Influence of Geometrical Parameters on Capillary Behavior with New Alternative Refrigerants

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ABSTRACT

In this paper, the experimental data obtained on capillary tube behavior, using various new alternatives under different geometrical parameters will be presented and analyzed. Capillary geometrical parameters will include length, diameter, as well as entrance conditions.

The results clearly showed that the pressure drop across the capillary tube is significantly influenced by the diameter of the capillary tube, inlet conditions to the capillary and refrigerant type. The data demonstrated that the capillary pressure drop decreases with the increase of the capillary diameter and that alternatives in general experience higher pressure drop than that of R-22.

Introduction

Various models and experimental studies have been reported in the literature on the capillary tube with pure CFCs and HCFCs refrigerants such as CFC-12 and HCFC-22 (2,3,4,5,7,9,12,13). Most of these studies covered the three flow regions encountered in capillary tubes; two-phase, saturated and sub-cooled flows. The numerical models employed the homogeneous flow equation approach. In these models, the thermo-physical properties were calculated using experimental based correlations limited to specific flow conditions through capillaries.

Recently, the HVAC& R industry has adapted a list of potential alternatives to HCFC-22 and CFC-502. To the authors' knowledge, there are very limited studies reported in the literature on the performance of capillary tubes with some zeotropic and azeotropic refrigerant mixtures proposed as alternatives to either HCHC-22 and or CFC-502 (2,9,12,13); R-404A, R-507, R-407C, and R-410A.

Therefore, the proposed research work has been undertaken to enhance our understanding of the capillary tube's performance using azeotropic and zeotropic binary and ternary refrigerants.

Experimental Apparatus and Measurements

An experimental setup composed of a water-source heat pump with a capacity of 25,000 BTUH and equipped with anti-freeze heated evaporator, has been fully instrumented with pressure, temperature, and power sensors as well as water, refrigerant and coolant flow metering devises. Figure 1 shows a schematic diagram of the experimental setup. The vapor-compression system was composed mainly of a hermetic compressor equipped with an accumulator, condenser, evaporator, and adjustable expansion device. The condenser and evaporator were respectively water cooled and anti-freeze heated and were made of enhanced surface fluted tubing heat exchangers. Both condenser and evaporator were equipped with pre and post heat exchangers to control the flow conditions at the capillary tube test section.

