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TWO-PHASE REFRIGERANT FLOW MEASUREMENT WITH LIQUID AND VAPOR SEPARATION TECHNIQUE

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ABSTRACT

Refrigerant flow rate measurement is always important in calculating the performance of refrigeration equipment. The task becomes difficult when the refrigerant is not fully condensed in the condenser. Conventional two-phase flow measuring techniques are either too expensive or have low accuracy or both. This paper presents an accurate measurement in which the liquid and vapor are separated and the flow rate of each phase is measured with conventional flow meters. A low-cost and low-pressure drop separator was built and tested on a split heat pump system. The results indicate that the separator worked as expected by separating the two-phase refrigerant for vapor quality from 6.1% to 14.7%, with refrigerant pressure drop ranging from 2 to 5 psi (13.8 to 34.5 kPa) in most tests.

INTRODUCTION

The measurement of two-phase refrigerant flow rate and vapor quality when the refrigerant is not fully condensed in the condenser is one of the most troublesome problems in laboratory testing of refrigeration equipment. It is difficult to calculate the system's performance accurately without knowledge of these qualities. The liquid line is usually small, rendering bulky measuring equipment impractical; excessive pressure drop caused by the addition of the measuring equipment is unacceptable. Continuous measurement with minimal disturbance of the system is necessary for monitoring system performance.

Commonly used methods often involve electronic instruments (Delhaye and Cognet 1983) that can be very expensive. Orifice plates have been studied for two-phase flow measurement (Chisholm 1983), but a lengthy calculation is needed and is not very accurate, and high pressure across the orifice plate could also be detrimental to system performance. The Coriolis meter was proven ineffective (Hawkin et al. 1985). Turbine meters are generally not considered good measuring devices for two-phase flow unless special calibrations are undertaken (Baker and Deacon 1983). The quick-closing-valves approach (Lockhart and Martinelli 1944; Hewitt et al. 1964) is a simple one, but response is very slow and operation of the system is disturbed.

In this study, a prototype low-pressure-drop liquid-vapor separator was designed and tested. Once the two-phase flow is separated, single-phase flow meters can be used for measuring each phase of the flow. The advantages of this device are that (1) it is reliable, (2) the two-phase flow can be measured continuously with minimal disturbance of operation, (3) it will be able to measure the flow rate of each phase, and (4), most importantly, it is low cost. With the additional measurements of the pressure and temperature of the two-phase refrigerant flow, the mass flow rate of each phase, as well as the vapor mass quality, can be determined.

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The novel separator was tested on a nominal 3.5-ton split heat pump system. The results indicate that the separator works as expected, with clear separation of the vapor and liquid over a wide operating range and with very low pressure drop. The experimental results have proved the concept of two-phase refrigerant flow measurement by the separation of phases.

Description of the Design of the Liquid-Vapor Separator

Figure 1 shows the schematic of the separator design. Copper tubing of different sizes constitutes the main body of the separator. The velocity-reducing section allows the two-phase flow to slow gradually to avoid excessive pressure loss due to sudden expansion. The separation tube is designed to separate the liquid and vapor phases of the flow by further reducing the flow velocity. The damping tube reduces the impact of the fluctuation of the flow. More damping tubes can be added as necessary to further reduce the flow fluctuation. Once the vapor and liquid are separated, vapor will flow through the top outlet of the damping tube and liquid will flow through the lower outlet. The flow rate of each phase can now be measured with conventional flow meters. The vapor and liquid are reunited downstream of the flow meters. By measuring the temperature and flow rates at the outlets, the density of each phase can be determined, and the mass flow rate of each phase can be calculated. By adding the two mass flow rates together, we get the total mass flow rate. Dividing the vapor mass flow rate by the total mass flow rate, the vapor mass quality is determined.

Test Setup

Figure 2 shows the schematic of the test setup. A nominal 3½-ton split heat pump system with R-22 as the refrigerant was set up in the laboratory. The prototype separator was placed on the liquid line between condenser and expansion device. Two turbine meters were installed at the two outlets of the separator. Thermocouples and pressure gauges were used for refrigerant temperature and pressure measurement at different locations. A condensing well was installed in the liquid line downstream of the separator after the vapor and liquid were reunited. Liquid nitrogen was used as a cooling medium to condense the two-phase refrigerant into liquid. A third turbine meter was placed between the refrigerant expansion device and the refrigerant condensing well.

