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EXPERIMENTAL STUDY ON TWO-PHASE FLOW PRESSURE DROP IN COPPER TUBE BENDS FOR THE ZEOTROPIC BLEND R-407C

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Abstract. *Evaporators and condensers of modern cooling systems are becoming increasingly compact, and as a consequence the heat exchangers are presenting larger numbers of return bends. Due to this fact, minor losses as return bends become more important on the system performance. In this work, a test bench was used to study the pressure drop in return bends, with a tube diameter (D) of 4.77 mm and the curvature ratio (2R/D) from 4.40 to 10.83. The experimental data set is obtained varying the refrigerant mass flux within the range from 100 kgm*$^{-2}$*s*$^{-1}$ *to 600 kgm*$^{-2}$*s*$^{-1}$*, and a saturated pressure of 12 bar. The goal of this work is to collect experimental data for the blend R-407C flowing in return bends and compare the experimental values against theoretical correlations. It was observed that the Padilla correlation showed the best results.*

Keywords: *Return bends, R-407C, two-phase flow, pressure drop, heat exchangers.*

1. INTRODUCTION

Theoretical and experimental researches have been carried out in order to quantify the losses in return bends and a large proportion refers to single-phase flow, and only a few for two-phase flows. Just to name a few of them, we can cite Geary (1975), Chisholm (1983), Chen *et al.* (2004), Domanski and Hermes (2008) and Padilla *et al.* (2009).

In this way, it is essential pay more attention in studies related to the thermodynamic and transport properties, particularly their coefficients of pressure drop. One must be able to predict not only the pressure drop in horizontal tubes (major losses), but also in singularities (minor losses), such as return bends.

The pressure drop in two-phase flow associated with return bends is a phenomenon significantly less studied compared to the major losses. In this work we used five correlations from the literature, which were produced using the fluids R-12, R-22, R-32, R-134a and R-410a. For example, Geary (1975) correlation used the friction factor approach, the same as used to determine major losses in horizontal tubes. Geary (1975) correlation is given by the product of the pressure drop, assuming that only one phase is flowing in the tube, and the friction factor. The friction factor, Eq. (1), varies with the radius of curvature, Reynolds number and the tube diameter. The pressure drop is expressed by Eq. (2):

$$f = \frac{8,03.10^{-4}.\mathrm{Re}_v^{0,5}}{\exp\left(0,215\frac{2R}{D}\right)x^{1,25}} \quad (1),$$

$$\Delta P_{rb} = f\,\frac{G^2x^2}{2\rho_v} \quad (2).$$

Chisholm (1983) correlation is given by the product of the pressure drop, assuming that only one phase is flowing in an adiabatic tube, and a correction factor is applied, as shown in Eq. (3).

$$\Delta P_{rb} = \Phi\Delta P_{sp} \quad (4)$$

Based on the work performed by Geary (1975) and data from their own experiments, Chen *et al.* (2004) proposed a correlation using the formulation presented by Geary (1975) with a change in the friction factor equation, Eq. (5). Chen *et al* (2004) included the Weber number order to explain the effects of surface tension and inertia of gas, Reynolds number of the vapor was replaced by the sum of the Reynolds number of the vapor and liquid.

$$f = \frac{10^{-2}.\mathrm{Re}_m^{0,5}}{We^{0,12}.\exp\left(0,194\frac{2R}{D}\right)x^{1,26}} \quad (5)$$

Recently, Domanski and Hermes (2008) proposed a correlation for calculating the pressure drop in the two-phase flow in return bends based on experimental datas of Geary (1975) for refrigerant R-22 and Chen *et al.* (2004) for the refrigerant R-410a. The model developed uses the correlation of Müller-Steinhagen and Heck (1986) for pressure drop in the two-phase flow in a straight tube associated with a multiplier that represents the radius of curvature of the return bends, Eq. (6).

$$\left(\frac{\Delta P}{L}\right)_{rb} = A\left(\frac{\Delta P}{L}\right)_{st} \quad (6)$$

Padilla *et al.* (2009) proposed a correlation for calculating the pressure drop in the two-phase flow in return bends based 325 points obtained from experimental data from literature. The model developed using the correlation of Müller-Steinhagen and Heck (1986) for pressure drop in two-phase flow in a straight tube plus a singular pressure gradient proposed by Padilla *et al.* (2009) , Eq. (7).

$$\left(-\frac{\Delta P}{L}\right)_{rb} = \left(-\frac{\Delta P}{L}\right)_{st} + \left(-\frac{\Delta P}{L}\right)_{\sin g} \quad (7)$$

2. MATERIALS AND METHODS

Figure 1 shows the experimental facility, it was designed with two parallel circuits without contaminated oil, the circuits were named as main and cooling. In this configuration we have the advantage of being able to work at different temperatures evaporation. Table 1 shows the variables measured with their respective uncertainties The experiments were performed in the Laboratory of Refrigeration and Heating of the Universidade Federal de Minas Gerais.

