

GENERALIZED PRESSURE DROP CORRELATION FOR EVAPORATION AND CONDENSATION IN SMOOTH AND MICRO-FIN TUBES

J. Y. CHOI

Korea Testing Laboratory for Industrial Technology, Seoul 152-848, Korea

M. A. KEDZIERSKI, P. A. DOMANSKI

National Institute of Standards and Technology, Gaithersburg, MD 20899-8631, USA

ABSTRACT

This paper presents a pressure drop correlation for evaporation and condensation in smooth and micro-fin tubes for lubricant-free refrigerants and refrigerant/lubricant mixtures. The form of the generalized correlation was taken from the Pierre pressure drop model. NIST micro-fin tube pressure drop data for R134a, R22, R125, R32, R407C, R410A, and R32/R134a (25175 % mass) were regressed to a modified Pierre correlation. The NIST database was post-predicted with an average absolute residual of 10.8 %. Further validations performed with extensive data from the literature for lubricant-free refrigerants in smooth and micro-fin tubes showed an average absolute residual between measurements and predictions not to exceed 17.6 % for the various data sets. The condensation and evaporation pressure drops for different refrigerant/lubricant mixtures were predicted with average absolute residuals not exceeding 19.6% and 28.0 %, respectively.

1. INTRODUCTION

One of the early refrigerant-dedicated pressure drop correlations was formulated by Pierre (1964) and was based on his convective evaporation experiments with R12 and R22. Several important advances in the prediction of the two-phase pressure drop for refrigerants have been made since 1964 including applicability to smooth and enhanced tubes and prediction for different refrigerants, including mixtures of refrigerants and mixtures of refrigerants and lubricants. Signal et al. (1983) used the Martinelli-Nelson (1948) approach to develop a correlation to predict the pressure drop during convective evaporation of R12 and four different mixtures of R13 and R12. The maximum deviation between the model predictions and the measured pressure drops was within ± 30 %. Jung and Radermacher (1989) measured the pressure drop during horizontal convective evaporation of R22, R114, R12, and R152a, and several mixtures of these refrigerants. They proposed a model based on the principle of thermodynamic corresponding states, which correlated the measured pressure drops to an average absolute residual of 8.4 %. Tichy et al. (1986) presented an experimental investigation of pressure drop in forced-convection evaporation and condensation of R12/lubricant mixtures. For condensation, they modified the Lockhart-Martinelli (1949) relations for frictional pressure drop and a homogeneous void fraction model. For evaporation, the authors modified the frictional pressure drop correlation by Dukler et al. (1964) and the homogeneous void fraction model. Overall, the evaporation and condensation models predicted 85 % of the data to within ± 35 %. Tichy et al. (1986) reported that

the effect of lubricant on the pressure drop was significantly more pronounced for evaporation than for condensation. Fukushima and Kudou (1990) and Eckels and Pate (1991) found that R134a/lubricant mixtures exhibited a greater evaporation and condensation pressure drop than pure R134a. Torikoshi and Kawabata (1992) confirmed the increase in evaporation pressure drop with the addition of lubricant; however, they found that lubricant had no significant effect on the condensation pressure drop.

This paper describes the development and validation of a generalized pressure drop correlation for refrigerants and refrigerant/lubricant mixtures in smooth and micro-fin tubes. Initial model development began with an evaluation of existing correlations by comparing their predictions with evaporation and condensation pressure drop data obtained at NIST in a micro-fin tube. The model that gave the best predictions of the NIST data, the Pierre correlation, was selected as a basis for a new correlation development. The new correlation was verified with three extensive data pools from the literature that included refrigerant/lubricant mixtures. All refrigerant properties were obtained using REFPROP (Huber et al. 1996).

