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ASSESSMENT OF DIFFERENT METHODS FOR PREDICTING THE MASS FLOW RATE THROUGH ADIABATIC CAPILLARY TUBES

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Abstract. *Capillary tubes are largely used as the expansion device in small scale refrigeration systems and many researches have been made to study the refrigerant flow characteristics inside them. In this paper, different strategies commonly used to analyze the mass flow rate for the refrigerants CO2 (R744), R600a and R134a through adiabatic capillary tubes are reviewed, including numerical models, approximate analytical (algebraic) equations and dimensionless correlations. The predicted mass flow rates by the equations and correlations have been checked with experimental data available in the literature. Apart from the numerical models, the algebraic equations, overall, performed better. Particularly, a correlation derived from the artificial neural network (ANN) showed better agreement for CO2, while an algebraic equation has found to be better for R600a and R134a. To verify if a better performance could be achieved, two dimensionless correlations were proposed for straight capillary tubes, being one for CO2 and other for R600a. The predicted mass flow rates by the proposed correlations showed better agreement with the experimental data when compared with all the equations and correlations previously assessed. The percentual of data points within an error band of ± 15% were 95.8% and 100%, for CO2 and R600a, respectively.*

Keywords: *capillary tube, adiabatic, mass flow rate, CO2, R600a.*

1. INTRODUCTION

The capillary tube is a type of expansion device commonly used in small scale refrigeration or heat pump systems and consists in a segment of tube with constant cross-section area. It connects the outlet of the condenser to the inlet of the evaporator and regulates the refrigerant mass flow rate between them, while promoting a pressure drop. Generally, its length varies from 1 to 6 m and the inner diameter from 0.5 to 2.0 mm (Rasti and Jeong, 2018). Some advantages of using it includes the low cost, zero maintenance and lower compressor starting torque, due to the pressure equalization between the condenser and the evaporator during the off-cycle (Melo et al., 1999). On the other hand, a major drawback is the low capacity to adapt to different load conditions. Regarding the geometry, the capillary tube can be straight or coiled and, depending if a heat transfer is desired or not, it can be categorized as adiabatic or diabatic. Despite being a simple component, the flow inside the capillary tube is quite complex, due to the simultaneous pressure drop and refrigerant phase-change. Hence, an analytic and explicit description of the total throttling process is not possible (Schenk and Oellrich, 2014).

Different thermodynamic states for the refrigerant fluid can occur at the inlet of the capillary tube, namely: supercritical, transcritical, subcooled liquid, saturated liquid and two-phase fluid. Figure 1 shows a representation of the refrigerant flow through a capillary tube in a broadest case of inlet condition (e.g. transcritical CO2 system). Initially (point 1), the fluid flows in a supercritical state up to the point 2, where, right after the temperature is below the critical temperature, but the pressure is still above the critical pressure, reaching the transcritical state. At point 3, starts the subcooled liquid region, remaining up to point 4, when the saturation pressure is reached. At this point, the liquid refrigerant should start flashing to vapor. However, the vaporization is delayed and the refrigerant remains as superheated liquid up to somewhere down (point 5). This non-equilibrium condition, when the refrigerant evaporates at pressure lower than saturation pressure is called metastability (Prajapati et al., 2014). At point 5, the vaporization takes place, but up to point 6 the flow is still at non-equilibrium state due to the existence of superheated liquid. Finally, from point 6 on, the flow reaches the two-phase thermodynamic equilibrium state up to the outlet of the capillary tube. Besides metastability, the "choked" flow can also occur. By decreasing the outlet pressure, the refrigerant mass flow rate increases up to a limit, remaining constant for further pressure reductions. In this case, will exist a sharp gradient pressure between the outlet of the capillary tube and the inlet of the evaporator (Zareh et al., 2014).

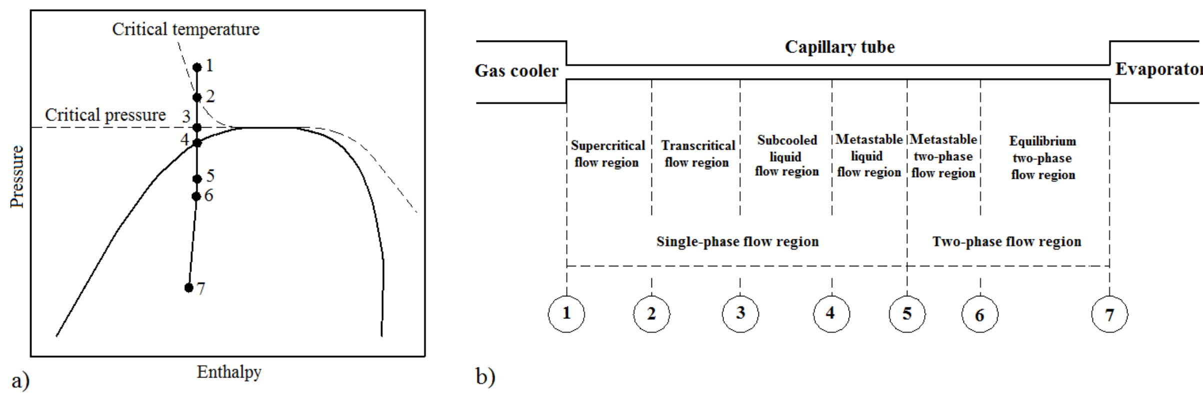

Figure 1. Schematic representation of the refrigerant flow through a capillary tube: a) p x h diagram; b) regions over the capillary length.