The test procedure was very simple. When a two-phase flow was separated in the separator, the flow rate of each phase of the fluid was measured by the turbine meters. With the measured refrigerant temperature and pressure, the mass flow rates of vapor and liquid flow were calculated. The vapor and liquid were then reunited into a two-phase flow. At the condensing well, liquid nitrogen was used to condense the vapor into liquid. A third turbine meter was used to measure the flow rate of the single-phase liquid volume. Again, the mass flow rate was calculated. The mass flow rates measured at the outlets of the separator were added together and then compared with the mass flow rate measured by the third turbine meter. These flow rates should be equal or almost so. The fraction of the vapor mass flow rate over the total mass flow rate gave the vapor mass quality of the two-phase refrigerant flow.

Test Results and Discussion

Table 1 shows the test results of the two-phase flow measurement. With the adjustment of the shutoff valve on the liquid line and the blocking of air circulation to the condenser, we were able to measure the vapor quality from 6.11% to 14.71%. Early tests indicated that the error in comparing the total mass flow rates was very small, which shows that the two-phase vapor and liquid mass flow rates can be added together and treated as the total refrigerant mass flow rate. Tests 7 through 9 and 11 through 15 were run without the liquid nitrogen condensing the vapor. The observed pressure drops across the separator were between 2 and 5 psi (13.8 to 34.5 kPa), except for a few runs that were around 7 psi (48.3 kPa). This pressure drop can be reduced by making the vapor and liquid outlet larger.

It was observed that when the vapor quality was low, liquid periodically surged into the vapor line, and when the vapor quality was high, the flow at the liquid outlet became two phase. The first problem could probably be solved by making the vapor header longer. The second problem could likely be corrected by making the damping tube liquid outlet lower and the liquid storage section narrower.

It was found that this type of measurement can only determine the vapor mass quality of the two-phase flow. Calculation of the velocities for the liquid and vapor phases requires the knowledge of the void fraction of the two-phase flow. If the empirical plotting of void fraction as a function of vapor mass quality and absolute pressure is available for R-22, such as those of steam-water two-phase flow (Martinelli and Nelson 1948), the velocities for each phase can then be easily determined for steady state flow under certain assumptions (Collier 1972).

CONCLUSION

A prototype liquid-vapor separator was built and tested on a split heat pump system. The separator successfully separated a two-phase refrigerant flow into a liquid and a vapor flow at the outlet of the condenser over a wide range of operating conditions. Each phase of the flow was measured by conventional single-phase flow meters. This prototype separator was able to separate a two-phase refrigerant flow, with vapor quality ranging from 6.43% to 14.71% and a total mass flow rate ranging from 323 lb/hr to 635 lb/hr (147 to 288 kg/hr). The pressure drop across the separator was from 2 to 5 psi (13.8 to 34.5 kPa) in most tests. Further design improvements are possible by increasing the operating range of vapor quality and decreasing the pressure drop across the separator. However, the concept of measuring the two-phase refrigerant flow with a low-cost liquid-vapor separator has been confirmed. The total mass flow rate and the vapor quality can now be measured continuously without interrupting the system's operation. It is conceivable that this technique could also be applied in other fields of two-phase flow measurement if the total mass flow rate and vapor mass quality are the only data needed.

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TABLE 1
Test Results of Two-Phase Flow Separator

Test No.	Two-phase mass flow rate [lb/h (kg/h)] Vapor[a]	Liquid[b]	Total	Single-phase total liquid mass flow rate[c] [lb/h (kg/h)]	Total mass flow rate diff [lb/h (kg/h)]	Error (based on single-phase flow rate, %)	Vapor quality (lb vapor/lb total mass)
1	35.9 (16.3)	309.9 (104.6)	345.8 (156.9)	340.8 (154.6)	-5.0 (2.3)	-1.47	10.39
2	56.1 (25.4)	433.4 (196.7)	489.5 (222.1)	495.1 (224.6)	5.6 (2.5)	1.10	11.45
3	52.5 (23.8)	417.7 (189.5)	470.3 (213.4)	477.7 (216.8)	7.4 (3.4)	1.50	11.17
4	46.3 (21.0)	375.7 (170.5)	422.0 (191.5)	413.2 (187.5)	-8.8 (4.0)	-2.13	10.97
5	39.9 (18.1)	338.3 (153.5)	378.3 (171.6)	376.3 (170.7)	-2.0 (0.9)	-0.50	10.55
6	29.6 (13.4)	301.0 (136.6)	330.6 (150.0)	320.2 (145.3)	-10.4 (4.7)	3.20	8.95
7	24.9 (11.3)	298.9 (135.6)	323.8 (146.9)				7.69
8	23.9 (10.8)	309.3 (140.3)	333.2 (151.2)				7.17
9	21.5 (7.7)	312.3 (141.7)	333.7 (151.4)				6.43
10	57.4 (26.0)	577.3 (261.9)	634.7 (288.0)	671.2 (304.6)	36.5 (16.6)	5.4	9.04
11	22.1 (10.0)	329.6 (149.5)	361.7 (164.1)				6.11
12	29.7 (13.5)	305.3 (138.5)	335.0 (152.0)				8.87
13	47.2 (21.4)	324.4 (147.2)	371.6 (168.6)				12.70
14	53.2 (24.1)	352.4 (159.9)	405.5 (184.0)				13.11
15	62.0 (28.1)	359.6 (163.2)	421.6 (171.3)				14.71