2. EVALUATION OF EXISTING CORRELATIONS

A total of 831 data points originating from the NIST test apparatus were analyzed in the present study: 626 points for evaporation (Kaul et al., 1996) and 205 for condensation (Kedzierski and Goncalves, 1999). For brevity, these two sets of data are later referred to as the “NIST database”. The test section in both studies was a copper micro-fin tube with the outside diameter $D_o = 9.52$ mm, root diameter $D_r = 8.92$ mm, and helix angle $\beta = 18^\circ$ (Choi et al. 1999). Figure 1 illustrates some of the various fin parameters. Using the above referenced measurements, we evaluated two homogeneous flow models and two separated flow models for pressure drop predictions. Homogenous flow models, also known as ‘the friction factor’ or ‘fog flow’ models, consider the two phases to flow as a single phase possessing mean fluid properties. Separated flow models consider the phases to be separated in a liquid and vapor streams. Since the models we considered were developed from smooth tube data, we applied the hydraulic diameter, D_h , of the micro-fin tube in lieu of the smooth tube diameter. We used the following equation for the hydraulic diameter (Kedzierski and Goncalves 1999):

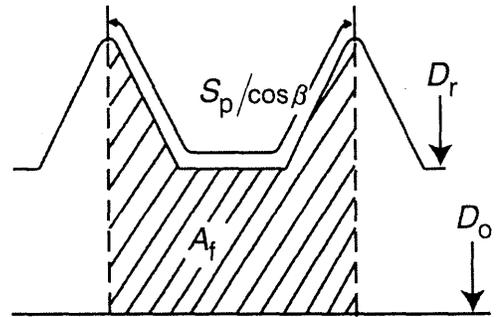


Figure 1. Detail Cross Section of Micro-fin Tube

$$D_h = \frac{4A_c \cos\beta}{NS_p} \quad (1)$$

The homogenous model proposed by Pierre (1964) for predicting evaporation pressure drop has the following form:

$$\Delta P = \Delta P_{friction} + \Delta P_{acceleration} = \left[f_{BP} + \frac{(x_{out} - x_m)D}{\bar{x} L} \right] \frac{G^2 \bar{x} v_g L}{D} \quad (2)$$

The two-phase friction factor for pure refrigerant, valid for $Re_{fo}/K_f > 1$, is based on experiments with R12 in horizontal, smooth tubes with diameters of 12 mm and 18 mm. It is expressed in terms of Re_f and K_f ; $f_{BP} = 0.0185 (K_f/Re_f)^{0.25}$ where Re_{fo} is the all liquid Reynolds number calculated as if the entire flow were liquid, and K_f is the Pierre boiling number defined as $K_f = (\Delta x h_{fg})/(Lg)$. Overall, the Pierre correlation predicted the NIST database with an average absolute residual of 15.8 %. However, a few of the low pressure drop data were underpredicted by 50 % to 60 %.

The homogeneous model given by Collier and Thome (1994) for predicting frictional pressure drop has the following form:

$$\Delta P_{friction} = \left[\frac{2f_B G^2 v_f L}{D} \right] \left[1 + \bar{x} \left(\frac{v_{fg}}{v_f} \right) \right] \left[1 + \bar{x} \left(\frac{\mu_{fg}}{\mu_f} \right) \right]^{-1/4} \quad (4)$$

In this model, the two-phase friction factor is calculated as $f_B = 0.079/Re_{fo}^{0.25}$. Overall, the model underpredicted the data on average by 31.4 % for all pressure drop ranges.

The separated flow pressure drop models examined in this study provided poorer predictions than the homogeneous models. The model based on the Lockhart and Martinelli (1949) approach overpredicted on average by 31.1 %. Overpredictions of over 100 % were evident for the small pressure drop range. Averaged over all pressure ranges and refrigerants, the pressure drop model by Jung and Radermacher (1989) overpredicted the NIST database by 57.3 % (Choi et al. 1999).

