E HEFAT2007
5th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
Sun City, South Africa
Paper number: KM1

FLOW CHARACTERISTICS OF HFC-134a IN AN ADIABATIC HELICAL CAPILLARY TUBE

Khan M. K., Sahoo P.K.* and Kumar R.
*Author for correspondence
P. Bag 0061, Department of Mechanical Engineering,
University of Botswana, Gaborone, Botswana
E-mail: sahoopk@mopipi.ub.bw

ABSTRACT

In this paper, an attempt is made to model the refrigerants flow through helical adiabatic capillary tubes used in domestic refrigerators and small residential air conditioners. The present study, based on homogenous two-phase flow model, predicts the performance of the helical capillary tube under adiabatic flow conditions. The variation of different physical parameters like pressure, temperature, quality, void fraction, velocity, and entropy with the length of adiabatic capillary tube has been investigated. The effect of varying capillary tube diameter and the pitch on pressure variation along the length is carried out. The simulation results are validated with experimental findings of the previous researchers for straight capillary tube as the literature lacks experimental work on helical capillary tube. It is found that when subjected to similar conditions, the helical capillary tubes are shorter than their straight counterparts.

INTRODUCTION

The capillary tube is a commonly used expansion device in small vapour-compression refrigeration system, where the load is fairly constant. It is a long simple hollow drawn copper tube with internal diameter ranging from 0.5 – 2.0 mm and length varies from 2 – 6 m. It is simple in construction, has no moving part, and requires no maintenance. In an adiabatic capillary tube, the subcooled liquid refrigerant enters the capillary and as the flow progresses the pressure drops linearly because of friction. As the pressure falls below its saturation value, a part of it flashes into vapour. Further downstream of the flashing point, more and more vapour starts generating that causes the fluid velocity to increase, which in turn gives rise to acceleration pressure drop.

Straight adiabatic capillary tubes have been extensively investigated by different researchers and some of the works are highlighted here. Marcy [1] employed graphical integration method to evaluate the adiabatic capillary tube length using the Moody’s friction factor. Mikol [2] established through flow visualization that the flow through the capillary tube is a homogenous two-phase flow. Koizumi et al. [3] used the flow visualization to observe the refrigerant flow through glass capillary tube and developed a method for calculating the length of two-phase flow region. Melo et al. [4] investigated experimentally the effects of the condensing pressure, size of capillary tube, degree of subcooling at the capillary tube inlet and the refrigerant types (R12, R134a and R600a) on the length of capillary tube.

NOMENCLATURE

A	[m^2]	cross sectional area of capillary tube
d	[m]	capillary tube internal diameter
D	[m]	coil diameter
ΔT_{sub}	[K]	degree of subcooling
e/d	[-]	relative roughness
F	[-]	friction factor
G	[kg/m^{2}s]	mass velocity (ρV)
h	[J/kg]	enthalpy
k	[-]	entrance loss coefficient
L	[m]	capillary tube length
m	[kg/s]	mass flow rate
P	[Pa]	pressure
p	[m]	pitch
Re	[-]	Reynolds number (Gd/μ)
s	[J/kgK]	entropy
T	[K]	temperature
V	[m/s]	fluid velocity
v	[m^3/kg]	specific volume
x	[-]	vapour quality

Special characters

α	[-]	void fraction

μ	[kg/m-s]	viscosity
ρ	[kg/m^3]	density
θ	[rad]	angle
τ_w	[N/m^2]	Wall shear Stress *($f\rho V^2/8$)*

Subscripts

F	liquid phase
g	vapour phase
fg	liquid-vapour mixture
I	capillary tube inlet
sp	single-phase
tp	two-phase
c	coil
s	straight

Flow through coiled tubes is far more complex phenomena than the flow inside straight tubes. In helical capillary tube, in addition to the friction and acceleration pressure drop, there exists another pressure drop acting in the radial direction due the presence of centrifugal forces. These centrifugal forces give rise to secondary flows as shown in Figure 1. Dean [5] was the first to conduct a theoretical study of incompressible fluids flowing through curved pipes. Ito [6] proposed empirical correlations for the various flow regimes inside helical pipe. Ali [7] presented various correlations available for helical coils.