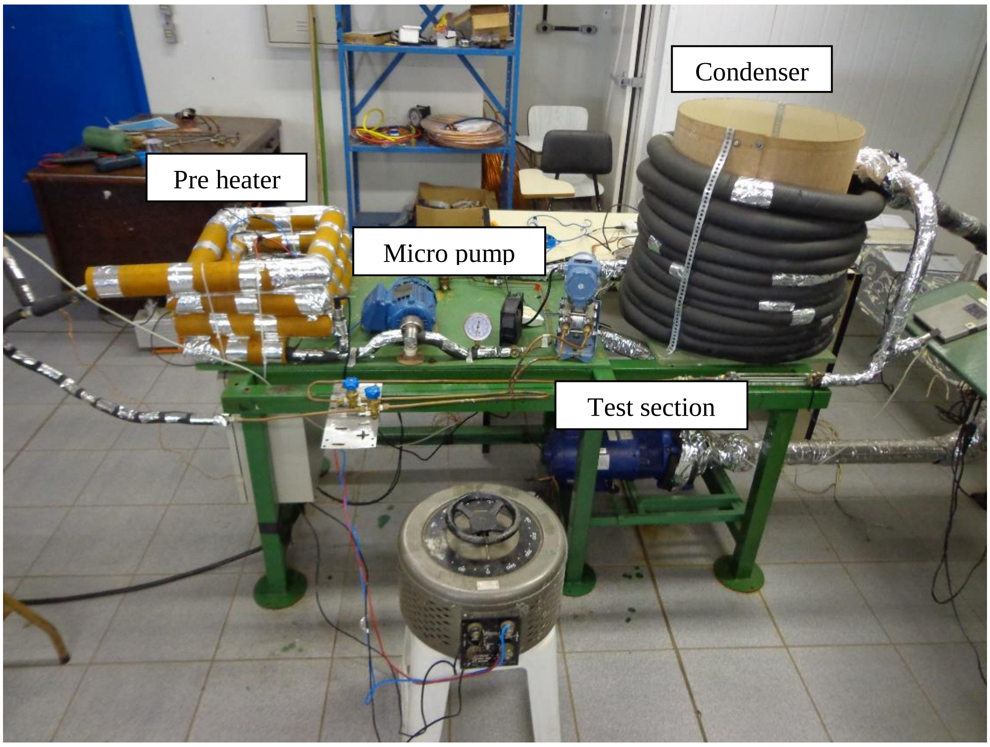

Figure 1. Experimental facility

The cycle in the main circuit occurs in three steps. Initially, the fluid R-407C enters in the liquid state in the micro-pump, which increases the pressure of the fluid. Then, the fluid receives heat into the pre-heater element responsible for phase change fluid and the vapor quality adjustment in the input test section: a return bend, which the pressure drop is measured. The vapor quality of the fluid at the entrance of the test section is obtained by equation Eq.(8), which provides the enthalpy of the fluid in the pre-heater output and input of the test section and hence the value of the vapor quality in this circuit position. Finally, the fluid enters the condenser giving heat to the cold water so that, on leaving the condenser, it is in the compressed liquid state. In this state, the fluid enters micro-pump, restarting the cycle.

$$\dot{Q}_p = \dot{m}(h_s - h_e) \tag{8}$$

For this study, we used the characteristics of the test section presented by Padilla *et al.* (2011), as shown in Fig.2. The downstream and upstream pressure tap have the same distance from the return bend: 20 internal diameters.

With the installation of pressure tap away from the return bend, it was necessary that the prediction methods were to be increased of the term referring to pressure drop in straight lines with correlation being chosen from Sun and Mishima (2009). According (Pabón, 2014), statistical and probabilistic analyzes were performed, indicating that the correlation Sun and Mishima was considered the best correlation to predict the experimental results for the pressure drop in horizontal channels with R-407C refrigerant.

