EXPERIMENTAL ANALYSIS OF ADIABATIC FLOW OF NON-AZEOTROPIC MIXTURE R407c THROUGH A CAPILLARY TUBE[1]

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ABSTRACT

The present work is related to the experimental evaluation of adiabatic flow of R22 and R407c, a nonazeotropic mixture, through a capillary tube. An experimental apparatus was erected to control and measure flow conditions across the capillary tube. Condensing temperature and degree of subcooling, i.e. upstream conditions, were kept within the range of 31°C and 45°C , and 7 e 24°C, respectively. Results have shown that R22 and R407c have similar performance, for giving operating conditions. One single geometry was tested. The capillary tube had a length of 1.3m, an internal diameter of 0.81 mm and a roughness of 0.7 μm.

INTRODUCTION

The present paper studies the flow of refrigerants R22 and R407c, this one a nonazeotropic mixture, through an adiabatic capillary tube. Capillary tubes are expansion devices that control the refrigerant flow in refrigeration vapor compression cycles, by establishing a pressure differential between the condenser and the evaporator. The geometry of the capillary tube affects the system operating equilibrium and each application requires a specific combination of diameter and length. Since Bolstad and Jordan [1] the flow through capillary tubes has been studied extensively. Recent reviews of the literature can be found, for example, in Wolf et al. [2] and Motta [3]. Adiabatic capillary tubes find application, for example, in small domestic air conditioning units. Refrigerant HCFC-22, the traditional working fluid for these units, is to be replaced, in the near future, by more environmentally benign refrigerants. One of the likely substitutes is refrigerant R407c, a nonazeotropic mixture of HFC-32 (CH_2F_2, 23% by weight), HFC-125 (CHF_2CF_3, 25%) and HFC-134a (CH_2FCF_3, 52%). Refrigeration capacity and operating pressure make the R407c one of the closest alternative to HCFC-22 [4]. As a nonazeotropic mixture (or a zeotrope), it presents a temperature glide of the order of 7,1°C [5] at atmospheric pressure. Concerning the study of flow of nonazeotropic mixtures through capillary tubes, new issues, such as the varying composition of the fluid alongside the tube length, will have to be tackled.

The literature on the flow of nonazeotropic mixtures through capillary tubes is still scarce. Chang and Ro [6,7] present a theoretical and experimental study, for adiabatic flow in capillary tubes, covering R22 and three substitutes: two binary mixtures, R32/R134a (30/70% by weight) and R32/R125 (60/40%), and R407c R32/R125/R134a (23/25/52%). A comparison was carried out between experimental results and model predictions for one single length and two diameters. Results have show similar performances for R22 and R407c. The present work aims to contribute to this subject with more experimental data.

EXPERIMENTAL APPARATUS

The experimental apparatus, shown in Figure 1, consisted of a vapor compression cycle, adapted to accommodate instruments and controls that allowed for the capillary tube performance to be evaluated. The test section comprised three capillary tubes displayed in parallel (only one tube was tested in the present work), with valves installed in both ends, in order to isolate the tube to be tested from the others. The capillary tube was straightened up and placed horizontally in the test section. Insulation, made from polyurethane foam, was 1.5 cm thick. Incidentally, Goldschmidt

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polyurethane foam, was 1.5 cm thick. Incidentally, Goldschmidt and Kuehl [8] have demonstrated that, even without this insulation, heat transfer from the capillary tube to its surroundings could be regarded as negligible. Mass flow rate control was achieved through an automatic expansion valve by-passing the capillary tube. Thus, both capillary tube and expansion valve acted as expansion devices.

A small capacity hermetic compressor, 1.8 hp of nominal power, was employed. In order to ensure that refrigerant flow was completely oil-free, two oil separators, of the helicoidal and coalescent types, were installed in series, at the compressor discharge. The oil removed in these separators was returned to the compressor crankcase. After some trial runs, capillary tube and connections were inspected, showing no trace of oil.

