EXPERIMENTAL MEASUREMENT OF ADIABATIC CAPILLARY TUBE PERFORMANCE ON A VAPOR COMPRESSION REFRIGERATION CYCLE

Gerson Koiti Kurosawa Shimizu, gerson.shimizu@gmail.com
Cristiano Bigonha Tibiriçá, bigonha@sc.usp.br

Heat Transfer Research Group, Mechanical Engineering Department, EESC-USP, Av. Trabalhador São-carlense, 400, Arnold Schimidt, São Carlos, SP, 13566-590, Brazil

Abstract. *A test facility composed of vapor-compression refrigeration cycle has been built for the investigation of the performance of adiabatic capillary tubes as expansion devices. This test facility has a compressor, a forced air circulation condenser and an evaporator installed inside a liquid tank for determination of the cooling effect. Experiments were conducted for R134a, capillary tube internal diameter of 0.78 mm and length of 3 m with different mass flow rates. For each experimental condition, the inlet and outlet thermodynamic state of the capillary tube were recorded together with the mass flow. The mass flow was evaluated based on an energy balance along the evaporator considering the cooling effect in the evaporator. Prediction methods from the literature were compared with the experimental data allowing identification of the performance of these methods for prediction of capillary tube operation.*

Keywords*: experimental data, capillary, correlations, two-phase flow boiling, cooling.*

1. NOMENCLATURE

$\dot{m}$	Mass flow rate [kg/s]
h	Enthalpy [J/kg]
Δh	Enthalpy variation [J/kg]
P	Pressure [kPa]
$\dot{Q}$	Refrigeration capacity [W]
λ20	Band error of ± 20%
MAE	Mean absolute error

Subscripts

meas	Measured
pred	Predicted

2. INTRODUCTION

The capillary tube is the most popular expansion device utilized in small sized refrigeration systems. Its use is due to the low cost, easy manufacture, durability and reliability, and it is commonly applied on domestic refrigerators and residences air conditioning and cars air conditioning. The main constructive characteristics of a capillary tube are a constant diameter, ranging from 0.33 mm to 2.00 mm, and a length, varying from 2 to 6 m (Yang and Wang, 2008). The capillary tube diameters determine the pressure drop that the tube will cause on system. Therefore, the smaller the diameter of the capillary tube, higher will be the pressure drop. Furthermore, the reason to the pressure drop, which occurs in a capillary tube, is that there is friction with the walls, changing of density, gravitational force and the capillary tube bending. In a steady flow condition, the refrigerant mass flow rate displaced by the compressor has to be the same mass flow rate that passes through the capillary tube. The dimension and geometry characteristics of the capillary tube must be determined through the compatibility with the compressor and the heat exchangers (condenser and evaporator). Thus, the wrong choice of capillary tube can result in a reduction of refrigeration system performance.

In spite of the widely application of the capillary tube, the methods to predict the mass flow rate on capillary are still in development. The reasons for this problem are that the flow is two-phase, compressible and chocked, which makes the analytical modeling a very difficult task to be performed (Tibiriçá and Ribatski, 2013). The refrigerant is introduced in capillary tube in a sub-cooled condition and can maintain the sub-cooled state until the pressure equalizes the saturation pressure, related to the temperature of the refrigerant. This point is known as "flash point" and marks the two-phase flow beginning, characterized by the presence of liquid and gas, simultaneously, on the flow. This fluid flow regime remains until the end of the capillary tube. However, in some cases, can occur the metaestability phenomenon that is caused when the pressure of refrigerant reaches the saturation pressure and no gas is formed, creating a supersaturated liquid. The existence of this metastable region increases refrigerant mass flow rate through the capillary tube due to a higher liquid density compared to the two-phase flow density (Choi et al, 2003).

Capillary tubes are usually operated in two configurations, adiabatic and a non-adiabatic, as shown in Figure 1. The adiabatic capillary tube is thermally insulated, therefore, the heat exchange with the external environment is assumed as negligible. In addition, the expansion process through an adiabatic capillary tube can be approximated by isenthalpic. On the other hand, the non-adiabatic configuration results in an enthalpy decrease during the expansion process. This enthalpy reduction results in a larger amount of liquid in the evaporator entry. This process is desirable due to the higher heat exchange coefficient on the liquid than the gas, presents on two-phase flow, resulting in an improvement of heat exchange on evaporator. Although non-adiabatic capillary tubes can increase the cooling effect of a refrigeration cycle, the adiabatic capillary tubes are still widely used due is simplicity of installation and maintenance.

