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Flow Regimes of Refrigerant Mixtures Condensing Inside Tubes

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Prepared by

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Date of Issue—June 1985

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ABSTRACT

In order to take full advantage of the energy-conservation potential of refrigerant mixtures, the heat-transfer coefficients should be maintained high. Several research projects have reported reductions in boiling and condensing heat-transfer coefficients with refrigerant mixtures in comparison to either constituent singly. Measurements of condensing heat-transfer coefficients on an operating system in a previous phase of this study reported degradation with increasing concentration of R-114 in R-12.

This study sought more insight into the condensation process by observing and photographing the flow regimes of the same nonazeotropic mixed refrigerants condensing in a single-tube glass condenser. Measurements of pressure and temperature profiles through the condenser as well as chromatographic analysis of samples at several points along the condenser were also taken.

The four principal flow regimes from the entrance to the exit of the condenser are (1) annular flow, (2) stratified flow, (3) slug flow, and (4) bubble flow.

The glass-tube condenser was essentially of the same diameter and length as the condenser in the operating refrigerating system used in the earlier phases of this work. The most significant reduction in heat-transfer coefficient occurred in the midrange of the condenser on the operating system, and the regime was shown in the glass condenser to be stratified flow. Several explanations for the reduction in heat-transfer coefficient are selective diffusivity, temperature and concentration gradients, and vapor-liquid slip. Slip was prominent in the region where the major reduction in heat-transfer coefficient occurred, so inhibiting this slip may prevent at least some of the heat-transfer degradation.

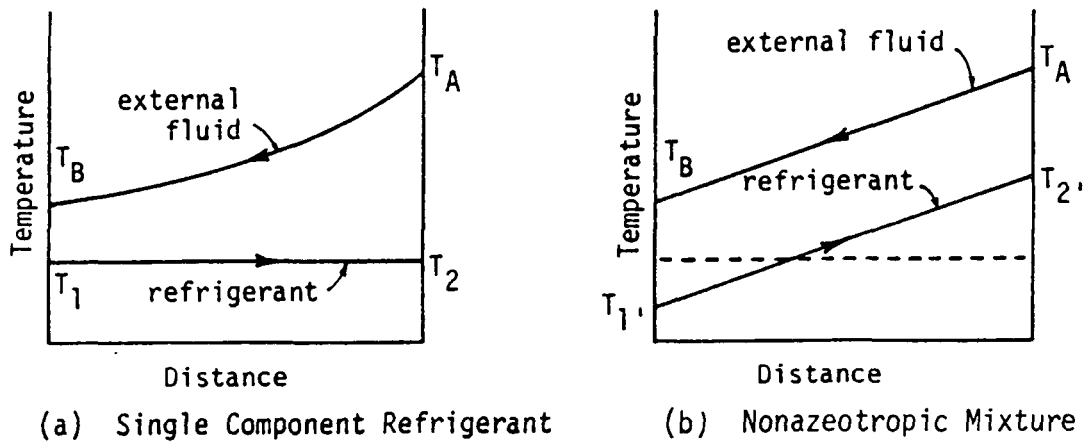
1. INTRODUCTION

1.1 Using Refrigerant Mixtures

The use of nonazeotropic mixtures of refrigerants in a vapor compression refrigeration system can theoretically reduce the compressor work load in those cases where the temperatures of both the fluid being chilled and the condenser cooling fluid change. The mixture alters the evaporator and condenser temperature profiles in such a way that the thermodynamic irreversibility of the system is lowered. Figure 1.1 shows for both a mixture and a single component the temperature profiles in a counterflow heat exchanger during evaporation. The large temperature differences occurring between the single refrigerant and the external fluid result in greater irreversibilities compared to the more "parallel" temperature profiles of the refrigerant mixture. Refrigerant mixtures can also be used for modulating heat-pump capacity, tailoring the pressures of the refrigerant for given temperatures, and improving oil behavior. The advantages and applications of refrigerant mixtures are already well defined in the literature [1,2,3,4].

1.2 Summary of Previous Research

In the research program sponsored by Oak Ridge National Laboratory at the University of Illinois, Launay [3] first conducted a simulation and optimization study of a vapor-compression refrigeration system with a mixture of refrigerants 12 and 114 (R-12 and R-114). He indicated that the power required for a given refrigeration capacity would decrease as the concentration of R-114 increased. The simulation computed the optimum concentration of R-114 to be at 68 percent at which condition the energy savings were 10 percent.



(a) Single Component Refrigerant (b) Nonazeotropic Mixture

Figure 1.1 Evaporator Temperature Profiles

Burr and Haselden [5] performed a simulation on an air-cooled mixed refrigerant air conditioning unit and achieved an optimized model that could reduce operating costs by 20 to 30 percent. Their experimental results however, were substantially lower than the model had predicted.

An experimental performance to verify Launay's results was followed by McCarthy [6]. McCarthy conducted a series of tests on a two-evaporator, two-condenser, two-heat-exchanger vapor-compression refrigeration system using mixtures of refrigerants R-12 and R-114. The system schematic diagram is shown in Fig. 1.2. The results showed the optimum concentration of R-114 to be 15 percent with an energy saving of 2 percent. Holding the refrigeration duty constant between tests while varying the concentrations of R-114, he discovered that as the R-114 concentration increased, the local heat-transfer coefficients in the condenser decreased. Conclusions on the heat-transfer coefficient performance in the evaporator were indefinite due to low refrigerant velocities and a large variance in the data. Condensing heat-transfer coefficients in the third pass of the high-temperature condenser (HTC) decreased as much as 43 percent between a test with a 50 percent mixture of R-114 and a test with pure R-12 (Fig. 1.3). The coefficients decreased about 18 percent in the first and second passes of the HTC. The condenser configuration is shown in Fig. 1.4. Further experimentation was performed during the summer of 1983 to substantiate these decreases. The results are shown in Fig. 1.5.

It is evident that these decreases in heat-transfer coefficients are counterbalancing the potential energy savings.

Arora [7] has also indicated that boiling coefficients drop significantly for an R-12/R-114 mixture in comparison to the value of the pure components. Some of his work is shown in Fig. 1.6.

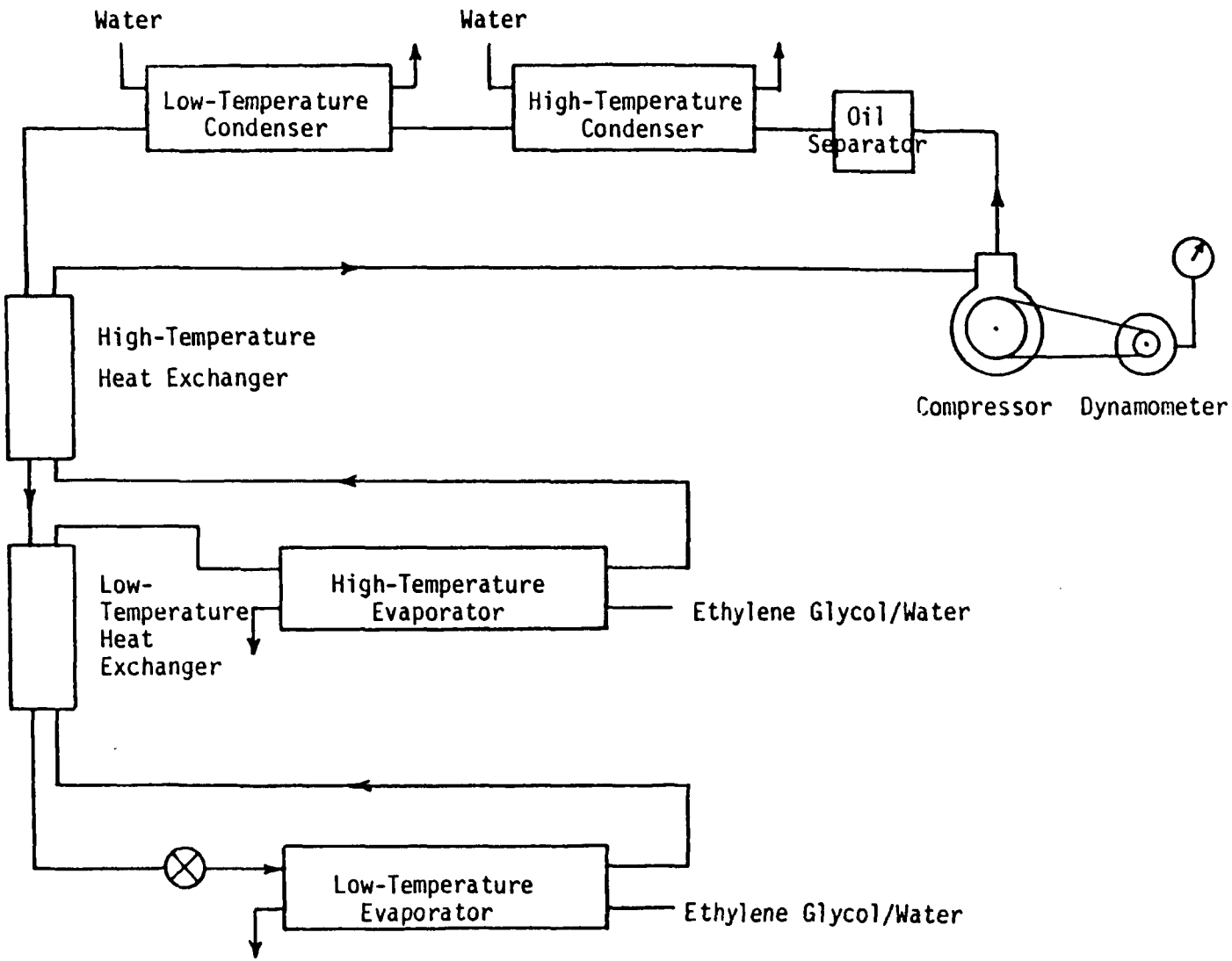


Figure 1.2 University of Illinois Refrigeration System Component Diagram, McCarthy [6]

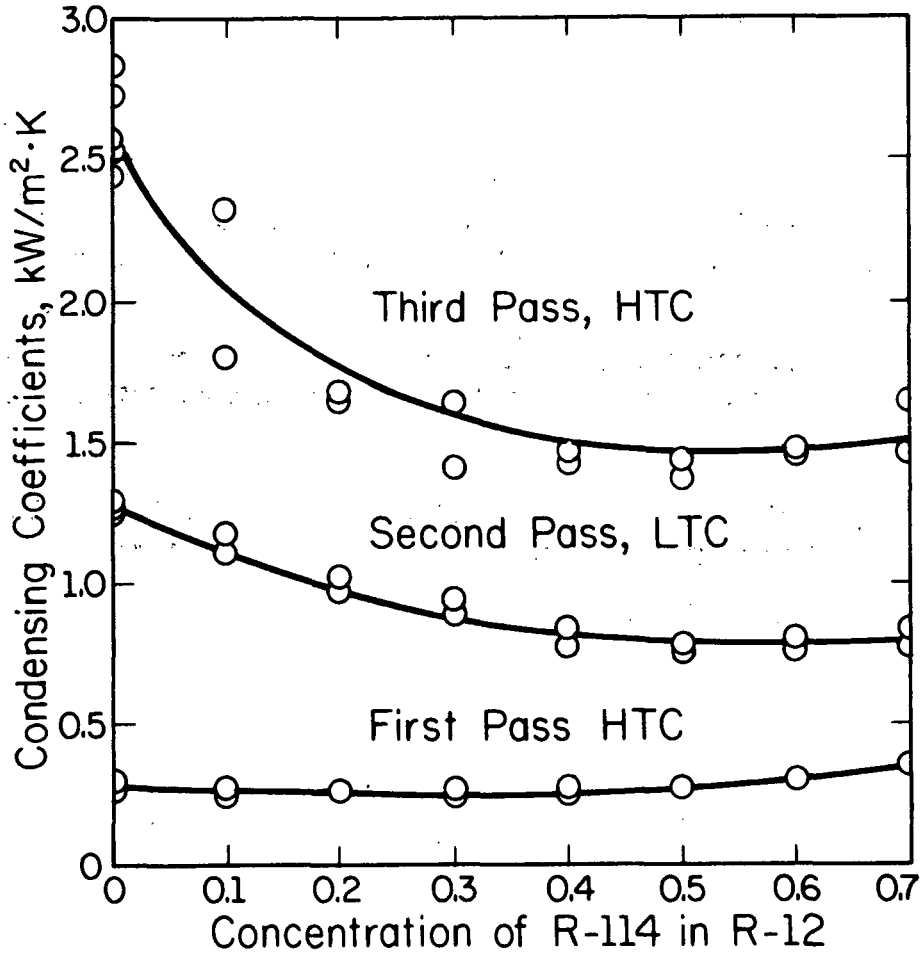


Figure 1.3 Heat-Transfer Coefficients as Functions of Mixture Concentration for Constant Refrigerating Capacity, McCarthy [6]