A liquid separator was also installed, upstream the compressor. Refrigerant subcooling was controlled via a double pipe heat exchanger. Condenser operated with water, and the subcooler, with ethylene glycol. The subcooler fluid temperature (which, ultimately, controls the degree of the subcooling at the capillary tube entrance) was controlled by a constant temperature bath. Water entered the shell-and-tube condenser at ambient temperature, from a reservoir. An electric pump and a needle valve controlled water mass flow rate. In order to achieve sub-zero evaporating temperatures, the evaporator, of the shell-and-coil type, exchanged heat with ethylene glycol, with the temperature also controlled by a second constant temperature bath. Liquid sight-glasses, to ensure only liquid phase entering the capillary tube, and dryers were also installed in the apparatus.

One single geometry was tested. The capillary tube had a length of 1.3 m (± 0.001 m), an internal diameter of 0.81 mm (± 0.01 mm) and a roughness of 0.7 μm (± 0.1 μm). It was sampled from commercially available specimens. Tube length was measured with a flexible measuring tape. The diameter of the tube was taken from measurements of six samples (1 mm long) with a profile projector, with computer interface and 20X magnification. Tube roughness was measured with a stereo microscope, 6X magnification, out of three samples, 5 cm long and longitudinally sectioned.

A discharge gas by-pass line ensured a better control of the evaporating temperature. Figure 2 depicts an overall view of the apparatus.

Pressure and temperature were taken upstream and downstream the capillary tube. Type T thermocouples, calibrated within the range of −25°C to +120°C (uncertainty of ± 0.23°C), were attached, with tape, to the external surface of the tube. To avoid any "fin effect", each thermocouple wire involved twice the tube circumference. According to Chang and Ro [6,7], the measuring error, with this technique, would stay within 1.5%. It was found acceptable to assume that the measured value is the