3. NEW CORRELATION FOR PRESSURE DROP

3.1 Lubricant-free Refrigerants

The Pierre correlation (Pierre 1964) was selected for further analysis because its predictions were in the best agreement with the NIST database. It was altered in two ways according to the modifications applied by Kedzierski and Goncalves (1999) for micro-fin condensation pressure drop data. First, the specific volume of liquid was included in the calculation of the average specific volume of the two-phase fluid. (Pierre neglected the specific volume of liquid). Second, the two-phase friction factor, f_N , was correlated to the NIST database. As before, we used the micro-fin tube hydraulic diameter, as defined in Equation (1) in lieu of the inner diameter for a smooth tube. The modified correlation has the form:

$$\Delta P = \Delta P_{friction} + \Delta P_{acceleration} = \left(\frac{f_N L (\dot{v}_{out} + \dot{v}_{in})}{D_h} + (v_{out} - v_{in}) \right) G^2 \quad (5)$$

Specific volumes of the two-phase fluid, v_{out} and v_{in} , are quality-weighted sums of the vapor and liquid specific volumes at either the outlet or inlet of the tube. The new two-phase friction factor is:

$$f_N = 0.00506 Re_{fo}^{-0.0951} K_f^{0.1554} \quad (6)$$

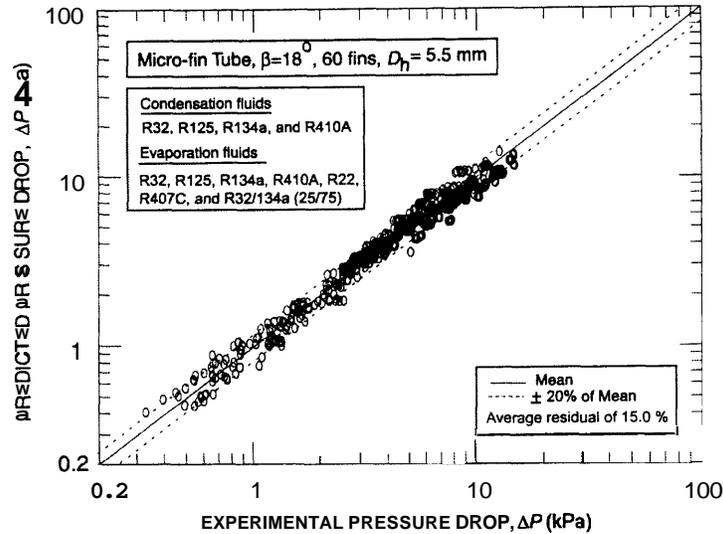


Figure 2. Post-predictions of NIST Pressure Drop Data With the New Correlation

The friction factor, valid for $Re_{fo}/K_f > 1$, is based on the all-liquid Reynolds number, $Re_{fo} = GD_h/\mu_l$ with G being the total mass velocity. The two-phase number (referred to by Pierre as a boiling number) is $K_f = \Delta x \cdot h_{fg}/(L \cdot g)$. The properties for the two-phase friction factor, f_N , are evaluated at a linearly averaged refrigerant temperature between the inlet and outlet. The procedure that was used to identify and possibly remove data that had high influence/leverage on the regression using the hat matrix and Cook's distance is described by Kedzierski and Goncalves (1999). Figure 2 shows post-predictions of the NIST database with the new correlation.

After the new correlation was developed, we also validated it with condensation pressure drop data from Eckels and Tesene (1999) and evaporation and condensation data from Schlager et al. (1989) and Eckels et al. (1993). Figure 3 presents predictions by the new correlation.