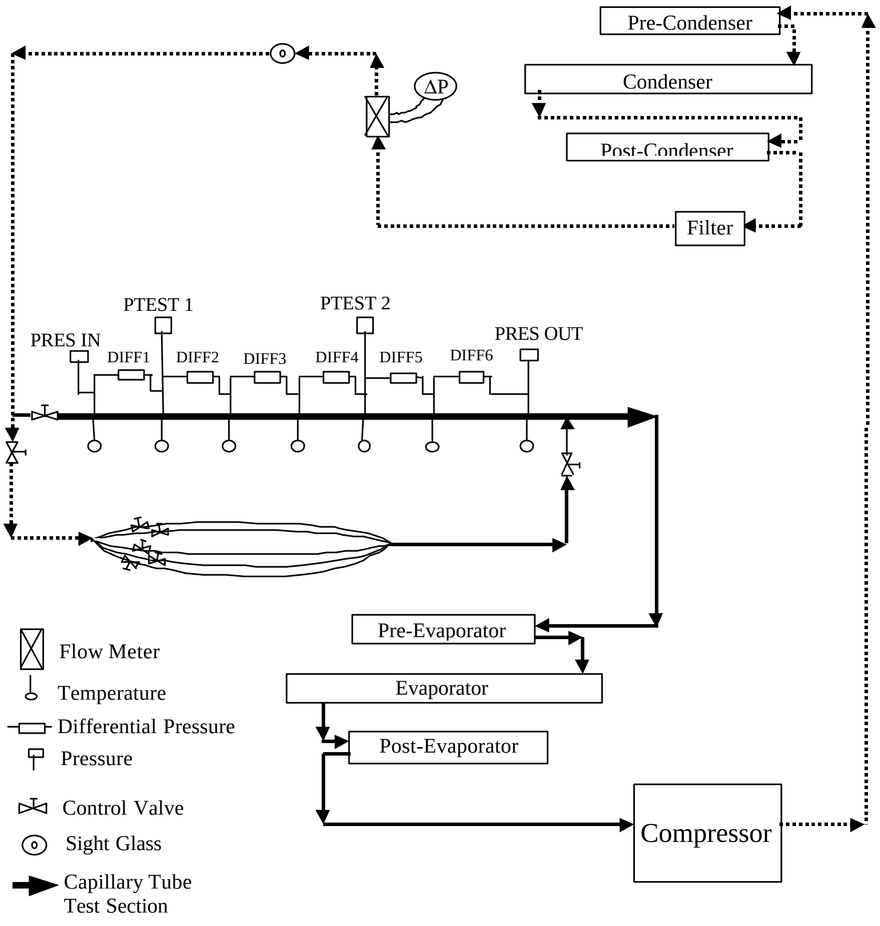

Figure 1 General Schematic Diagram of the Experimental Setup.

A straight run of capillary tube was installed together with various measuring stations equipped with sensors for temperature, pressure and differential pressure. Those sensors were necessary for measurement of the temperature and the pressure profiles along the capillary tube length. Three sets of capillary tube geometry have been tested under different conditions. Tables 1 and 2 present the test conditions and the capillary tubes geometrical parameters.

1	Temperature of Water at the Condenser Inlet	21 °C
2	Temperature of Anti-Freeze at the Evaporator Inlet	4 °C
3	Condenser Water Flow Rate	575 g/s
4	Evaporator Anti-Freeze Flow Rate	400 g/s
5	Condenser Pressure	1100 to 2000 kPa
6	Condenser Temperature	31 to 71 °C
7	Evaporator Pressure	103 to 393 kPa
8	Evaporator Temperature	-24 to –9 °C

Table 1 Test Conditions

Capillary Tube Diameter	2.159 mm (0.085”)	1.905mm (0.075”)	1.778mm (0.070”)
Capillary Tube Length	222.3 cm	126.1 cm	123 cm
Pressure Port # 1	0 cm	0 cm	0 cm
Pressure Port # 2	55.57 cm	27.7 cm	29.35 cm
Pressure Port # 3	95.589 cm	58 cm	50.75 cm
Pressure Port # 4	125.599 cm	76.7 cm	67.27 cm
Pressure Port # 5	176.73 cm	97.1 cm	92.95 cm
Pressure Port # 6	204.52 cm	117.4 cm	108.8 cm
Pressure Port # 7	222.3 cm	126.1 cm	123 cm

Table 2 Capillary Tube Geometry

To minimize the heat loss to the surroundings, each capillary tube run was insulated with layers of pipe insulation with a thermal conductivity of 0.39 W/m ºK (0.27 Btu/h ft^2 ºF). This was necessary to ensure that testing the capillary tube was under adiabatic conditions.

Standards test conditions were used at the condenser inlet; however, the refrigerant temperatures were varied at the evaporator entrance from -2 to -20°C, to simulate various severe conditions encountered in many applications. The oil content in the refrigerant loop was estimated to be about 1% using gas chromatography. Polyolester oil was used during the testing.

A schematic view of the experimental capillary tube/heat pump setup is shown in figure 1. Table 1 gives the test conditions and information on the key parameters of the system. Pressure, differential pressure, temperature, power consumed and flow rate measuring stations are also shown in figure 1. All pressures were measured using calibrated pressure transducers (0-3400 kPa). The accuracy of the pressure transducers was ±2.5%. Differential pressure transducers were employed to measure the refrigerant pressure drop. RTD temperature sensors were employed for temperature measurements. The accuracy of RTD was within ±1K.

All recorded measurements were obtained during heating mode operation and at a heat sink entering temperature of 21°C while the source coolant temperature was kept constant at 4°C at the evaporator inlet. The temperature difference across the evaporator and condenser coils was controlled to achieve the desired conditions.

