EXPERIMENTAL ANALYSIS OF PRESSURE DROP IN SINGLE AND TWO PHASE IN MINI CHANNELS

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Abstract. *Evaporators designed using reduced diameter channels are one of the main focus in the development of compact refrigeration equipment. The objective of this work is to experimentally investigate the single-phase pressure drop of natural refrigerant, isobutane (R600a), in two mini-tubes, with 1.0 and 2.6 mm of internal diameter (ID) and adiabatic conditions. Pressure drop during boiling flow is also analyzed in a mini tube with 2.6 mm ID. The experimental tests included mass velocities of 188, 280 and 370 kg/m²s, heat fluxes in the range from 0 to 134 kW/m². In boiling tests a saturation temperature of 22 ºC and vapor quality up to 0.8 were considered. Significant influence of the mass velocity and diameter on the total pressure drop and the frictional pressure drop is observed in both types of flow.*

Keywords*: pressure drop, natural refrigerant, boiling, mini channel*

1. NOMENCLATURE

D	diameter [m]
e	absolute internal roughness [μm]
f	friction factor [-]
G	mass velocity [kg/m²s]
ID	internal diameter [m]
L	length [m]
$\dot{m}$	mass flow rate [kg/s]
p	pressure [kPa]
P	electrical power supplied [W]
PH	pre-heater
q''	heat flux [kW/m²]
Re	Reynolds number $= 4\dot{m}/(\pi D_i \mu)$ [-]
T	temperature [ºC]
TS	test section
VS	visualization section
x	vapor quality [-]

Greek Symbols

α	void fraction [-]
ρ	density [kg/m^3]
Δp	pressure drop [kPa]
μ	viscosity [kg/ms]
υ	specific volume [m³/kg]

Subscripts

ac	acceleration
exp	experimental
f	frictional
G	gas
i	internal
in	inlet
L	liquid
out	outlet
sat	saturation
tot	total

2. INTRODUCTION

Compact heat exchangers should be able to dissipate high heat fluxes and, at the same time, achieve better thermal performance and reliability, with little pressure drop. These devices are employed in small size refrigeration systems, which find use in air conditioning applications, heat pumps, cooling of electronic devices and in advanced applications with microprocessors. In comparison with single-phase flow, boiling is a good option to be applied in mini-channels because of its high heat transfer efficiency, with small wall temperature rises.

However, a penalty of flow boiling is the increase of pressure drop and pressure fluctuations, which can limit the applicable range of this process in such devices. Therefore, a comprehensive understanding of pressure drop in mini-channel is important for accurate design, performance evaluation and optimization of these heat exchangers.

Experimental results have been presented in recent years. Qi *et al.* (2007) described the characteristics of pressure drop in single phase in turbulent flow of liquid nitrogen in tubes of internal diameter ranging from 0.53 to 1.93 mm. They concluded that the experimental friction factor for liquid nitrogen is higher than that obtained by correlations used for such diameters and suggest modifications to the Colebrook correlation. Flow boiling results of different refrigerants have been reported by Greco and Vanoli (2006), in a horizontal tube of 6 mm ID, using six different refrigerants and comparing their results with pressure drop prediction methods. In their experiments, all refrigerants tested presented similar results in terms of comparison among the predictive methods and the experimental results. The work of Pamitran *et al.* (2010) showed results for mini tubes with 0.5, 1.5 and 3.0 mm ID and refrigerants like R-744, R-134a, R-22, R-410 and R-290. According to the authors, the results indicate the strong influence of physical properties such as density, viscosity and surface tension on the pressure drop and suggest a new pressure drop correlation. Tran *et al.* (2000) analyzed the pressure drop during boiling of R-113, R-12 and R-134a in tubes of 2.92 and 2.46 mm ID. In general the results have showed that pressure drop depends on mass velocity, vapor quality and, also, heat flux.

The objective of the present experimental study is: (*i*) develop an accurate data base for pressure drop of natural fluid, R600a, during single-phase and flow boiling in small tubes, in order to gather new data for heat exchanger design; (*ii*) verify the effects of mass velocity and diameter on the pressure drop in mini-tubes; (*iii*) compare the measured data with available correlations to predict the frictional pressure drop in single-phase flow.