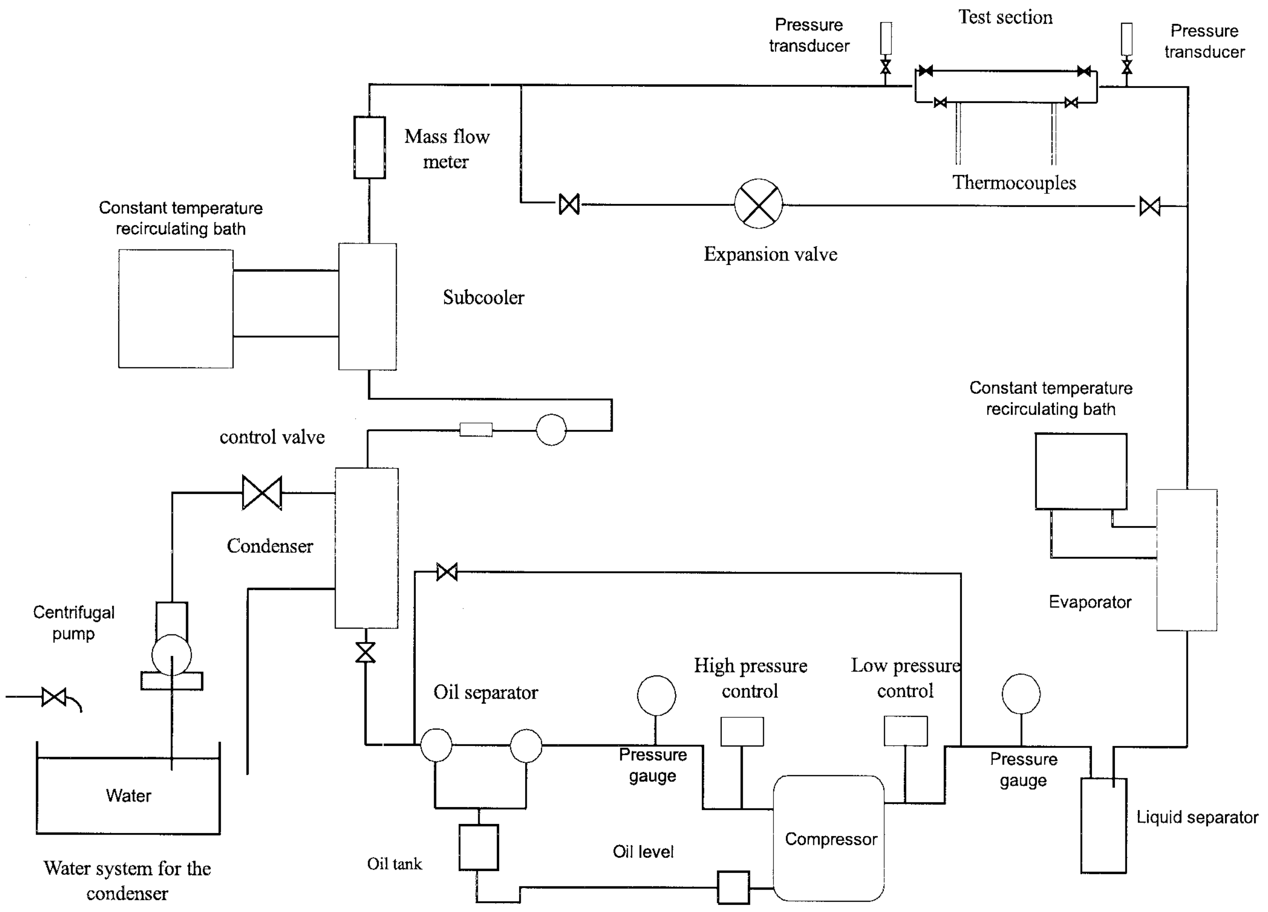

Fig. 1 - Schematics of the experimental apparatus.

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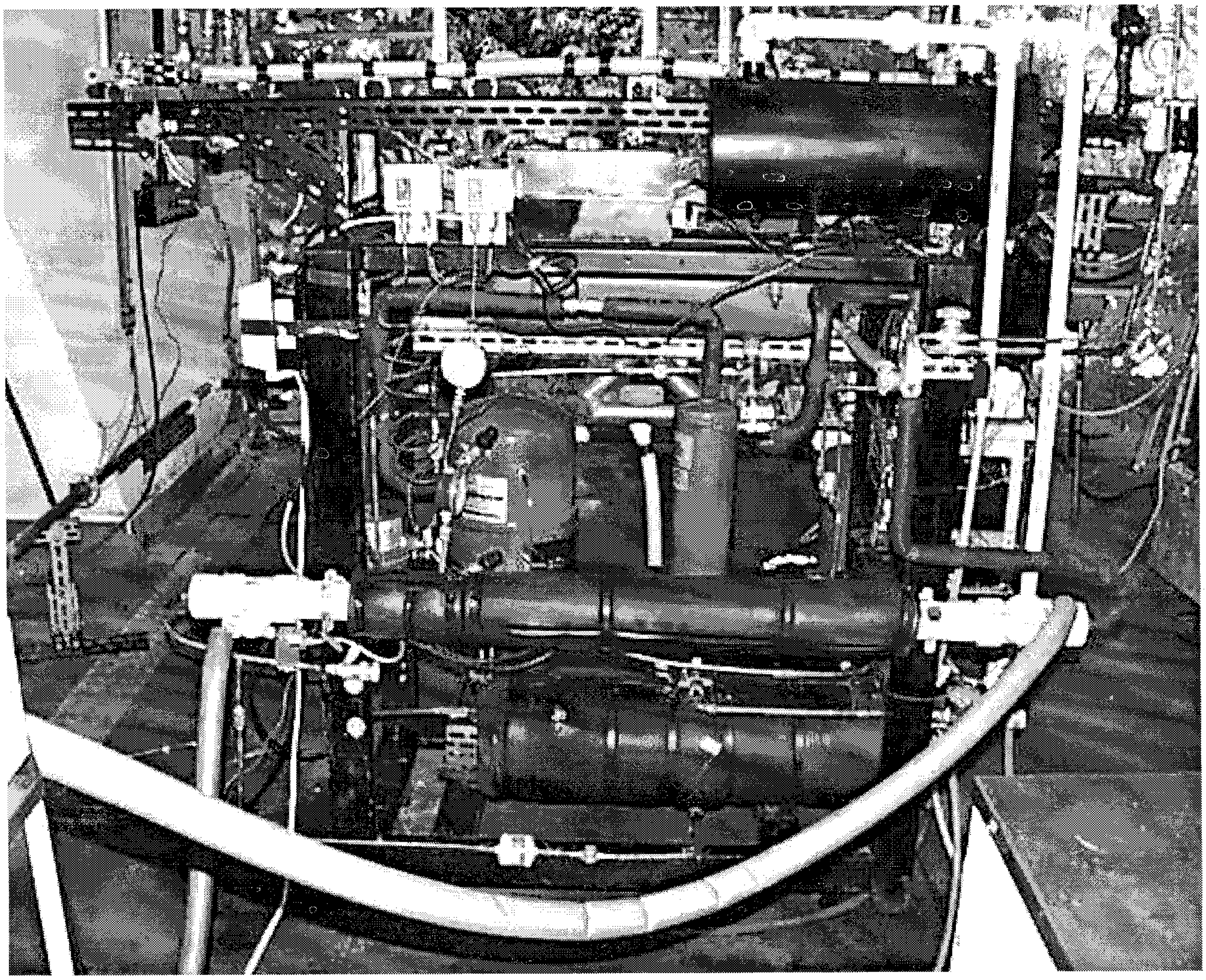