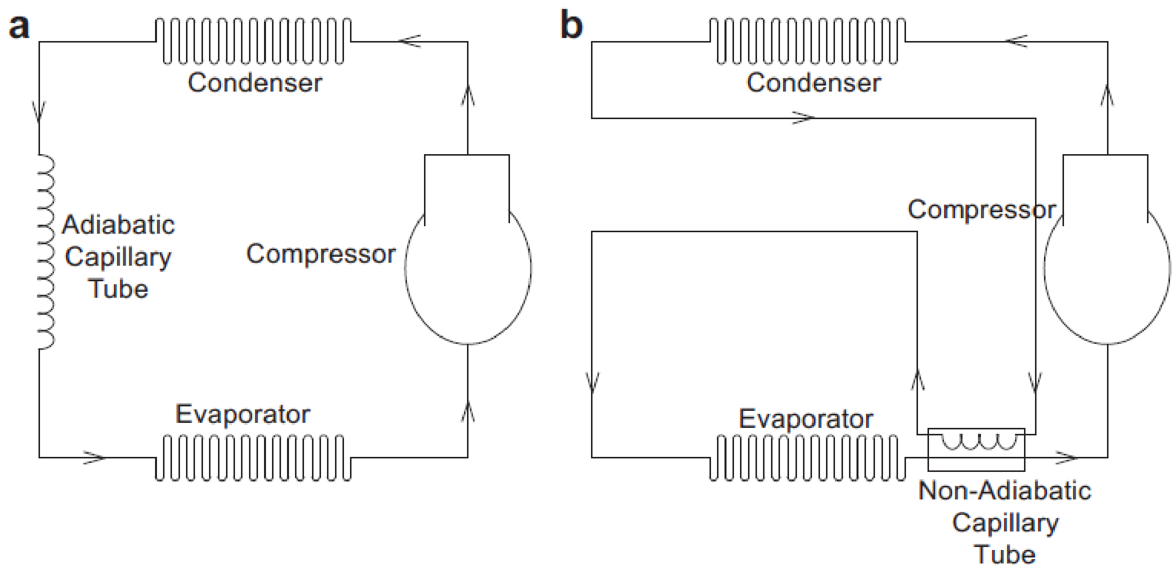

Figure 1. Schematic of a refrigeration system incorporating a capillary tube: (a) adiabatic capillary tube, (b) non-adiabatic capillary tube.

3. Experimental setup

The experimental setup shown in Figure 2 was used to measure the adiabatic capillary tube performance. A hermetic compressor was used to pumps the gas from the evaporator to the condenser and to increase the refrigerant pressure. After that, the refrigerant, with a high pressure due to the compression, passes through the condenser where its temperature is decreased until reaches a subcooled liquid state. The condensed refrigerant passes through the capillary tube and expands until the pressure drops to evaporation pressure.

After the refrigerant expansion, the gas has to reach a superheated state before to return to compressor. Thus, the refrigerant passes through de evaporator where the heat exchange between the refrigerant and a hot fluid occurs. The evaporator was made using a water-heated tank where the temperature was controlled. To achieve this, an electrical resistance and a variable transformer were used, respectively, for heating the water and controlling the water temperature. The water-heated tank was thermally insulted with the purpose to decrease the heat exchange with the environment. Lastly, before the fluid refrigerant returns to the compressor, it was included a liquid receiver to ensure only steam enter in compressor, preventing damage to the component.

Besides that, was added a throttle valves in the inlet and outlet of the capillary tube for facility installation and also prevent refrigerant losses during the capillary tube replacement. In this way, it was possible repurpose the refrigerant maintaining the valves closed during the capillary replacement, staying the refrigerant allocated on condenser and compressor.

The pressures and temperatures measurement of the refrigerant at the inlet and the outlet of capillary tube and at the evaporator outlet were mounted using a pressure transmitter and T-type thermocouples. In the tests was employed a capillary tube with 0.78 mm diameter and 3 m length and R134a as system refrigerant.