3. EXPERIMENTAL SET UP AND TESTS

An experimental apparatus was used to investigate the pressure drop of refrigerants in single phase and boiling flow in a horizontal mini channel electrically heated. The experimental apparatus, according to Fig. 1, comprises a circuit which provides mass velocity controlled to a wide range of flow conditions. The main part of the circuit has a preheater section (*PH*), the test section (*TS*) and a visualization section view (*VS*). The secondary part consists of a refrigerant reservoir, condenser, and sub-cooler, with separate circuits using a solution of ethylene glycol and water as a secondary coolant. The sub-cooler is used to compensate any increase of temperature experienced by the refrigerant when passing the pump. The preheater establishes the inlet conditions (vapor quality) in the test section. Both consist of horizontal stainless steel tubes thermally insulated with 445 mm and 185 mm length, respectively, and 2.6 mm ID, heating by Joule effect controlled by power supply. Downstream the test section there is a visualization section constituted by a glass tube with 158 mm length and the same internal diameter of the test section.

The measurements of pressures and temperatures at the inlet and outlet of the preheater are held respectively by two absolute pressure transducers and thermocouples type E of 0.076 mm, in contact with the refrigerant, and three thermocouples in external wall. In the test section the pressure drop are measured by a differential pressure transducer and the refrigerant temperature by thermocouples in the inlet and exit of the section, besides the wall temperatures along the tube.

A frequency inverter is used to control the pump flow rate and a bypass line downstream the pump and parallel to the preheater and the test section is used for more precise adjustments of flow and is controlled by a needle-valve.

The pressure transducers, thermocouples and the mass flow meter are connected to a data acquisition system controlled by a computer.

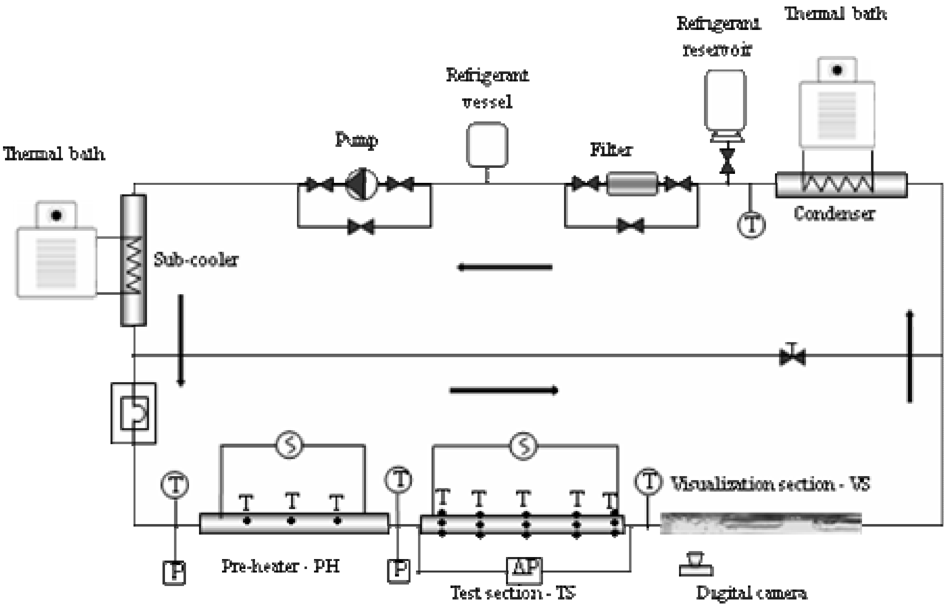

Figure 1. Schematic diagram of experimental apparatus.

All experiments were carried out with isobutane (R-600a) to measure and analyze the behavior of pressure drop in single-phase and flow boiling. The single-phase tests were carried out in adiabatic conditions for pressure drop. Table 1 shows the single phase and boiling tests conditions. During boiling tests different heating powers in the preheater were used to establish the vapor quality at the entrance of test section (*TS*) in each experiment.

Table 1. Summary of test conditions using experimental apparatus with 2.6 mm ID.