Once the capillary tube is installed, it is not possible to modify or to regulate it and, therefore, the proper sizing before installation is essential to the system performance. In this sense, many researches, comprising experimental and numerical studies, have been made to study the refrigerant flow characteristics inside the capillary tubes. Different strategies are used to depict the throttling process, spanning from numerical models to algebraic equations and dimensionless correlations.

Over the last years, some studies have been published to reviewed the flow of refrigerants through capillary tubes, but they presented some limitations. Khan et al. (2009) and Dubba and Kumar (2017) only included dimensionless correlations for mass flow rate predictions. Shao et al. (2013) and Rasti and Jeong (2017) did not evaluate the correlations with experimental data from the literature. In order to address this drawback, the first objective of the present paper is to review the existing models, equations and correlations to predict the mass flow rate through adiabatic capillary tubes with CO2, R600a and R134a. The predictions from the algebraic equations and dimensionless correlations are, then, verified with available experimental data collected in the literature. The second objective is to verify if better agreement between predicted and measured mass flow rates can be achieved, by proposing two dimensionless correlations for adiabatic straight capillary tubes, one for CO2 and other for R600a. A single correlation for both fluids could be proposed. However, a loss in accuracy occurs to achieve a better generality.

2. REVIEW OF NUMERICAL MODELS

The numerical models are one of the most popular methods used by researchers for analyzing and designing capillary tubes, due to its general mechanism and acceptable precision (Yang and Wang, 2008). Finite differences or finite volumes methods are the commonly approaches employed to solve the set of mass, energy and momentum conservation equations. These models can be less or more complex, depending if the two-phase are considered as homogeneous (no slip between phases) or separated (different velocities between phases) and if the metastability is regarded or not. The case considering homogeneous flow and neglecting the metastable phenomenon is generally called homogeneous equilibrium model (HEM). Despite of the mentioned advantages, the numerical solution is time-consuming and require some programming skills (Cecchinato et al., 2009).

Da Silva et al. (2009) experimentally and numerically studied a straight adiabatic capillary tube in a transcritical CO2 refrigeration cycle. The refrigerant mass flow rate predicted by the HEM was verified with their experimental data, being found an agreement of 95% within a ±10% error band.

Nunes et al. (2015) numerically analyzed a straight adiabatic capillary tube in a transcritical CO2 refrigeration cycle. They proposed a separated flow model neglecting the metastable phenomenon. To validate the model, comparisons were made with experimental data from the open literature. The predicted results for the mass flow rate fell within a ±10% error band, considering all the 66 experimental points.

Wang et al. (2012) numerically studied the flow of CO2 through adiabatic straight and coiled capillary tubes in a transcritical system. They developed a separated flow model considering the metastable phenomenon, but also investigated the HEM. The model was validated with experimental data from the literature for straight capillary tubes, predicting 97% of the mass flow rate within a ± 15% error band. For the simulation conditions, the authors reported a 7% increase in the refrigerant mass flow rate when the coil diameter changed from 40 mm to 600 mm. Besides, they found that the length proportion of the metastable flow region to the total capillary length is small, unless the capillary inlet pressure is low enough. Therefore, nearly there is no difference in the capillary length when the model neglects the metastable flow.

Zareh et al. (2014) numerically studied the refrigerant flow through straight and coiled capillary tubes. They proposed a drift flux model neglecting the metastability phenomenon. To validate the model, numerical simulations and experimental data from the literature, as well as own experimental points were used for comparison. A 5.5% maximum deviation was reported between the model and the experimental points, including own and literature data. Under the same conditions and capillary tube length, the mass flow rate through a 40 mm diameter coiled capillary tube is 11% less than a straight one. For the same mass flow rate, the helical length is reduced about 14% compared to the straight length.

As can be seen, these models exhibited good agreement with the experimental data. However, once they need to be implemented in an algorithm and are not direct available for application, they will not be further discussed and used for comparison along this paper.