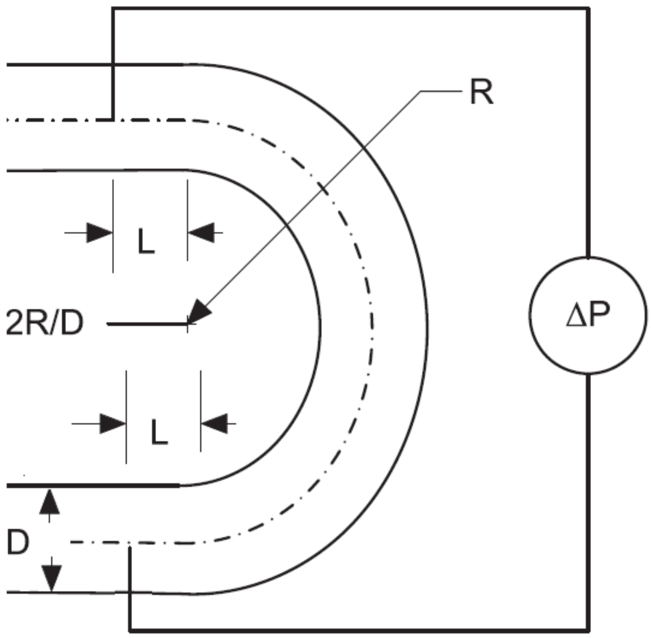

Figure 2. Test section

Table 1. Variables measured with their respective measurement uncertainties

Variable	Uncertainty
Temperature	0.6°C
Pressure	1.6 % *
Differential pressure	0.175% *
Electric current	8% *
Voltage	2% *

*read value

3. RESULTS

This section presents the experimental results for the pressure drop to two-phase flow (liquid-vapor) of refrigerant R-407C in the test sections with vapor quality varying between 0% to 100%, mass flux of the fluid between 100 kg/m²s to 660 kg m²s and evaporation pressure of 12 bar.

3.1 Evaluation of correlations for pressure drop in two-phase flow

The prediction methods are evaluated according to mean relative error (MRE) and the mean absolute error (MAE).Table 2 shows the statistical parameters from the evaluation of prediction methods. It is observed that the correlation of Geary (1975) had the highest accuracy, with smaller MAE and MRE than 45% and -15%, respectively. The other correlations showed also moderate precision, with MARD and MRD between 55% and 40%, except for the correlation of Chisholm (1983). Comparisons between experimental and theoretical results are shows in the Fig. 3.

Table 2. Statistical results MRE and MAE.

Correlations	**MRE**	**MAE**
Padilla *et. al*(2009)	34.8	**40.6**
Chen, Lin and Wang,(2004)	35.4	**52.2**
Chisholm (1983)	273.0	273.0
Geary (1975)	-12.61	**37.2**
Domanski and Hermes (2008)	24.1	**41.3**