Calibrated orifices were installed in the liquid line after a liquid receiver and used to measure the total refrigerant mass flow rate and the mass flow rate to the capillary tube test section. Both orifice pressure taps were connected to a differential pressure transducer (0 to 70 kPa). The measurement of the total mass flow rate was necessary for the energy balance calculations. The accuracy of the mass flow measurements was ±3% of the normal flow.

Power supplied to the compressor was measured to close the heat balance and also to evaluate the coefficient of performance. An AC/DC amperage clamp-on device was calibrated for power or current measurements as well as power factor with accuracy of ±2.5%.

Data collection was carried out using a P133 personal computer equipped with a data acquisition system having a capacity of 112 channels. This enabled us to record, with a single scan, local properties such as pressure drops, pressures, temperatures, flow rates, heat flux, and power.

All tests were performed under steady-state conditions according to the ASHRAE and ARI Standards (1). Following each test, the system was drained and evacuated and charged with appropriate refrigerant mixture. Similar procedures were followed when testing the various capillary tube geometries. The data channels were scanned every second and stored every 10 seconds. The stored values were averaged over a period of 10 seconds.

All baseline tests for R-22 were performed as reference for comparison purposes. The primary parameters observed during the course of this study were; pressure and temperature profiles along the capillary tubes length, mass flux, heat flux, quality, thermal capacities, power consumption, temperature and pressure ratios for the alternative refrigerants under investigation. The following alternate refrigerants were tested during the course of this study; R-410B (R32/R125: 45/55%), R-407C (R32/R125/R134a: 23/25/52%), R-410A (R32/R125: 50/50%) at different conditions.

In order to evaluate the performance characteristics, the thermodynamic properties, as well as transport properties of azeotropic or zeotropic refrigerant mixtures should be known. The NIST/REFPROP database version 6.01 (6) was employed with caution to determine the transport properties of the mixed refrigerants. This is important since interaction parameters influence the calculation of thermodynamic properties (6,8). Recommended interaction parameters were employed.

Results and Discussion

During the course of this study, three diameters of capillary tubes were tested; 2.159mm (0.085"), 1.905mm (0.075") and 1.778mm (0.070"), with different lengths; 222.3, 126.1 and 123 cm respectively. The anti-freeze solution temperature was at 4 ºC with a flow rate of 400 g/sec. The condenser water flow was 575 g/sec at constant temperature of 21º C. During testing, refrigerant mass flow rate through the capillary tubes varied between 9 to 15 g/sec. However, the total refrigerant mass flow rate through the heat pump system was between 15 to 35 g/sec. The system condenser pressure varied between 1100 to 2000 kPa and the evaporator pressure also varied between 103 to 393 kPa. Other testing key parameters are presented in tables 1 and 2. In the following sections, those key parameters will be outlined and discussed.

Pressure Profile

Samples of the tests experimental data on the sub-cooled flow in the 2.129mm (0.085”) capillary tube diameter are shown in figure 2 and 3 as a function of the capillary tube length for the different refrigerants under question. It appears from these graphs that as the capillary tube length increases, the refrigerant temperature and pressure decrease. The same trend was observed for R-22 and reported in the literature by various investigators (2,3,4,5,7,9,12,13). The two-phase flow pressure profile data in the capillary tube were characterised by the rapid decrease of the pressure towards the end of the capillary tube. No choke flow phenomena was observed. This has been observed by others such as Wolf et al. (13). The capillary tube pressure profile data suggest that the same phenomena occurred with the alternatives to R-22.