Mass velocity, G [kg/m²s]	188 to 590
Average temperature, T (°C), and pressure, p [kPa] in single phase tests	8/290
Heat flux, q'' [kW/m²]	0, 28, 56, 100 e 134
Saturation temperature, T_{sat} [°C], and pressure, p_{sat} [kPa]	22/323.50

Another test section with 1.0 mm ID and 148 mm in length was developed with the purpose of analyzing the effects of diameter on the pressure drop in adiabatic single-phase flow, keeping the same parameters used in section with 2.6 mm ID. The absolute internal roughness (e) of both tubes is of 2.05 μm.

3.1 Adiabatic single-phase tests

The total pressure drop in the preheater and test section during single phase tests were evaluated and they are the sum of frictional pressure drop (Δp_f) and the inlet and exit losses (Δp_{out-in}), as in Eq. (1). The inlet and exit losses are due to the contraction or enlargement of the flow area.

$$\Delta p_{tot} = \Delta p_f + \Delta p_{out-in} \tag{1}$$

From the frictional pressure drop in adiabatic conditions, it is possible to calculate the experimental friction factor, f_{exp}, using Eq. (2).

$$f_{\exp} = \frac{2\Delta P_f \rho D_i}{G^2 L} \tag{2}$$

The results obtained with respect to $f_{\exp}$ are compared with the correlations for fully developed turbulent flow proposed by Blasius (1913), Petkhov (1970), and Colebrook (1939), given by Eqs. (3), (4) and (5), respectively. This comparison procedure has the purpose of ensure the validation of the experimental apparatus.

$$f = 0.316\, Re^{-0.25} \qquad (\mathrm{Re} < 2\times10^4) \tag{3}$$

$$f = [0.79\, ln(Re) - 1.64\,)^{-2}\,] \qquad (3000 \le \mathrm{Re} \le 5\times10^6) \tag{4}$$

$$f = \left\{-1.8\, log\left[\frac{6.9}{Re} + \left(\frac{e}{3.7D}\right)^{1.11}\right]\right\}^{-2} \qquad \left(\frac{e}{D} > 1\times10^{-6}\right) \tag{5}$$

3.3 Flow boiling tests

In the flow boiling the total pressure drop also includes the momentum pressure drop, ΔP_{ac}, according to Eq. (7).

$$\Delta p_{tot} = \Delta p_f + \Delta p_{out-in} + \Delta p_{ac} \tag{7}$$

The momentum pressure drop, caused by acceleration of both phases, is a result of the refrigerant specific volume enhancement in evaporation. This component is calculated by Eq. (8):

$$\Delta p_{ac} = G^2 \left\{ \left[\frac{(1-x)^2}{\rho_L (1-\alpha)} + \frac{x^2}{\alpha \rho_G} \right]_{out} - \left[\frac{(1-x)^2}{\rho_L (1-\alpha)} + \frac{x^2}{\alpha \rho_G} \right]_{in} \right\} \tag{8}$$

where the void fraction, α, is calculated according homogenous model, given by Eq. (9).

$$\alpha = \frac{v_G x}{v_G x + v_L (1-x)} \tag{9}$$

4. RESULTS

4.1 Adiabatic single-phase tests

4.1.1 Effect of the flow regime (Re)

It was studied the influence of flow regime on pressure drop and on friction factor in the test section. It is observed that with the increasing of mass velocity, the pressure drop increases and experimental friction factor decreases. Table 2 shows the results of pressure drop in the test section (*TS*) and experimental friction factors obtained from Eq. (2) for different mass velocities, *G*.

Table 2. Results on pressure drops and experimental friction factors obtained with 2.6 mm ID.

G **[kg/m²s]**	***Re*** **[-]**	**$\Delta p_{(TS)}$ [kPa]**	**$f_{(exp)}$ [-]**
196	2774	0.116	0.04898
272.4	3762	0.207	0.04567
367.2	5130	0.318	0.03836
587	6873	0.880	0.03409

Comparison of the experimental friction factors in the test section with 2.6 mm ID with that predicted by the correlations is shown in Fig. 2. It is possible to observe that, in most cases, $f_{(exp)}$ is slightly greater than the value predicted by correlations. It is probably due to inlet and exit effects. It can be seen that the friction factors better agree with values predicted by Petkhov correlation, followed by Colebrook correlation which considers the absolute internal roughness of the tube.

