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Extending ORNL HPDM Capabilities for Design and Optimization of New Refrigerant Blends – FY18 1st Quarter Milestone Report: Perform Literature Review to Collect Heat Transfer, Pressure Drop Correlations and Compressor Mapping Method for Alternative Refrigerants

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Extending ORNL HPDM Capabilities for Design and Optimization of New Refrigerant Blends – FY18 1st Quarterly Milestone: Perform literature review to collect heat transfer, pressure drop correlations and compressor mapping method for alternative refrigerants

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Perform literature review to collect heat transfer, pressure drop correlations and compressor mapping method for alternative refrigerants
(Regular Milestone)

Executive Summary

Through a comprehensive literature survey, we identified heat transfer and pressure drop correlations for two-phase evaporation and condensation in fin-and-tube coils using microfin tubes and micro-channel heat exchangers. We also developed a compressor mapping method to convert the maps originally developed for R-22 or R-410A to be used by the alternative lower GWP refrigerants. The correlations and method will be implemented in HPDM for design and optimization of air conditioners and heat pumps using the new refrigerants/blends.

Heat Transfer and Pressure Drop Literature Survey for Alternative Low GWP Refrigerants

Through an extensive literature survey for heat transfer and pressure drop correlations for low GWP refrigerants/blends, we found most studies are related to pure refrigerant, i.e. R-1234yf, R-1234ze(E) and R-32. The collected papers are introduced in Appendix. Because HFO blends, proposed as replacements of R-22 and R-410A were recently developed, fundamental heat transfer and pressure drop investigations are still at the beginning stage. Among them, Kedzierski (2016) [4] from NIST investigated convective boiling R-448A, R-449A, and R-452B within a micro-fin Tube, and these three blends were provided by Chemours, as alternatives of R-404A, and R-452B can be used as a direct drop-in replacement of R-410A. Kedzierski (2016) [4] investigated convective boiling in both counter flow and parallel flow configurations, using water as the heating fluid. R-452B had the highest heat transfer coefficient in the three HFO blends. On average, the heat transfer coefficient of R-452B was about 5% lower than that of R-410A, at the qualities from 10% to 70%. The R-452B heat transfer coefficient was approximately 13% larger than that of R404A for qualities between 10 and 70%. The heat transfer coefficient for R-452B was predicted to be, on average, approximately 73 to 90% larger than R-448A and approximately 59 to 70% larger than R-449A. The heat transfer coefficients for R-449A and R-448A were 26 to 43% and 31 to 48%, respectively, less than that of R404A for qualities between 10 and 70%. Measured convective boiling coefficients of the test refrigerants, as a function of the thermodynamic quality, are given in the figure below.