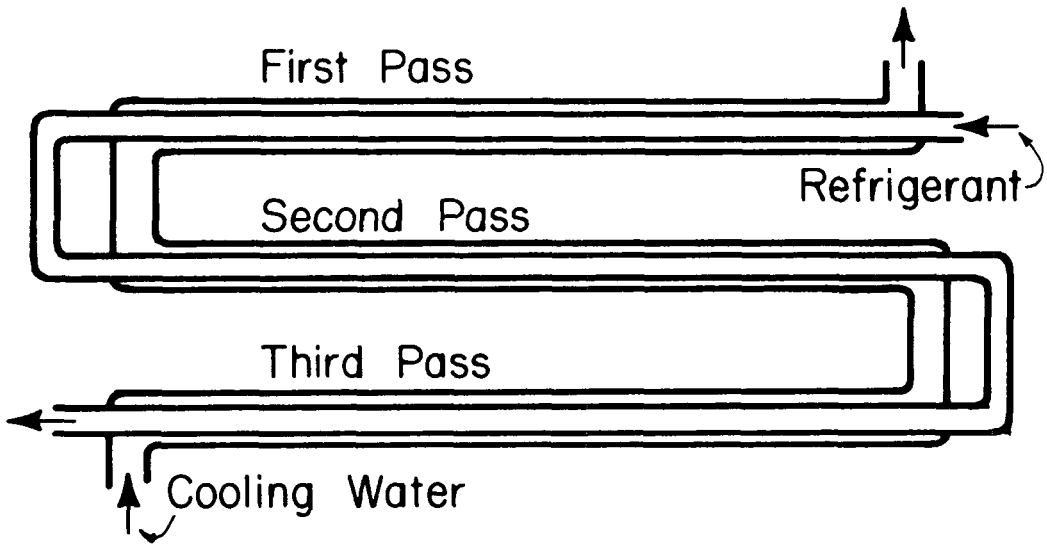


Figure 1.4 High- and Low-Temperature Condenser Configurations, McCarthy [6]

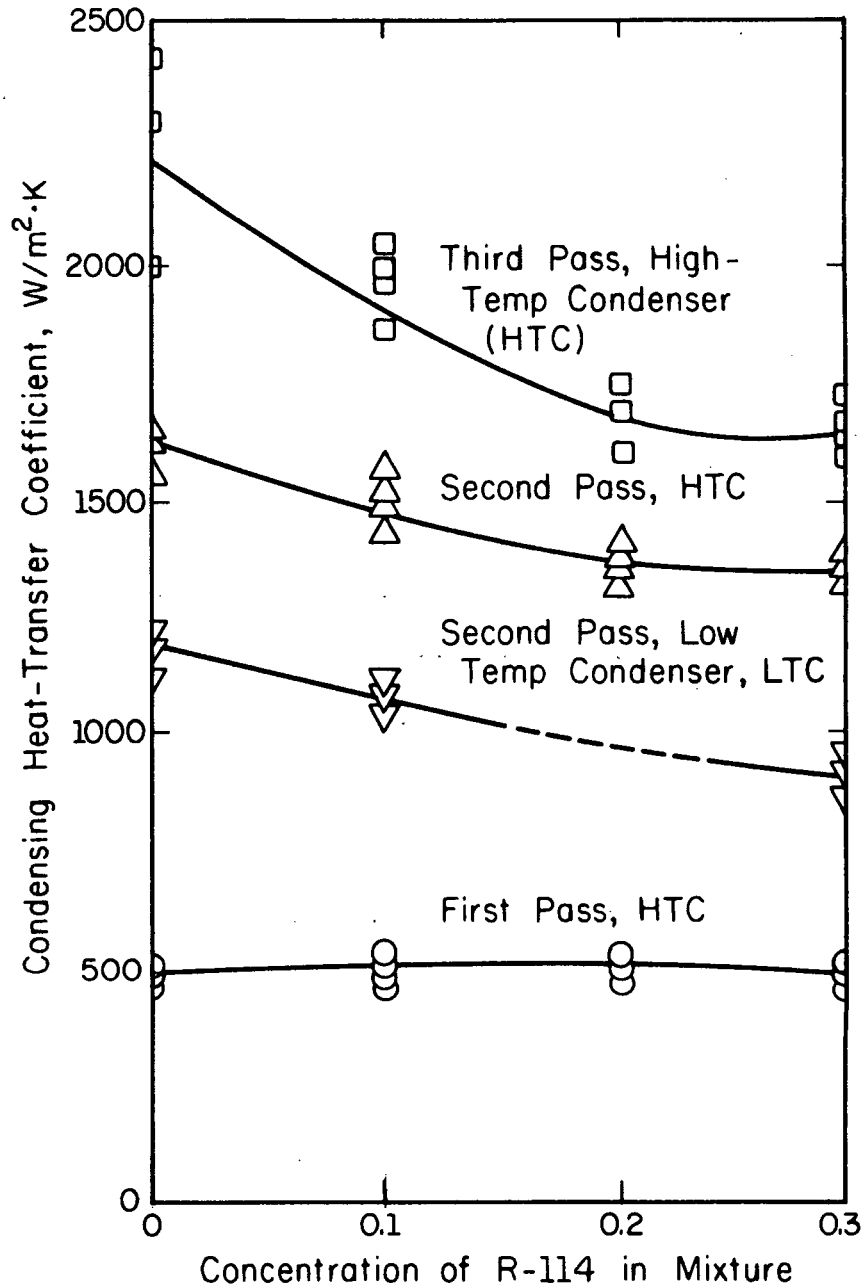


Figure 1.5 Condensing Heat-Transfer Coefficients with Refrigerant Flow Rates 0.024 to 0.027 kg/s

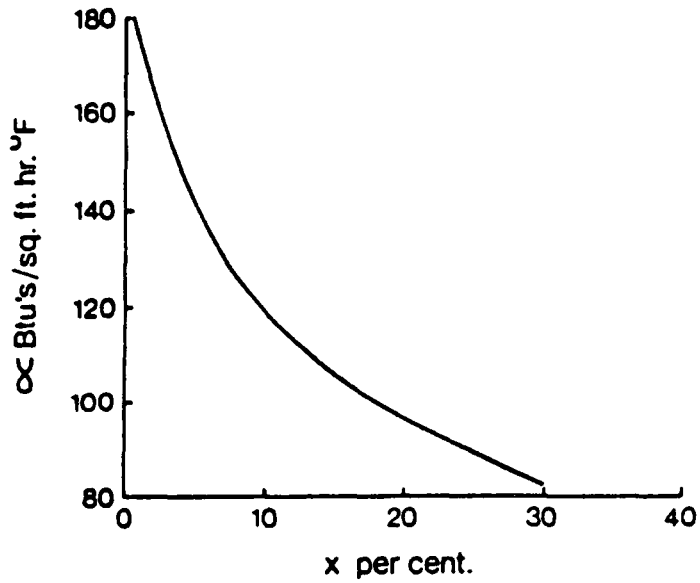


Figure 1.6 Boiling Heat-Transfer Coefficient as a Function of Concentration of R-114 in the R-12/R-114 Mixture, Arora [7]

Bokhanovskiy [8] measured the mean heat-transfer coefficients of a mixture of R-12 and R-22 during condensation. He found that the mixture behaved much like pure refrigerants at high heat-flux densities. However, at heat fluxes less than 18,000 W/m^2, the experimental curves formed families with concentration as the parameter (Fig. 1.7). The coefficients were found to be lower than for pure substances. He attributes these decreases to the thermal resistance of the condensate film and the diffusion resistance in the vapor phase. The condenser heat fluxes in the University of Illinois studies conducted by McCarthy [6] did not exceed 5600 W/m^2.

Signal, Sharma and Varma [9] have found, for a binary mixture of R-13 and R-12, that the local heat-transfer coefficients, during forced-convection boiling, decreased with the increase of the concentration of R-13 for vapor qualities up to 0.30. Further increases in vapor quality reversed the effect of the R-13 concentration. The average heat-transfer coefficients for the binary mixture, however, were found to be slightly greater than that for pure R-12.

Jungnickel, Wassilew, and Kraus [10] conducted pool boiling heat-transfer tests for various binary refrigerant mixtures and pure refrigerants. The measured results clearly showed heat-transfer deterioration in the case of a vaporizing mixture (Fig. 1.8). The reduction was attributed to the resistance of the mass transport in the liquid phase which, in addition to the heat transport, is necessary for evaporation.

Some researchers have observed that mixtures have no effect on the heat-transfer characteristics. Rojey [11] performed experiments on a heat pump test loop using pure R-12 and a mixture composed of 70 percent R-22 and 30 percent R-11. The heat-transfer coefficients were measured during the stages of vaporization and condensation. Rojey found no significant differences between the mixture and the pure refrigerant.