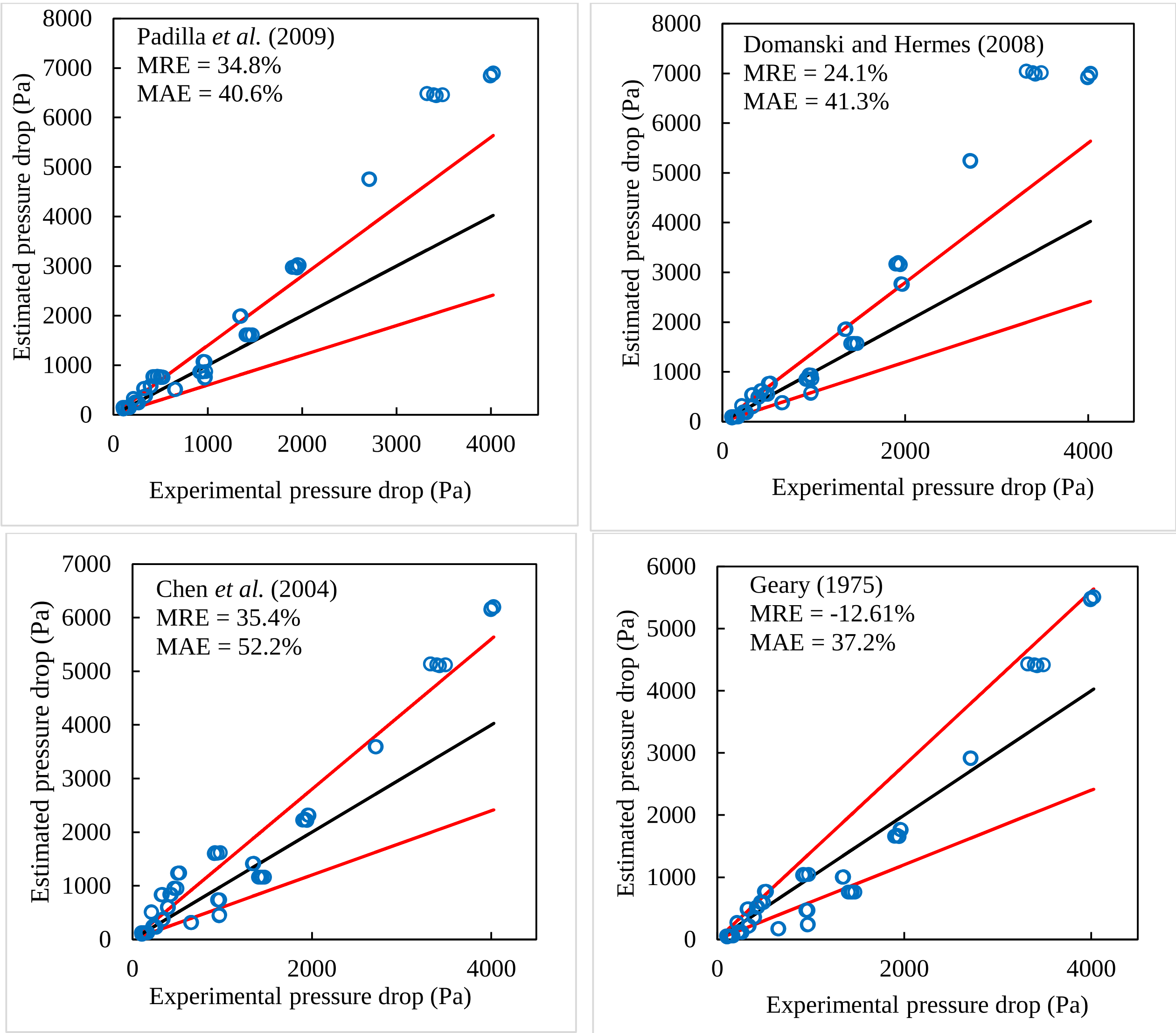

Figure 3. Experimental pressure drop data in return bends compared to prediction methods.

Figure 4 shows a probabilistic analysis of all the correlations in terms of the cumulative distribution function that gives the probability that a random amount of data with a normal distribution must have a certain maximum error. The analysis allowed to estimate the accuracy of the correlations, the correlation of Padilla *et al.* (2009), was wich provided results closer the experimental values, provided that for almost 85% of the tested points, the maximum error was 60%.

The correlations of Geary (1975) and Domanski and Hermes (2008) showed results somewhat lower, followed the correlation Chen, Lin and Wang (2004). The correlation Chisholm (1983) did not show satisfactory results.