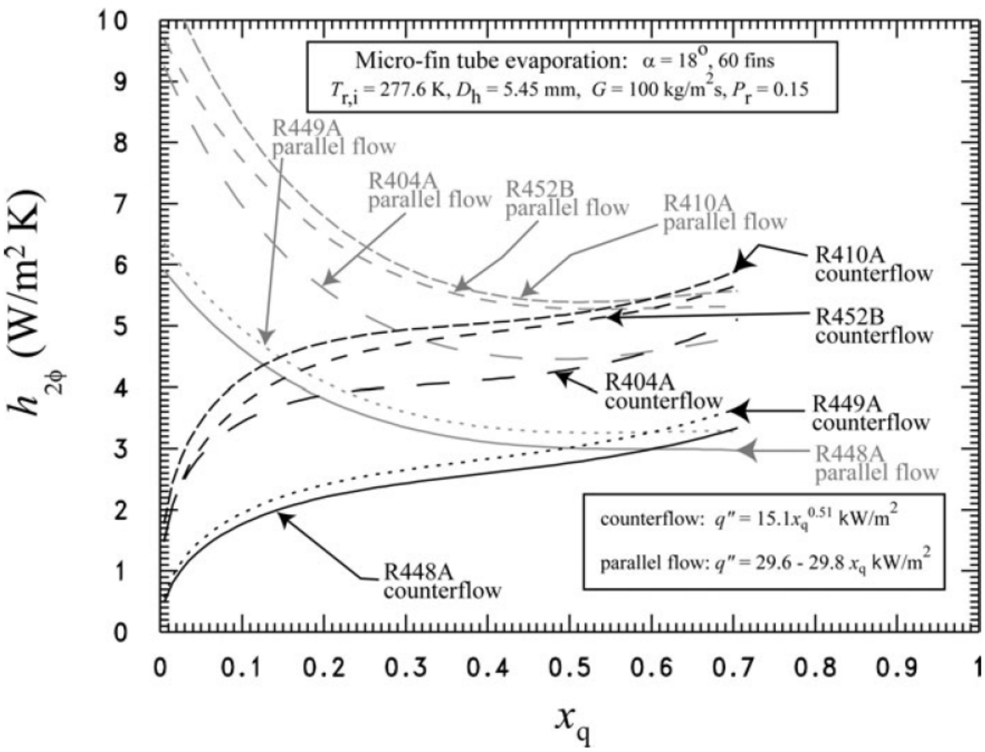

Figure 1. Flow boiling heat transfer coefficient versus quality for test refrigerants, from Kedzierski (2016) [4] .

Kedzierski (2016) [4] suggested the following correlation to predict the convective boiling coefficients of the low GWP HFO blends.

$$\mathrm{Nu}_p = 482.18\mathrm{Re}^{0.3} \ \ \mathrm{Pr}^{C_1} \left(\frac{P_s}{P_c}\right)^{C_2} Bo^{C_3} \left(-\log_{10}\frac{P_s}{P_c}\right)^{C_4} M_w^{C_5} \quad \text{(Eq. 1)}$$

Where C_1 to C_5 are empirical coefficients.

$$C_1 = 0.51x_q$$
$$C_2 = 5.57x_q - 5.21x_q^2$$
$$C_3 = 0.54 - 1.56x_q + 1.42x_q^2$$
$$C_4 = -0.81 + 12.56x_q - 11.00x_q^2$$
$$C_5 = 0.25 - 0.035x_q^2$$

x_q is the two-phase quality. Nu_p is the Nusselts Number of a pure refrigerant. Re is the Renolds Number, Pr is the Prandtl Number, Bo is the local boiling number. M_w is the molar mass for the refrigerant [g/Mole], P_s/P_c gives the reduced pressure, i.e. the local refrigerant pressure divided by the critical pressure.

To consider the effect of multi compositions in a refrigerant mixture and the resultant temperature glide, Nu_p shall be corrected as following.

$$\mathrm{Nu} = \mathrm{Nu}_p \left(1 - 36.23 \left[\frac{T_d - T_b}{T_b}\right] e^{-0.007 \mathrm{Re} \mathrm{Bo}^{0.47}}\right) \quad \text{(Eq. 2)}$$

Where Td and Tb are the dew point and bubble point temperatures [K], respectively, evaluated at the local saturation pressure and overall composition of the mixture. And the corrected Nusselts Number is defined in Equation 3.

$$\mathrm{Nu} = \frac{h_{2\phi}\, D_h}{k_l} \quad \text{(Eq. 3)}$$

$h_{2\Phi}$ is the two-phase convective boiling coefficient, D_h is the hydraulic diameter, k_l is the liquid refrigerant thermal conductivity.

Sethi (2013) [8], from Honeywell, compared heat transfer and pressure drop correlations for condensation and evaporation within micro-fin round tubes, against their experimental data for L-41 as an R-410A replacement. The measured L-41 average evaporation heat transfer coefficient was about 60% lower than R-410A, and L-41's average condensation heat transfer coefficient was comparable to R-410A. He recommended Cavallini et al. (1999) [6] to model evaporation heat transfer of the low GWP refrigerant within microfin tubes, and Cavallini et al. (2009) [7] to model the condensation heat transfer, and Kedzierski and Choi (1999) [5] to model both the condensation and evaporation pressure drops.

Compressor Performance Mapping Method

HPDM uses AHRI 10-coefficient compressor maps (ANSI/AHRI 540-99, 2010) [1] to calculate mass flow rate and power consumption, and enable calculation of the refrigerant-side vs. air-side energy balance from inlet to outlet by inputting a compressor shell loss ratio relative to the power input. It also considers the actual suction state to correct the map mass flow prediction using the method of Dabiri and Rice (1981) [3].