Fig. 2 - View of the experimental apparatus

refrigerant temperature. Another option would be to immerse the thermocouples in the flow. However, such immersion could affect refrigerant flow rate and pressure drop, given the small diameter of the capillary tube [6,7]. Omega pressure transducers (0-300 psig), calibrated to +/- 0.16 kgf/cm^2, were employed. Thermodynamic properties of refrigerant R-407c were calculated from available literature [9].

Refrigerant mass flow rate was measured with a Coriolis type Micromotion flowmeter, model CHF025H319NU, with uncertainty of ± 0,044%. Experimental data (pressure, temperature and mass flow rate) were recorded through a data acquisition system (Omega, TempScan/1100), with 32 channels. Data collection period was set to 5 min.

EXPERIMENTAL PROCEDURE

All runs were carried out in steady-state conditions. These were assumed to be reached when the following conditions were attained:

Δ (inlet pressure):	± 1.5 psig
Δ (inlet temperature):	± 0.2 °C
Δ (mass flow rate):	± 0.25 kg/h

From start-up, 60 to 90 minutes were necessary to establish steady state regime. In fact, the conditions above were the best that the system could attain. Condensing temperature was controlled by the condenser water mass flow rate, covering from 31°C to 45°C. These limits were imposed by the systems characteristics, such as compressor controls and refrigerant inventory. The degree of subcooling was controlled by the temperature of the water constant temperature bath. Ranging from 7°C to 24°C, it was limited by the effectiveness of the heat exchanger and by the refrigerant capacity of the ethylene glycol cooler. Evaporating pressure was always kept low enough to guarantee critical flow at the capillary tube. Control was enabled by manipulation of both the by-pass and expansion valves and by establishing the ethylene glycol temperature. All the measures described above ensured that the compressor would operate continuously throughout the experimental run, without interruption.

For the retrofit to R-407c, all the usual procedures were undertaken, including oil change, cleaning of the system with nitrogen and refrigerant charging with liquid phase only.

RESULTS

Preliminary runs were carried out with R-22. Figure 3 shows refrigerant mass flow rate as a function of the degree of subcooling and condensing temperature. The experimental data were also compared with predicted results from a simulation model from Motta [10], which had been previously validated against experimental data from the available literature [2]. Table 1, in Appendix A, summarizes these results (experimental data, model prediction and discrepancy).

Figure 4 shows the mass flow rate of refrigerant R-407c, flowing through the same capillary tube, for given condensing temperature and degree of subcooling. Being a nonazeotropic mixture, an equivalent "condensing temperature", T_{cd}, was defined as the arithmetic mean between dew point, T_d, and bubble point, T_b, assuming a fixed temperature glide of 7°C. The degree of subcooling of the liquid is taken from the bubble point, of course. In future, presentation of results should depart from the traditional condensing temperature to the condensing pressure, which allows for an unambiguous interpretation of the prevailing conditions, even for zeotropes.

The mean uncertainties of the results were as follows:
Mass flow rate: ± [1% (flow rate)+0,054] kg/h
Pressure: ± 1,8 psi
Temperature: ± 0,23 °C

Figures 5 and 6 present a comparison of the mass flow rates obtained with R-22 and R-407, for condensing temperatures of 38.5 °C and 41.5 °C respectively. It can be seen that, for larger degrees of sucooling, mass flow rates for both refrigerants are very close. At moderate degrees of subcooling, below 11- 12°C, the capillary tube capacity becomes slightly