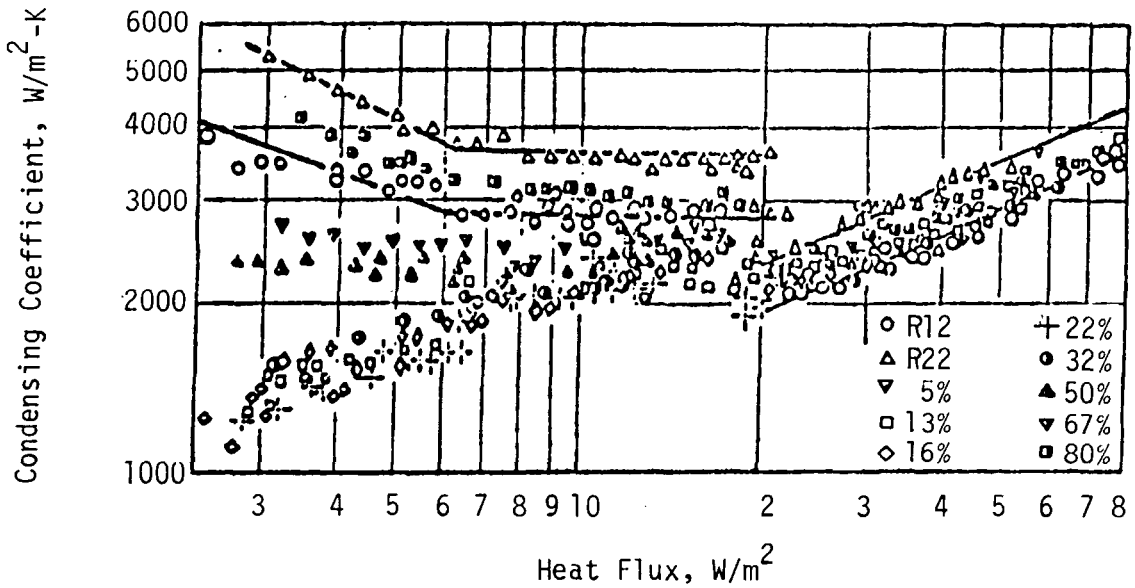


Figure 1.7 Experimental Data on Condensation of Refrigerant 12 and 22 and their Mixtures in a 14 mm ID Pipe (the concentrations are those of Refrigerant-22, Bokhanovskiy [8]

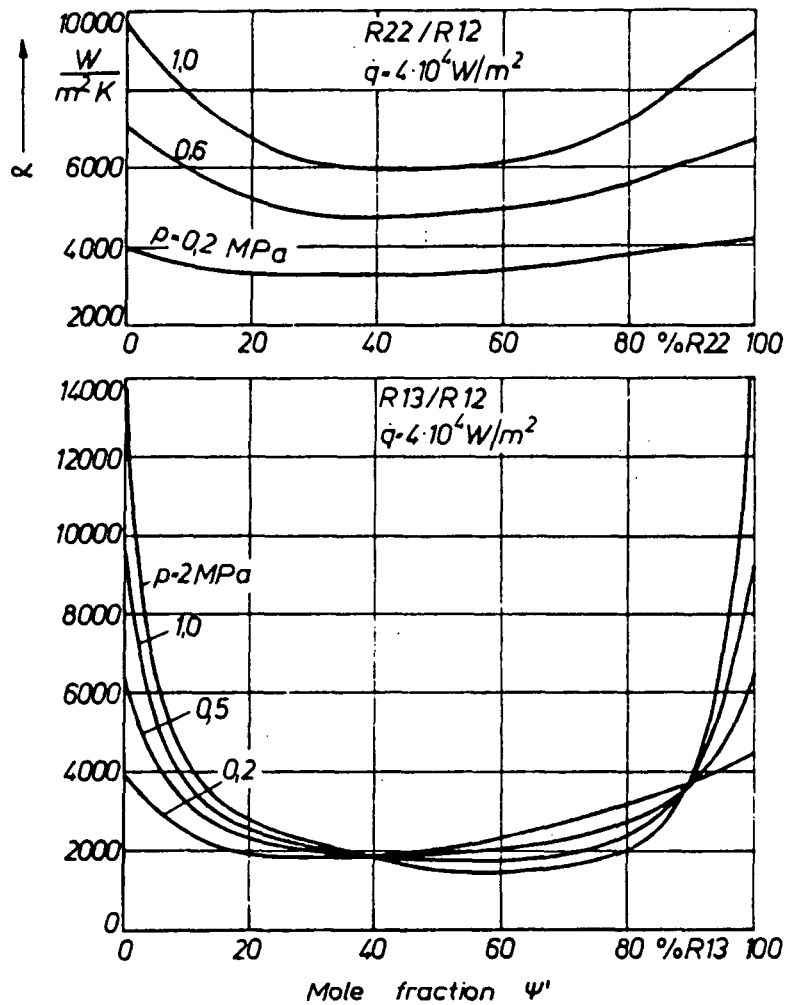


Figure 1.8 Experimental Boiling Heat-Transfer Coefficients for R-22/R-13/R-12 Mixtures, Jungnickel, Wassilew, and Kraus [10]

1.3 Importance of Studying Heat Transfer Characteristics

It is apparent from the literature that the phenomena behind the heat-transfer degradation must be a complex function of many variables. The results of the previous studies indicate that conserving energy through the use of refrigerant mixtures will remain a challenge. The heat-transfer coefficients for the mixtures must be maintained near those of the pure component in order to benefit from the thermodynamic advantages. The phenomena responsible for the heat-transfer coefficient degradation must be addressed in order to better predict refrigerant-mixture performance which is the purpose behind our study. The efforts of the study are directed to find whether the coefficients do indeed drop, and if so, how much. Of even greater importance is to determine how the reduction could be eliminated so that the benefits of refrigerant mixtures mentioned earlier can be obtained. As a start, we have chosen to investigate the flow regimes of refrigerant mixtures during the condensation process. We decided to study condensation rather than evaporation, since McCarthy's results showed more definite heat-transfer reductions in the condenser. Also, our efforts will complement the work of others already investigating boiling of refrigerant mixtures.

2. EXPERIMENTAL FACILITY

2.1. Purpose of Experimental Facility

The experimental facility was designed to permit complete flow visualization of refrigerants during condensation. The condenser is constructed of glass tube so that the refrigerant can be seen and photographed. The purpose is to observe and record the effects that velocity, heat flux, and refrigerant mixture concentrations may have on the various flow regimes. At a later date, when a copper-tube condenser is constructed, the measured heat-transfer coefficients can be correlated to the flow regimes observed in the glass tube. Recommendations for this facility and the techniques in correlating the data are developed in Chapter 7. Observing the flow regimes can provide important information leading to better qualitative interpretations of the heat-transfer characteristics of refrigerant mixtures compared to the separate components. Such information will also be important to refrigeration research engineers intending to model the heat-transfer coefficients.

Another purpose behind the study is to help determine the reason behind the decreases in heat-transfer coefficients in hopes of determining how to eliminate these reductions. One condition believed to contribute to the reduction is the "slip" occurring between the liquid and vapor phases in which the vapor moves at a faster velocity than the liquid. This slip condition results in nonequilibrium of the two phases with respect to concentration as well as temperature (refer to Chapter 6 for a detailed discussion on slip).

The facility is designed to allow removal of refrigerant samples along the condenser tube. The samples were analyzed using gas chromatography to help quantify the extent of the nonequilibrium. Comparing the results of the analyzed samples removed at different condenser locations can also provide insight into the rates of condensation of the various refrigerant mixtures.

2.2 Description of Test Facility

The test facility is located in the Mechanical Engineering Laboratory at the University of Illinois at Urbana-Champaign. This test facility is designed to simulate the conditions occurring during condensation in an actual refrigeration cycle in general, and the refrigerant-mixture energy-characteristics test facility [6] in particular. A photograph of the facility is shown in Fig. 2.1. A simplified schematic diagram of the system is shown in Fig. 2.2. For clarity, the components will be described as they appear in the refrigerant flow path.

2.2.1 Refrigerant Pump

The pump is a positive-displacement gear-type driven by a 3/4-hp, 1,725-rpm motor. The pump speed is 1/4.3 of the motor speed. Immediately after the pump is a sight glass followed by a liquid-line filter/dryer.

2.2.2 Refrigerant Boiler and Hot-water Loop

The refrigerant boiler is a copper tube-in-tube counterflow heat exchanger used to vaporize and superheat refrigerant just prior to its entrance into the condenser. The refrigerant flows through the inside tube which is 0.952-cm (3/8-in.) OD. A heated solution of water and Durex, an antifreeze containing a corrosion inhibitor, is circulated through the annulus by a 1/4-hp centrifugal pump. A rotameter measures the volumetric flowrate of the water/antifreeze solution.

The heater consists of three 2000-watt/240-volt heating elements inserted in a 7.62-cm (3-in.) diameter galvanized piping arrangement. Elements number 1 and 2 are connected in parallel so that the power output of the three

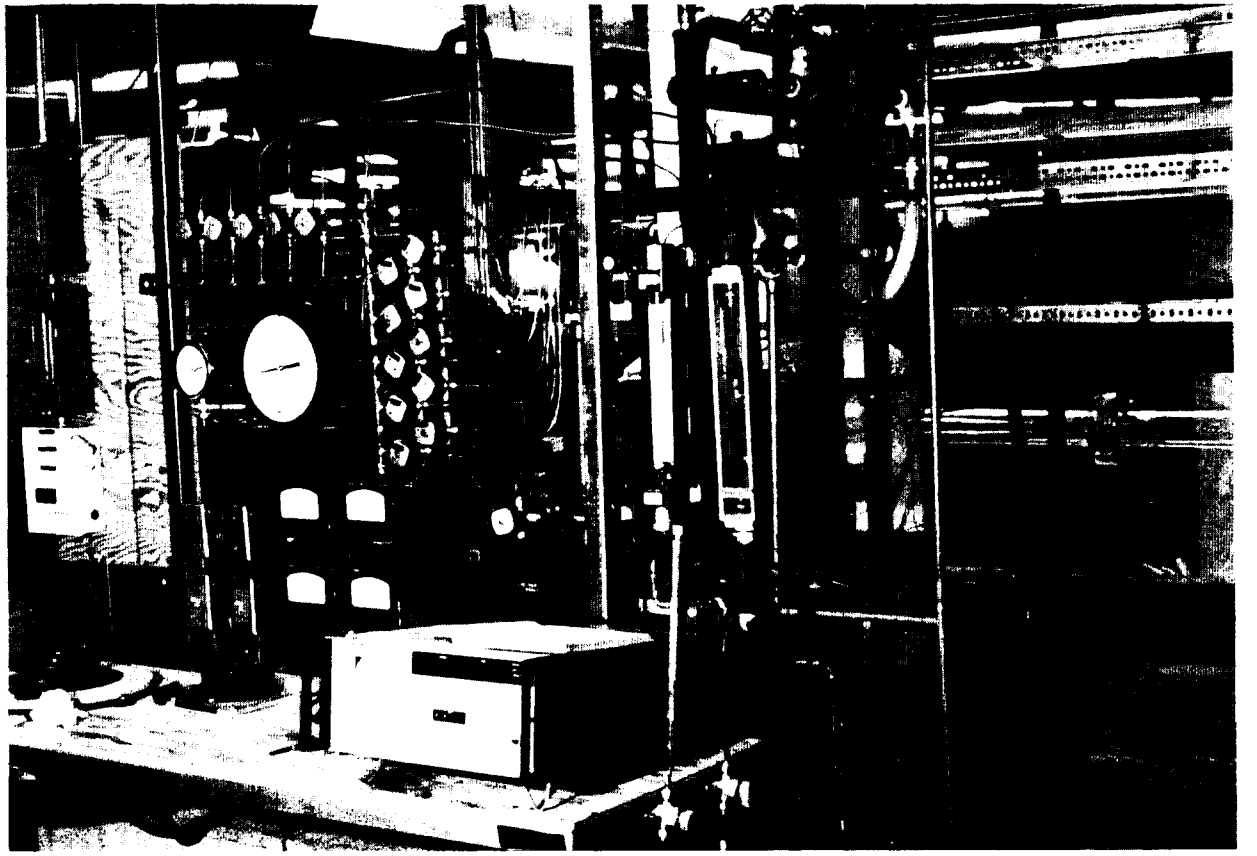


Figure 2.1 Photograph of the Test Facility (the transparent condenser is shown in the upper right-hand corner)