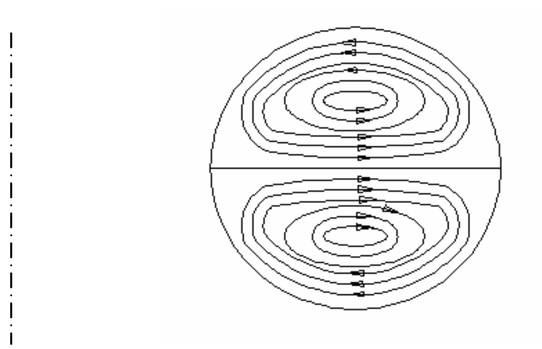

Figure 1 Secondary flow in the cross section of a helical capillary tube

Straight capillary tubes are hardly used in practice while the helical capillary tubes are widely used in domestic refrigerators and room air conditioners. Therefore, an attempt is made to model the adiabatic helical capillary tube, based on the homogenous two-phase flow model. To the best of authors' knowledge no work has been reported for helical capillary tubes. Thus, for validation purpose a separate model based on the homogenous two-phase model is developed for adiabatic straight capillary tube as the literature lacks the experimental data on helical capillary tube. The REFPROP 7 database [8], which is based on the Carnahan-Starling-DeSantis equation of state, has been used to determine the thermodynamic and transport properties of the refrigerants.

MATHEMATICAL MODELING

In Figure 2, section 1 – 2 represents pressure drop due to sudden contraction at capillary inlet, section 2 – 3 single-phase subcooled flow, and section 3 – 4 liquid-vapour two-phase flow region. Assumptions used for the purpose of analysis are as follows:

- the flow is one dimensional, steady, adiabatic and homogenous in two-phase region,
- capillary tube is assumed to have constant cross section and roughness, and
- metastabilty is ignored.

The present mathematical model is based on the conservation mass, momentum, and energy equations and is discussed in the following paragraphs.

In a steady state the conservation of mass for capillary tube can be written as

$$G = \frac{\dot{m}}{A} = \rho V = constant \qquad (1)$$

Applying momentum balance across a differential element gives the pressure drop as

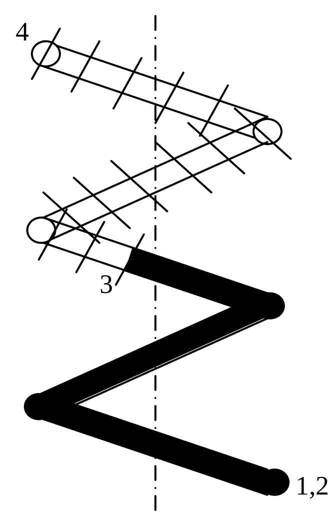

Figure 2 Computational domain of adiabatic helical capillary tube.

$$-dP = \frac{f}{2d}\rho V^2 dL + \rho V dV \qquad (2)$$

Eqn. (2) reduces to

$$dL = \frac{2d}{f}\left(\frac{-\rho dP}{G^2} + \frac{d\rho}{\rho}\right) \quad (3)$$

For flow through a coil, the critical Reynolds number is higher than that of a strait tube and is given by Ito [6] correlation

$$\mathrm{Re}_{crit} = 20000\left(\frac{d}{D}\right)^{0.32} \quad (4)$$

The flow is turbulent for the given input conditions. Ito [6] friction factor correlations for turbulent flow (i.e., $Re > Re_{crit}$) is given by

$$f_c\sqrt{\frac{D}{d}} = 0.029 + 0.324\left[\mathrm{Re}\left(\frac{d}{D}\right)^2\right]^{-0.25} \quad (5)$$

The single phase liquid length is evaluated by integrating equation (3), and considering entrance effects,

$$L_{sp} = \frac{d}{f_{sp}}\left[\frac{2}{\rho V^2}(P_1 - P_3) - k\right] \quad (6)$$

where the entrance loss coefficient $k=1.5$.

The two-phase region of the tubes, i.e., 3 – 4, is divided into 'n' number of small section with a uniform pressure differential 'dP' across each section as shown in Fig.2. Applying continuity equation between sections 3 and 4

$$\dot{m} = \frac{V_3 A}{v_3} = \frac{V_4 A}{v_4} \quad (7)$$

Applying steady flow energy equation, with no external work, heat transfer and potential energy, between sections 3 and 4 one can get

$$h_3 + \frac{V_3^2}{2} = h_f + x h_{fg} + \frac{G^2}{2}(v_f + x v_{fg})^2 \quad (8)$$