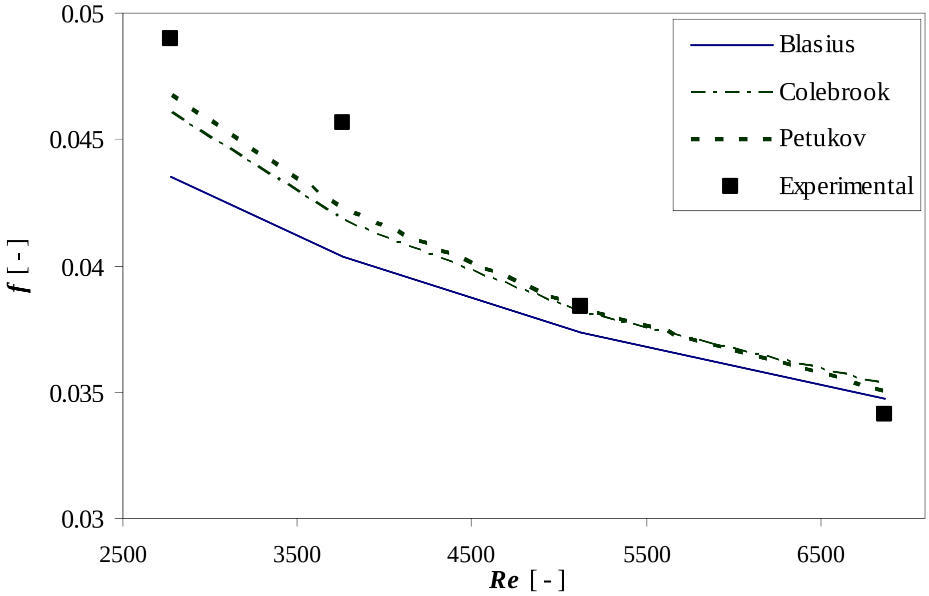

Figure 2.Comparison among experimental friction factors and friction factors predicted by the correlations.

Moreover, the pressure drop of the refrigerant in adiabatic condition was determined both in the pre-heater (*PH*), as in the test section (*TS*). Figure 3 shows the variation of the pressure drop in the two sections with respect to Reynolds number, Re. It is observed that in both sections, increasing the pressure drop is proportional to the increase in *Re*. For *Re* < 3000, the influence of the mass flow is not as strong in both sections, thus indicating very similar values. However, with the increase in mass flow rate it becomes apparent difference in the increase of the pressure drop between the test section and the pre-heater. However, due to the greater length of pre-heater with respect to test section, we observe a greater pressure drop in this last for all mass flow rates tested.

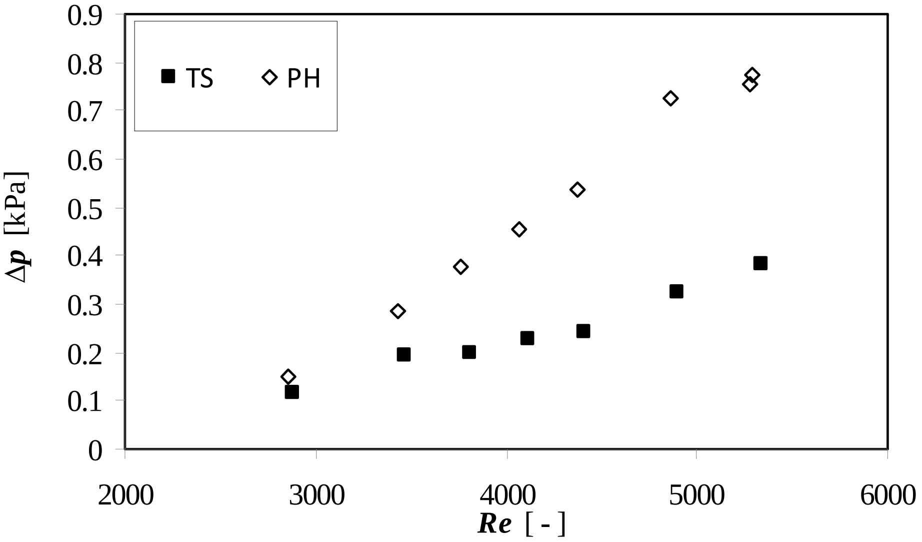

Figure 3. Single phase flow results for pressure drop variation with flow regime.