For modeling the alternative refrigerants, it is assumed that the compressor would maintain the same volumetric and isentropic efficiencies at the same suction and discharge pressures. Thus, the efficiencies were reduced from the original refrigerant, e.g. R-22 and R-410A maps as a function of the suction and discharge pressures. The volumetric efficiency is defined in Equation 4, and isentropic efficiency is shown in Equation 5.

$$m_r = Volume_{displacement} \times Speed_{rotation} \times Density_{suction} \times \eta_{vol} \quad (4)$$

$$Power = m_r \times (H_{discharge,s} - H_{suction})/\eta_{isentropic} \quad (5)$$

Where $\boldsymbol{m_r}$ is compressor mass flow rate; $\boldsymbol{Power}$ is compressor power; $\boldsymbol{\eta_{vol}}$ is compressor volumetric efficiency; $\boldsymbol{\eta_{isentropic}}$ is compressor isentropic efficiency; $\boldsymbol{H_{suction}}$ is compressor suction enthalpy; $\boldsymbol{H_{discharge,s}}$ is the enthalpy obtained at the compressor discharge pressure and suction entropy.

We used the experimental data from our low GWP drop-in tests to validate the compressor mapping approach, as introduced in Abdelaziz et al. (2016) [2]. Table 1 presents max and standard deviations using the compressor mapping method, i.e. the efficiencies were reduced from the original R-22 and R-410A maps as a function of the suction and discharge pressures, to predict refrigerant mass flow rates (m_r) and compressor power (*Power*), in comparison to the measured values for each alternative refrigerant, as the ambient temperature changing from 95°F (35°C) to 131°F (55°C). It can be seen that the converted, efficiency-based compressor map can be used for the alternative refrigerants, and the predictions reach similar levels of accuracy as for the baseline refrigerant, i.e. R-22 or R-410A, for which the compressor map was developed.

Table 1. Deviations in predicting compressor mass flow rate and power

	R-22	**R-444B**	**R-454A**	**ARM-20A**	**ARM-20B**
Max Deviation, Mr	3.1%	2.6%	1.7%	2.7%	1.1%
Standard Dev, Mr	0.5%	0.3%	1.3%	1.3%	1.1%
Max Deviation, Power	4.5%	2.5%	3.4%	4.8%	3.0%
Standard Dev, Power	0.1%	1.4%	1.5%	0.6%	1.5%
	R-410A	**R-452B**	**ARM-71A**	**R-447A**	**R-32**
Max Deviation, Mr	1.1%	3.9%	2.8%	4.2%	7.0%
Standard Dev, Mr	0.5%	0.8%	0.5%	0.8%	1.9%
Max Deviation, Power	4.4%	3.9%	2.9%	3.2%	2.6%
Standard Dev, Power	0.3%	0.5%	0.2%	0.3%	0.9%

The above analysis indicates that this compressor mapping approach can be employed with reasonable accuracy to represent the performance of existing compressors when used with the alternative lower-GWP alternatives, in lieu of actual compressor test data with such alternatives.

Conclusions

Through an extensive literature survey, we identified heat transfer and pressure drop correlations best for modeling and optimizing air conditioners and heat pumps using low GWP refrigerants. Professor Cavallini's group, from University of Padova, Italy, appears having done the most comprehensive investigations on low GWP refrigerants and their results have been recommended by several other researchers including Honeywell. Therefore, we decide to incorporate their published or recommended correlations to HPDM if available. Below tabulates the selected refrigerant heat transfer and pressure drop correlations for fin-tube coils (FTC) using microfin (MHX) tubes, and micro-channel heat exchangers.

Table 2. Selected correlations for heat transfer and pressure drop

Application	Correlation	Comment
FTC-Evaporation heat transfer	Kedzierski (2016) [4]	Recently developed for HFO blends of R-448A, R-449A, and R-452B
FTC-Condensation heat transfer	Cavallini et al. (2009) [7]	Recommended by Honeywell [8] and validated in [28]
FTC-Evaporation pressure drop	Kedzierski and Choi (1999) [5]	Recommended by Honeywell [8]
FTC-Condensation pressure drop	Kedzierski and Choi (1999) [5]	Recommended by Honeywell [8]
MHX-Evaporation heat transfer	Kim and Mudawar [22]	Recommended by Cavallini's group in [21,29,24]
MHX-Condensation heat transfer	Cavallini et al. (2006) [10]	Recommended in [9,11, 37]
MHX-Evaporation pressure drop	Friedel [23]	Recommended in [21, 29]
MHX-Condensation pressure drop	Friedel [23]	Recommended in [26]

Appendix – Literature Review

Evaporation:

Giovanni et al. (2017) [21] studied flowing boiling of HFC404A, HC290 (propane), and HC1270 (Propylene) inside a smooth tube with 4 mm inside diameter. They reported that nucleate boiling was the dominant component in the flow boiling. HFC404A demonstrated better heat transfer than HC290 and HC1270. The authors compared the heat transfer and pressure drop data to published correlations, and recommended Kim and Mudawar [22] to predict boiling heat transfer coefficient, and Friedel [23] to predict boiling frictional pressure drop.