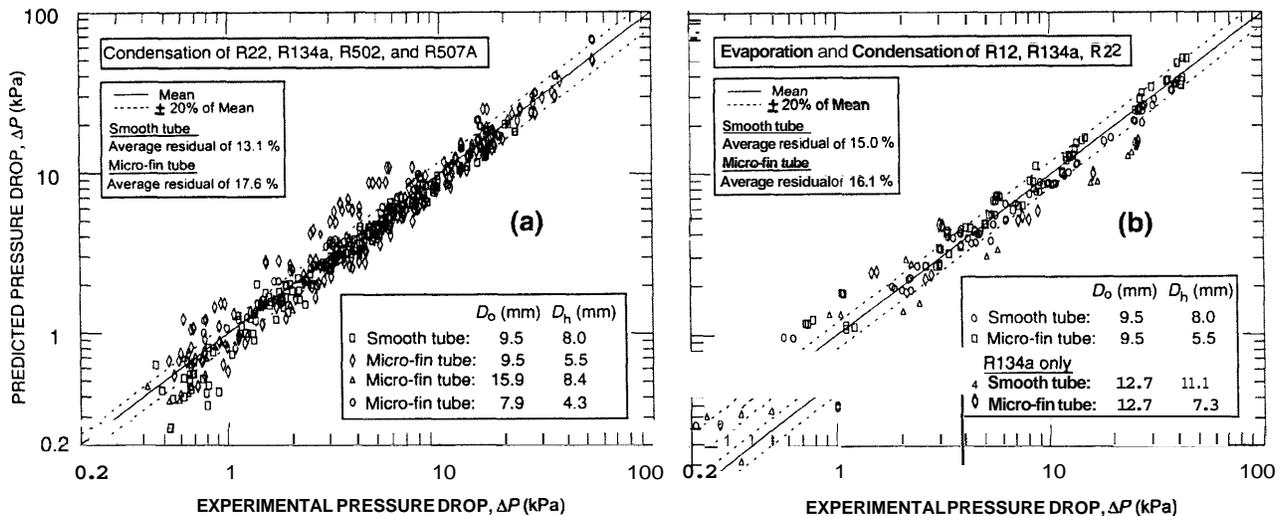


Figure 3. Predictions of Eckels and Tesene (1999) (a) and Schlager et al. (1989) and Eckels et al. (1993) (b) Lubricant-free Refrigerant Pressure Drop Measurements With the New Correlation

The new correlation predicted the smooth-tube and micro-fin-tube data of Eckels and Tesene (1999) with average absolute residuals of 13.1 % and 17.6 %, respectively, for all flow ranges and refrigerants. For the data of Schlager et al. (1989) and Eckels et al. (1993), these residuals were 15.0% and 16.1 %, respectively.

3.2 Refrigerant/Lubricant Mixtures

In practice, the refrigerant that circulates in refrigeration and air-conditioning equipment contains a small fraction of lubricant. For this reason, the applicability of the new pressure drop correlation to refrigerant/lubricant mixtures was investigated. In this analysis, the pressure drop correlation developed of lubricant-free refrigerants, shown in Equations (5) and (6), remained unchanged, however, the relations for calculating the vapor quality and liquid Reynolds number were modified to account for the lubricant present in the flow.

The vapor quality for the refrigerant/lubricant mixture was calculated as a mass fraction of the total flow, which includes the lubricant:

$$x = \frac{m_{ref,g}}{m_{tot}} = \frac{m_{ref,g}}{m_{ref,g} + m_{ref,f} + m_{oil}} \quad (7)$$

The liquid Reynolds number for the refrigerant/lubricant mixture, $Re_m = G_{tot} D_h / \mu_m$, was calculated using the total mass flux, $G_{tot} = m_{tot} / A_c$, and local viscosity of the liquid (refrigerant/lubricant mixture), μ_m . We assumed that all liquid refrigerant is uniformly mixed with the lubricant. We calculated liquid viscosity using the Yokozeki (1994) viscosity model, which was further verified for refrigerant/lubricant mixtures by Michels and Siemel (1996):

$$\ln \mu_m = \sum_i \xi_i \ln \mu_i = \xi_{ref} \ln \mu_{ref} + \xi_{oil} \ln \mu_{oil} \quad (8)$$

$$\text{where } \xi_i = W_i^k \Psi_i / \sum_j W_j^k \Psi_j \quad (9)$$

Ψ_i and W_i are the mole fraction and molar mass of component i , respectively. The molar mass of the lubricant was estimated to be 600 g/mol. The exponent k is an empirical parameter, often modeled by a low-order polynomial in temperature. Each refrigerant/lubricant mixture has a particular value of k . However, Yokozeki (1994) found that setting $k = 0.58$ gave accurate predictions for many refrigerant/lubricant mixtures, and we used this value in our calculations. The mole fraction of lubricant in the liquid phase can be expressed as follows in terms of the mass fraction and molar masses of the lubricant and refrigerant:

$$\Psi_{oil} = \frac{w_{f,oil} \left(\frac{W_{ref}}{W_{oil}} \right)}{1 - w_{f,oil} + w_{f,oil} \left(\frac{W_{ref}}{W_{oil}} \right)} \quad (10)$$

where the mass fraction of lubricant in the liquid phase is $w_{f,oil} = m_{oil} / (m_{oil} + m_{ref,f})$.