3. REVIEW OF ALGEBRAIC EQUATIONS

Once the numerical models are complex and a total algebraic and explicit description for the flow through the capillary tube is not possible, approximate analytical solutions were developed. They are able to balance the generality of numerical models with the simplicity of empirical correlations (Cecchinato et al., 2009). This approach was first introduced by Yilmaz and Ünal (1996) and their solution for the capillary tube length can be seen in Eq. (1) and (2).

$$L=\frac{2D}{f}\left[ln\left(\frac{p/p_r}{k_1+(1-k_1)p/p_r}\right)-\frac{1}{\frac{v_rG^2}{p_r}(1-k_1)}\left\{\frac{p}{p_r}-1-\frac{k_1}{1-k_1}ln[k_1+(1-k_1)p/p_r]\right\}\right] \tag{1}$$

$$k_1=2.62*10^5\left(p_r^{-0.75}\right) \tag{2}$$

where L is the capillary tube length, D is the capillary inner diameter, f is the friction factor, p is pressure, v is the specific volume, G is the mass flux and the subscript r stands for the reference point – calculated at the flash point.

Hermes et al. (2010) developed a semi-empirical algebraic equation, derived from the approximate analytical solution and considering some simplifications introduced by Yilmaz and Ünal. Their solution includes one parameter (Φ) that can be calculated based on the friction factor or can be experimentally adjusted. The proposed model is seen in Eq. (3) and Eq. (4).

$$\dot{m}=\Phi\sqrt{\frac{D^5}{L}\left[\frac{p_{in}-p_r}{v_r}+\frac{p_r-p_{out}}{v_r(1-k)}+\frac{v_rP_rk}{\left(v_r(1-k)\right)^2}ln\left(\frac{v_r(1-k)p_{out}+v_rP_rk}{v_r(1-k)p_r+v_rP_rk}\right)\right]} \tag{3}$$

$$k=1.63*10^5\left(p_r^{-0.72}\right) \tag{4}$$

where $\dot{m}$ is the mass flow rate and the subscripts in and out stands for the inlet and outlet of the capillary tube, respectively.

4. REVIEW OF DIMENSIONLESS CORRELATIONS

The dimensionless correlations can be derived from a combination of a physical and experimental background (semi-empirical) or from a totally experimental (empirical) method and in its majority are developed using the dimensional analyses described by the Buckingham-Pi-Theorem. To form the correlations, the dimensionless groups are combined and can be fitted to the experimental data by two principal means: multiple regression (power-law) or artificial neural networks (ANN). The dimensionless parameter groups used in Eq. (5) to Eq. (12) are presented in Tab. 1, where ρ is density, μ is the dynamic viscosity, ε is the capillary tube roughness, σ is the surface tension, x is the quality, T is temperature, ΔT is the subcooling, h is enthalpy, c_p is the specific heat at constant pressure and the subscripts are: f for saturated liquid, g for saturated vapor, c for condensing and $crit$ for critical. The other parameters are the same as first mentioned. The recommended ranges for utilization or the experimental parameters ranges used to derive the correlations can be seen in the respective original papers.

Table 1. Dimensionless Pi groups used in the correlations.

Authors	Melo et al. (1999)	Yang and Wang (2008)	Yang and Zhang (2009)	Vins and Vacek (2009)	Yang and Zhang (2014)	Rasti and Jeong (2018)	Proposed correlations
Equations	(5)	(6)	(9)	(10)	(11)	(12)	(16) (17)
π_1	$\frac{\dot{m}}{D\mu_f}$	$\frac{1.273\dot{m}}{D^2\sqrt{P_{in}\rho_{in}}}$	$\frac{1.273\dot{m}}{D^2\sqrt{P_{in}\rho_{in}}}$	$\frac{P_{in}-P_r}{P_{crit}}$	$\frac{1.273\dot{m}}{D^2\sqrt{P_{in}\rho_{in}}}$	$\frac{L}{D}$	$\frac{1.273\dot{m}}{D^2\sqrt{P_{in}\rho_{in}}}$
π_2	$\frac{D^2\rho_f P_f}{\mu_f^2}$	$\frac{P_{in}}{P_r}$	$\frac{P_r}{P_{in}}$	$\frac{T_{in}-T_c}{T_{crit}}$	$\frac{P_r}{P_{in}}$	$\frac{D^2 h_{fg}}{v_f^2\mu_f^2}$	$\frac{P_r}{P_{in}}$
π_3	$\frac{L}{D}$	$\frac{\rho_f}{\rho_g}$	$\frac{\rho_g}{\rho_f}$	$\frac{L}{D}$	$\frac{\rho_g}{\rho_f}$	$\frac{D\sigma}{v_f\mu_f^2}$	$\frac{\rho_g}{\rho_f}$
π_4	$\frac{D^2\rho_f^2 c_p\Delta T}{\mu_f^2}$	$\frac{D}{L}$	$\frac{L}{D}$	$\frac{\rho_f}{\rho_g}$	$\frac{L}{D}$	$\frac{D^2 P_{in}}{v_f\mu_f^2}$	$\frac{L}{D}$
π_5	-	$\frac{D\sqrt{P_{in}\rho_{in}}}{\mu_{in}}$	$\frac{D\sqrt{P_{in}\rho_{in}}}{\mu_{in}}$	$\frac{\mu_f-\mu_g}{\mu_g}$	$\frac{D\sqrt{P_{in}\rho_{in}}}{\mu_{in}}$	$1+\frac{(h_{in}-h_f)}{h_{fg}}$	$\frac{D\sqrt{P_{in}\rho_{in}}}{\mu_{in}}$
π_6	-	$1-x_{in}$	-	$\frac{\sigma}{P_{in}D}$	-	$\frac{v_g}{v_f}$	-
π_7	-	$1+\frac{\Delta T}{T_c}$	-	$\frac{\rho_f(h_g-h_f)}{P_r}$	-	-	-
π_8	-	-	-	$\frac{\dot{m}}{D^2\sqrt{P_{in}\rho_f}}$	-	$\frac{\dot{m}}{D\mu_f}$	-