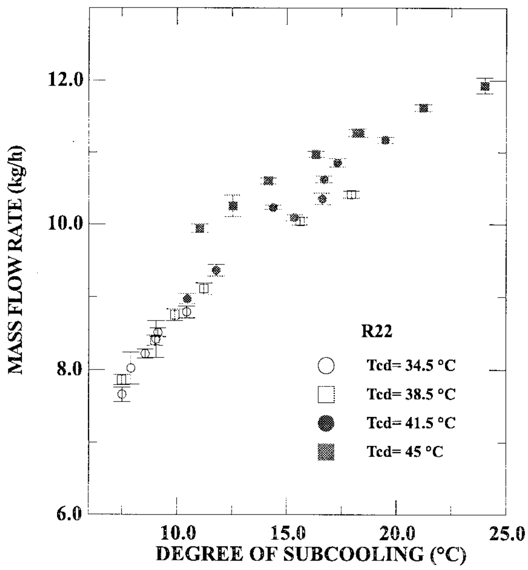

Fig. 3 - Mass flow rate for adiabatic flow R-22 through a capillary tube 1.3 m long, with an internal diameter of 0.81 mm and roughness Of 0.7 μm (condensing temperature: 34.5°C, 38.5°C, 41.5°C and 45.0°C)

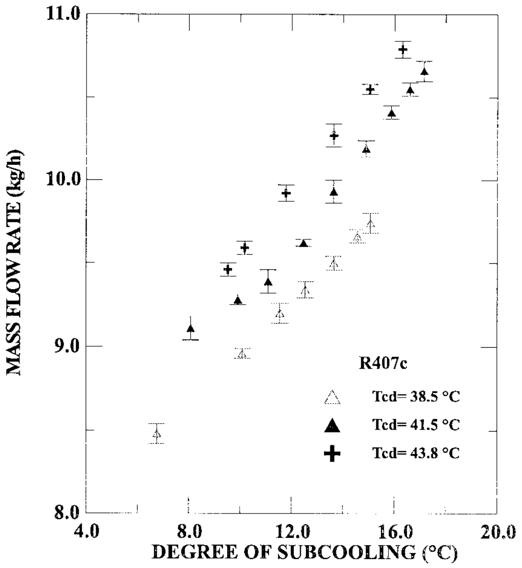

Fig. 4 - Mass flow rate for adiabatic flow R-407C through a capillary tube 1.3 m long, with an internal diameter of 0.81 mm and roughness of 0.7 μm (condensing temperature: 38.5°C, 41.5°C and 43.8°C)

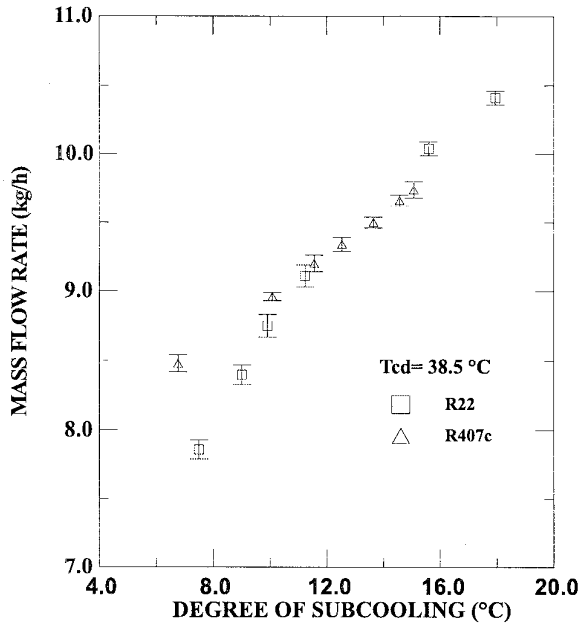

Fig. 5 - Comparison between R-22 and R-407c mass flow rates, for a condensing temperature of 38.5°C.

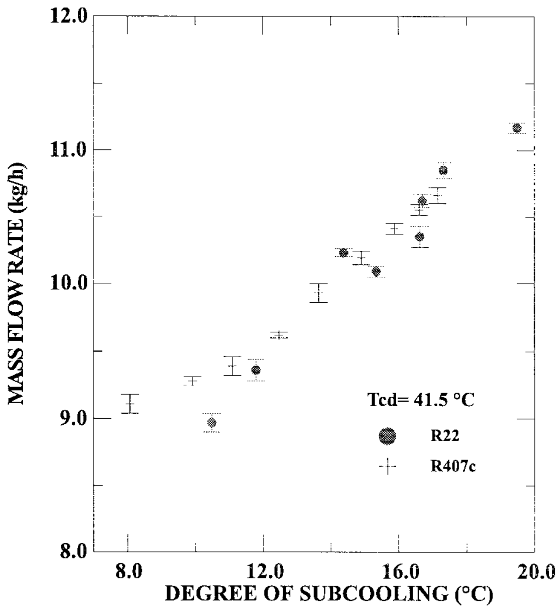

Fig. 6 - Comparison between R-22 and R-407c mass flow rates, for a condensing temperature of 41.5°C.