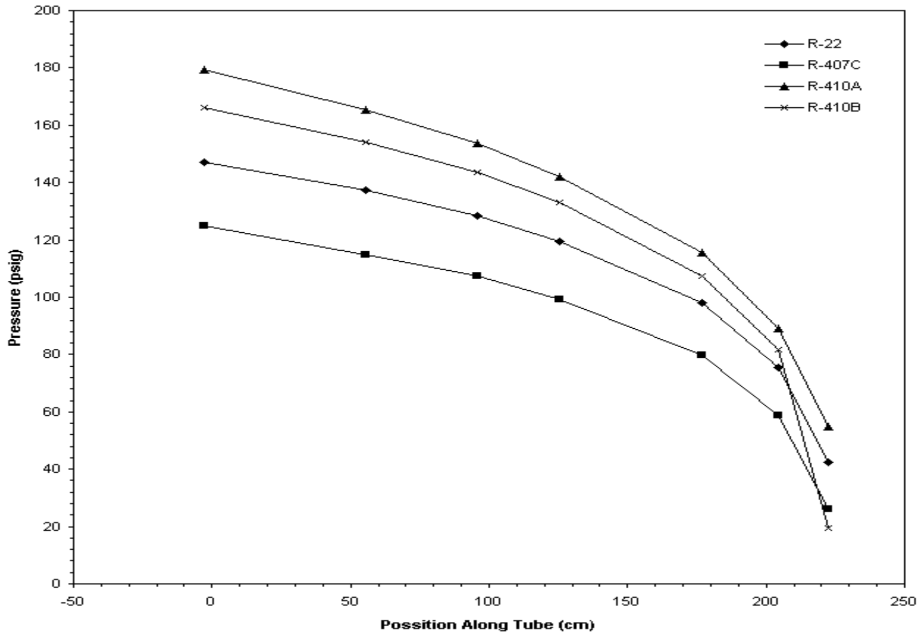

Figure 2 Pressure In Capillary Tube versus Position Along 2.159mm (0.085”) Æ Tube at Subcooled Conditions

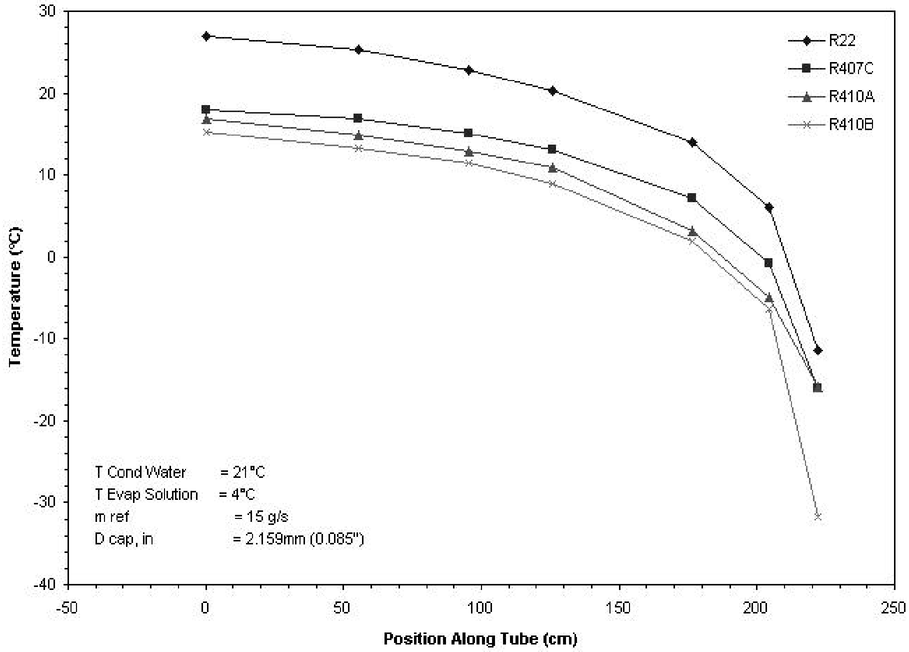

Figure 3 Temperature In Capillary Tube versus Position Along 2.159mm (0.085”) Æ Tube at Subcooled Conditions

Furthermore, the data depicted in these figures also showed that R-407C has similar pressure drop along the capillary tube compared to R-22. On the other hand, the data also showed that R-410A and R-410B have the highest-pressure drop compared the other alternatives including R-22. This is mainly attributed to the components and their compositions, particularly R-32 which is a high-pressure refrigerant. Similar behavior trends have been observed for the other capillary tube diameters of 1.778mm and 1.905mm (0.07” and 0.075”).