Melo et al. (1999) proposed the following correlation, Eq. (5), based on their own experimental data for the refrigerants R12, R134a and R600a.

$$\pi_1=0.195\pi_2^{0.448}\pi_3^{-0.528}\pi_4^{0.164} \tag{5}$$

Yang and Wang (2008) proposed the correlation, seen in Eq. (6), based on experimental data for R12, R22, R134a, R290, R600a, R410A, R407C, R404A.

$$\pi_1=4.2579x10^3\pi_2^{0.7338}\pi_3^{-0.2220}\pi_4^{0.4671}\pi_5^{0.1226}\pi_6^{1.5956}\pi_7^{0.7061} \tag{6}$$

Da Silva et al. (2009) developed an empirical correlation for transcritical/supercritical CO2, seen in Eq. (7). The dimensionless form in given by Eq. (8).

$$\tilde{m}=11.47+0.14\tilde{p}_e-0.09\tilde{T}_e-0.10\tilde{L}+\tilde{D}\left[0.35+0.01\left(0.25\tilde{D}+0.22\tilde{p}_e-0.10\tilde{T}_e-0.15\tilde{L}\right)\right] \tag{7}$$

$$\tilde{y}=100\left(\frac{y-y_{min}}{y_{max}-y_{max}}\right) \tag{8}$$

where m is the mass flow rate, p_e is the capillary tube inlet pressure, T_e is the capillary tube inlet temperature, "~" stands for the dimensionless form of the parameter y and y_{max} and y_{min} are the maximum and minimum values, respectively, of the corresponding parameters, seen in the original paper.

Yang and Zhang (2009) developed a correlation based on the ANN, with experimental data for the refrigerants R12, R22, R134a, R404A, R407C, R410A, R600a and CO2. The general structure of the correlation is presented in Eq. (9), while the weights ($w_{1,j}$ and $u_{j,i}$) and biases ($b_{1,j}$ and $b_{2,1}$) are seen in the original paper.

$$\pi_1=\sum_{j=1}^{3}\frac{w_{1,j}}{1+exp\left[-\left(\sum_{i=1}^{4}u_{j,i}\ \pi_{i+1}+b_{1,j}\right)\right]}+b_{2,1} \tag{9}$$

Vins and Vacek (2009) derived an ANN correlation for the refrigerant R218, but also compared the predicted results with experimental data for R12, R22, R134a, R290 and R600a. The general structure of their correlation is seen in Eq. (10), while n_1, n_2 and other definitions can be seen in the original paper.

$$\bar{\pi}_8=-\frac{3.8314}{1+e^{-n_1}}+\frac{0.7616}{1+e^{-n_2}}+2.3454 \tag{10}$$

Yang and Zhang (2014) proposed the correlation seen in Eq. (11), based on experimental data for R12, R22, R134a, R407C, R410A, R600a and CO2.

$$\pi_1=\frac{1-3.6622463\pi_2^{-1.4311445}}{-12.377615-4.4141877\pi_4\pi_5^{-0.2874146}\pi_3^{-0.0662179}} \tag{11}$$

Rasti and Jeong (2018) developed a correlation, seen in Eq. (12), based on experimental data for R22, R134a, and R600a.

$$\pi_8=150.26\pi_1^{-0.5708}\pi_2^{-1.4636}\pi_4^{1.953}\pi_5^{c5}\pi_6^{1.4181} \tag{12}$$

where $c5 = 0.6436$ for subcooled inlet condition and $c5 = -1.971$ for two-phase inlet condition.

5. ASSESSMENT OF THE EQUATIONS AND CORRELATIONS

In order to verify the performance of the equations and correlations summarized above, experimental data for CO2, R600a and R134a were collected in the open literature for adiabatic straight capillary tubes. The sources for each refrigerant and the number of data points can be seen in Tab. 2. All the thermophysical properties required to calculate the predicted mass flow rates were obtained with the software REFPROP 8.0.