4.1.2 Effect of diameter

The effect of internal diameter on the total pressure drop for adiabatic single phase flow was analyzed for four different flow regimes. Figure 4 shows the results of total pressure drop as a function of Reynolds number, *Re*. It is possible to observe a greater influence of diameter with increasing Re. For the tube with 1.0 mm ID and in turbulent flow the pressure drop was around 95,6 % more than in the tube with 2.6 mm ID. This effect is caused by the increase of shear stress in the inner wall of the tube due to the decrease of the diameter. With the increase of shear stress on the inner wall, friction factor increases, making the contribution of the pressure drop by friction greater. These results are in agreement with the works presented by Qi *et al*. (2006), Yang and Lin (2007).

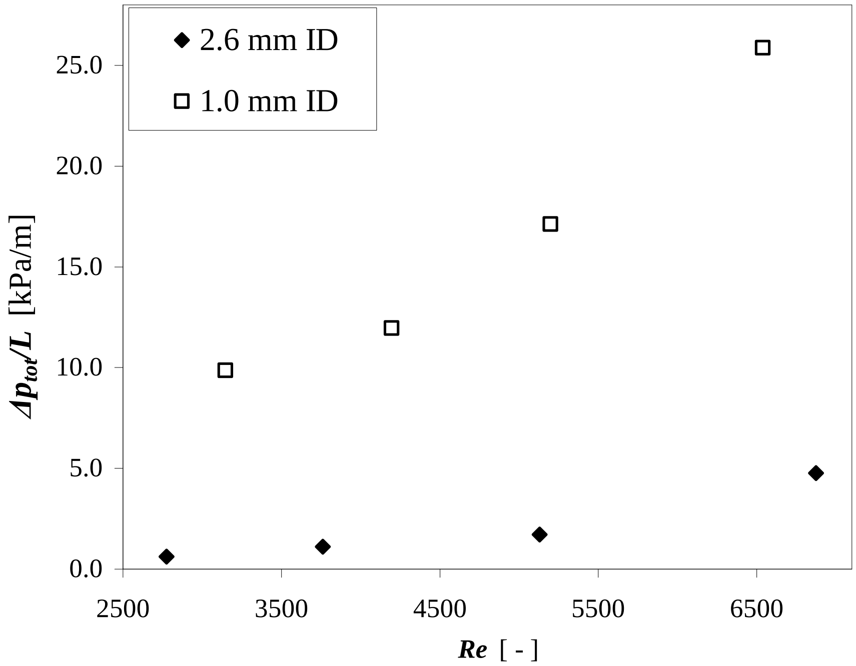

Figure 4. Effect of diameter on total pressure drop.

4.2 Flow boiling tests

The variation of frictional pressure drop, Δp_f, in the test section with vapor quality, *x*, for different mass velocities, *G*, is shown in Fig 5. It is observed that with increasing *G*, the pressure drop increases. It can be related to the vapor velocity increasing and the effects caused by acceleration losses. Similar trends were presented by Pamitran *et al.* (2010) using five different refrigerants in their experiments.

Figure 6 presents the effect of heat flux on frictional pressure drop per unit length for different mass velocities. Although it was expected that the effect of the heat flux would be negligible, it was found, for the tested conditions, a small influence, which tends to reduce with increasing *G*. This trend is due to the dependence of pressure drop with respect to volumetric flow rate, whose increasing is proportional to the increase in liquid and vapor mass velocities. These results were also observed in the works of Saisorn *et al.* (2010) and Ould Didi *et al.* (2002).