Flow Regimes

During the course of this study, three flow regimes were investigated; sub-cooled, saturated, and two-phase flow. Samples of the data collected during these tests are presented in figures 2 through 7, where the local refrigerant pressure and temperatures are depicted along the capillary tube length. The results were depicted for capillary tube diameter of 2.159mm (0.085”) and the figures clearly show the impact of flow regimes on the capillary behavior. However, it is worthwhile mentioning that similar behavior have been observed with the other capillary tube geometry. Results for the other capillary diameters will be presented elsewhere in this paper.

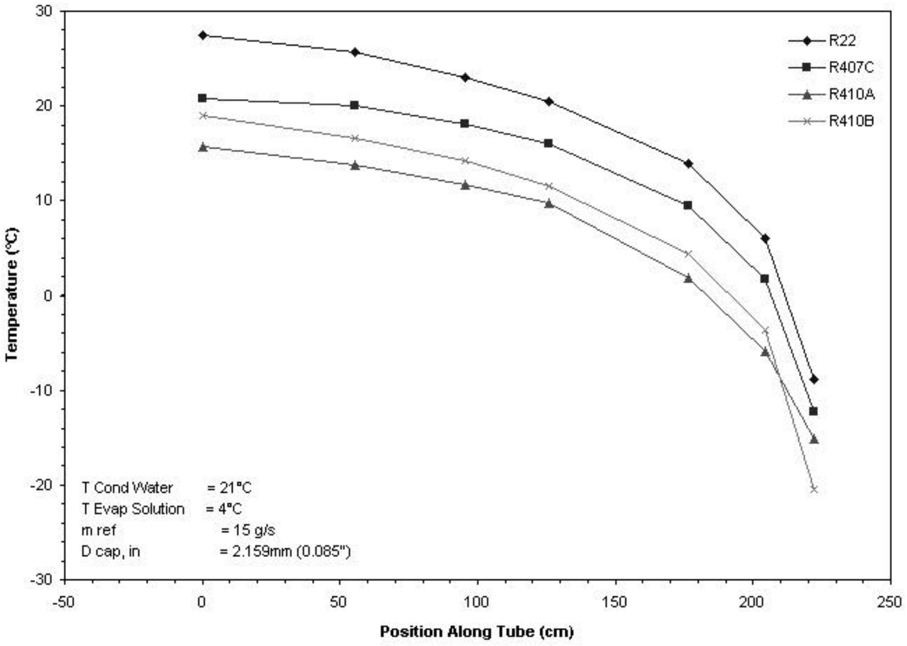

Figure 4 Temperature In Capillary Tube versus Position Along 2.159mm (0.085") Æ Tube at Saturated Conditions