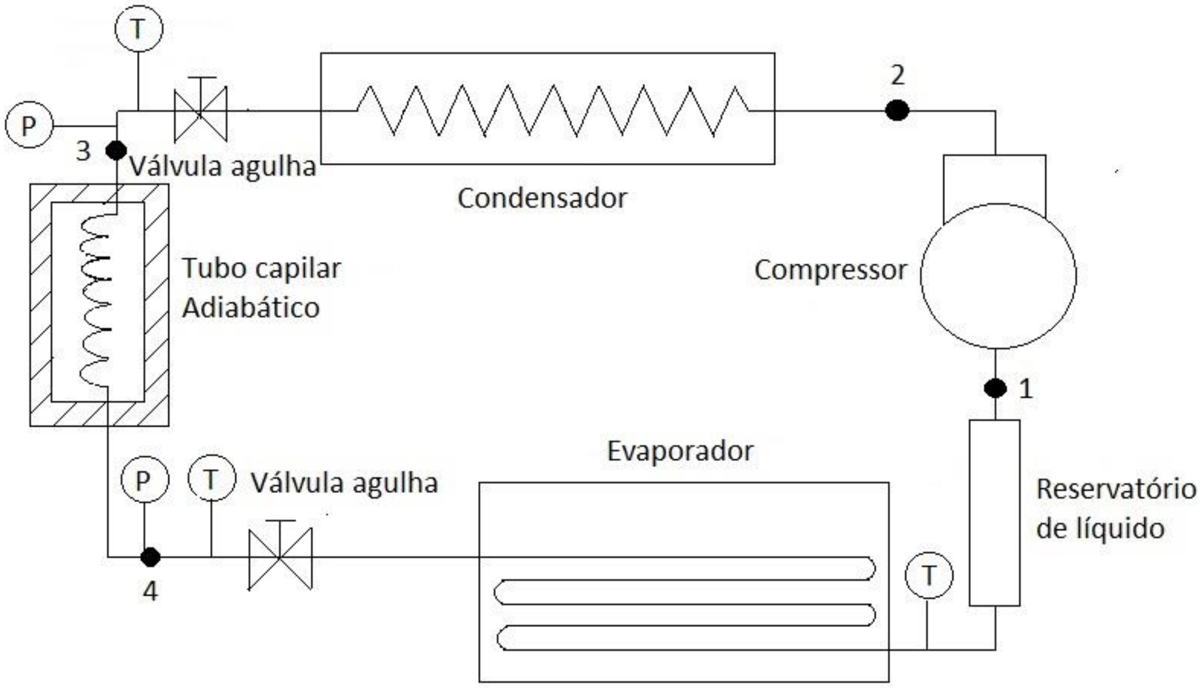

Figure 2. Schematic diagram of the experimental setup

4. Data reduction

The method to calculate the experimental mass flow rate on the vapor compression cycle was the energy balance on evaporator. It was noted that the energy transferred from the hot water to the refrigerant, called refrigeration capacity, should be offset by de electric power provided by the electrical resistance through the law of conservation of energy.

In the equation (1), the term Δh refers to the enthalpy difference between the outlet state and the inlet state on evaporator. The enthalpy is obtained through the pressure and temperature. According to the Figure 3, the point 1 refers to evaporator outlet condition and the point 1 refers to evaporator inlet condition.

The refrigeration capacity ($\dot{Q}$) is assumed to be the electrical power, provided by the electrical resistance, to maintain constant the water temperature in the evaporator water-heated heat exchanger. Although thermally isolated, the loss to environment, in evaporator, was measured being lower than 5 W and it was included on the calculation. The experimental database developed during the present work is provided on Table 1.

$$\dot{m} = \frac{\dot{Q}}{\Delta h} \tag{1}$$

Three correlations to predict the mass flow rate through an adiabatic tube capillary (Choi et al., 2003; Choi et al., 2004; Yang and Wang, 2008) share some common groups of non-dimensional numbers and similar structure and were investigated in this study. The correlation of Zhang (2005) used artificial neural network to determine the coefficients of the correlation. The Yang and Zhang correlation (2014) tried to improve the accuracy by the conventional power-law correlation and used a "local" power law correlation based on the momentum equation for the one-dimensional steady-state homogenous flow.

In correlations, the refrigerant flow rate in adiabatic capillary tube is mainly governed by the fluid properties, the refrigerant condition at entrance and exit, and the tube geometry parameters.