[a] Maximum turbine meter variation from known data: 2.95%

[b] Maximum turbine meter variation from known data: 0.57%

[c] Maximum turbine meter variation from known data: 0.33%

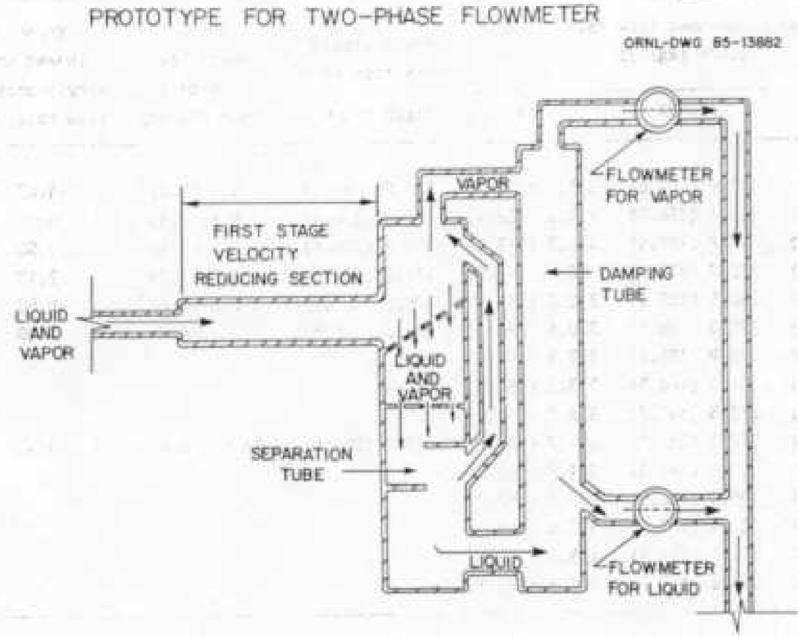

Figure 1 Schematic of prototype separator design

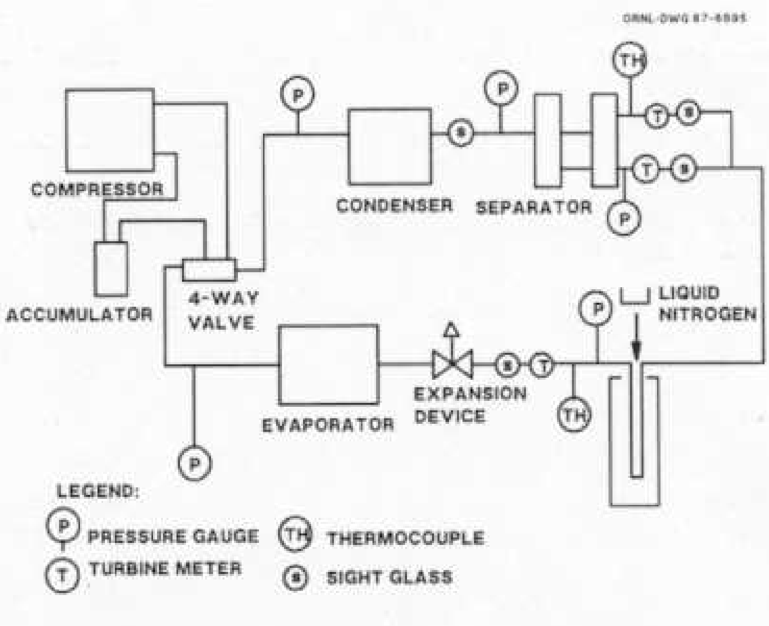

Figure 2 Schematic of two-phase flow separator test setup

DISCUSSION

C. Banerjee, Staff Engineer, Admiral Home Appliances, Galesburg, IL: What was the mass flow rate over which the testing was done?

V.C. Mei: The tests were performed over a mass flow range of 300 to 650 lb/h (136 to 295 kg/h).

Banerjee: How much insulation was applied to prevent heat loss that might change the quality of fluid during two-phase measurement?

Mei: We didn't apply any insulation on the separator. The heat loss, we figured, would be very small, and should not affect the vapor quality in any appreciable amount. However, applying the insulation on the separator is a good suggestion.