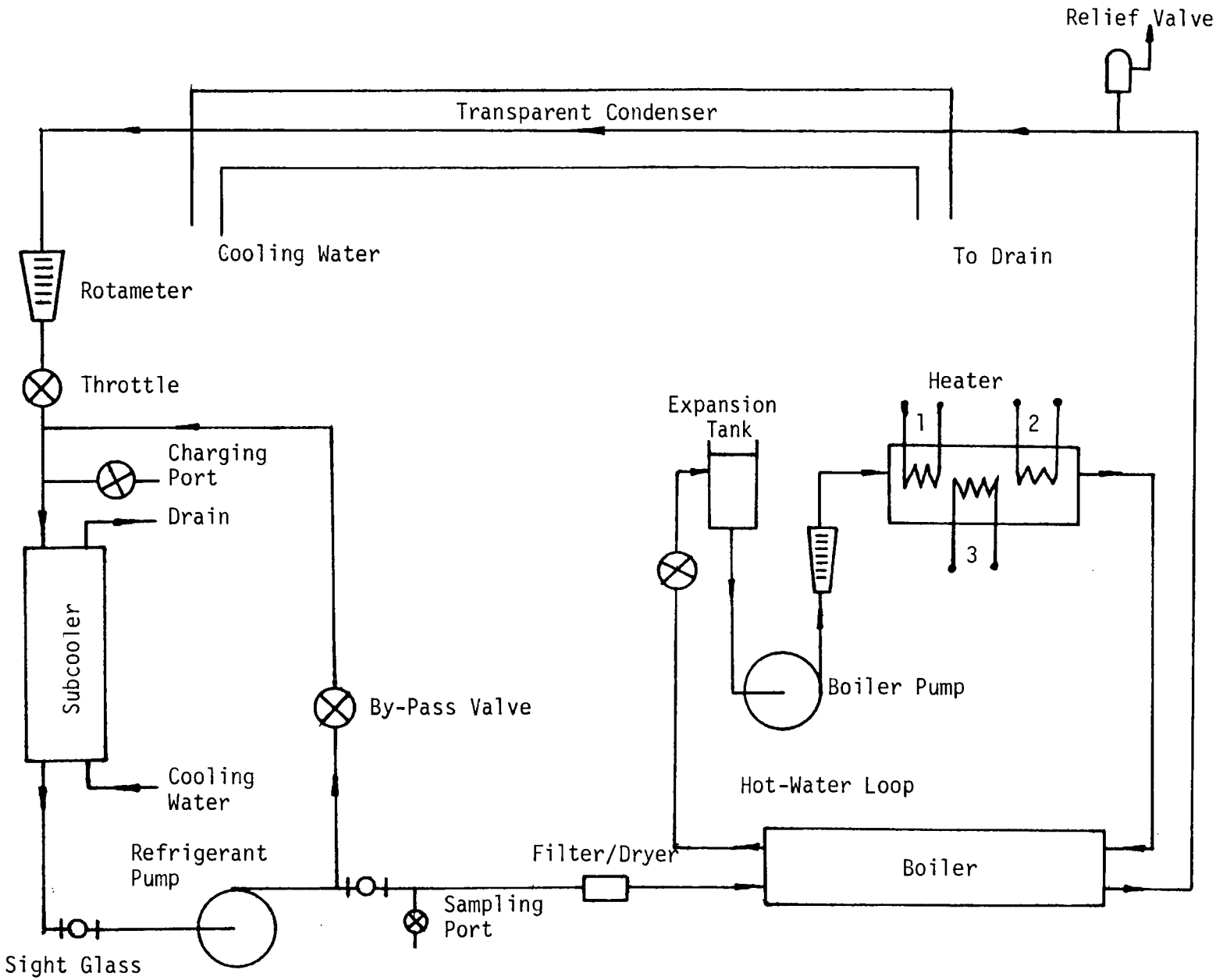


Figure 2.2 Heat Transfer Studies System Schematic Diagram

elements is controlled by two variable transformers. Four meters monitor the currents and voltages from which the electric power can be computed.

2.2.3 Transparent Condenser

The component of special interest in this facility is the glass-tube condenser. It allows observation of the entire refrigerant condensation process from the superheated-vapor through the subcooled-liquid regions. It is also a tube-in-tube counterflow heat exchanger. The condenser is in a U-shaped or two-pass configuration as shown in Fig. 2.3. The refrigerant condenses in the inside tube and the cooling water, directly fed from the city main, runs through the annulus. A 3/4 in. rotameter is used to measure the cooling water flow rate.

The inside tube is composed of twelve 1.5 m (5 ft) glass tubes 13-mm (1/2-in.) ID, 19-mm (3/4-in.) OD. The glass tubes have been pressure tested to 1041 kPa (150 psig). Working pressures greater than 696 kPa (100 psig) are not recommended by the manufacturer. Inserted between every pair of glass tubes, except between glass tube numbers 6 and 7 where there is a U-bend, is a 165-mm (6 1/2-in.) brass "test section." The condenser numbering system for the tubes and test sections is shown in Fig. 2.3. The total length of the condenser is 20.7 m (68 ft).

Each test section is instrumented with a thermocouple probe and a pressure tap. Test section numbers 6, 8, and 9 include a refrigerant-sample removal port. The instrumentation is inserted through two "quick-connect" couplings that are brazed 3.8 cm (1-1/2 in.) apart onto each test section. Instrumentation details are discussed further in Section 2.3. Brazed onto the ends of the brass tubes are machined brass fittings that closely resemble the contour of the bead on the ends of the glass tubes. This permits the brass

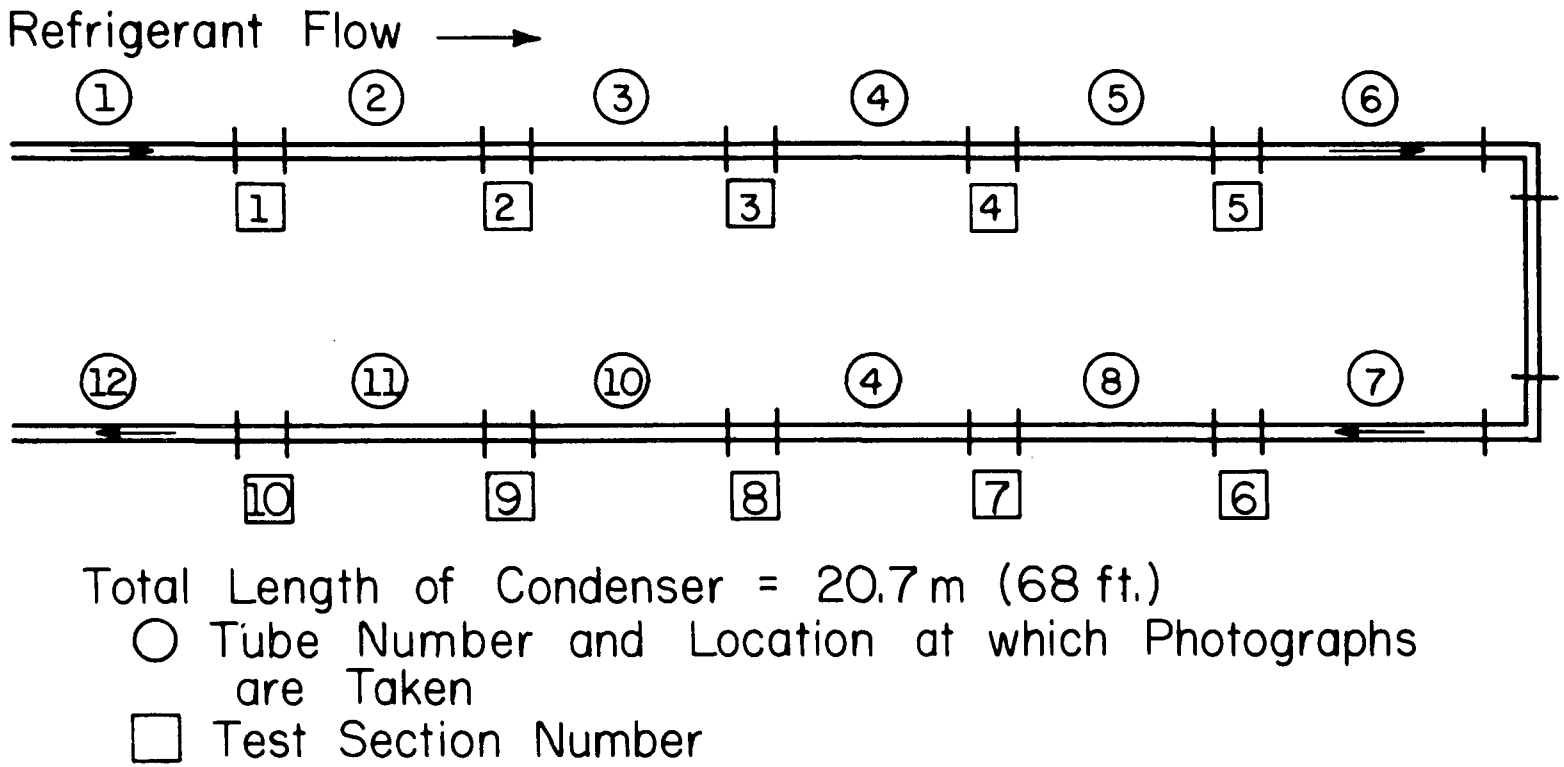


Figure 2.3 Condenser Numbering System for the Tubes, Test Sections, and Photograph Locations

test section to be joined with the glass using the 13-mm (1/2-in.) bead-to-bead glass-tube couplings. Figure 2.4 shows a picture of the glass coupled to the brass test section. When coupled together, there are no internal obstructions to the flow other than the thermocouple probes. A relief valve was installed immediately before the condenser to protect the glass from working pressures in excess of 800 kPa gauge (120 psig).

The annulus was constructed from 63.5-mm (2-1/2-in.) ID "plastic" tubes equal in length to the glass tubes and brass test sections. A section of the plastic tube used in constructing the annulus is also shown in Fig. 2.4. The large inside diameter of the annulus is necessary to accommodate the compression bolt on the glass tube coupling which was already cut approximately 1/4 in. Plastic flanges were machined and then glued to the ends of the plastic tubes to provide a means of joining the lengths together. The plastic tube surrounding the brass test section, see Fig. 2.5, was designed to facilitate the removal or insertion of the instrumentation. A hole cut into the plastic annulus accesses the two quick-connects on the test section. The instrumentation is inserted through these quick-connects. Weather stripping is used as the gasket between the half circle and plastic annulus. Three hose clamps compress the gasket to seal out the water running through the annulus. Figure 2.6 shows a diagram of the access port to the quick-connects on the brass test section.

The glass tube is supported and centered in the annulus by either of two methods shown in Fig. 2.7.

2.2.4 Refrigerant Flow Rate

A by-pass loop and a 13-mm (1/2-in.) needle valve, the throttle, is used to regulate the refrigerant flow rate through the condenser. A rotameter is used to measure the refrigerant flow rate.

