the six correlations over the whole quality range.

3.2 Comparison of R409a and R12

Figure 3 shows average heat transfer coefficient ratio of R-409a and R-12 at condensing temperature 45 ˚C. The ratio is nearly constant over the whole range of mass flux for the six correlations, with values ranging from 1.11 to 1.33. Figure 4 shows average heat transfer coefficient ratio of R-409a and R-12 at condensing temperature 45 ˚C and mass flux of 100 kg/m^{2}s. The ratio varies from 1.11 to 1.33 for the six correlations over the whole quality range.

3.3 Comparison of R134a and R409a

Figure 5 shows average heat transfer coefficient ratio of R-134a and R-409a at condensing temperature 45 ˚C. The ratio is nearly constant over the whole range of mass flux for the six correlations, with values ranging from 0.92 to 1.29. Figure 6 shows local heat transfer coefficient ratio of R-134a and R-409a at condensing temperature 45 ˚C and mass flux of 100 kg/m^{2}s. The ratio varies from 0.92 to 1.29 for the six correlations over the whole quality range.

4. Conclusions

Acomparison of heat transfer coefficient for R-12, R-134a and R-409a at condensing temperature 45 ˚C on the basis of existing correlations have been carried out. Key findings from the study are as follows:

Average heat transfer coefficient for R-12, R-409a and R-134a increases as the mass flux increases for all the six correlations.

Bohdal correlation predicts local and average heat transfer coefficient for R-409a is higher than R-134a and R-12 because of negative power of Prandtl number.

Cavallini& Zecchin, Shah, Traviss, Huang and Park Correlation predict local and average heat transfer coefficient for R-134a is higher than R-409a and R-12 because of positive power of Prandtl number.

Variation in local and average heat transfer coefficient ratio over a wide range of qualities (dryness fraction) and mass fluxes for R-134a to R-12 = 1.19 to 1.46, for R-409a to R-12 = 1.11 to 1.33, for R134a to R409a = 0.92 to 1.29

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