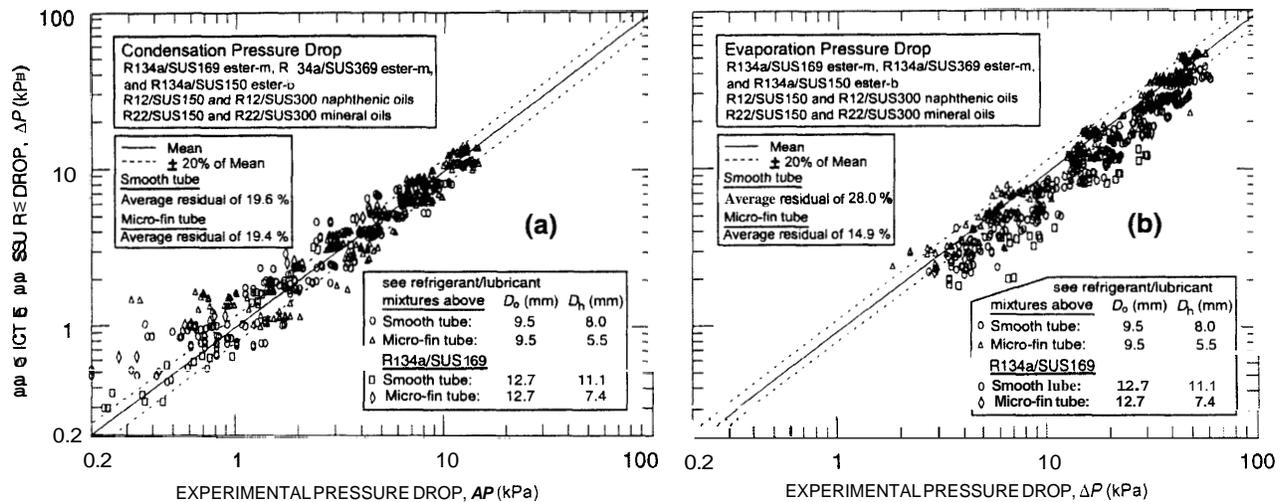


Figure 4. Predictions of Schlager et al. (1989) and Eckels et al. (1993) Refrigerant/lubricant Pressure Drop Measurements With New Correlation; (a) Condensation, (b) Evaporation

Figure 4 shows the results of validation of the above described methodology against two data sets. The data included convective condensation and evaporation pressure drops in smooth and micro-fin tubes for 28 different refrigerant/lubricant mixtures with lubricant contents in the range of 0.5 % to 5 %. The new correlation predicted the condensation pressure drop in the smooth and the micro-fin tubes with average absolute residuals of 19.6 % and 19.4 %, respectively. With the exception of pressure drops less than 1 kPa, the data scatter is centered about the mean of the predictions for both smooth and micro-fin tubes and for all refrigerants. The evaporation pressure drops were predicted with average absolute residuals of 28.0 % and 14.9 % for the smooth and the micro-fin tubes, respectively. The data was not centered about the mean for the evaporation data as the model tended to underpredict much of the data for all pressure drop ranges and refrigerants.

4. CONCLUSIONS

The paper presents a pressure drop correlation for convective evaporation and condensation in smooth and micro-fin tubes. The new Correlation employs a hydraulic diameter for micro-fin tubes and includes a methodology that extends its applicability to refrigerant/lubricant mixtures. The new correlation post-predicted the NIST database used in its development to an average absolute residual of 10.8 %. The lubricant-free refrigerant pressure drop data of Schlager et al. (1989), Eckels et al. (1993), and Eckels and Tesene (1999) for several different micro-fin tube geometries were predicted with an average absolute residual not exceeding 17.6 %. The new correlation predicted the evaporative pressure drop data of Schlager et al. (1989) and Eckels et al. (1993) for refrigerant/lubricant mixtures in smooth and micro-fin tubes with average absolute residuals of 28.0 % and 14.9 %, respectively. The condensation pressure drop data of Schlager et al. (1989) and of Eckels et al. (1993) for refrigerant/lubricant mixtures were predicted with an average absolute residual of 19.6% for both smooth and micro-fin tubes.