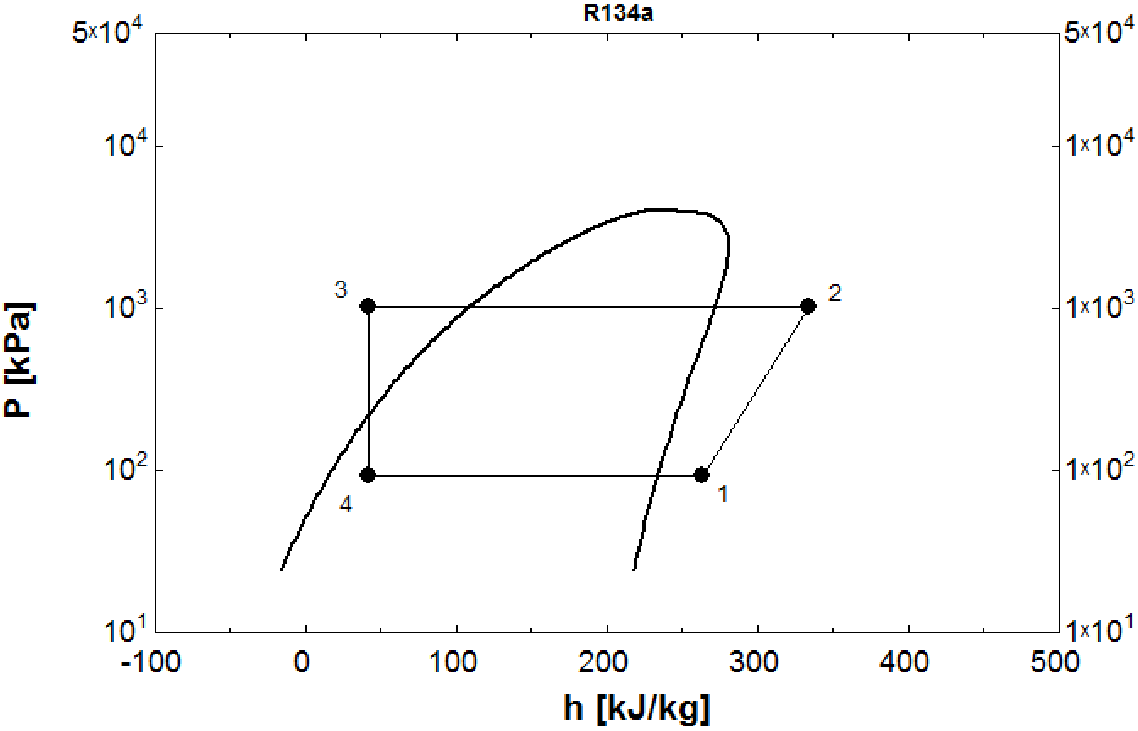

Figure 3. P-h diagram for R134a refrigerant.

The results predictions by the correlations were evaluated using the mean absolute error, the mean error and the total percentage of data inside 20% error band. The errors are defined in the following equations:

$$\text{Mean absolute error} = \frac{1}{n}\sum_{1}^{n} ABS\frac{(\dot{m}_{pred} - \dot{m}_{meas})\,x100}{\dot{m}_{meas}} \quad (2)$$

$$\text{Mean error} = \frac{1}{n}\sum_{1}^{n} \frac{(\dot{m}_{pred} - \dot{m}_{meas})\,x100}{\dot{m}_{meas}} \quad (3)$$

4. Results

Table 1 presents the parameter ranges obtained in the experimental campaign of the present work. A total of 53 experimental points were obtained for different flow rates and evaporating and condensing temperatures.

Table 1. Parameter limitations of the present database.

Parameter ranges for the present experimental data	
Parameter	Range
Refrigerant	R134a
Length [m]	3
Inner diameter [mm]	0.7874
Inlet pressure [MPa]	809.1 - 2499
Condensing temperature [°C]	24.1 - 31.8
Inlet subcooling [°C]	3.305 - 45.73
Evaporator outlet temperature [°C]	30.7 - 40.2

The comparisons between the correlations and the experimental data are illustrated in Figs 4 to 8 for correlation proposed by Choi et al. (2003), Choi et al. (2004), Zhang (2005), Yang and Wang (2008) and Yang and Zhang (2014) respectively. Figure 4 indicates 98.11% mass flow rate through Choi correlation fall into ± 20% error band. By comparison, the results by Choi et al. correlation (2004), Zhang (2005) correlation and Yang and Zhang (2014) correlation are a little bit worse than of Choi et al. (2003) correlation. Figure 5 to 7 shows 62.26%, 60.38% and 86.79% of the experimental data are correlated within a relative deviation of ± 20% error band, for Choi et al. (2004) correlation, Zhang (2005) correlation and Yang and Zhang (2014) correlation, respectively. Lastly, the correlation by Yang and Wang (2008) proved the less effective. Its percentage of point within a relative error of ± 20% was 11.32% using the experimental database.

