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AN EXPERIMENTAL STUDY OF RETURN BEND EFFECTS ON PRESSURE DROP AND VOID FRACTION.

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ABSTRACT

Evaporative two phase flow conditions in return bends were studied. The void fraction of the system was examined as well as the pressure drop across the bends. Both a low pressure refrigerant, R134a, and a high pressure refrigerant, R410A, were used to test the return bends under horizontal, upward, and downward orientations. Negligible effects on void fraction were measured. Pressure drop data showed some trends due to changes in quality, refrigerant, and orientation.

NOMENCLATURE

C_d	Center-to-Center Distance in Bend (m)
D	Inside Diameter in Bend (m)
f_g	Friction Factor [Geary]
G	Mass Flux (kg/m^2 s)
l	Bend Length [Geary]
p	Pressure (kPa)
v	Specific Volume
x	Quality
z	Distance (m)

Greek Symbols

α	Void Fraction
δ	Bend Characterization Parameter = $\sqrt{D/C_d}$
μ	Viscosity (kg/m s)
ρ	Density (kg/m^3)

Dimensionless Parameters

ε	Resistance Factor [Pierre, Christoffersen]
Fr	Froude Number
Ft	Modified Froude Rate [Graham]
Φ^2	Multiplier [Souza, Jung and Radermacher]
Re	Reynolds Number
X, Xtt	Lockhart-Martinelli Parameter

Subscripts

ave	Average
b	Bend [Pierre, Christoffersen]
f	Frictional [Pierre, Christoffersen]
l	Liquid
lo	Liquid Only
t	Turning [Pierre]
tp	Two Phase
v	Vapor

INTRODUCTION

Void fraction and pressure drop in an air-conditioning or refrigeration system are important design factors. The void fraction allows designers of reduced-charge systems to minimize refrigerant charge within the refrigerant system as well as better predict the heat transfer characteristics of a system. Studies have been performed by Wilson [1998] and others to determine the void fraction in straight tube, however, refrigerant void fraction in return bends appears to have not been studied.

Pressure drops within an air conditioning or refrigeration system create inefficiencies for the compressor and cause more work due to increasing the high-to-low side pressure difference. Pressure drop in return bends have been studied by Pierre [1964], Geary [1975], and Christoffersen [1993]. This paper will compare the current data with the models by Pierre, Geary, and Christoffersen, as well as discuss the discrepancies in the results. Trends due to quality, refrigerant, and orientation will also be presented.

BACKGROUND

Considerable work has been performed for correlations in pressure drop for straight tubes. Significantly less work on pressure drop has occurred on return bend fittings. Three pressure drop correlations for pressure drops in return bends have been found and will be discussed.

Two straight tube pressure drop correlations are used to compare with the data from this experiment. These correlations are based on the separated flow model developed by Lockhart and Martinelli [1949]. They postulated that the pressure drop of a two-phase flow can be correlated to that of the pressure drops due to pure liquid flow and pure vapor flow. They developed the Lockhart-Martinelli parameter, X, which is given as follows:

$$X = \left[\frac{\left(\frac{\Delta p}{\Delta z} \right)_l}{\left(\frac{\Delta p}{\Delta z} \right)_v} \right]^{0.5}$$

Assuming both phases of flows are turbulent, the Lockhart-Martinelli parameter can be defined as:

$$X_{tt} = \left(\frac{1 - x_{ave}}{x_{ave}} \right)^{0.9} \left(\frac{\rho_v}{\rho_l} \right)^{0.5} \left(\frac{\mu_l}{\mu_v} \right)^{0.1}$$

Relations for multipliers to find two phase pressure drops used Xtt. The relation is:

$$\Phi^2 = \frac{(\Delta p)_{tp}}{(\Delta p)_{lo}}$$

Jung and Radermacher [1989] developed a two-phase multiplier to be:

$$\Phi^2 = 12.82 X_{tt}^{-0.147} (1 - x)^{1.8}$$

This multiplier actually takes into account both the frictional and acceleration pressure drops. The acceleration pressure drop was less than 10% of the total pressure drop for the conditions tested by Jung and Radermacher. Souza [1993] developed the following pressure drop correlation:

$$\Phi^2 = (1.376 + c_1 X_{tt}^{-c_2})(1-x)^{1.75}$$

For $0 < Fr_l \leq 0.7$

$$c_l = 4.172 + 5.480Fr_l - 1.564Fr_l^2$$

$$c_2 = 1.773 - 0.169Fr_l$$

For $Fr_l > 0.7$

$$c_l = 7.242$$

$$c_2 = 1.655$$

Souza separated the friction and acceleration pressure drops for the multiplier. A Froude number effect was also included in order to take the flow regime into account.