Table 2. Experimental data used for evaluation.

Source	Refrigerant	Data Points
Da Silva et al. (2009)	CO2	66
Cecchinato et al. (2009)	CO2	148
Melo et al. (1999)	R600a	19
Schenk and Oellrich (2014)	R600a	22
Dubba and Kummar (2018)	R600a	12
Deodhar et al. (2015)	R134a	7
Melo et al. (1999)	R134a	19
Huerta et al. (2007)	R134a	30

The equations and correlations analyzed for R600a showed big deviations with the experimental data from Dubba and Kummar (2018). E.g. Hermes et al. (2010) presented a difference ranging from 173% to 354%, while Yang and Zhang (2014) gave deviations from 215% to 432%. The same trend was observed in all the cases, indicating some inconsistence with the experimental data from Dubba and Kummar (2018). For this reason, these data points were discarded in all the analyses along this paper.

Table 3 summarizes the statistical results for the predicted mass flow rates by all the authors. The average deviation (AD), the absolute average deviation (AAD) and the root mean square (RMS) were calculated by Eq. (13), (14) and (15), respectively. The percentual of predicted data points within error bands of ±10%, ±15% and ±20% are also showed in Tab. 4.

$$AD=100\%\left(\frac{1}{n}\sum_{n}\frac{\dot{m}_{predicted}-\dot{m}_{measured}}{\dot{m}_{measured}}\right) \tag{13}$$

$$AAD=100\%\left(\frac{1}{n}\sum_{n}\left|\frac{\dot{m}_{predicted}-\dot{m}_{measured}}{\dot{m}_{measured}}\right|\right) \quad (14)$$

$$RMS=100\%\sqrt{\frac{1}{n-1}\sum_{n}\left(\frac{\dot{m}_{predicted}-\dot{m}_{measured}}{\dot{m}_{measured}}-AD\right)^2} \quad (15)$$

Table 3. Statistical results for the predicted mass flow rates.

Authors	Deviation	CO2	R600a	R134a	Authors	Deviation	CO2	R600a	R134a
Yilmaz and Ünal (1996)	**AD**	-	-6.3	-9.2	Yang and Zhang (2009)	**AD**	**-0.1**	26.1	3.3
	AAD	-	8.0	10.9		**AAD**	**6.5**	26.1	11.1
	RMS	-	7.1	9.8		**RMS**	**9.2**	13.3	13.5
Hermes et al. (2010)	**AD**	-	**0.4**	0.6	Vins and Vacek (2009)	**AD**	-	-0.7	-17.2
	AAD	-	**4.0**	9.7		**AAD**	-	10.3	18.1
	RMS	-	**5.5**	11.3		**RMS**	-	13.2	11.3
Melo et al. (1999)	**AD**	-	-13.1	-20.9	Yang and Zhang (2014)	**AD**	7.0	3.2	-4.5
	AAD	-	13.2	21.2		**AAD**	13.7	5.4	11.0
	RMS	-	6.6	10.7		**RMS**	15.1	6.3	11.4
Yang and Wang (2008)	**AD**	-	-11.6	-13.0	Rasti and Jeong (2018)	**AD**	-	4,0	-11.8
	AAD	-	12.0	14.0		**AAD**	-	7.1	13.3
	RMS	-	7.8	11.0		**RMS**	-	8.6	10.3
Da Silva et al. (2009)	**AD**	-3.6	-	-	Proposed correlations	**AD**	**0.3**	**-0.2**	-
	AAD	9.7	-	-		**AAD**	**5.6**	**4.2**	-
	RMS	11.7	-	-		**RMS**	**7.7**	**5.2**	-

Table 4. Percentual of predicted data points within error bands of ±10%, ±15% and ±20%.

Authors	Error band	CO2	R600a	R134a	Authors	Error band	CO2	R600a	R134a
Yilmaz and Ünal (1996)	**±10%**	-	65.8	42.9	Yang and Zhang (2009)	**±10%**	**78.5**	2.4	67.9
	±15%	-	87.8	51.8		**±15%**	**89.2**	12.2	82.1
	±20%	-	100	92.9		**±20%**	**95.8**	43.9	87.5
Hermes et al. (2010)	**±10%**	-	**95.1**	71.4	Vins and Vacek (2009)	**±10%**	-	58.5	28.6
	±15%	-	**97.6**	85.7		**±15%**	-	78.0	41.1
	±20%	-	**100**	94.6		**±20%**	-	87.8	48.2
Melo et al. (1999)	**±10%**	-	31.7	21.4	Yang and Zhang (2014)	**±10%**	44.9	85.4	39.3
	±15%	-	58.6	25.0		**±15%**	59.8	95.1	78.6
	±20%	-	78.0	35.7		**±20%**	73.4	100	94.6
Yang and Wang (2008)	**±10%**	-	31.7	42,9	Rasti and Jeong (2018)	**±10%**	-	68.3	42.9
	±15%	-	51.2	46.4		**±15%**	-	80.5	46.4
	±20%	-	90.2	60.7		**±20%**	-	100	69.6
Da Silva et al. (2009)	**±10%**	56.5	-	-	Proposed correlations	**±10%**	**83.6**	**95.1**	-
	±15%	74.8	-	-		**±15%**	**95.8**	**100**	-
	±20%	88.8	-	-		**±20%**	**96.7**	**100**	-