As shown in Table 2, the predictions using the correlations are compared with the experimental. The Choi et al. (2003) correlation yields good agreement with the experimental data in the tested conditions with mean absolute and mean deviation of 6.42% and 2.58%, respectively. The Choi et al. (2004) correlation and Zhang (2005) correlation yields a mean absolute error of 14.70%and 19.38%, respectively. While the Yang and Wang (2008) correlation provides a mean absolute deviation of 11.32%, the Yang and Zhang (2014) correlation obtained a mean absolute error of 14.37%.

Table 2. Assessment of the correlation using the experimental data

Assessment of the correlations for adiabatic capillary tube					
	Correlations				
	Choi et al., 2003	Choi et al., 2004	Zhang, 2005	Yang and Wang, 2008	Yang and Zhang, 2014
Mean absolute error	6.42	14.70	19.38	38.92	14.37
Mean error	2.58	12.96	-19.35	38.92	12.06
$\lambda 20$	98.11	62.26	60.38	11.32	86.79

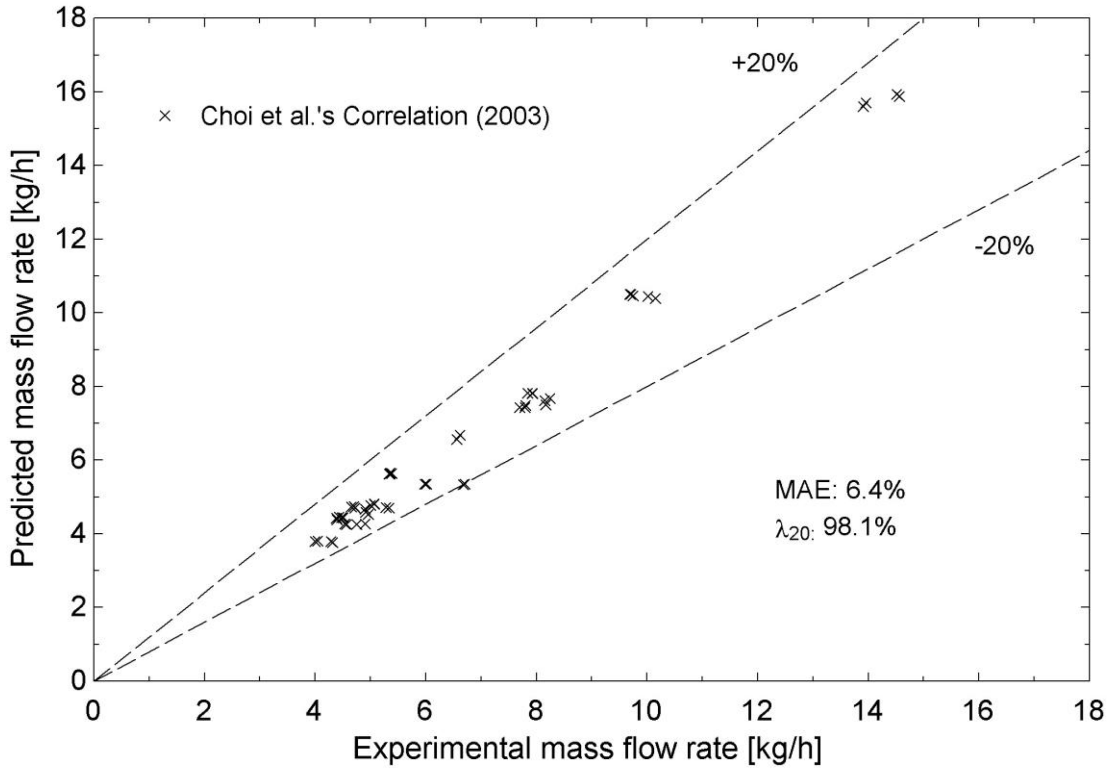

Figure 4. Comparison of predicted mass flow rate (Choi et al., 2003) with the measured data in this study, for R134a refrigerant.