For the return bends, three correlations for pressure drop have been examined. These models are based on two classes. The first class decomposes the pressure drop due to the bends into one part that turns the flow and another part that resists the flow due to friction as seen in the following equation:

$$\Delta P_b = \Delta P_t + \Delta P_f$$

Pierre [1964] developed a resistance factor, ε, that was used to calculate the turning of the flows. This equation is given as:

$$\varepsilon = \frac{2\Delta P_t}{G^2 v_{ave}}$$

The resistance factor was found to be within a value of 0.8 to 1.0 when oil was not present. Christoffersen [1993] felt the constant resistance factor was valid for single phase flows, however, due to the viscous effects, secondary flows, and separation, Christoffersen created a correlation that allowed for a varying resistance factor. The correlation is:

$$\frac{2\varepsilon}{\delta \mathrm{Re}_l} = C_1 X_{tt}^{C_2}$$

Geary [1975] created a correlation for the entire pressure drop of the bend without separating the turning and frictional pressure drops. Geary determined a friction factor with the form:

$$f_g = \frac{5.58 * 10^{-6} \mathrm{Re}_v^{0.5}}{\exp(0.215 C_d / D) x^{1.25}}$$

The constant 5.58 in the equation has dimensions of ft^2/in^2. The equation Geary used to calculate the pressure drop in the bend is:

$$\Delta P_g = f_g \frac{l}{D} \frac{G_v^2}{2\rho_v}$$

EXPERIMENTAL DESIGN

The evaporation test loop was used to condition the inlet mass flux, quality, and temperature. Mass flux ranges from 65 to 440 kg/m^2 s and qualities from 5 to 70% were obtained. The inlet temperature was 5° C. Adiabatic conditions were tested. Conditions were monitored using a computerized data acquisition system. A schematic of the loop is shown in Figure 1.

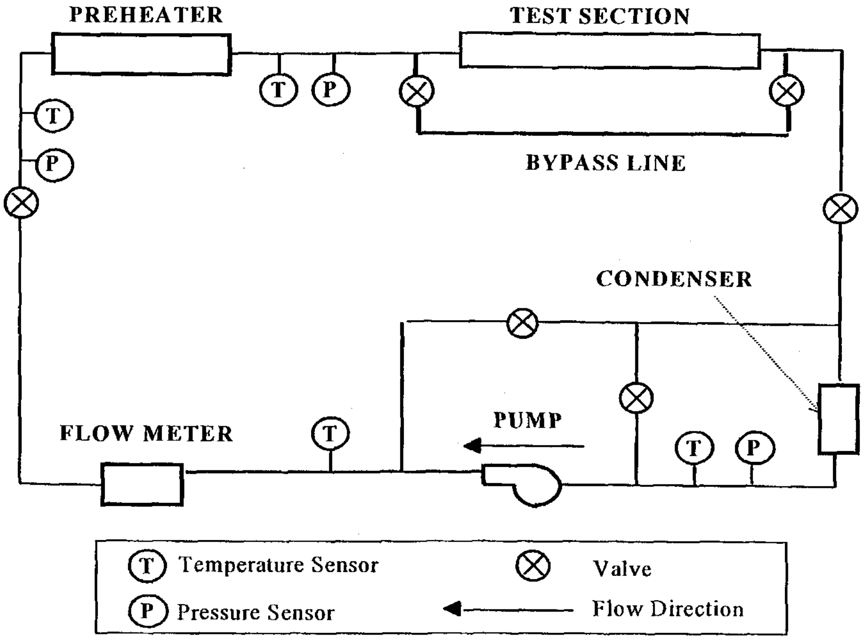

Figure 1: Test Section Schematic

Subcooled R134a or R410A refrigerant is driven through the loop using a pump. The pump is used to control the mass flux of refrigerant going though the loop. The refrigerant goes to a test section conditioning section, labeled preheater in the figure, where electrical heater strips are used to add energy to the refrigerant and change the quality to a specified value. This conditioned refrigerant goes into the return bend test section and is subcooled after the test section using a condenser. The return bend test section was oriented in three ways so that the refrigerant would flow horizontal, vertical downward, and vertical upward in the return bends. A schematic of the test section is shown in Figure 2.