For CO2, the predictions from Yang and Zhang (2009) presented the best agreement to the experimental data, with the lowest AAD and RMS and with the larger percentual of data points within the error bands. Da Silva et al. (2010) strictly recommend to not extrapolate the application range of their correlation. But even discarting such points, the results did not show a major improvement, with AD, AAD and RMS of -5.1, 8.9 and 10.3. Regarding R600a, Hermes et al. (2010) presented the best statistics and with 95.1 % and 100% of the data point being predicted within ±10% and ±20% error bands. The Φ parameter was adopted equal to 6. Yang and Zhang (2014) also showed a reasonable level of agreement with the experimental data, while Yang and Zhang (2009) demonstrated to be not suitable for this refrigerant. For R134a, Hermes et al. (2010) gave, again, the best results, considering the Φ parameter equal to 6.82. For this refrigerant, all the equations and correlations provided worse results compared to R600a and none of them was able to predict 100% of the points within ±20% error band. Melo et al. (1999) and Vins and Vacek (2009) presented poor results, being not recommended for this refrigerant. The deviations of the predictions regarding the measured mass flow rates for all data points can be seen from Fig. 2 to 4.

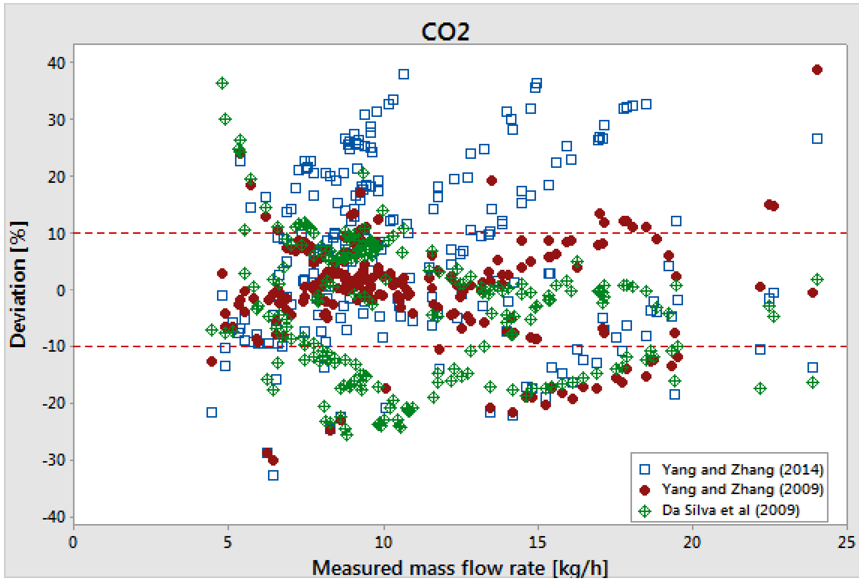

Figure 2. Deviations from predicted and measured mass flow rates for CO2.

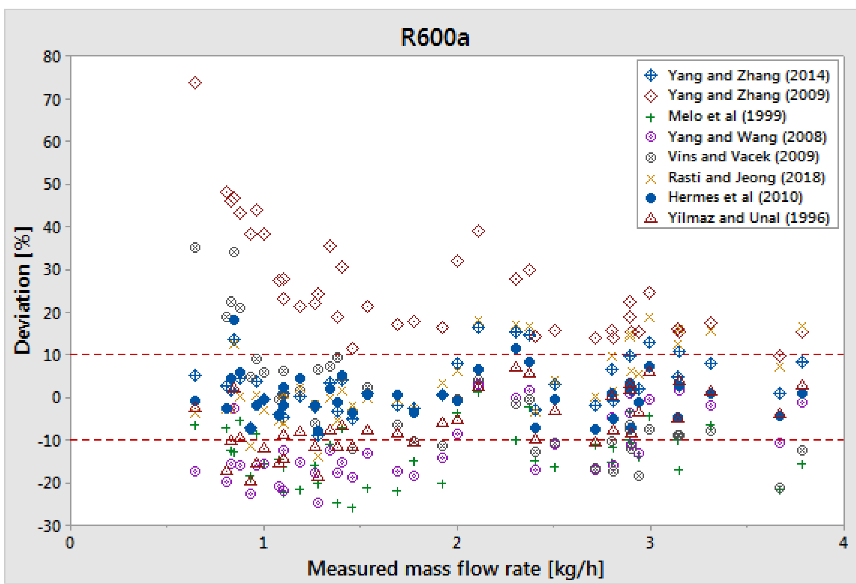

Figure 3. Deviations from predicted and measured mass flow rates for R600a.