5. NOMENCLATURE

| | |
|--|---|
| <p>A = area (mm²)</p> <p>$A_c = \pi D_o^2/4 - NA_f$; cross sectional flow area (mm²)</p> <p>A_f = cross sectional area perpendicular to tube axis associated with one fin (mm²)</p> <p>D = diameter (mm)</p> <p>D_h = hydraulic diameter of micro-fin tube (mm)</p> <p>D_o = outside diameter (mm)</p> <p>D_r = maximum inside diameter of micro-fin tube (mm)</p> <p>f = Fanning friction factor</p> <p>G = mass flux (kg/m²s)</p> <p>g = acceleration due to gravity (m/s²)</p> <p>h = enthalpy (kJ/kg)</p> <p>$K_f = (\Delta x h_{fg})/(Lg)$; two-phase number</p> <p>L = tube length (m)</p> <p>m = mass flow rate (m/s)</p> <p>N = total number of micro fins</p> <p>P = pressure (kPa)</p> <p>$Re = GD/\mu$; Reynolds number</p> <p>S_p = perimeter of one fin and channel taken perpendicular to the axis of the fin (mm)</p> <p>v = specific volume (m³/kg)</p> <p>W = molecular mass</p> <p>w = mass fraction</p> <p>x = mass vapor quality</p> | <p><u>Greek symbols</u></p> <p>β = helix angle of the fin (degree)</p> <p>μ = viscosity (N/ms)</p> <p>ξ = Yokozeki's factor</p> <p>ψ = mole fraction</p> <p>ΔP = pressure drop (kPa)</p> <p><u>Subscripts</u></p> <p>B = Blasius</p> <p>BP = Bo Pierre</p> <p>f = friction or liquid</p> <p>fo = total flow assumed liquid</p> <p>fg = between liquid and vapor</p> <p>g = vapor</p> <p>i = component</p> <p>in = inlet</p> <p>lo = liquid phase only flowing</p> <p>m = mixture</p> <p>o = lubricant</p> <p>out = outlet</p> <p>ref = refrigerant</p> <p>tot = total</p> |
|--|---|

6. REFERENCES

- Choi, J. Y., Kedzierski, M., and Domanski, P. A.,** 1999, "A Generalized Pressure Drop Correlation for Evaporation and Condensation of Alternative Refrigerants in Smooth and Micro-fin Tubes", NISTIR 6333, National Institute of Standards and Technology, Gaithersburg, MD, USA.
- Collier, J. G., and Thome, J. R.,** 1994, "Convective Boiling and Condensation", 3rd Edition, Clarendon Press, Oxford, pp. 34-68.
- Dukler, A.E., Wicks, M., and Cleveland, R.G.,** 1964, "Frictional Pressure Drop in Two-Phase Flow: B. *An Approach Through Similarity Analysis.*" AICHE Journal 10, pp. 44-51.
- Eckels, S. J., and Pate, M. B.,** 1991, "In-Tube Evaporation and Condensation of Refrigerant-Lubricant Mixtures of HFC-134a and CFC-12" ASHRAE Transactions, Vol. 97, Pt. 2, pp. 62 – 70.
- Eckels, S. J., Doerr, T. M., Pate, M. B.,** 1993, "Heat Transfer and Pressure Drop During Condensation and Evaporation of R-134a/Oil Mixtures in Smooth and Micro-Fin Tubes", ASHRAE RP-630, Engineering Research Institute, Iowa State Univ., USA.
- Eckels, S.J. and Tesene, B.,** 1999, "A comparison of R-22, R-134a, R-410A, and R-407C condensation performance in smooth and enhanced tubes: Part II, Pressure Drop", ASHRAE Transactions, Vol. 105, Pt. 2, pp. 442-452.