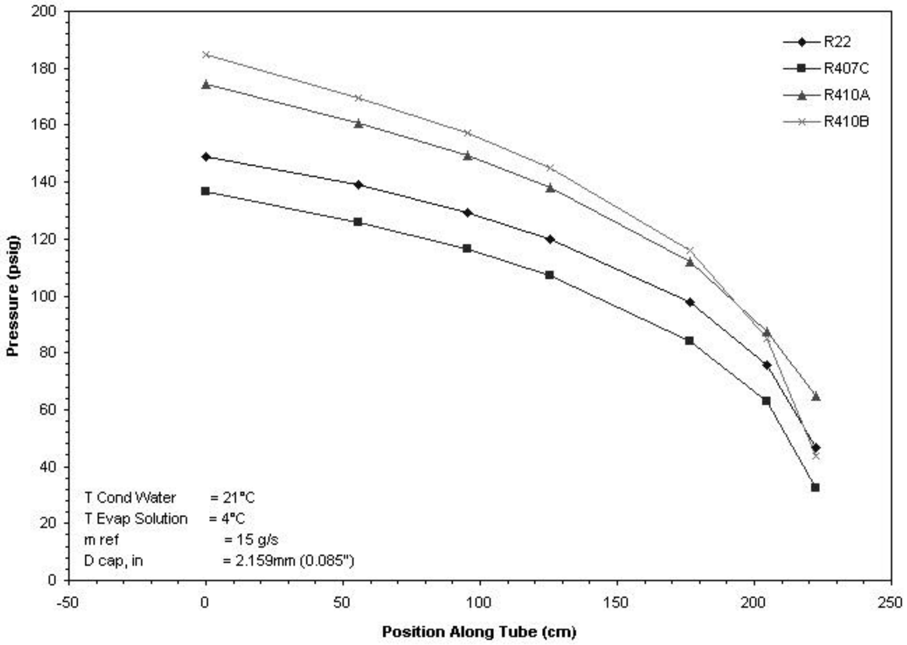

Figure 5 Pressure In Capillary Tube versus Position Along 2.159mm (0.085") Æ Tube at Saturated Conditions

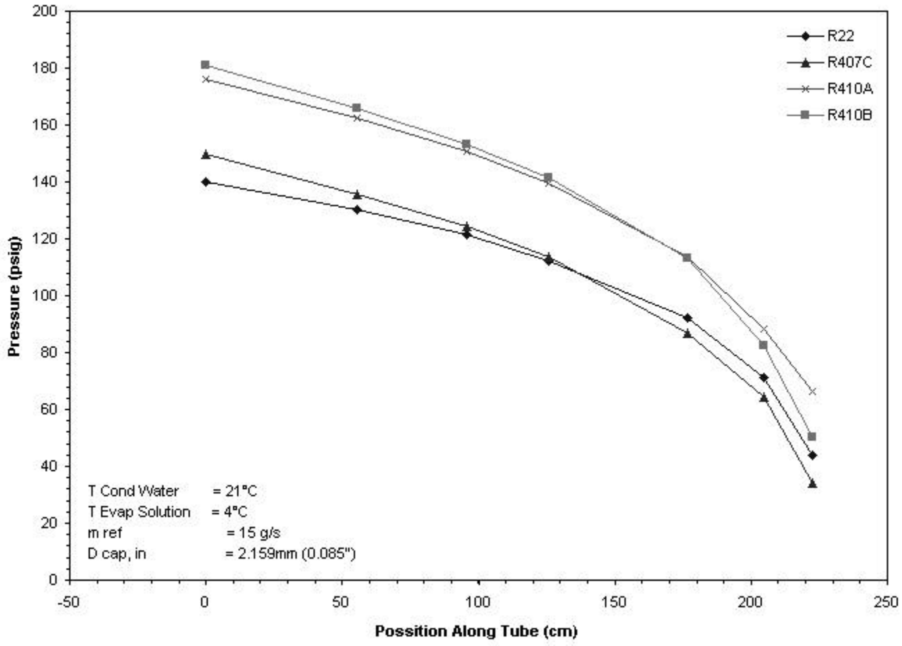

Figure 6 Pressure In Capillary Tube versus Position Along 2.159mm (0.085") Æ Tube at 2-Phase Conditions