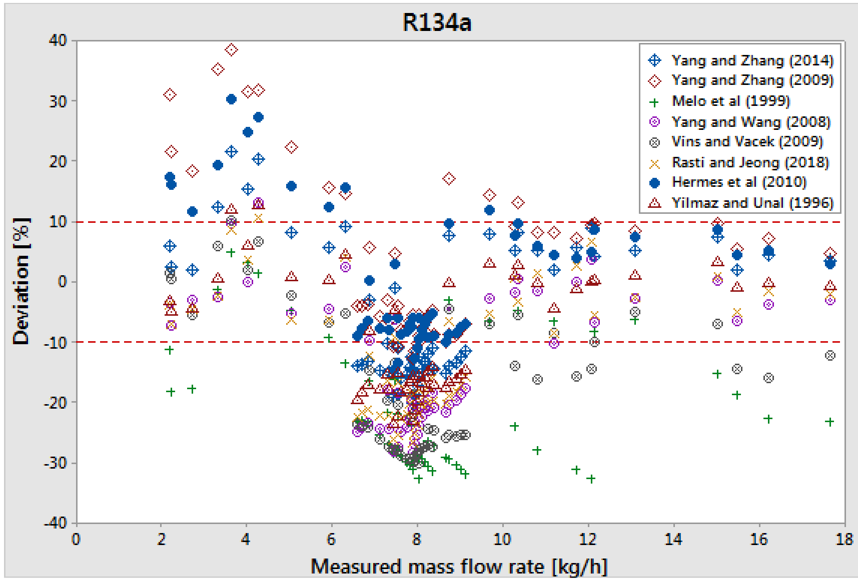

Figure 4. Deviations from predicted and measured mass flow rates for R134a.

For CO2, it can be seen that the maximum deviation for all three correlations were about 40% and the minimum were about -30%. For R600a, Yang and Zhang (2009) presented a maximum deviation close to 80%, while the minimum value for all points was about -25%. In both cases (CO2 and R600a), the random distribution of data points indicates a good consistency of the experimental data. For R134a, the maximum deviation, presented by Yang and Zhang (2014), was about 40%, while the minimum, presented by Melo et al. (1999), was about 35%. In Fig. 4, one can notice a concentration of data points ranging from about 6 kg/h to 9 kh/h and from about -5% to 30%. This interval matches the experimental points of Huerta et al. (2007), indicating a possible issue with their data. However, this fact is not evident and their experimental data were not discarded from the analyses.

6. PROPOSED CORRELATIONS

In order to give a step further, two dimensionless correlations were proposed, one for CO2 and another for R600a, to verify if better predictions for the mass flow rate can be achieved, despite of the good result presented by Yang and Zhang (2009) for CO2 and the great result showed by Hermes et al. (2010) for R600a. The dimensionless Pi-groups introduced by Yang and Zhang (2009, 2014) were selected in this study due to the good performance achieved with CO2 and R600a. These dimensionless parameters were listed in Table 1. The thermophysical properties with the subscript "in" should be calculated at the capillary tube inlet condition, i.e. inlet temperature and inlet pressure. The saturated liquid and vapor densities are calculated considering the inlet temperature. For supercritical condition, $\rho_g = \rho_f$ and $\pi_3 = 1$. The reference pressure (P_r), for subcooled and transcritical conditions, is calculated at the flash point, obtained by an isenthalpic expansion from inlet condition until the saturated liquid line. For supercritical conditions, P_r is calculated following the methodology adopted in Yang and Zhang (2009, 2014). The general structure of the proposed correlations can be seen in Eq. 15.

$$\pi_1 = A\pi_2^{\,b}\pi_3^{\,c}\pi_4^{\,d}\pi_5^{\,e} \tag{15}$$

The coefficients in Eq. 15 were fitted to the experimental data from Tab. 2 by a multiple regression, using the least-squares method and 95% of significance level. The final correlations for CO2 and R600a can be seen in Eq. 16 and 17, respectively.

$$\pi_1 = \pi_2^{-0.4152}\pi_3^{0.0961}\pi_4^{-0.5450}\pi_5^{0.1601} \tag{16}$$

$$\pi_1 = 5.9894\pi_2^{-0.8890}\pi_3^{0.0590}\pi_4^{-0.5421}\pi_5^{0.0020} \tag{17}$$

Tables 3 and 4 show the statistical results and the percentual of data points within the error bands, respectively. For CO2, the AD, AAD and the RMS were lower than that presented by Yang and Zhang (2009) and the percentual of data point in all error bands were higher. The comparison of the deviations for all data points can be seen in Fig. 5 a). Again, the proposed correlation showed better performance, with maximum positive and negative deviations of 29.5% and -

25.5%, respectively, versus 38.8% and -30.2% presented by Yang and Zhang (2009). Despite adopting the same dimensionless groups, the proposed correlation achieved a better performance. One of the reasons is the use of experimental data exclusive for CO2, loosing, on the other hand, the generality.