Equation (8) is quadratic in x, hence, the quality x can be expressed as

$$x = \frac{-h_{fg} - G^2 v_f v_{fg} + \sqrt{\left(G^2 v_f v_{fg} + h_{fg}\right)^2 - 2G^2 v_{fg}^2\left(\frac{G^2 v_f^2}{2} - h_3 - \frac{V_3^2}{2} + h_f\right)}}{G^2 v_{fg}^2} \quad (9)$$

The two phase friction factor for straight capillary tube f_{tp} can be calculated from any of the correlations provided with Re is replaced by Re_{tp}

$$\mathrm{Re}_{tp} = \frac{Vd}{\mu_{tp} v_{tp}} \quad (10)$$

where μ_{tp} is the two-phase dynamic viscosity, given by two-phase viscosity correlation by Mc Adams [9]

$$\frac{1}{\mu_{tp}} = \frac{x}{\mu_g} + \frac{1-x}{\mu_f} \quad (11)$$

Specific volume for homogenous two-phase mixture

$$v_{tp} = v_f + x v_{fg} \quad (12)$$

and the mixture velocity

$$V = G v_{tp} \quad (13)$$

The pressure at any section 'i' is given by

$$P_i = P_3 - i\,dP \quad (14)$$

where P_3 is the saturation pressure corresponding to the refrigerant temperature at capillary tube inlet, i.e., T_2. With the pressure P_i corresponding quality, x_i, can be calculated from equation (9), the entropy at the *i-th* section can be determined from

$$s_i = s_f + x_i s_{fg} \quad (15)$$

The incremental length (dL) is calculated sequentially. For each section pressure, temperature, quality, friction factor and entropy are calculated. It is found that the entropy keeps on increasing until a maximum and then decreases. The moment it starts decreasing, the flow becomes supersonic and the second law of thermodynamic is violated with decreasing entropy and the calculation is stopped at the point of maximum entropy.

Integrating equation (3),

$$L_{tp} = 2d\left(\frac{-1}{G^2}\int_{P_3}^{P_{s\max}} \frac{\rho}{f_{tp}}\,dP + \int_{P_3}^{P_{s\max}} \frac{d\rho}{\rho f_{tp}}\right) \quad (16)$$

The incremental length of each section is calculated using

$$\Delta L_i = \frac{2d}{f_{tp,i}}\left(\frac{-\rho_i \Delta P}{G^2} + \frac{\Delta\rho}{\rho_i}\right) \quad (17)$$

The total length of two-phase region is

$$L_{tp} = \sum_{i=1}^{n} \Delta L_i \quad (18)$$

Equation (17) is used to determine the elemental length of adiabatic capillary tube in two-phase region. The total two-phase length of the helical adiabatic capillary is the summation of these elemental lengths as given by equation (18). The total length of capillary tubes is the sum of single and two-phase lengths.

$$L = L_{sp} + L_{tp} \quad (19)$$

RESULTS AND DISCUSSION

The simulation results are validated with experimental findings of the previous researchers for straight capillary tube as the literature lacks experimental work on helical capillary tube. Hence, a separate mathematical model for adiabatic straight capillary tube has been developed, which employs Churchill's friction factor correlation [10] in place of equation

(5) of the helical capillary tube model. Churchill's friction factor correlation is given by the following equation:

$$f_s = 8\left[\left(\frac{8}{\mathrm{Re}}\right)^{12} + \left(\frac{1}{(A+B)^{1.5}}\right)\right]^{\frac{1}{12}} \tag{20}$$

where,

$$A = 2.457\ln\left(\frac{1}{(7/\mathrm{Re})^{0.9} + 0.27(e/d)}\right)^{16} \tag{21}$$

and

$$B = \left(\frac{37530}{\mathrm{Re}}\right)^{16} \tag{22}$$

The present model is validated with the experimental data of Wijaya et al. [11], shown in Figure 3. The results of the present model for straight adiabatic capillary tube are in good agreement with the experimental data. In Figure 3, it can be seen that for same mass flow rate the length of helical capillary tube is shorter than that of straight capillary tube.