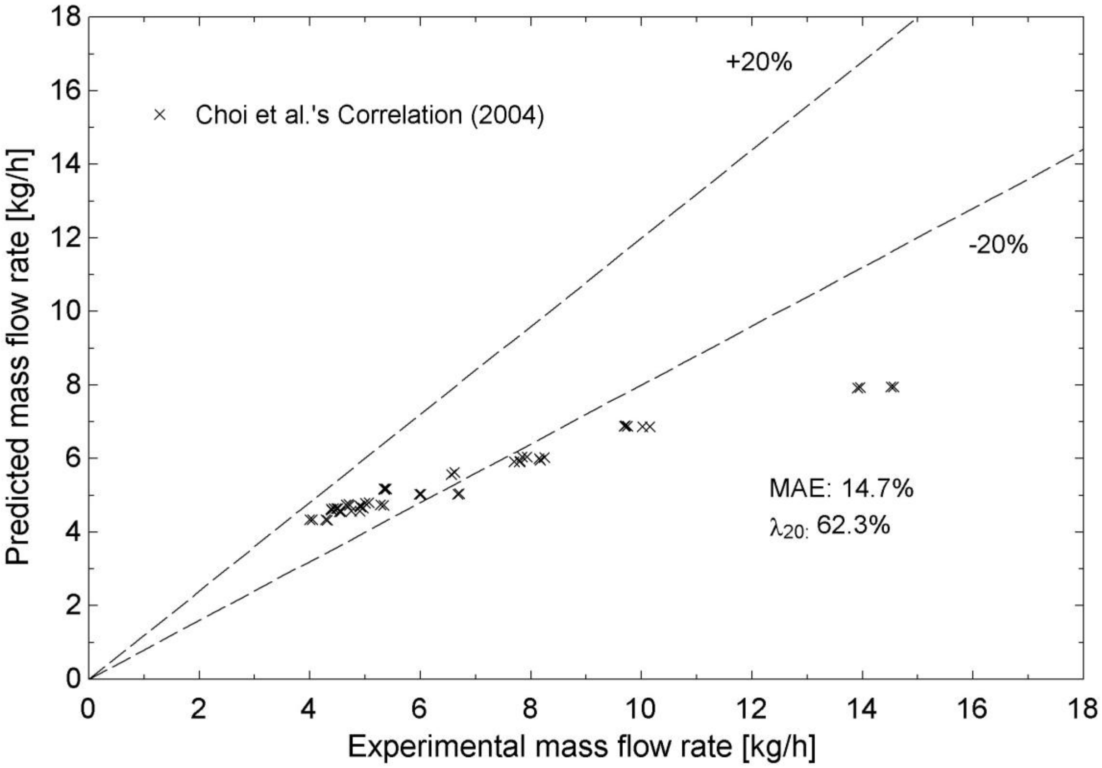

Figure 5. Comparison of predicted mass flow rate (Choi et al., 2004) with the measured data in this study, for R134a refrigerant.