For R600a, the statistical results were close to that showed by Hermes et al. (2010), with 0.2% higher AAD and 0.3% lower RMS. However, the proposed correlation showed 100% of data points within ±15% error band, versus 97.1% presented by Hermes et al. (2010). The comparison of the deviations for all data points can be seen in Fig. 5 b).

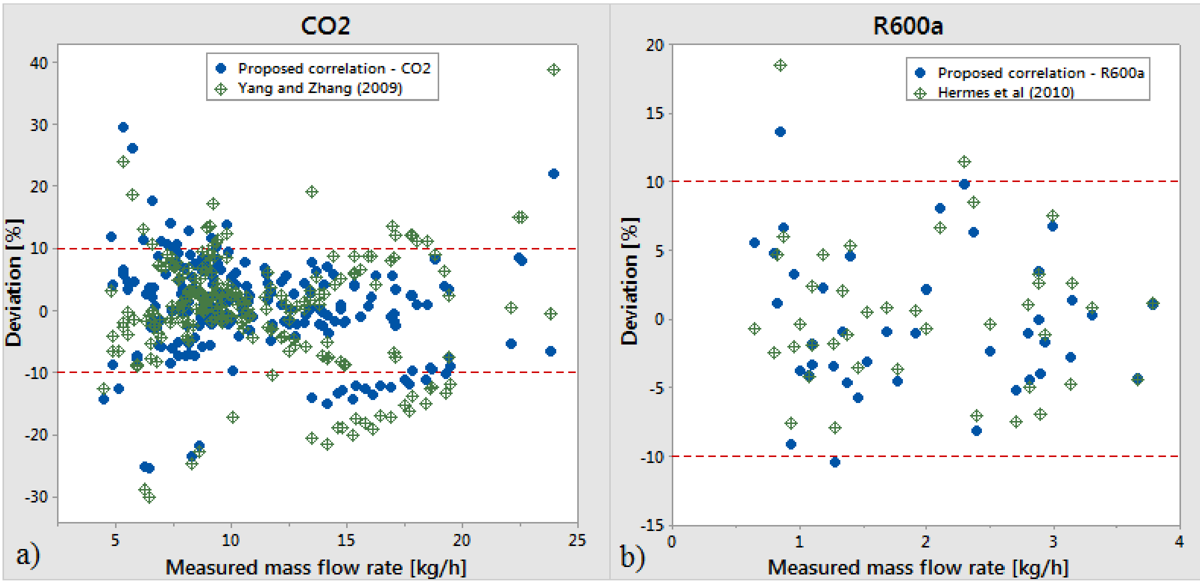

Figure 5. Deviations from predicted and measured mass flow rates for the proposed correlations: a) CO2 – Eq. 16; b) R600a – Eq. 17.

7. CONCLUSIONS

Different approaches commonly used to predict the mass flow rate through adiabatic capillary tubes are reviewed, including numerical models, algebraic equations and dimensionless correlations. The predictions from the equations and correlations summarized were compared with experimental data for CO2, R600a and R134a, collected from the open literature. The dimensionless correlation of Yang and Zhang (2009) gave the better agreement with experimental data for CO2, presenting AD, AAD and RMS of -0.1%, 6.5% and 8.2%, respectively. The percentual of data points within ±15% error band was 89.2%. For R600a and R134a the algebraic equation of Hermes et al. (2010) showed the better performance, highlighting the R600a predictions, with AD, AAD and RMS of 0.4%, 4.0% and 5.5%, respectively, and 95.1% of the data points being predicted within ±15% error band.

In order to give a step further, two dimensionless correlations were proposed to verify if a better performance could be achieved. The proposed correlation for CO2 showed AD, AAD and RMS of 0.3%, 5.6% and 7.7%, respectively, with 95.8% of the data points being predicted within ±15% error band. Regarding R600a, the proposed correlation presented AD, AAD and RMS of -0.2%, 4.2% and 5.2%, respectively, and 100% of the data points being predicted within ±15% error band. Then, it can be concluded that the proposed correlations presented better agreement with experimental data for CO2 and R600a, when compared with all the equations and correlations assessed.

8. ACKNOWLEDGEMENTS

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