- Fukushima, T., and Kudou, M.**, 1990, “Heat Transfer Coefficients and Pressure Drop for Forced Convection Boiling and Condensation of HFC134a”, *Proc. Int. Refrig. Conf.*, Purdue Univ., USA, pp. 196-204.
- Huber, M., Gallagher, J., McLinden, M., Morrison, G.**, 1996, “NIST Thermodynamic Properties of Refrigerants and Refrigerant Mixtures Database (REFPROP)”, Version 5.0, NIST Standard Reference Database 23, National Institute of Standards and Technology, Gaithersburg, MD, USA.
- Jung, D. S., and Radermacher, R.**, 1989, “Prediction of Pressure Drop During Horizontal Annular Flow Boiling of Pure and Mixed Refrigerants”, *Int. J. Heat Mass Transfer*, Vol. 32, No. 12, pp. 2435-2446.
- Kaul, M. P., Kedzierski, M. A., and Didion, D. A.**, 1996, “Horizontal Flow Boiling of Alternative Refrigerants Within a Fluid Heated Micro-Fin Tube”, *Process, Enhanced, and Multiphase Heat Transfer: A Festschrift for A. E. Bergles*, Begell House, Inc., New York, pp. 167-173.
- Kedzierski, M. A., and Goncalves, J. M.**, 1999, “Horizontal Convective Condensation of Alternative Refrigerants Within a Micro-Fin Tube”, *Journal of Enhanced Heat Transfer*, Vol. 6, pp. 161-178.
- Lockhart, R. W., and Martelli, R. C.**, 1949, “Proposed Correlation of Data for Isothermal Two-Phase, Two-Component Flow in Pipes”, *Chemical Engineering Progress*, Vol. 45, Pt. 1, pp. 39-48.
- Martinelli, R.C. and Nelson, D.B.**, 1948, “Prediction of Pressure Drop During Forced Circulation Boiling of Water”, *ASME Transactions*, No. 6, pp. 695 – 702.
- Michels, H. H., and Siemel, T. H.**, 1996, “Viscosity Modeling of Refrigerant/Lubricant Mixtures”, *Proc. Int. Ref. Conf.*, Purdue Univ., USA, pp. 96-105.
- Pierre, B.**, 1964, “Flow Resistance With Boiling Refrigerants-Part 1”, *ASHRAE Journal*, Vol. 6, No. 9, pp. 58-65.
- Signal, L. C., Sharma, C. P., and Varma, H. K.**, 1983, “Pressure Drop During Forced Convection Boiling of Binary Refrigerant Mixtures”, *Int. J. Multiphase Flow*, Vol. 9, No. 3, pp. 309-323.
- Schlager, L. M., Pate, M. B., Bergles, A. E.**, 1989, “Effect of Oil on Heat Transfer and Pressure Drop Inside Augmented Tubes During Condensation and Evaporation of Refrigerants”, ASHRAE RP-469, Engineering Research Institute, Iowa State Univ., USA.
- Tichy, J.A., Duque-Rivera, J., Macken, N. A., and Duval, W. M. B.**, 1986, “An Experimental Investigation of Pressure Drop in Forced-Convection Condensation and Evaporation of Oil-Refrigerant Mixtures”, *ASHRAE Transactions*, Vol. 92, Pt. 2A, pp. 461-472.
- Torikoshi, K. and Kawabata, K.**, 1992, “Heat Transfer and Pressure Drops Characteristics of HFC-134a in a Horizontal Heat Transfer Tube”, *Proc. Int. Refrig. Conf.-Energy Efficiency and New Refrigerants*, Vol. 1, Purdue Univ., USA., pp. 167-176.
- Yokozeki, A. M.**, 1994, “Solubility and Viscosity of Refrigerant-Lubricant Mixtures”, *Proc. Int. Ref. Conf.*, Purdue Univ., USA, pp. 335-340.

7. ACKNOWLEDGMENTS

J. Y. Choi’s NIST sabbatical was funded by NIST and KTL, Korea. M. Kaul and J. Goncalves took the evaporation and condensation pressure drop measurements at NIST, respectively. The authors thank S. J. Eckels of the Kansas State University and M. Pate of the Iowa State University for sharing their experimental pressure drop data.