Giovanni et al. (2017) [29] investigated flow boiling of R-1234ze(E) in a 4mm ID smooth tube, to be compared with R-134a. R-1234ze(E) showed similar heat transfer but higher pressure drop than R-134a, where convective boiling appeared to be a dominant factor. The authors evaluated published correlations using the experimental data, and recommended Kim and Mudawar [22] to predict boiling heat transfer coefficient, and Friedel [23] to predict boiling frictional pressure drop.

Daniel et al. (2017) [24] studied flow boiling heat transfer of R134a and its low GWP alternative refrigerants, including R1234ze(E), R1234yf and R600a in a horizontal micro-scale channel having 1.0 mm inside diameter. The heat transfer coefficients (HTC) for R134a and R1234yf were similar. For low vapor qualities, the HTC of R1234ze(E) was lower than the heat transfer coefficient of R134a and R1234yf. This trend became more apparent with increasing heat flux. For high vapor qualities, the HTC of R1234ze(E) was higher than the HTC of R134a. The HTC for R600a was lower than the HTC of the fluids R1234a, R1234ze(E) and R1234yf for vapor qualities lower than 0.2. However, the HTC for R600a increased drastically with increasing the vapor quality reaching values up to 120% higher than the other fluids. 14 predictive methods of the literature were compared to the experimental data. The correlations of Kanizawa et al. [25] and Kim and Mudawar [22] provided the best predictions of the overall database. An updated version of the predictive method of Kanizawa et al. (2016) [25] was proposed to improve the overall prediction accuracy.

Evraam (2016) [20] investigated nucleate boiling of three low GWP refrigerants, R-1234ze, R-1233zd(E), and R-450A, on a highly enhanced tube surface, in comparison to R-134a. From the test results, R-1234ze performed similar to R-134a while R-450a showed performance degradation of 28% compared to R-134a. For the R-123 replacement, R-1233zd(E) demonstrated a noticeable 19% performance increase.

Li et al. (2013) [38] [39] studied flow boiling of R-1234yf and R-32 refrigerant mixtures in a smooth horizontal tube with an inner diameter (ID) of 2 mm. The heat transfer coefficient of R-1234yf was noticeably less than R-32. Heat transfer coefficient of the refrigerant mixture R-1234yf+R32 at R32 mass fraction of 20% is less than that of pure R-1234yf. The heat transfer coefficient of the mixture at 50% mass fraction is greater than that of pure R-1234yf at large heat and mass fluxes. Both mixtures had heat transfer coefficients less than pure R-32 due to the mass transfer resistance. Several existing correlations were applied to predict the heat transfer coefficients of pure R-1234yf, R-32, and R-1234yf + R-32 (80/20 and 50/50 by mass%). The correlations of Yoshida et al. [41] and Chen [40] predicted the heat transfer coefficient of R-1234yf and R-1234yf + HFC32 (50/50 by mass%) with acceptable accuracy. However, these two correlations underestimated the heat transfer coefficients of R-32 under some conditions. A new semi-empirical correlation based upon the superposition of the contributions from nucleate boiling and convection was in very good agreement with the magnitudes and trends of the heat transfer coefficients of pure R-1234yf, R-32, and R-1234yf + R-32 (50/50 by mass%) with a relative mean absolute error of approximately 20%. The average properties of the mixture were used in the calculation. The correlation proposed by Müller-Steinhagen and Heck [42] can predict the pressure drops of the mixtures and pure HFO1234yf and HFC32. In the case of the predicted results for the HFO1234yf + HFC32 mixtures, 80%–90% are in good agreement with the measured pressure drops within a deviation of ±30%.