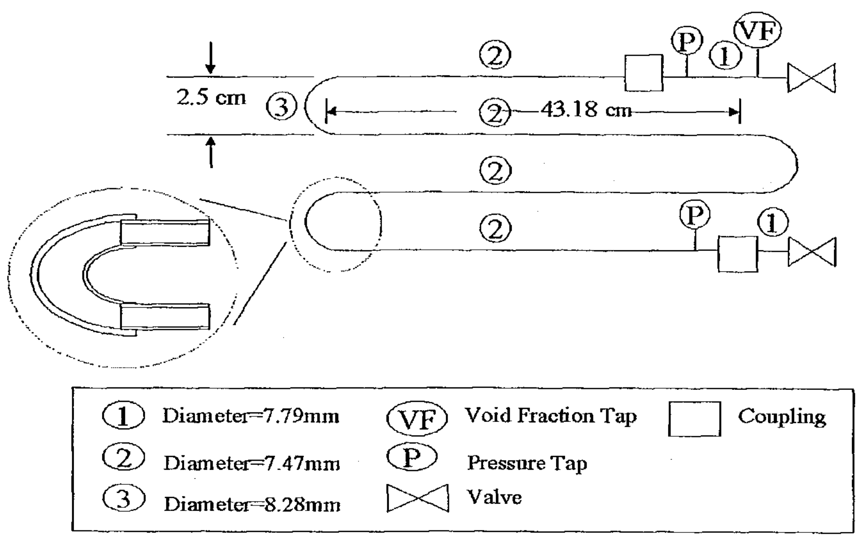

Figure 2: Return Bend Diagram

After the refrigerant reached and remained at conditions for at least 30s, the pressure transducer valves on the test section would first be closed, followed by the valves for the test section. After the test section is closed off, an evacuated receiver tank would be connected to the test section void fraction tap. The refrigerant would be discharged into the tank and the mass of the refrigerant would be determined. The final vapor mass remaining in the test section would be calculated from the temperature and pressure condition. With the total mass, test section volume, and test section temperature/pressure, the void fraction can be determined. The test section pressure drop was averaged from a set of readings taken from the differential pressure transducer while the loop was running under steady state and before the test section was closed off.

RESULTS

Void Fraction

The void fraction was obtained using the procedure mentioned previously. More details on this procedure can be found from Wilson [1998]. Previous testing has been done to find the void fraction in straight tubes. From the study at the University of Illinois, the void fraction was found to be a function of the Lockhart-Martinelli parameter (Xtt) and the Froude rate (Ft) as given in Graham [1999]. This relation is:

$$\alpha = \left[1 + \frac{1}{Ft} + X_{tt}\right]^{-0.321}$$

Straight tube void fractions were compared with the void fractions found for the return bend test section. As seen from Figure 3, the effects on void fraction due to the return bend in evaporative conditions appears to be small. This may not be true in the condenser, however, because the higher temperatures in condenser conditions lead to higher vapor densities. At a given mass flux, increased vapor density reduces the vapor velocity, which causes less shearing of the liquid film on the tube wall, which results in more liquid mass in the tube. A similar study under condenser conditions may lead to substantially different results.