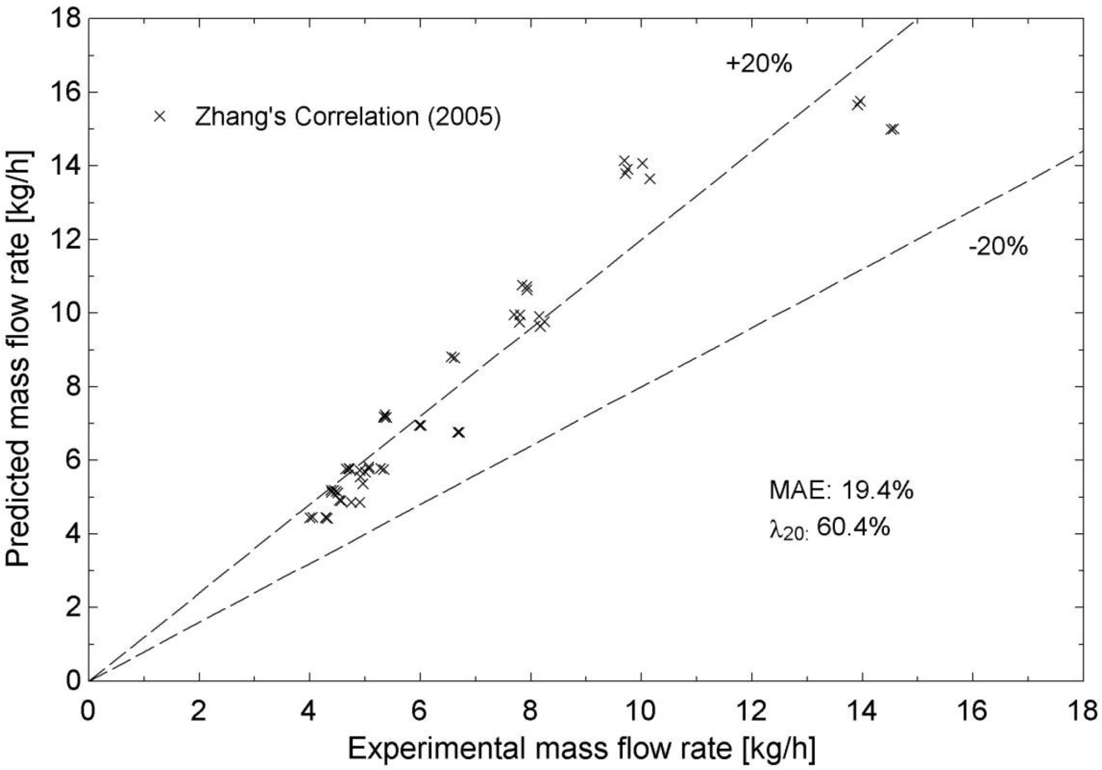

Figure 6. Comparison of predicted mass flow rate (Zhang, 2005) with the measured data in this study, for R134a refrigerant.

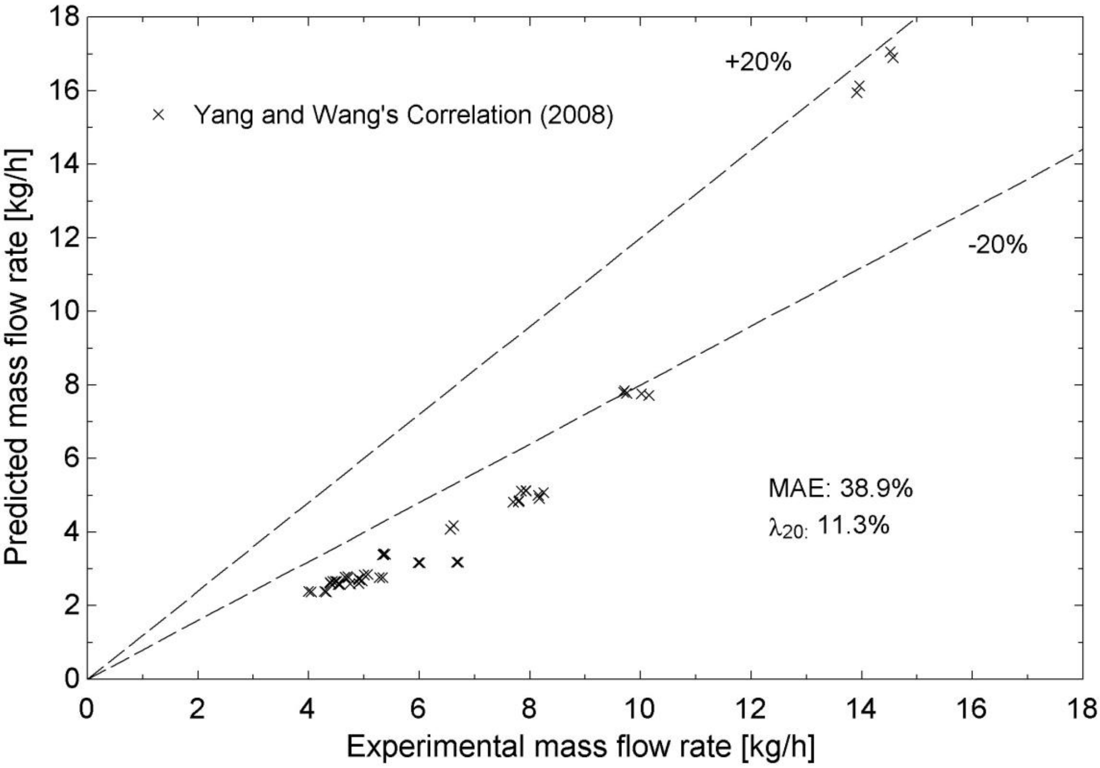

Figure 7. Comparison of predicted mass flow rate (Yang and Wang, 2008) with the measured data in this study, for R134a refrigerant.