Diani et al. (2016) [45] investigated R1234ze(E) flow boiling inside a 2.4 mm ID horizontal microfin tube. The experimental tests show that the flow boiling mechanism is governed by nucleate boiling and two phase forced convection: at low vapor quality and high heat flux, nucleate boiling prevails over convective boiling, whereas at high vapor quality and low heat flux convective boiling overcomes nucleate boiling. The experimental values of heat transfer coefficient, frictional pressure drop, and vapor quality at the onset of dryout were also compared against the values estimated by empirical correlations available from the open literature. The correlations proposed by Diani et al. (2014) [46] were able to estimate the heat transfer coefficients and the frictional pressure drops with absolute deviations of 21% and 14%, respectively, whereas the vapor quality at the onset of dryout was estimated with sufficient accuracy by the correlation proposed by Mori et al. (2000) [47].

Kim et al. (2018) [43] studied the flow boiling heat transfer characteristics of R-1234ze(E) and R-134a in plate heat exchangers with different Chevron angles are measured and analyzed as a function of the mass flux, saturation temperature, vapor quality, and heat flux. The effect of the mass flux on the heat transfer and pressure drop of R-1234ze(E) is substantial. The heat transfer coefficient of R-1234ze(E) for a Chevron angle of 60 is approximately 3.7 times higher than that for a Chevron angle of 30 at high vapor qualities owing to the intensified turbulent flow. Moreover, for a Chevron angle of 60, the average heat transfer coefficient of R-1234ze(E) is on average 4.7% higher than that of R-134a due to its higher equivalent Reynolds number. However, the average pressure drop of R-1234ze(E) is higher than that of R-134a owing to the lower vapor density of R-1234ze(E). Finally, the correlations for the heat transfer and pressure drop of R-1234ze(E) are developed in the plate heat exchangers with different Chevron angles.

Byun et al. (2017) [15] investigated pool boiling characteristics of R-134a and R-1234ze(E) and R-1233zd (E) on a plain tube and two type of enhanced tubes. The heat transfer coefficients of R-1234ze(E) and R-1233zd(E) for the plain tube showed approximately 10.8–19.0%, 54.1–62.8% lower than those of R-134a, respectively. The authors validated pool boiling correlations developed by Cooper et al. (1984) [16], Stephan-Abdelsalam [17], Jung and Kim (2003) [18] and Ribatski (2003) [19], and concluded that they provided satisfactory predictability for all conditions.

Juan et al. (2016) [30] evaluated R448A and R450A as low-GWP alternatives for R404A and R134a using a micro-fin tube of 8 mm inner diameter. It was observed that the evaporator performance of R450A is very similar to that of R134a, although it only presents 42% of R134a in its composition. Besides, R404A and R448A present a great difference for all parameters studied, mostly caused by glide effects, different HTCs and enthalpy difference. Based on the model validation, they recommended the Akhavan-Behabadi et al. correlation (2011) [31] for predicting the evaporation heat transfer.

Condensation:

Li et al. (2018) [9] studied condensation heat transfer characteristics of R447A (R32/R1234ze/R125) having a GWP of 572. The authors also measured condensation heat transfer performance of R1234ze, R134a, R32 and their binary mixtures. The tested tube was a multi-port micro-channel tube with round channels having 0.86 mm inside diameter. The heat transfer measurements demonstrated that R-32 has the highest heat transfer coefficient. The condensation heat transfer of binary mixtures increased with increasing the R-32 concentration. The mixtures of R-32/R-134a had higher heat transfer coefficients than the mixtures of R-32/R-1234ze. Under the same mass flux and quality conditions, the order of condensation heat transfer was given as R32>R134a>R447A> R32/R1234ze(45%/55% by mass)>R32/R134a(24.5%/76.5%)>R410A>R1234ze. The authors used their experimental data to assess six correlations, corrected by Silver-Bell-Ghaly (SBG) [44] balance method to account for the mass transfer resistance in mixtures. They pointed out the revised Cavallini et al. (2006) [10] correlation have the best accuracy for the five non-azeotropic mixtures within deviation of 30%. And, the correlation has a broader applicability.