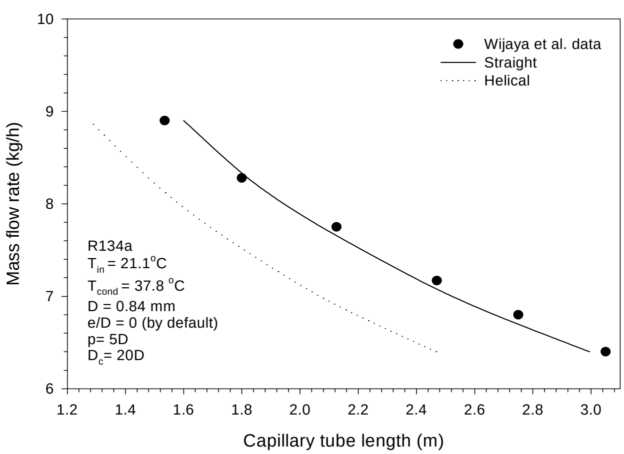

Figure 3 Comparison of the present model with Wijaya et al. [11] experimental data.

Figure 4 shows the effect of pitch on the length of helical capillary tube. It is observed that the length of capillary tube increases with the pitch. This is because the coil friction factor reduces with increasing the pitch of helix.

A parametric study of the adiabatic capillary tubes, both helical and straight, are conducted using refrigerant R-134a as the working fluid flowing in a capillary of 0.77 mm diameter. The upstream pressure is 9 bar, degree of subcooling is 2 °C, mass flow rate is 3 kg/h, and the relative roughness (e) is 0.75μm. The pitch and coil diameter of the helical capillary are 5d and 20d respectively. Figures 5 to 10 represent the variation of physical parameters with adiabatic capillary tube lengths.

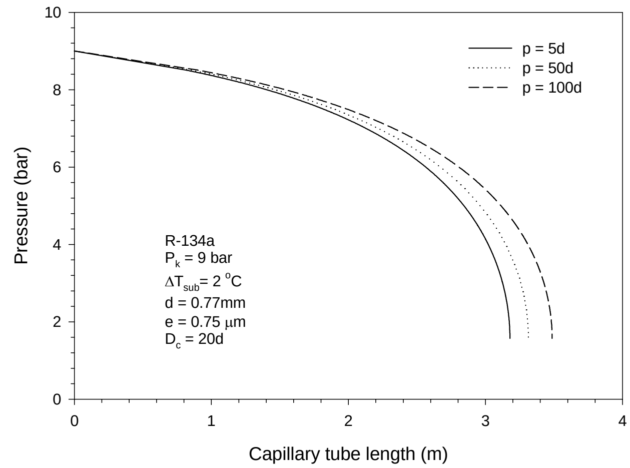

Figure 4 Effect of varying pitch of helical capillary tube on the length of capillary tube.

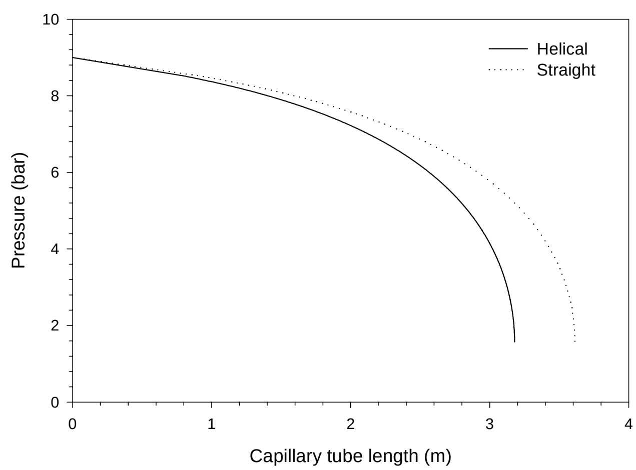

Figure 5 Pressure variation along the length of capillary tube

Figure 5 shows the variation of pressure of refrigerant along the length of capillary tube. In single-phase subcooled region, the pressure drops linearly due to frictional effects only. As soon as the flashing starts, pressure drops rapidly. In the two phase region, in addition to frictional pressure drop, there exists the acceleration pressure drop as well. It is found that the slope of two-phase region for helical capillary tube is higher than that of the straight capillary tube. For helical capillary tube the pressure drop is higher than that for a straight capillary tube because of the additional pressure drop due to secondary flows in radial direction.

Figure 6 shows the variation of temperature of refrigerant along the capillary tube. As the flow inside the capillary tube is considered to be adiabatic, the temperature of the refrigerant remains constant as long as it is in liquid state. In the two-phase region the saturation temperature is a function of saturation pressure, the temperature falls according to the pressure inside the tube. As the pressure drops at a faster rate in a helical capillary tube than that of a straight tube, the corresponding pressure also drops at a faster rate.