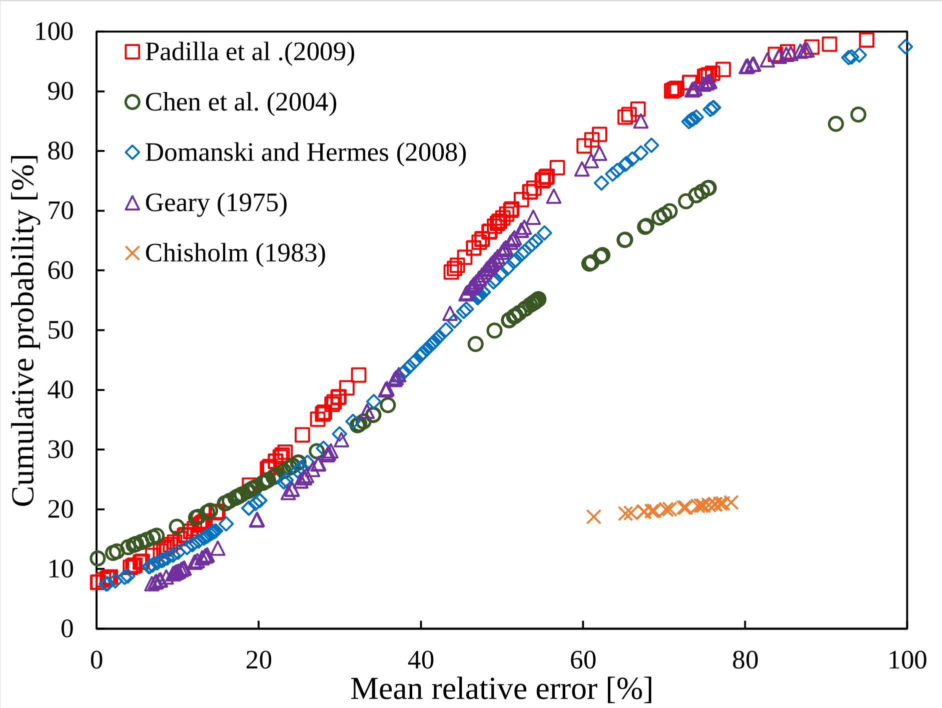

Figure 4. Distribution of cumulative probability of the mean relative error

3.2 Effect of mass flux and vapor quality

The effect of the vapor quality under the pressure drop in return bends is also shown in Fig. 4 for different mass velocities. It was observed that the pressure drop increases linearly with the increase of the vapor quality. For low vapor quality (less than 40%), the flow regime is generally intermittent and the pressure drop is mainly influenced by the friction of the liquid with the tube wall, with increasing vapor quality, the flow tends to become annular and involve completely the tube wall, a fact which further increases the pressure drop. To vapor quality higher than 80%, the liquid layer on top of the dry, and this reduces friction, causing thus a decrease in pressure drop.

Figures 5A and 5B present comparisons between the experimental data and correlations of Chen *et al.* (2004), Domanski and Hermes (2008), Padilla *et al.* (2009) and Geary (1975) in a return bend for two mass velocities. It can be observed that vapor quality to smaller than 30% correlation of Domanski and Hermes (2008) and Padilla *et al.* (2009) showed better accuracy and from the vapor quality 50% correlation of Chen *et al.* (2004) and Geary (1975) showed the best results.

In a more detailed analysis of the effect the vapor quality of Tab.3 presents the statistical parameters stratified for vapor quality lower than 50% and above 50%. It is observed that, for each vapor quality range, there was a correlation with a better accuracy in the evaluation of error: Padilla *et al.* (2009) is the most accurate for smaller vapor quality than 50%, and the correlation Geary (1975) to vapor quality higher than 50%.

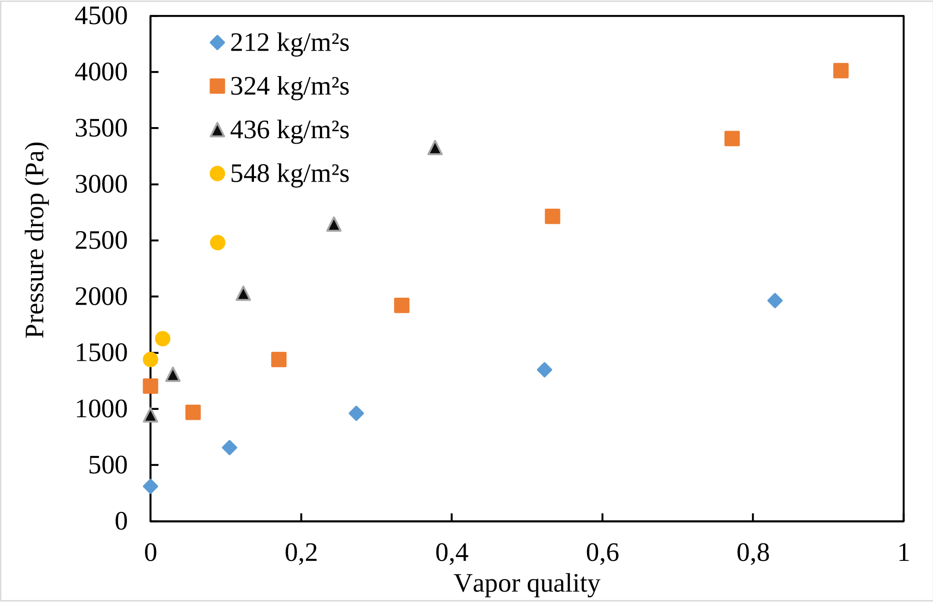

Figure 4. Pressure drop in return bend (Psat=12 bar, D=4.77mm, 2R/D=10.83)