APPENDIX A. EXPERIMENTAL DATA

Experimental data									
capillary tube				Evaporator	Operating conditions			Predicted values	
T inlet	T oulet	P inlet	P oulet	Pevap	Mass Flow	Tcond.	Subcooling	Mass Flow	Error
°C	°C	psig	psig	psig	kg/h	°C	°C	kg/h	%
24,74	-6,60	166,21	41,65	27,53	**7,59**	31,00	6,26	**7,64**	0,66
26,98	0,52	180,33	53,43	27,75	**7,66**	34,00	7,02	**8,03**	4,86
26,58	0,53	180,30	52,61	27,85	**8,02**	34,00	7,42	**8,13**	1,48
25,93	-1,15	180,42	47,25	28,21	**8,22**	34,00	8,07	**8,28**	0,72
25,44	-2,13	180,52	45,74	28,26	**8,42**	34,00	8,56	**8,39**	-0,33
25,30	-16,00	180,41	25,00	16,39	**8,51**	34,00	8,65	**8,50**	-0,13
24,05	-4,15	179,67	41,09	28,52	**8,79**	34,00	9,95	**8,68**	-1,16
25,02	-15,39	181,09	27,32	16,76	**8,51**	34,50	9,48	**8,68**	2,01
23,92	-14,82	181,49	26,53	16,99	**8,76**	34,50	10,08	**8,72**	-0,41
23,02	-9,95	182,61	36,88	17,19	**8,92**	35,00	11,98	**9,16**	2,70
31,00	15,40	200,40	109,00	17,19	**7,86**	38,00	7,00	**8,03**	2,27
29,49	10,98	200,95	92,71	17,19	**8,40**	38,00	8,51	**8,54**	1,77
28,59	6,62	200,45	78,75	17,18	**8,75**	38,00	9,41	**8,87**	1,38
27,27	0,72	200,51	63,06	17,02	**9,11**	38,00	10,73	**9,25**	1,60
22,90	-10,11	200,53	35,83	18,00	**10,04**	38,00	15,10	**9,56**	-4,76
20,55	-11,48	200,66	32,94	17,98	**10,41**	38,00	17,45	**9,90**	-4,94
31,02	4,86	215,60	73,39	17,79	**8,97**	41,00	9,98	**9,42**	5,05
29,71	0,50	215,77	59,94	17,82	**9,36**	41,00	11,29	**9,75**	4,21
27,12	2,05	215,82	65,80	17,97	**10,23**	41,00	13,88	**10,18**	-0,44
26,16	-6,63	214,83	43,12	17,75	**10,09**	41,00	14,84	**10,38**	2,89
24,88	-9,54	215,52	37,09	17,67	**10,35**	41,00	16,12	**10,62**	2,64
24,80	-12,06	215,66	32,81	17,19	**10,62**	41,00	16,20	**10,58**	-0,33
24,18	-4,05	215,84	49,90	17,70	**10,85**	41,00	16,82	**10,68**	-1,52
22,01	-8,42	215,79	39,79	17,72	**11,17**	41,00	18,99	**11,00**	-1,50
33,96	6,38	235,63	78,49	18,01	**9,94**	45,00	11,04	**10,14**	2,03
32,46	4,50	235,86	72,75	18,00	**10,25**	45,00	12,54	**10,48**	2,20
30,83	2,18	235,74	66,00	18,29	**10,60**	45,00	14,17	**10,80**	1,92
28,67	-0,75	235,60	57,23	18,44	**10,97**	45,00	16,33	**10,98**	0,07
26,80	-3,01	235,51	51,84	18,78	**11,27**	45,00	18,20	**11,43**	1,44
26,67	0,08	235,73	61,06	17,30	**11,27**	45,00	18,33	**11,47**	1,82
23,77	7,36	235,39	81,00	17,53	**11,62**	45,00	21,23	**11,76**	1,26
20,98	11,80	235,33	95,31	17,71	**11,93**	45,00	24,02	**11,95**	0,21