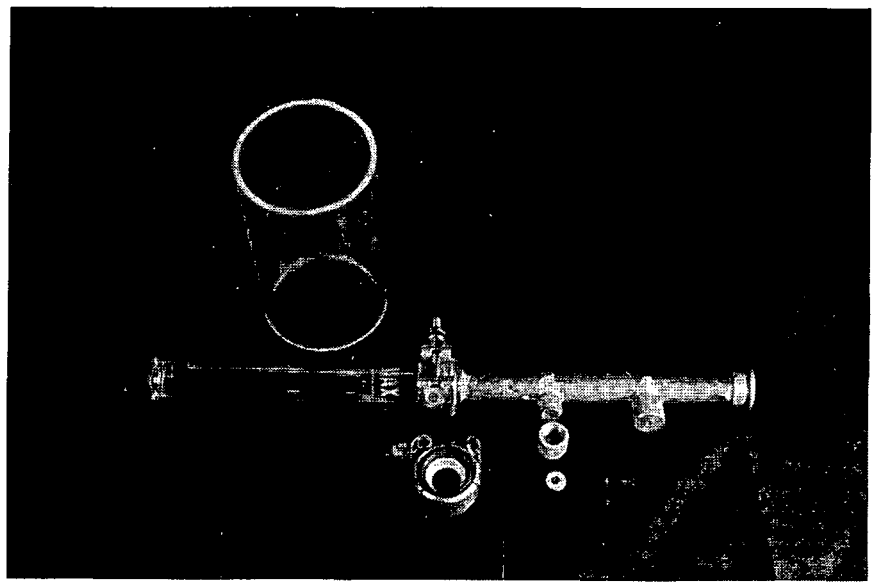


Figure 2.4 Photograph Showing Cross Section of Plastic Annulus and the Glass Tube Coupled to the Brass Test Section

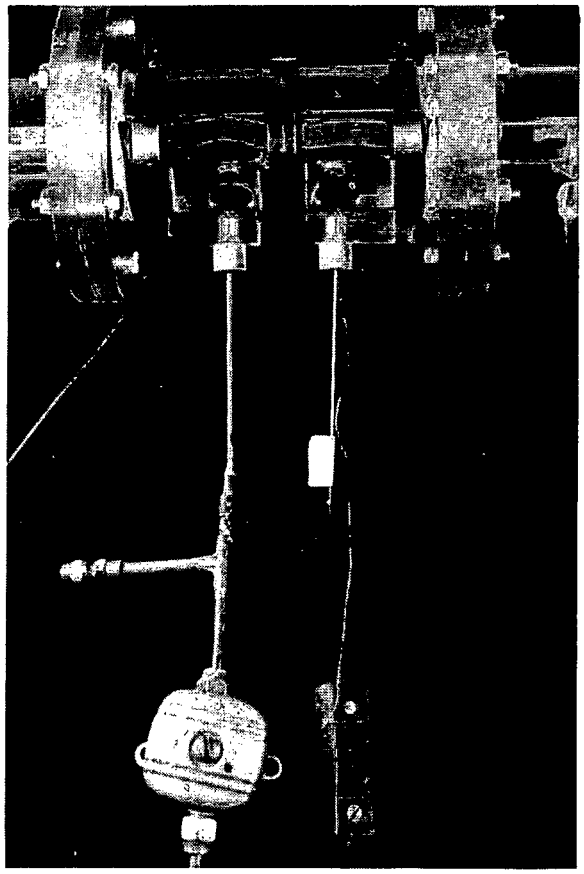


Figure 2.5 Photograph of Test Section within the Plastic Annulus

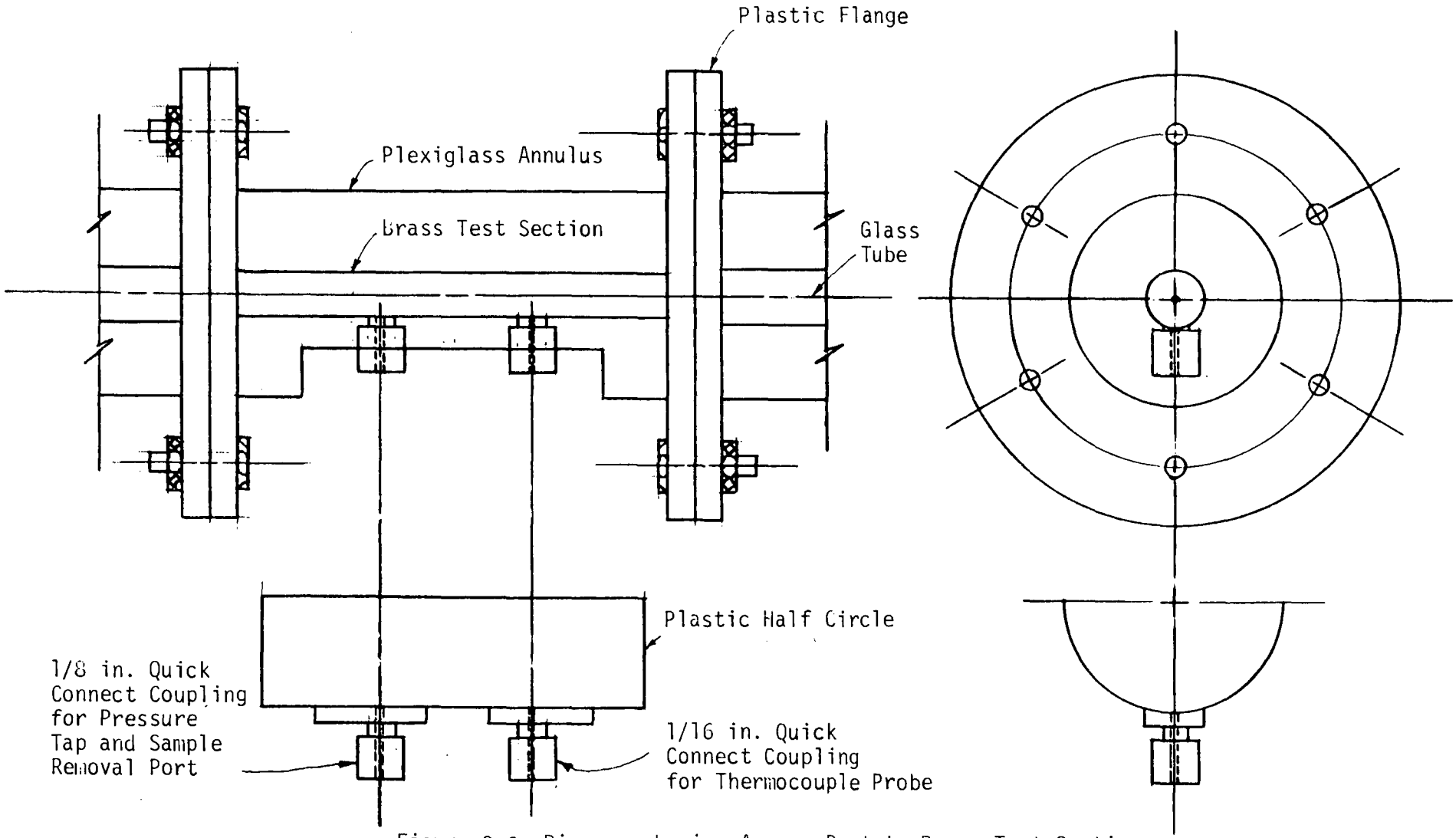


Figure 2.6 Diagram showing Access Port to Brass Test Section

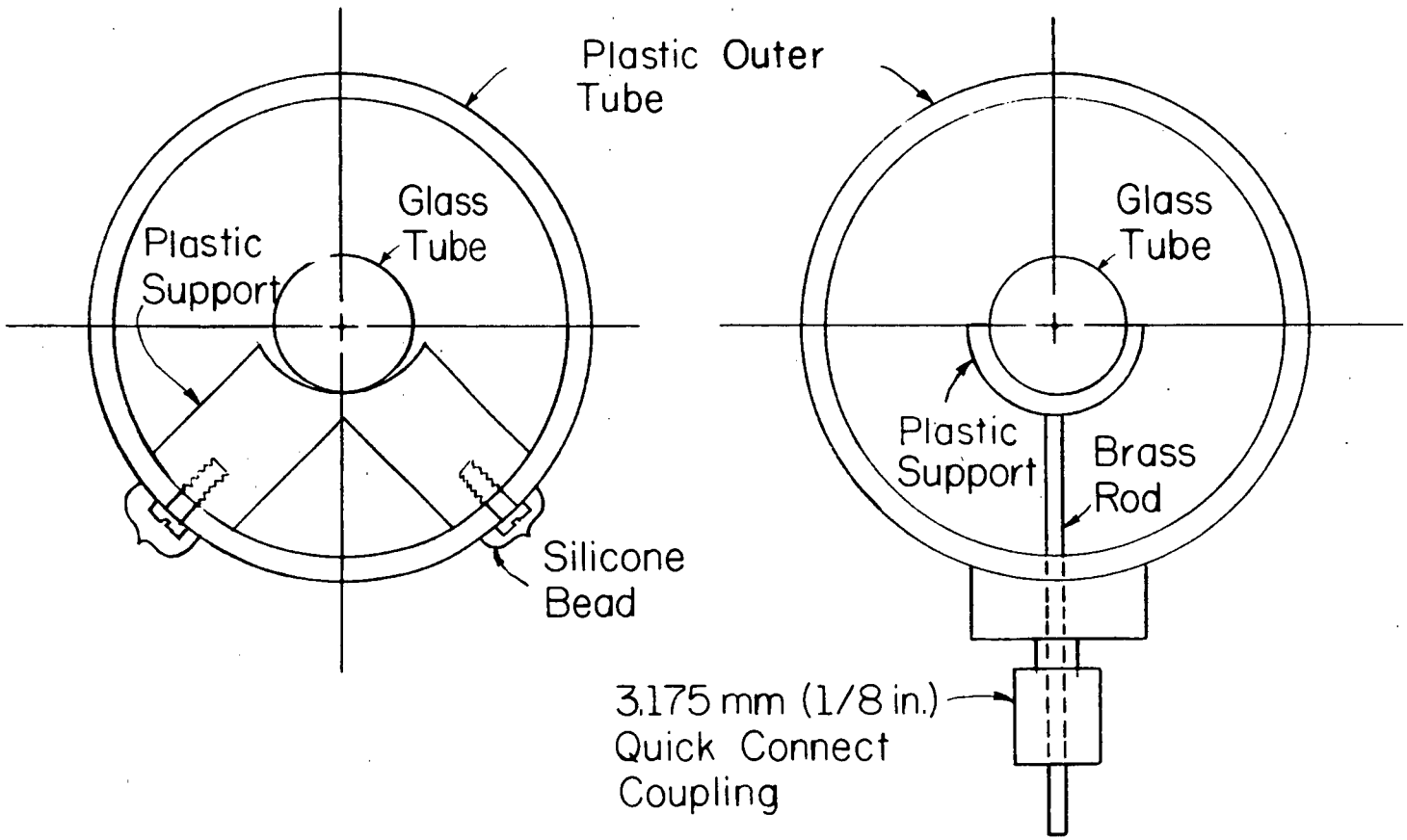


Figure 2.7 Cross Sectional Diagram of the Condenser showing the Supports Used to Center the Glass Tubes in the Annulus

2.2.5 Subcooler

The throttling process may cause some of the liquid to flash into vapor. The function of the subcooler is to insure that only liquid refrigerant enters the pump. The subcooler is a copper tube-in-tube counterflow heat exchanger with city tap water passing through the annulus used for cooling. A sight glass is located just after the subcooler for the purpose of checking whether any vapor bubbles are entering the pump.

2.3 Description of Instrumentation

2.3.1 Condenser Instrumentation

Since it is not feasible to insert any instrumentation into the glass pipes, the condenser includes ten brass test sections instrumented with thermocouple probes, pressure taps and sample-removal ports. The location of each brass test section and its corresponding number is shown in Fig. 2.3. Figure 2.8 includes a diagram of the instrumentation inserted into one of the brass test sections.

The thermocouple probes were machine-welded using coated 0.076-mm (0.003-in.) diameter copper/constantan wires. The thermocouple was then inserted through a 16-gauge stainless steel tube approximately 15 cm (6 in.) long. Using a vacuum process, the tube was then filled with an epoxy to provide a refrigerant seal. The bead was exposed directly to the refrigerant to allow for a fast response time. The quick-connect coupling secures the probe in place. Between tests, the thermocouple probe can be shifted up or down along the diameter of the condensing tube.