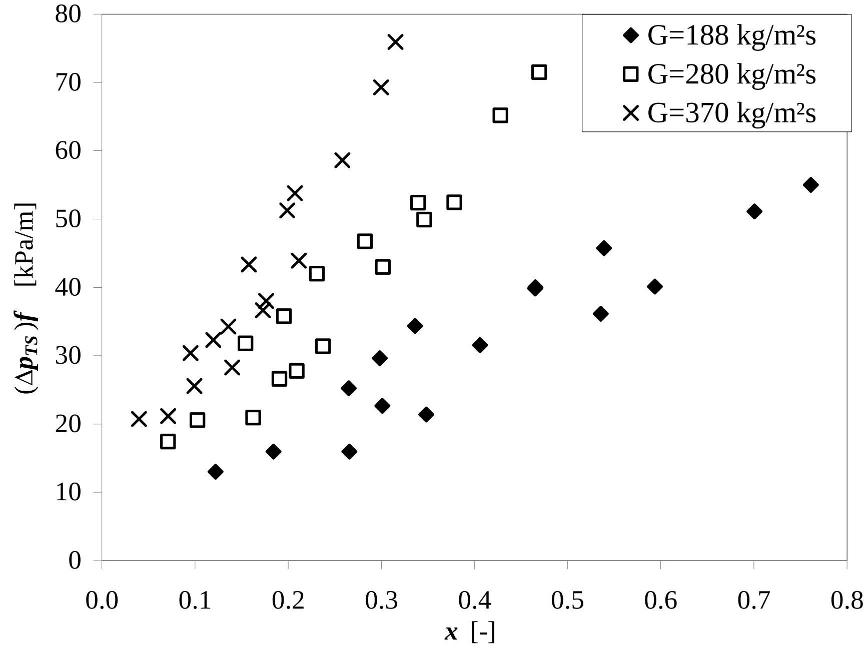

Figure 5. Effect of mass velocity and vapor quality on frictional pressure drop for T_{sat}=22 ºC.

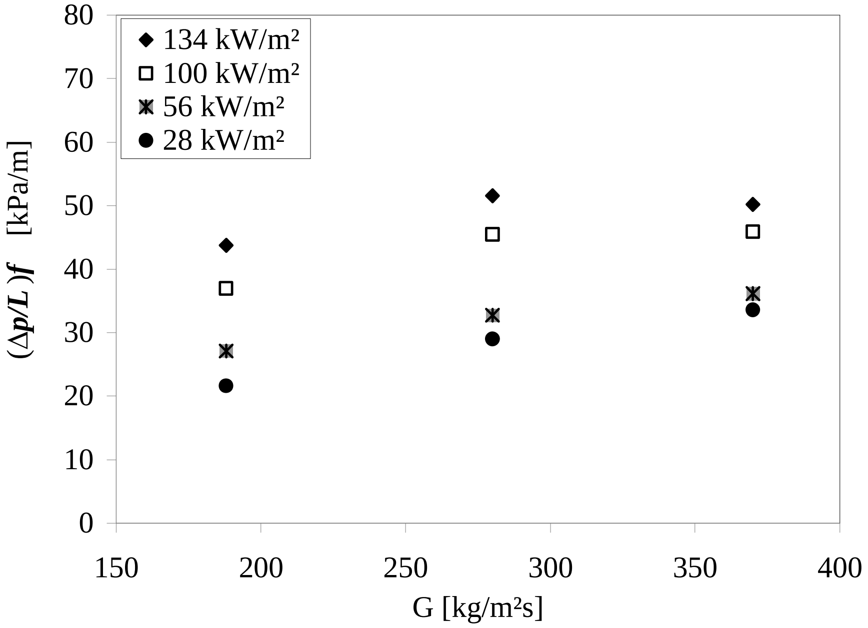

Figure 6. Effect of heat flux on frictional pressure drop for different mass velocities, *G*.

5. CONCLUSIONS

Experimental results for flow boiling of R-600a in a horizontal mini channels under the variation of mass velocity, heat flux and vapor quality were presented. The behavior of frictional pressure drop was investigated. The frictional pressure drop increased with the increase in vapor quality and mass velocity, as expected, and one could detect some influence of the heat flux for higher mass velocities. It was observed the influence of the diameter on the total pressure drop in adiabatic single-phase testes.

6. ACKNOWLEDGEMENTS

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