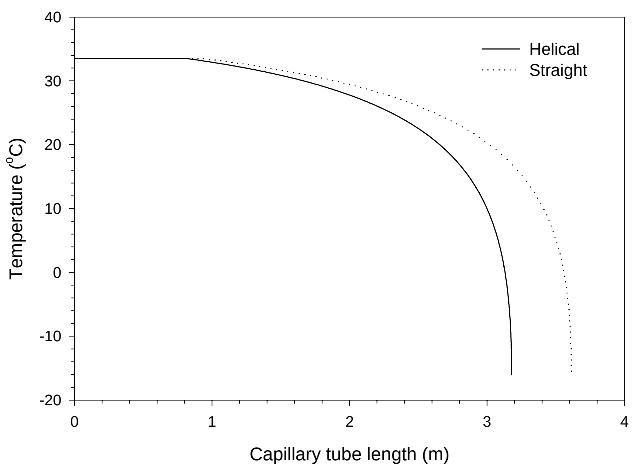

Figure 6 Temperature variation along the length of capillary tube

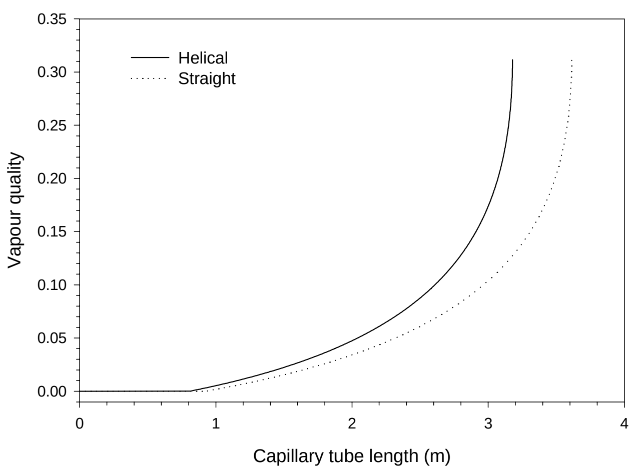

Figure 7 Vapor quality variation along the length of capillary tube

Figure 7 and Figure 8 show the variation of vapour quality and void fraction, respectively, along the length of capillary tube. It is evident from the figure that for same length of tube, the helical capillary tube will have higher vapour quality and void fraction than a straight capillary tube.

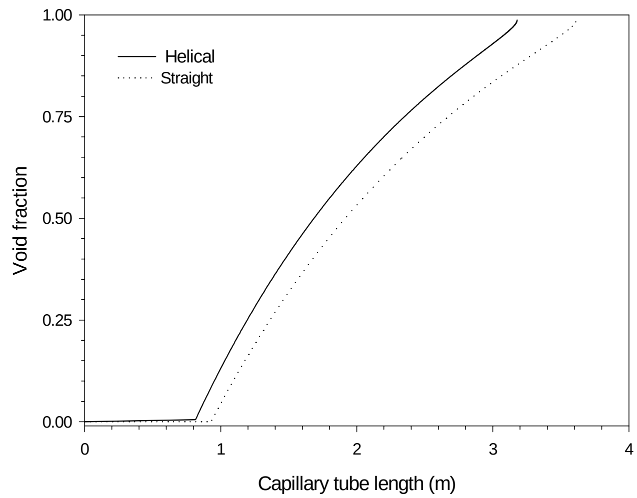

Figure 8 Void fraction variation along the length of capillary tube

Figure 9 shows the velocity variation with the length from the inlet of capillary. In subcooled region the velocity is constant. With the generation of vapour, the density of the fluid reduces resulting in acceleration of the fluid, because the mass flow is constant.

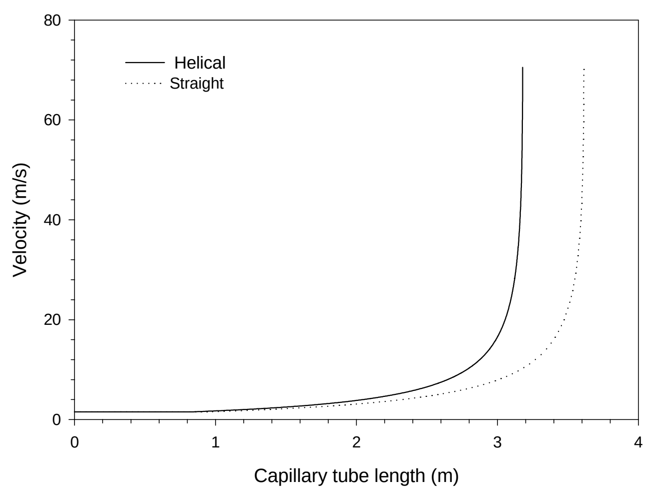

Figure 9 Velocity variation along the length of capillary tube.