A 3.2-mm (1.8-in.) brass tube was used as the pressure tap at all ten locations. Test sections number 6, 8, and 9 have sample-removal ports as

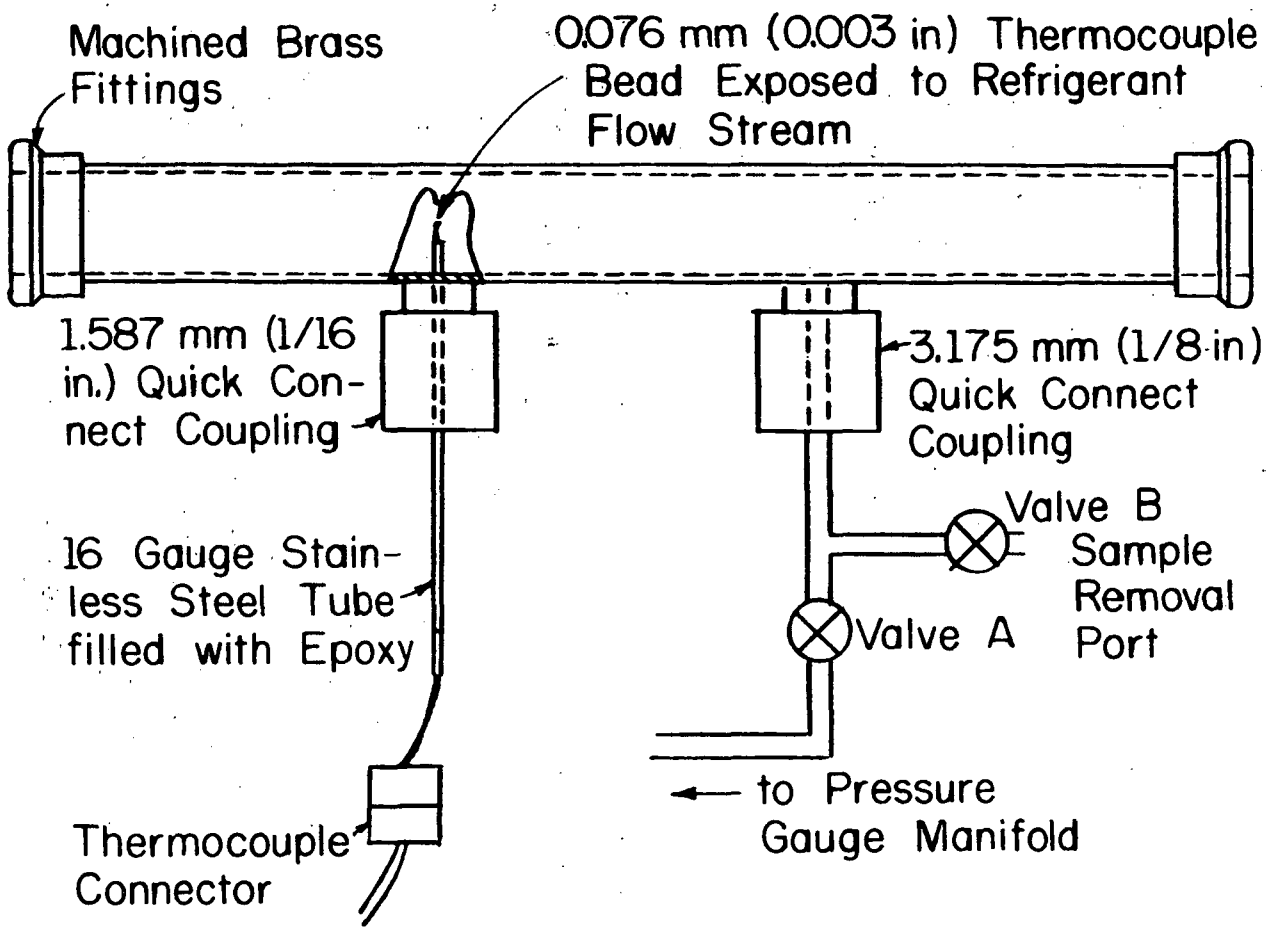


Figure 2.8 Diagram of the Test Section and Its Instrumentation

shown in Fig. 2.8. A pressure gauge with a 0-to-1000 kPa range and a scale division of 10 kPa was used to measure the pressure. Valve A, in Fig. 2.8 is a 64-mm (1/4-in.) packless line valve that is opened to pass the pressure of that location to the pressure gauge. We have attempted to remove only liquid samples of refrigerant; therefore, the brass tubes have been positioned so that they are flush with the bottom surface of the brass test sections. Prior to removing a sample, Valve A must be closed. Valve B is a spring loaded valve with an access valve connected to it. The sample is removed from this location and stored in a stainless steel canister. A gas chromatograph is used to analyze the mixture composition of these samples. Procedures used in the gas chromatography and methods of taking samples are discussed further in Chapter 4.

2.3.2 System Instrumentation

Figure 2.9 shows a numbering diagram of the instrumentation for the entire system. There are a total of 23 thermocouples, ten of which are the thermocouple probes located in the condenser. The remaining 13 thermocouples were installed to supply data for heat-balance calculations so as to insure proper system operation. These thermocouples are made of 30-gauge copper/constantan wire, and are inserted in 3.2-mm (1/8-in.) brass tubes that are soldered shut at one end. The tubes were filled with several drops of oil to improve conductivity and sealed at their other end with tape. These probes are inserted through an elbow fitting in the flow stream, as shown in Fig. 2.10. A data logger is used to monitor the temperatures. The stated accuracy when measuring copper/constantan thermocouple temperatures is 0.5°C. Worst-case resolution is 0.1°C.

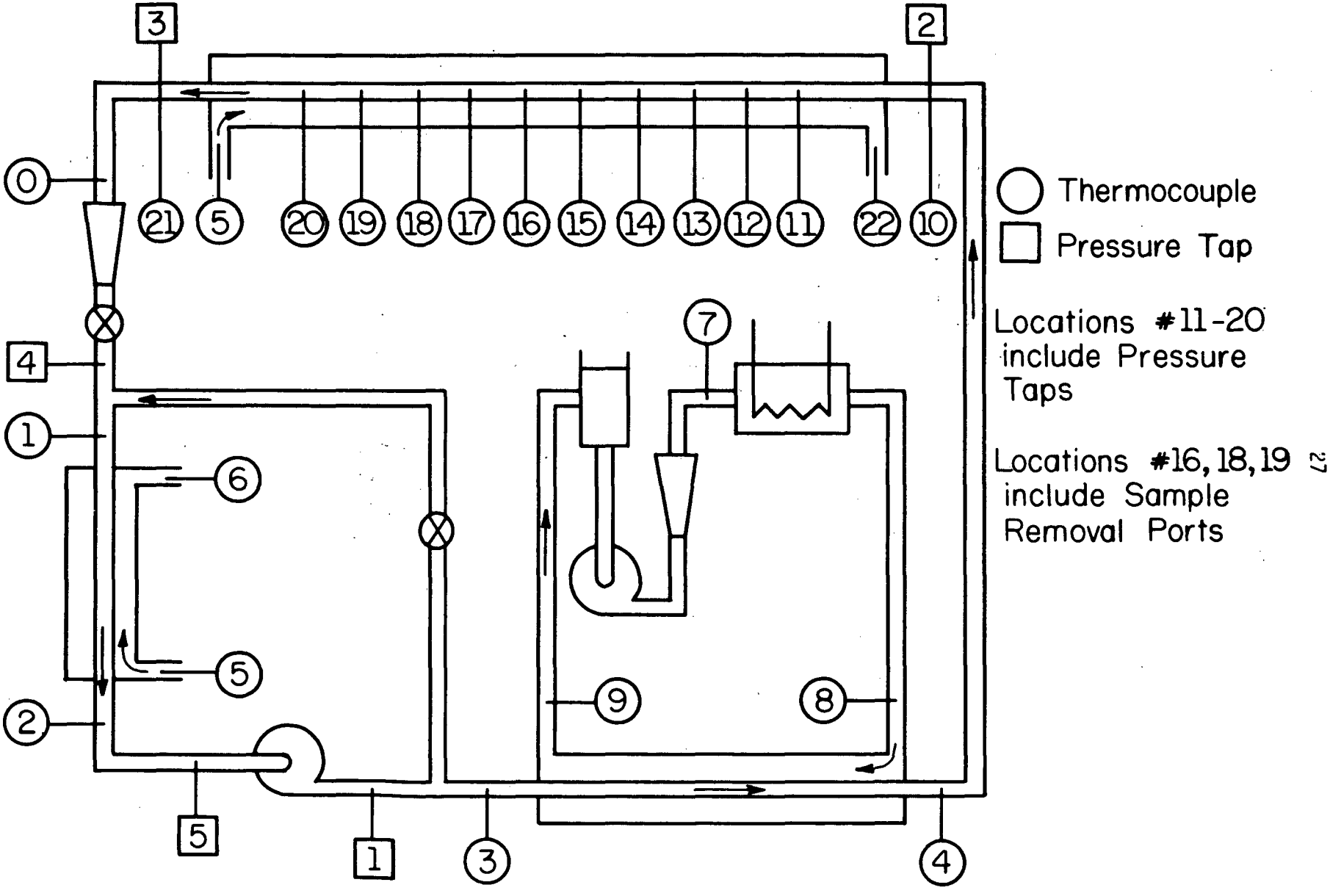


Figure 2.9 Diagram showing Location of Instrumentation (Numbers correspond to those on the Data Sheet)

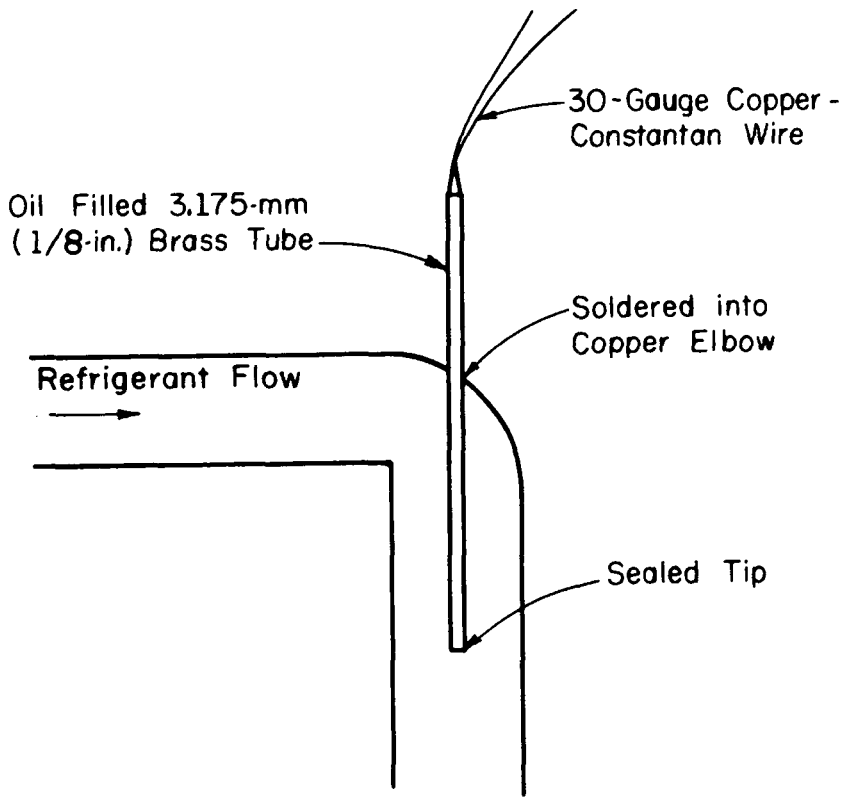


Figure 2.10 Facility Thermocouples inserted into Copper Elbow

There are five locations other than in the glass condenser at which pressures are measured. These locations are numbered using the square symbols in Fig. 2.8. The pressures are measured with a gauge with a range of 0 to 1000 kPa and scale divisions of 10 kPa.