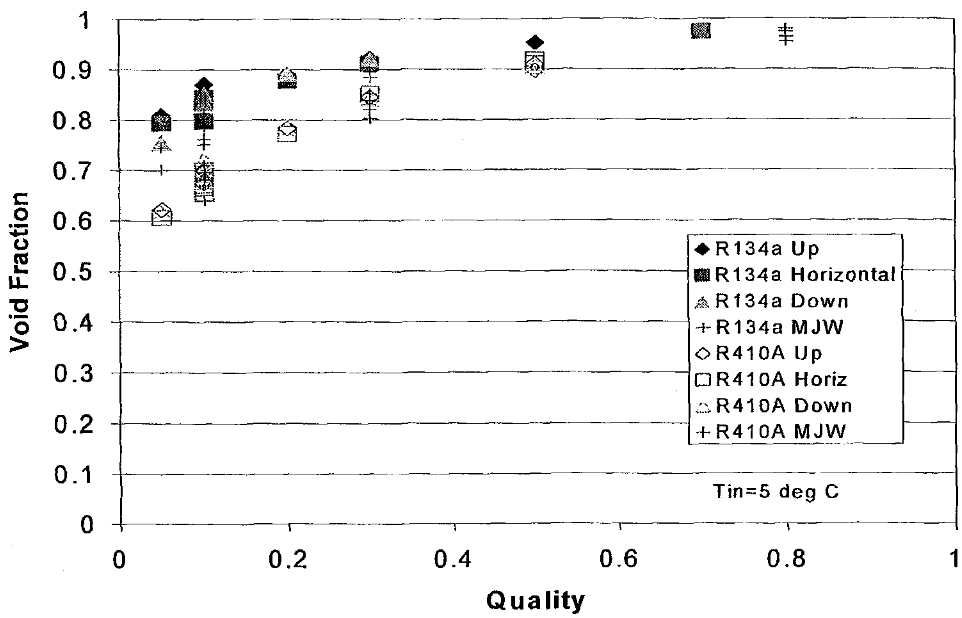

Figure 3: Return Bend Void Fraction Plot

Pressure Drop

Pressure drop was measured across the test section at the pressure taps as seen in Figure 2. The accuracy of the transducer is ±0.25% full scale. This gave the test section pressure drops as seen in Figure 4.

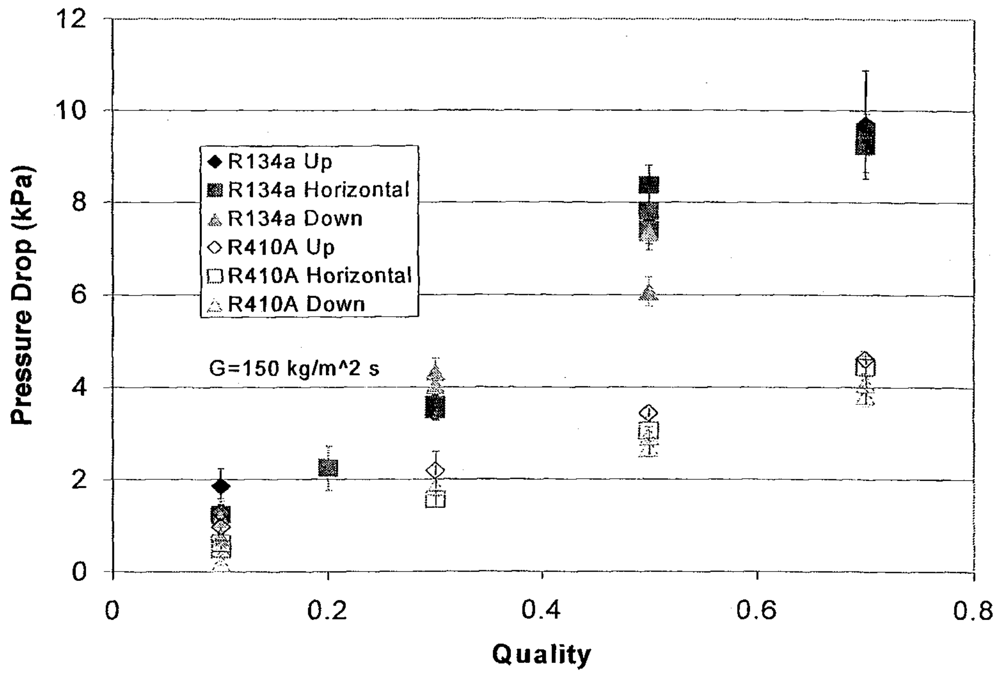

Figure 4: Test Section Pressure Drop Plot

Figure 4 shows that the pressure drop increases with quality. At higher qualities there is a much greater mass of vapor than at lower qualities. The quality increases cause the vapor velocity to increase, creating a greater frictional pressure drop. This greater vapor velocity is also the reason why the pressure drop for a lower pressure refrigerant has a higher pressure drop. Figure 4 also shows a slight trend of increasing pressure drop as the test section is oriented from downflow to upflow orientations. This small effect is most likely due to gravity.

The pressure drops for the return bends were found by subtracting the estimated pressure drop due to the straight sections of tubing. The Souza correlation as well as the Jung and Radermacher correlation for straight, horizontal tubes were examined. Both correlations generated similar results for straight tube pressure drop. The Souza correlation was chosen for comparison purposes. The resulting return bend pressure drop is shown in Figure 5.