In Figure10, it can be seen that there is a linear increase in entropy of the flowing refrigerant in the single-phase region of the capillary tube. In two-phase region of the capillary tube, the entropy increases rapidly with the generation of vapour. After a certain distance, the incremental length for same pressure drop becomes negligibly small and the corresponding entropy shoots up. For the above mentioned inputs, it is found that the helical capillary tube is 12 % shorter than the straight capillary tube.

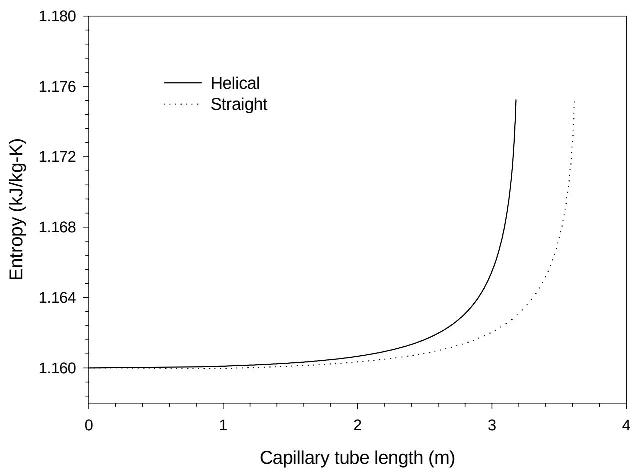

Figure10 Entropy variation along the length of capillary tube.

CONCLUSIONS

In the present work, Ito's friction factor correlation for coiled tubes has been used to evaluate the helical capillary tube length and Churchill's friction factor correlation for straight capillary tube. The present model is used to evaluate the length of both helical and straight adiabatic capillary tubes. The two geometries when subjected to the similar conditions, it is found that the length of helical capillary tube is 12% shorter than that of the straight capillary tube. Moreover, it is found that the length the capillary tube increases with the pitch of the helix.

REFERENCES

[1] Marcy, G.P., Pressure drop with change of phase in a capillary tube, *Refrigerating Engineering*, vol. 57, 1949, pp. 53 – 57

[2] Mikol, E.P., Adiabatic single and two-phase flow in small bore tubes, *ASHRAE Journal,*1963, pp. 75-86

[3] Koizumi, H. and Yokoyama, K., Characteristics of refrigerant flow in a capillary tube", *ASHRAE Trans*., vol. 86, 1980, pp. 19 – 27

[4] Melo C., Ferreira, R.T.S., Neto, C.B., Goncalves, J.M., Mezavila, M.M., An experimental analysis of adiabatic capillary tube, *Applied Thermal Engineering*, vol.19,1999, pp.669 – 684

[5] Dean, W. R., Note on the motion of fluid in a curved pipe, *Phil. Mag,*, Vol.4, 1927, pp. 208 – 223

[6] Ito, H., Friction factors for turbulent flow in curved pipes, *Journal of Basic Engineering*, D81, 1959, pp. 123-134

[7] Ali, S., 2001,Pressure drop correlations for flow through regular helical coil tubes, *Fluid Dynamics Research*, vol. 28: p. 295-310

[8] McLinden, M.O., Klein, S.A., Lemmon E.W., REFPROP-thermodynamic and transport properties of refrigerants and refrigerant mixtures, NIST Standard Reference Database – version 7, 2002.

[9] McAdams, W.H., Wood, W.K., Bryan, R.L., Vaporization inside horizontal tubes. II. Benzene-oil mixture, *Trans. ASME*, Vol. 64, 1942, pp. 193

[10] Churchill, S.W., Frictional equation spans all fluid flow regimes, *Chemical Engineering*, Vol. 84, 1977, pp. 91-92

[11] Wijaya, H. Adiabatic capillary tube test data for HFC-134a. *Proceedings of the IIR- Purdue Conference*, West Lafayette, USA, vol.1, pp.63-71, 1992.