3. EXPERIMENTAL CRITERIA AND PROCEDURES

3.1 Test Conditions

The test facility was focused on the R-12/R-114 mixture to better interpret the degradation of the heat transfer coefficients with increasing R-114 concentrations as presented in McCarthy [6]. We have conducted tests with pure R-12 and R-114 as well as 10, 20, 30, 40, and 50 percent by weight concentrations of R-114, while attempting to hold the average heat flux from the condenser and the refrigerant mass-flow rates constant. To standardize the tests, the following operating conditions for each test were used:

(1) Maintain the refrigerant inlet temperature to the condenser at 45.0°C ±0.5°C regardless of the concentration of the mixture. The amount of superheat will change with refrigerant concentrations.

(2) The refrigerant leaving the condenser should contain no more than a few small vapor bubbles.

(3) The condenser cooling water is fed directly from the tap water at a temperature of 14.5°C ± 0.6°C.

(4) The mass-flow rate of the refrigerant was maintained between 0.0227 kg/s to 0.0243 kg/s, depending on the refrigerant concentrations.

(5) The cooling-water flow rate was maintained at approximately 0.3 kg/s.

(6) The boiler water flow rate was maintained between 0.23 kg/s and 0.24 kg/s.

Three series of tests were conducted. In the first two series, the thermocouple probes were located in the center of the cross-section of the condenser tube. The purpose of the second series of tests was to check whether the first series could be duplicated. The third series was an attempt to duplicate the second series of tests; however, the thermocouple probes were moved down to the bottom surface of the condenser tube. Table 3.1 summarizes

the and actual conditions of the tests used for analysis. Some preliminary tests that were run at different control settings are not included in the listing on Table 3.1.

3.2 Test Procedure

All relevant information is recorded for each test on a data sheet. A sample is shown in Fig. 3.1. The start-up procedure is as follows:

1. Close the shutoff valves at the pressure gauges.
2. Evacuate the system for at least two hours. Make sure the valves on the pressure manifolds and sample removal ports are open.
3. When evacuated, close the charging valve and all valves except one on each manifold. Keep the valves to the pressure lines on the sample removal ports open.
4. Shut-off the vacuum pump.
5. Prepare a pail of hot water if R-114 is to be charged into the system.
6. Submerge the R-114 container in the pail of hot water.
7. With the charging hose connecting the refrigerant container to the system, weigh the R-114 container in the pail of water using the double-beam balance.
8. Bleed the charging hose.
9. Set the scale so that it will be level after the desired amount of refrigerant has been charged into the system.
10. Open the charging valve and let the refrigerant fill the system until the balance beam levels. As refrigerant enters the system, open the pressure gauge shutoff valves.

Table 3.1 Summary of Actual Test Conditions

	Test No.	% R-114	Refrig. Flow Rate (kg/s)	Average Heat Flux $\frac{kW}{m^2}$	Condenser Entering Refrig. Temp. (°C)	Condenser Entering Pressure (kPa Gauge)	Cooling Water Entering Temp. (°C)	Boiler Flow Rate (kg/s)	Condenser Flow Rate (kg/s)
	3	46.7	0.0228	4.22	45.1	478	14.9	0.238	0.295
	4	38.4	0.0233	4.37	45.1	503	15.1	0.245	0.297
	5	29.	0.0227	4.24	45.1	543	14.6	0.243	0.296
Series 1	6	20.	0.0232	4.33	44.8	579	14.8	0.238	0.299
	7	10.	0.0227	4.25	45.0	610	14.4	0.241	0.295
	8	100.	0.0238	4.14	45.0	208	14.5	0.236	0.297
	9	0.	0.0230	4.32	45.1	639	14.5	0.236	0.299
	10	50.	0.0239	4.44	45.1	420	13.9	0.236	0.300
	11	40.	0.0237	4.44	45.1	475	14.0	0.234	0.299
	12	30.	0.0236	4.45	45.0	537	14.3	0.232	0.299
Series 2	13	20.	0.0229	4.25	45.0	575	14.5	0.233	0.292
	14	10.	0.0229	4.29	45.0	593	14.0	0.233	0.302
	15	100.	0.0243	4.23	44.9	193	13.9	0.233	0.296
	16	0.	0.0231	4.32	45.0	638	13.8	0.232	0.299
	17	48.4	0.0241	4.50	44.9	465	14.5	0.233	0.299
Series 3	18	29.	0.0234	4.50	44.9		13.6	0.233	0.298
	19	10.	0.0234	4.44	45.1	592	13.3	0.232	0.294
	20	0.	0.0230	4.35	45.1	609	13.0	0.233	0.300

HEAT TRANSFER STUDIES DATA SHEET

Date: _____ Time: _____ Test No.: _____

Recorder(s): _____ Mixture Composition: _____

Condenser Pressures (kPa gauge):

Test Section	1	2	3	4	5	6	7	8	9	10
Pressure										

System Pressures (kPa gauge):

1. Pump Discharge _____
2. Condenser Inlet _____
3. Condenser Outlet _____
4. After Throttle _____
5. Pump Suction _____
6. Barometric _____

Temperatures:

Rotameter Flow Rates:

1. Refrigerant _____%
2. Condenser Water _____%
3. Boiler Water _____%

   Specific Gravity _____ @ _____ °C

Heaters:

1. _____V. _____A.
2. _____V. _____A.
3. _____V. _____A.

Gas Chromatography Samples:

1. Test Section No. _____, _____ °C @ _____ kPa
2. Test Section No. _____, _____ °C @ _____ kPa
3. Test Section No. _____, _____ °C @ _____ kPa
4. Pump Discharge _____ °C @ _____ kPa

Photography Comments:

General Comments:

Figure 3.1 Sample Data Sheet

11. Repeat steps 7 through 10 for the R-12, except that warming the R-12 container is not necessary.
12. Connect the data logger to the system by inserting the three isothermal input blocks.
13. Turn on the boiler pump to begin circulating the hot-water loop.
14. Bleed the air out of the hot-water loop from the stopcock. Do this several times throughout the test.
15. Check the concentration of the corrosion inhibitor in the hot water loop by removing a sample from the stopcock and measuring its specific gravity and temperature.
16. Return water sample to system.
17. Remove inlet-cooling-water hose to condenser by loosening the hose clamp.
18. Run condenser water for a few seconds to rid any rust particles from the line.
19. Reconnect the cooling-water hose.
20. Make sure the condenser-cooling-water valve near the rotameter is open.
21. Begin running the condenser cooling water through the annulus.
22. The cooling-water pressure should not exceed 8 psig.
23. Turn on the heating elements and increase the power until the voltage readings across each element is about 150 volts.
24. Open the throttle completely.
25. Set the by-pass valve half open.
26. Wait approximately five minutes, then turn on the refrigerant pump.

27. Check the sight glass just before the refrigerant pump. If there are vapor bubbles after 30 seconds of operation, turn off the refrigerant pump and add more refrigerant. Repeat steps 26 and 27 until there are no vapor bubbles entering the pump.
28. Fill out the heading of the data recording sheet.
29. Adjust the flow rate using the throttle and by-pass valve. After throttling always check for vapor bubbles entering the pump.
30. Adjust the heaters, flow rates and refrigerant charge in order to meet the test conditions described in Section 3.1.
31. Because of the initial low temperatures and pressures during start-up, the system is always intentionally overcharged to insure that only liquid refrigerant is entering the pump during start-up.
32. When venting the refrigerant out of the charging port, be sure to open the throttle valve completely. This will insure the presence of only liquid near the charging port. When venting a refrigerant mixture, this will help maintain the original concentration in the remaining charge.
33. After venting return the throttle valve to its original position.
34. Once all target conditions have initially been met, at least 15 minutes operation should be allowed to insure that conditions are at steady state.
35. When the steady-state target conditions have been achieved, the data recording sheet should be filled out completely and any comments should be noted in the space provided. A printout of all thermocouple readings by the datalogger should be pasted to the data recording sheet.

36. Use the data logger to record 30 seconds of data in order to record a pattern of the temperatures that are fluctuating due to the alternate presence of liquid and vapor.
37. For tests during which photographs are taken, focus on the flow regimes at the twelve designated locations along the condenser. Photography procedures are discussed further in the next section.
38. For tests during which samples are removed for chromatographic analysis, follow the procedures discussed in Chapter 4.
39. The shutdown procedure begins with turning off the refrigerant pump first, then
40. Turn off the heaters, the boiler water pump and the condensing cooling water supply.
41. If the next test is to be run with a different concentration, then release the refrigerant by opening the charging valve.
42. The system is now ready to be evacuated for another test.

3.3 Photography Procedures

Tests run with different refrigerant mixture concentrations will produce different flow patterns along the length of the condenser tube. In order to document these results, the condenser was photographed at twelve different locations (see Fig. 2.2). Pictures were taken at these same locations for each test in order to better compare the differences in the regimes from one test to the other.

Black-and-white "Tri-X" pan film was used in a 35 mm camera supported on a tripod and resting on a mobile cart. Two tungsten-filament lamps with diffusers, positioned on each side of the camera, were used for artificial lighting. The background consisted of a white cardboard sheet with a 76-mm

(3-in.) wide black cardboard strip pasted on it. When taking pictures, the black strip was aligned directly behind the condenser tube. The first picture was taken near the entrance to the condenser where the refrigerant is superheated. The cart with the camera, the lamps, and the background were then moved to the second location downstream of the first, and a picture was taken. This procedure was continued until the final 12th location was reached where the refrigerant is exiting the condenser as a subcooled liquid. The corresponding positions along the condenser where each photograph was taken are shown below every picture presented in Section 5.6.

Several Super 8-mm movies were also taken of the various flow regimes. When the techniques of this procedure are refined, the movies will be very useful in documenting and studying the results.

4. CONCENTRATION MEASUREMENTS USING GAS CHROMATOGRAPHY

4.1 Purpose of Chromatographic Measurements

It was found that during the condensation of a refrigerant mixture, the heat-transfer coefficients were substantially reduced as compared to a pure component [6]. Some of the possibilities for this reduction include counter diffusion of the two components and "slip" of the vapor. The vapor moves at a greater velocity than the liquid. This slip condition results in local non-equilibrium of the two phases with respect to temperature and concentration when using a refrigerant mixture (for a further discussion on "slip" refer to Chapter 6). Knowing the refrigerant concentrations in the liquid and vapor at various points along the tube would be valuable information needed to quantify the extent of the nonequilibrium. We may never be able to achieve this goal completely but we are making a start by determining the concentration of the liquid at various positions along the tube.

4.2 Extracting Liquid Samples

Removing a liquid-only and a vapor-only sample simultaneously at the same position along the condenser tube is indeed a challenge considering the annular- and slug-flow regimes present throughout most of the condenser. As a first step, we have chosen to remove only a liquid sample at three different locations along the condenser, namely Test Section numbers 6, 8, and 9 (see Fig. 2.2). The locations are at regimes that facilitate the removal of liquid-only samples. Samples are also removed near the pump discharge where the refrigerant is all liquid and probably well mixed. The concentrations of the analyzed samples are then compared to the concentration determined from the masses of the two refrigerants used to charge the system. Several samples are taken at this location throughout the test to check for repeatability and homogeneity.