Rossato et al. (2017) [11] measured R-32 and R-1234ze(E) condensation heat transfer coefficient and pressure drop during condensation in the parallel rectangular minichannels of a bar-and-plate heat exchanger using perforated fins as the turbulator. The measured heat transfer coefficient of R-32 was better than R-1234ze(E). The authors implied that the condensation heat transfer in the mini-rectangular channels was more dominated by surface tension than mass flux. The experimental data was used to validate heat transfer and pressure drop correlations. The correlations developed by Cavallini et al. (2006) [10] and Jige et al. (2016) [12] provided more accurate heat transfer predictions. For validating the pressure drops, Jige et al. (2016) [12] led the best accuracy because it was developed for similar channel geometries and working fluid. Del Col et al. (2013) [13] and Da Silva et al. (2013) [14] had better consistencies than the other correlations.

Longo et al. (2017) [26] studied condensation of HFC404A, HC290 (Propane) and HC1270 (Propylene) inside a 4 mm ID smooth tube. The experimental heat transfer coefficients in the forced convection condensation regime were very well predicted by the Akers et al. (1959) model, whereas the Friedel (1979) [23] correlation was able to reproduce the frictional pressure drop data in the whole experimental range. HC290 and HC1270 exhibit heat transfer coefficients higher and frictional pressure drops lower than those of HFC404A.

Andrea et al. (2018) [28] investigated low GWP refrigerants condensation inside a 2.4 mm ID microfin tube. The refrigerants include R134a, R1234yf and R1234ze(E). In general, R1234ze(E) shows heat transfer coefficients similar to those of R134a, whereas R1234yf shows slightly lower values. R1234ze(E) frictional pressure drops are some 30% higher than those of R134a, whereas R1234yf shows values similar to R134a. The experimental results of heat transfer coefficient and frictional pressure drop were also compared against values predicted by empirical correlations. Cavallini et al. (2009) [7] provided better heat transfer predictability.

Del and Cavallini (2010) [37] measured Heat transfer and pressure drop during condensation of the low GWP refrigerant R1234yf in a within a single circular 0.96 mm diameter minichannel and compares them to the ones of R134a. R-1234yf exhibited lower heat transfer coefficients than R134a at the same operating conditions, but the heat transfer penalties were compensated by the lower pressure drop of R-1234yf. The model by Cavallini et al. (2006) [10] were recommended to predict the condensation heat transfer.

Giovanni et al (2014) [32] studied HFO-1234ze(Z) saturated vapor condensation inside a commercial Brazed Plate Heat Exchanger (BPHE) and compares this data with similar measurements previously obtained for refrigerant HFC-236fa, HFC-134a, HC-600a, HFO-1234ze(E) in order to experimentally assess refrigerant HFO-1234ze(Z) for high temperature heat pumps. HFO-1234ze(Z) exhibited heat transfer coefficients much higher than those of all the refrigerants now used in heat pumps and frictional pressure drop similar to HC-600a at the same refrigerant mass flux. The heat transfer coefficients show weak sensitivity to saturation temperature and great sensitivity to refrigerant mass flux. The heat transfer coefficients are sufficiently well predicted by the Nusselt [33]) analysis for vertical surface in the gravity controlled region and by the Akers et al. [34] model in the forced convection region. A linear equation based on the kinetic energy per unit volume of the refrigerant flow is proposed for the computation of frictional pressure drop.

Giovanni et al. (2013) [35] investigated condensation of R-1234yf in a vertical brazed plate heat exchanger, as an R-134a replacement. They studied the effects of saturation temperature, refrigerant mass flux and vapour super-heating. The heat transfer coefficients showed weak sensitivity to saturation temperature and great sensitivity to refrigerant mass flux. At low refrigerant mass flux, the heat transfer coefficients were not dependent on mass flux and condensation was controlled by gravity. For higher refrigerant mass flux, the heat transfer coefficients depended on mass flux and forced convection condensation occurs. The condensation heat transfer coefficients of super-heated vapour were from 8 to 11% higher than those of saturated vapour. R-1234yf exhibited heat transfer coefficients lower and frictional pressure drop lower (10-20%) than those of HFC134a under the same operating conditions. The heat transfer coefficients for saturated vapour were well predicted by the Nusselt (1916) [33] analysis for vertical surface in the gravity controlled region and by the Akers et al. (1959) [34] model in the forced convection region. The heat transfer coefficients for super-heated vapour were accurately predicted by the Webb (1998) [36] model in the forced convection region. A linear equation based on the kinetic energy per unit volume of the refrigerant flow was proposed for the computation of frictional pressure drop.

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