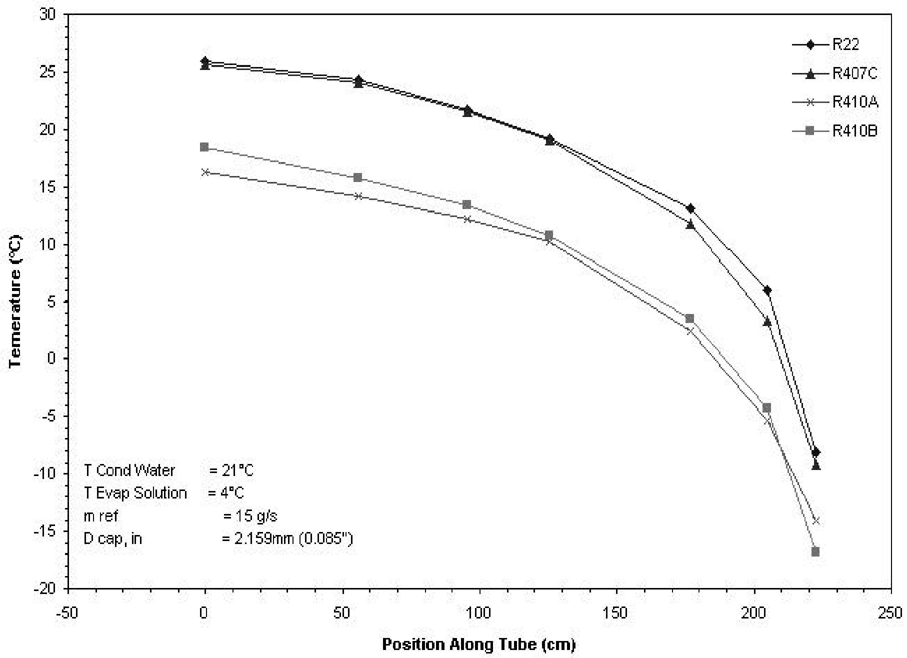

Figure 7 Temperature In Capillary Tube versus Position Along 2.159mm (0.085") Æ Tube at 2-Phase Conditions

Geometry

It has been reported in the literature that the capillary tube geometry plays an important role in the system design, therefore, figure 8 has been constructed. Samples of the data collected during this study on the capillary pressure drop at different diameters 1.778mm (0.07”), 1.905mm (0.075”) and 2.159mm (0.085”) were plotted for saturated R-410A. The results clearly show that the pressure drop is significantly influenced by the diameter of the capillary tube. The data demonstrates that the capillary pressure drop decreases with the increase of the capillary diameter. However the rate of increase depends upon the refrigerant type and certainly the blend’s concentration. This can be observed from the data presented in this paper (figures 2 through 7) on the R-410A and R-410B blends, where, the difference in concentration of the refrigerant mixture resulted in different capillary tube pressure drop.

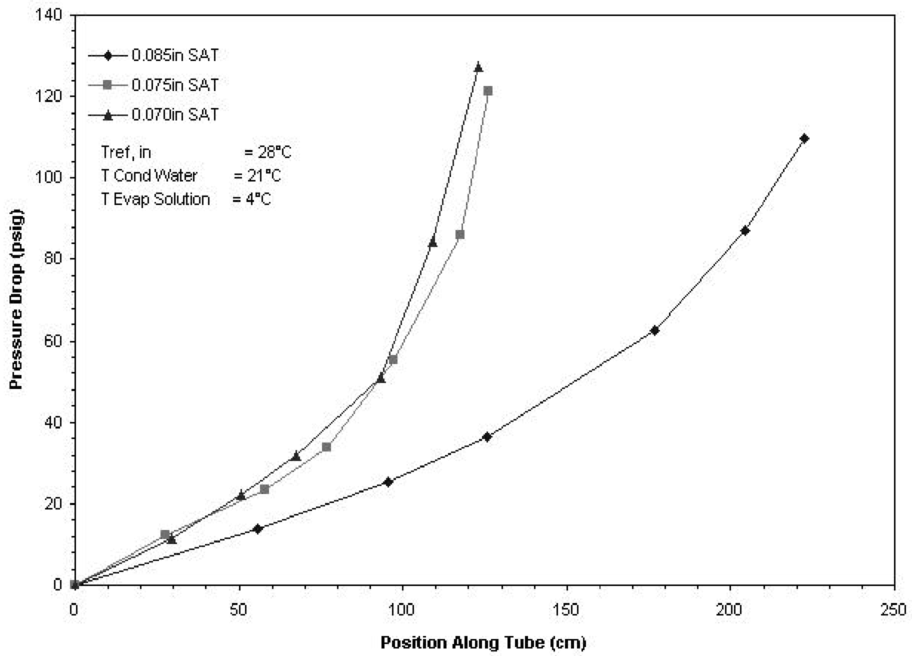

Figure 8 Pressure Drop Across Capillary Tube versus Position Along Capillary Tube for the 3 tested Geometries using R-410A

Refrigerant Flow Rate

As previously discussed, the behavior of the capillary tube principally depends upon the geometry and inlet conditions. However, refrigerant flow through the capillary plays an important role.