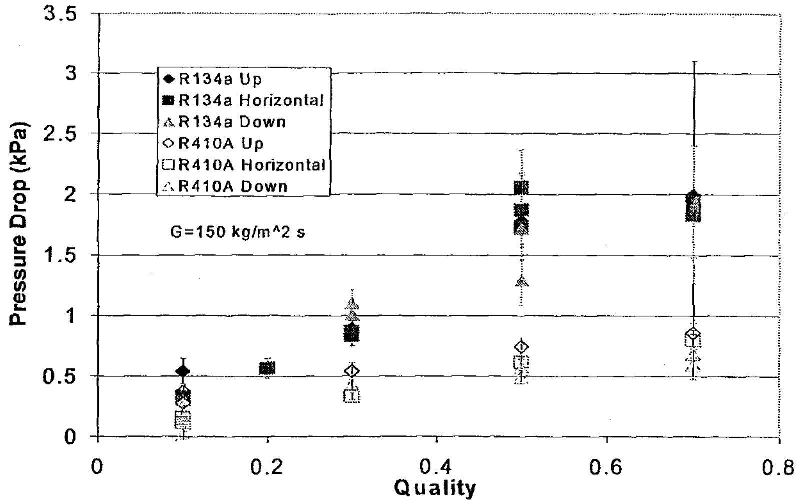

Figure 5: Return Bend Pressure Drop Plot

DISCUSSION

The pressure drop data was compared with other pressure drop correlations developed for return bends. Three correlations were described in the background section. As seen from Figure 6, the return bend pressure drops from this study were significantly higher than that predicted by the Christoffersen, Pierre, and Geary correlations. This may be due to several reasons. First, from the construction of the test section, the straight sections of tubing were inserted into the return bend tubes rather than butted or coupled together. This abrupt change in diameter from the return bends to the straight sections may have increased the return bend pressure drop. Additional error was due to the sensing of the equipment. Although the differential pressure transducer has an accuracy of ±0.25%, its range was from 3.4 to 170 kPa. Thus, the lower pressure drops are less accurate. The thermocouples had uncertainties of ±0.1° C. The absolute pressure transducers had uncertainties of ±0.75%. These errors and others contributed to the overall inaccuracies in measurement. Error resulted from using the Souza correlation as well. The reported accuracy of the correlation is ±10%.

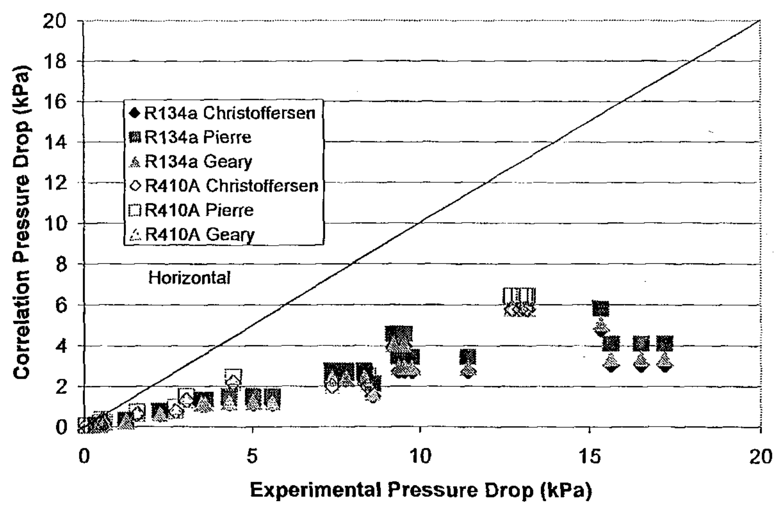

Figure 6: Comparison of Experimental and Correlation Test Section Pressure Drops

CONCLUSION

Void fraction and pressure drop data are presented here for return bends for two refrigerants over a range of mass flux and quality conditions. Return bend results from this investigation appear to have minimal effect on the void fraction in evaporative conditions. The return bends did seem to have considerable effect on the pressure drop, however. An increase in pressure drop occurred with increasing quality. Also, the lower pressure refrigerant had a higher pressure drop. Some gravitational effects due to orientation were seen to effect the pressure drop. The return bend pressure drops measured did not correlate well with existing correlations, however, the primary differences may be due to the connection between the return bend and the straight tubes and due to the size of the return bend relative to those examined in the development of the correlations.

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