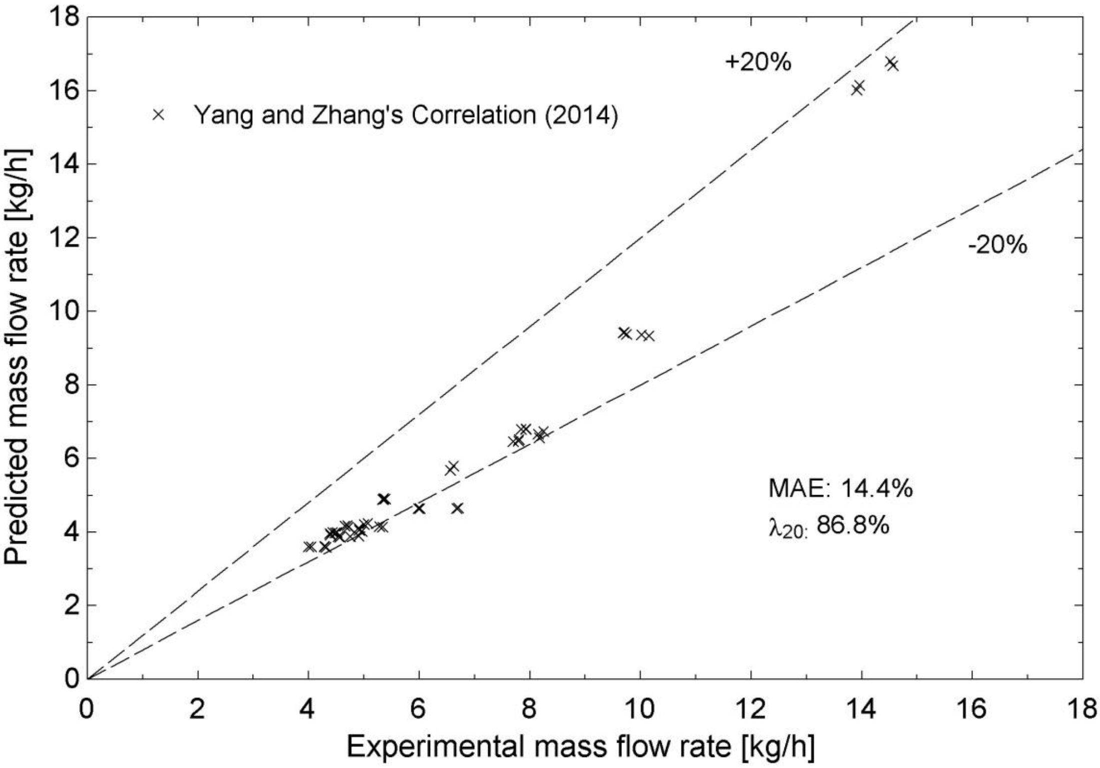

Figure 8. Comparison of predicted mass flow rate (Yang and Zhang, 2014) with the measured data in this study, for R134a refrigerant.

4. Conclusions

A simple and accurate test facility has been built for the measurement of the performance of adiabatic capillary tubes used in refrigeration cycles. The data were obtained for R134a flowing as refrigerant, at different tube inlet and outlet conditions and mass flow rates. Based on these experimental data, correlations to predict refrigerant mass flow rate through adiabatic capillary tubes were compared with the experimental data. The correlation with the smallest error was the Choi et al. (2003) with a mean absolute deviation of 6.42%.

5. REFERENCES

Choi, J.; Kim, Y.; Chung, J. T., 2004. An empirical correlation and rating charts for the performance of adiabatic capillary tubes with alternatives refrigerants. Applied Thermal Engineering 24, 29-41.

Choi, J.; Kim, Y.; Kim, H. Y.,2003. A generalized correlation for refrigerant mass flow rate through adiabatic capillary tubes. International Journal of Refrigeration 26, 881-888.

Tibiriça. C. B.; Ribatski G., 2013. Flow boiling in microscale channels – synthesized literature review. International Journal of Refrigeration 36, 321-324.

Yang, L.; Wang, W.,2008. A generalized correlation for the characteristics of adiabatic capillary tubes. International Journal of Refrigeration 31, 197-203.
22

Yang L.; Zhang, C. L.; 2014. A generalized dimensionless local power-law correlation for refrigerant flow through adiabatic capillary tubes and short tube orifices. International Journal of Refrigeration 46, 69-76.

Zhang, C.L., 2005. Generalized correlation of refrigerant mass flow rate through adiabatic capillary tubes using artificial neural network. International Journal of Refrigeration 28, 506-514.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.