Table 1 Comparison with predicted values of Motta's model [10].

greater for refrigerant R-407c. This may be explained by the fact that both refrigerants have similar properties in the liquid region whereas pressure drop may differ to a greater extent in the two-phase portion of the capillary tube. When the liquid length (i.e., the length of tube covered by subcooled liquid) does not have a predominant effect on the overall pressure drop (small degrees of subcooling) mass flow rates of R-22 and R-407c will differ to a certain extent. Table 2, in Appendix A, presents the experimental data for R-407c.

CONCLUDING REMARKS

Although refrigerant R-407c is a strong candidate for the substitution of R-22, little information is still available in the literature about the capacity of capillary tubes operating with this nonazeotropic mixture. In the present work, tests were conducted for the study of adiabatic flow of refrigerants R-22 and R-407c through a capillary tube. For the particular geometry under study results have shown that, with large degrees of subcooling (above 12°C), refrigerant mass flow rates are very similar. As the subcooling decreases, refrigerant R-407c mass flow rate becomes a fraction larger. A total of 54 points, 32 for R-22 and 22 for R-407c, were obtained for different operating conditions (condensing temperature and degree of subcooling).

Although limited to one single geometry, the experimental data here may be used for the validation of simulation models. In this respect, the testing of other tube geometries, extending the range of the present results, is suggested. The investigation of the influence of the oil content on the capillary tube capacity is also planned. Comparisons between the performance of R22 and R407c will be beneficial to the retrofit of air-conditioning systems.

ACKNOWLEDGEMENTS

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Experimental data								
Capillary tube				Evaporator	Operating conditions			
Tinlet	Toulet	P inlet	P oulet	Pevap	Mass Flow	Tcond	Tbubble	Subcooling
°C	°C	psig	psig	psig	kg/h	°C	°C	°C
28,24	-17,98	205,29	24,46	16,51	**8,48**	38,50	35,00	6,76
24,92	-18,07	205,46	24,63	16,58	**8,96**	38,50	35,00	10,08
23,45	-17,59	205,47	24,95	17,16	**9,20**	38,50	35,00	11,55
22,46	-17,60	205,67	25,24	17,45	**9,34**	38,50	35,00	12,54
21,35	-17,57	205,47	25,63	17,76	**9,50**	38,50	35,00	13,65
20,43	-18,08	205,50	24,92	17,13	**9,66**	38,50	35,00	14,57
19,93	-17,50	205,44	25,98	18,32	**9,74**	38,50	35,00	15,07
29,93	-16,21	225,52	26,79	17,99	**9,11**	41,50	38,00	8,07
28,09	-16,70	225,45	26,85	18,75	**9,28**	41,50	38,00	9,91
26,91	-16,43	225,46	27,56	19,63	**9,39**	41,50	38,00	11,09
25,53	-17,33	225,23	26,28	18,04	**9,62**	41,50	38,00	12,47
24,36	-17,29	225,50	26,12	17,85	**9,93**	41,50	38,00	13,64
23,10	-17,09	225,33	26,34	18,21	**10,19**	41,50	38,00	14,90
22,12	-16,88	225,44	27,29	18,60	**10,41**	41,50	38,00	15,88
21,40	-16,82	225,53	27,16	18,81	**10,55**	41,50	38,00	16,60
20,85	-16,68	225,62	27,52	19,14	**10,66**	41,50	38,00	17,15
30,18	-16,96	235,41	26,70	17,49	**9,46**	43,20	39,70	9,52
29,53	-16,68	235,68	27,09	17,97	**9,59**	43,20	39,70	10,17
27,92	-16,09	235,79	28,54	19,28	**9,92**	43,20	39,70	11,78
26,06	-16,05	235,37	28,44	19,10	**10,27**	43,20	39,70	13,64
24,65	-15,95	235,42	28,60	19,36	**10,55**	43,20	39,70	15,05
23,39	-15,88	235,17	28,70	19,46	**10,79**	43,20	39,70	16,31

Table 2 - Experimental data for R407c.

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