Therefore, figure 9 has been constructed to study the refrigerant flow variation on the capillary behavior. The data depicted in this figure clearly illustrated that the pressure drop and related capillary parameters depend upon the mass flow rate of refrigerant. Increasing the refrigerant mass flow rate will result in increasing the pressure drop along the capillary tube. This behavior is not unique to the blends and has been observed for pure refrigerants (2,3,4,5,7,9,10,12,13). However, it is worthwhile mentioning that higher refrigerant flows result in higher rates of capillary tube pressure drops.

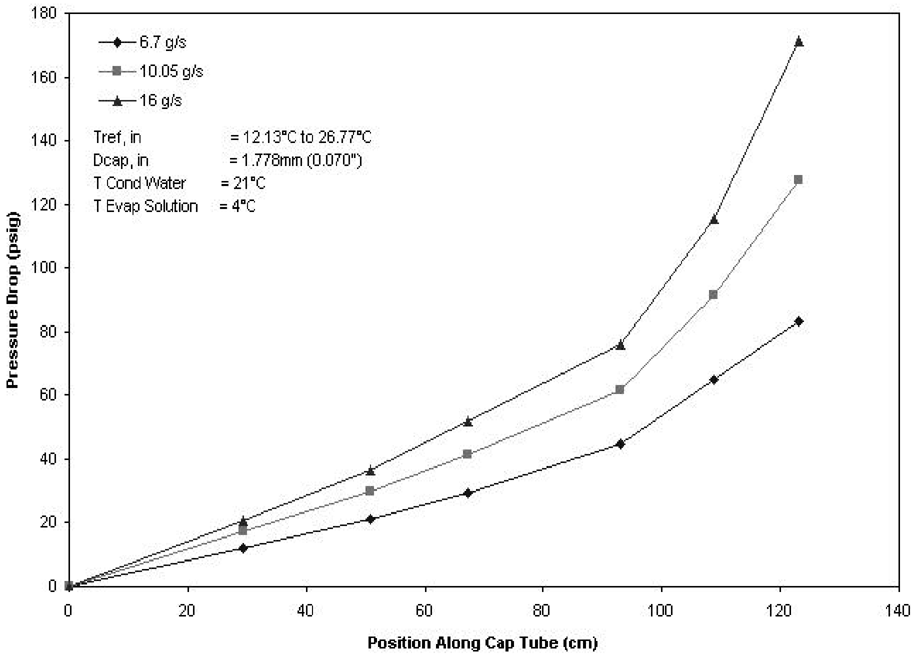

Figure 9 Pressure Drop Across Capillary Tube versus Position Along Capillary Tube at Different Test Section Refrigerant Flow Rates Using R-407C and the 1.778mm (0.070") Æ Tube

It quite clear from the data presented hereby in this paper that most alternatives to R-22 experience pressure drop higher than R-22 and the alternatives exhibit a similar behavior to that of pure refrigerants. However, it is also worthwhile mentioning that the data presented in figures 8 and 9 clearly demonstrated that special attention should be given to the use and design of capillary tube in systems using alternatives to R-22 since each single alternative has its own characteristics.

Other matters related to the significance of changing the pressure drop and temperature drop along the capillary tubes for alternate refrigerants are presented in some of our other publications namely, Sami and Maltais (11).

Conclusion

Experimental data showed that R-410B has the highest-pressure drop along the capillary tubes compared to the alternatives under question and also has the highest temperature drop along the capillary tube. The data also showed that R-407C has similar capillary behavior to that of R-22.

It can be observed from the data that the general trend of these data is that the pressure drop across the capillary tube decreases with the increase of the pressure ratio as has been observed for pure refrigerants.

The results clearly showed that the pressure drop across the capillary tube is significantly influenced by the diameter of the capillary tube, inlet conditions to the capillary and refrigerant type. The data demonstrated that the capillary drop decreases with the increase of the capillary diameter and that alternatives in general experience higher pressure drop than that of R-22.

Acknowledgement

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