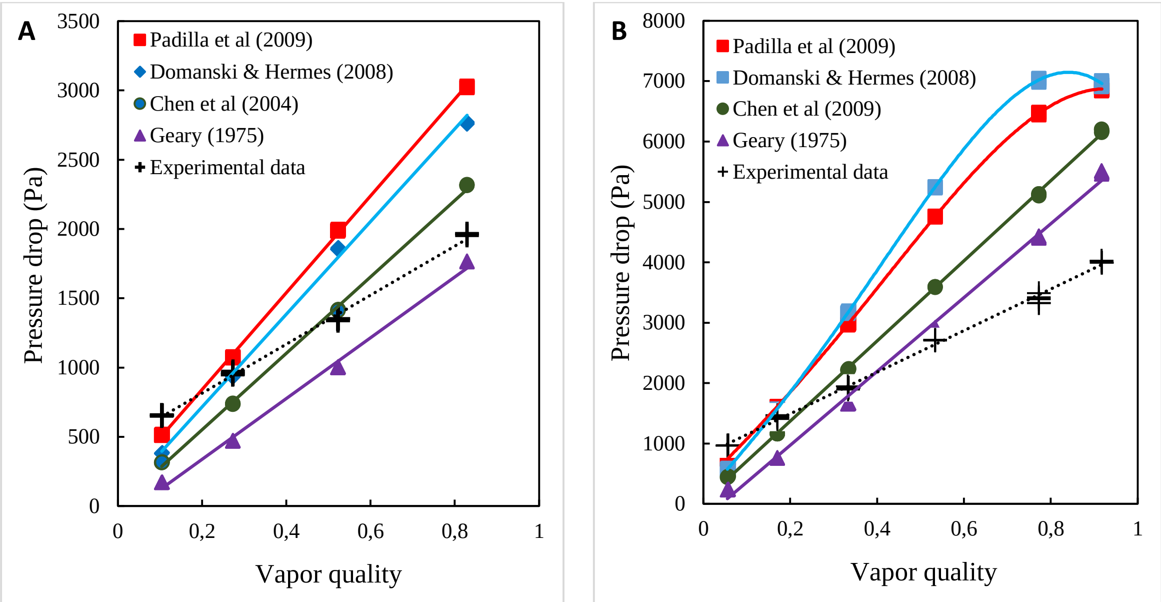

Figure 5. Pressure drop in return bend (Psat=12 bar, D=4,77mm, 2R/D=10,83). (A) Pressure drop for G =212 kg/m²s. (B) Pressure drop for G =324 kg/m²s

Table 3. Statistical results MRE and MAE.

Correlations	**MRE**		**MAE**	
x (%)	< 50	>50	< 50	>50
Padilla (2009)	16.83	35.29	**26.33**	40.60
Chen,(2004)	14.79	36.22	46.17	52.13
Domanski (2008)	2.52	24.70	32.84	41.22
Geary (1975)	34.80	12.11	48.90	**36.85**

Correlations	**MRE**			**MAE**		
G (kg/m²s)	100	212	324	100	212	324
Padilla (2009)	31.90	22.72	74.07	34.80	33.45	74.07
Chen (2004)	67.66	-3.74	39.59	71.87	**23.69**	39.59
Domanski(2008)	13.70	8.53	85.66	**31.18**	30.60	85.66
Geary (1975)	-3.34	40.97	16.79	36.34	40.97	**23.53**

4. CONCLUSIONS

In this work, it was developed a theoretical and experimental study of pressure drop in return bends for the refrigerant R-407C. The influences of the operating parameters (mass flux and vapor quality) in the curves of the pressure drop in different flow conditions were analyzed.

As from the literature review, it is observed that the two-phase flow of R-407C fluid in convective boiling has been little studied in straight stretches, with no references in the literature on studies in return curves.

It was observed that the pressure drop increases linearly with the increase of vapor quality a maximum value around 80% for all correlations analyzed in this study.

Statistical and probabilistic analyzes were performed. The best correlations to predict experimental results for the pressure drop in return bends with R-407C refrigerant are, in this order, the correlations of Padilla *et al.* (2009), Geary (1975), Domanski and Hermes (2008) and Chen *et al.* (2004). The correlation Chisholm (1983) did not show satisfactory results for the conditions examined in this study. The correlation Padilla, Revellín and Bonjour (2009) was the closest that provided the results of experimental values, and to almost 85% of the tested points, the maximum error was 60%.

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