Each sample from the condenser is removed from an access valve as was shown in Fig. 2.7. A refrigerant-charging hose connects the access valve to a spring-loaded valve on a stainless steel canister. The sample is stored in the canister and transported to the University of Illinois Chemistry Department for analysis. A photograph of the canister and charging hose is shown in Fig. 4.1.

Before the sample was removed, the canister and charging hose were evacuated of air and of any refrigerant remaining from a previous test. The valve on the line that runs to the pressure manifold, as was shown in Fig. 2.7, must be shut to prevent any refrigerant in that line from entering the canister and changing the true composition of the sample. The charging hose is then connected to the access valve and bled at the spring-loaded valve on the canister. Next the hand valve on the canister is opened to allow the refrigerant to enter. The liquid sample flashes into vapor as it enters the canister. Because of the large pressure differential between the condenser and canister, the valve is only opened for a short duration--perhaps a second or two. This is done in order to prevent too much refrigerant from entering, otherwise the sample may become saturated at room temperature. Because we are working with a binary refrigerant, if saturation should occur, the gas removed from the canister for chromatographic analysis would not be representative of the original liquid sample. A pressure gauge on the canister, located between the hand valve and the spring-loaded valve, indicates whether the proper amount of refrigerant has been removed from the condenser. The cooling effect, due to the liquid flashing into vapor, may cause some liquid droplets to form in the neck of the canister, therefore the canister is allowed to reach room temperature before the hand valve on the canister is closed. Great care must be taken at all steps to preserve the integrity of the original liquid sample.

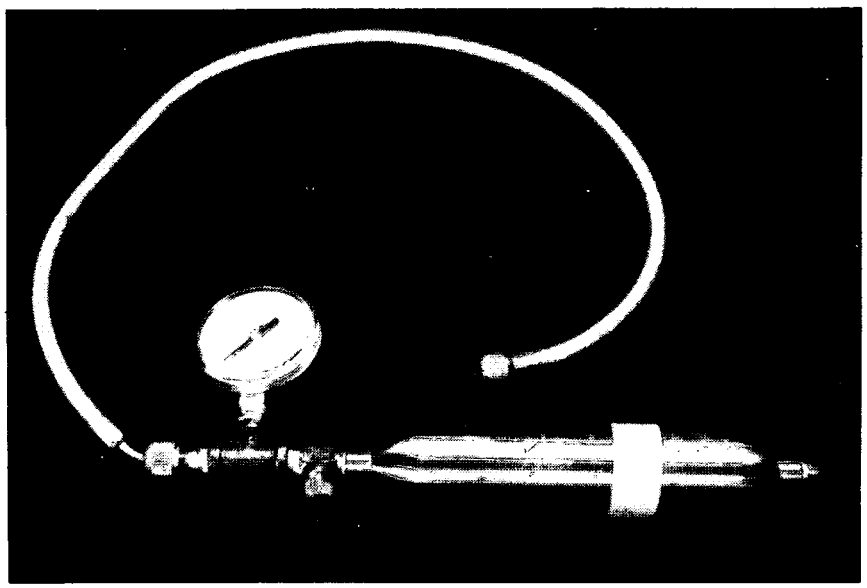


Figure 4.1 Sample-containing Canister with Charging Hose Attached

4.3 Sample Preparation

After the liquid refrigerant has been extracted from the condenser and is in vapor form in the canister, the sample must be prepared for chromatographic analysis [12]. Twenty milliliters of liquid hexane is added to a 25 ml screw-cap vial with a lined silicone rubber septum. The weight of the vial of hexane is measured to the nearest 0.1 mg on an analytical balance. The balance is then adjusted to zero. Next, the canister containing the refrigerant sample is submerged in warm water to insure that it contains only vapor. The refrigerant vapor in the canister is then released into a rubber tube with a balloon on the end of it, (see Fig. 4.2). Depending on the concentration to be measured, a 10-ml or 20-ml sample is withdrawn from the tube using a 10-ml pressure-tight gas syringe. The sample is then injected into the head space of the hexane bottle which is then reweighed (see Fig. 4.3). A history of the weights of the samples injected into the solvent are kept to check for repeatability and trends. The hexane is then thoroughly swirled and allowed to stand for at least 15 minutes to allow the refrigerant to fully dissolve into the solvent. It is this hexane-refrigerant solution that is injected into the chromatograph for analysis.

A known standard must be prepared and analyzed on the chromatograph to determine the relative sensitivity of the chromatograph to R-114 and R-12. The concentrations of the refrigerants in the unknown sample can then be calculated. Standards are prepared in a similar fashion. For example, 10 ml of R-12 and 10 ml of R-114, both in vapor form, are dissolved in 20 ml of hexane. After each addition the hexane bottle is weighed.

The hexane-refrigerant solution, now referred to as the sample, is "solvent flushed" into the chromatograph. One microliter of pure hexane is

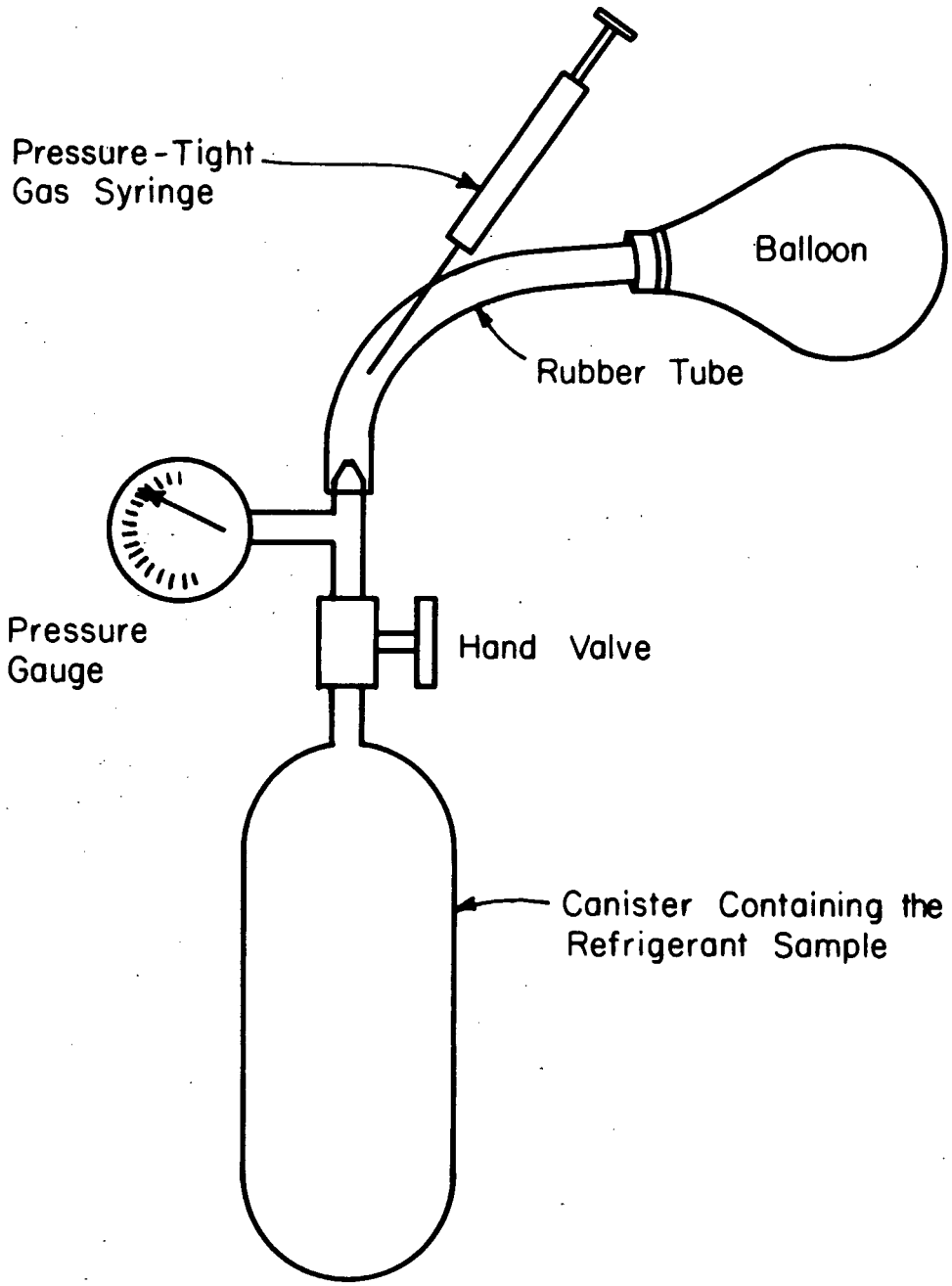


Figure 4.2 Diagram showing the Removal of the Refrigerant Sample from the Canister

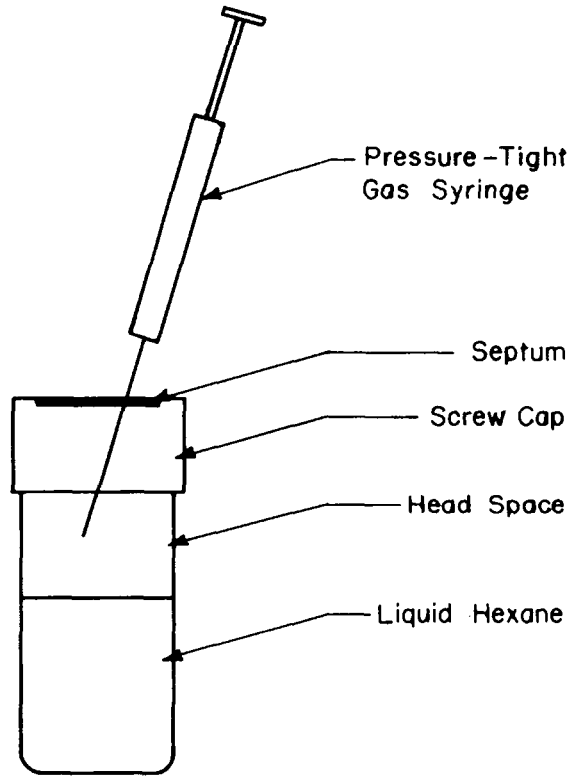


Figure 4.3 Diagram showing the Injection of the Refrigerant Sample into the 25 ml Screw Cap Vial containing Liquid Hexane

withdrawn into a 10-μℓ liquid syringe, followed by 1 μℓ of air, and then 8 μℓ of sample. Injecting this mixture into the chromatograph insures that the entire sample is injected into the chromatograph, including the dead volume in the syringe needle. This technique insures that partial vaporization of residual sample in the syringe needle in the injection port of the chromatograph does not occur.

4.4 Gas Chromatograph Conditions

A gas chromatograph with a flame ionization detector (FID) is used for the analysis. The column used is a 1.8-m x 3.2-mm (6-ft x 1/8-in.) diameter stainless steel tube packed with "Porapak O." The carrier gas used is ultra-pure nitrogen. The gas chromatograph working conditions are as follows:

air pressure to FID	27 psig
hydrogen pressure to FID	20 psig
carrier gas pressure	60 psig
carrier gas flowrate	30 ml/min
oven temperature	150°C
injector port temperature	200°C
FID temperature	250°C
sensitivity setting	1 x 4 or 1 x 1
chart speed	5 s/cm

4.5 Determining Concentration from the Chromatograph Output

After injecting a sample into the gas chromatograph, the machine produces a graph with two peak areas as shown in Fig. 4.4. The first peak corresponds to the R-12 and has a retention time of 1.8 minutes. The second peak represents the amount of R-114 present in the sample and its retention time is

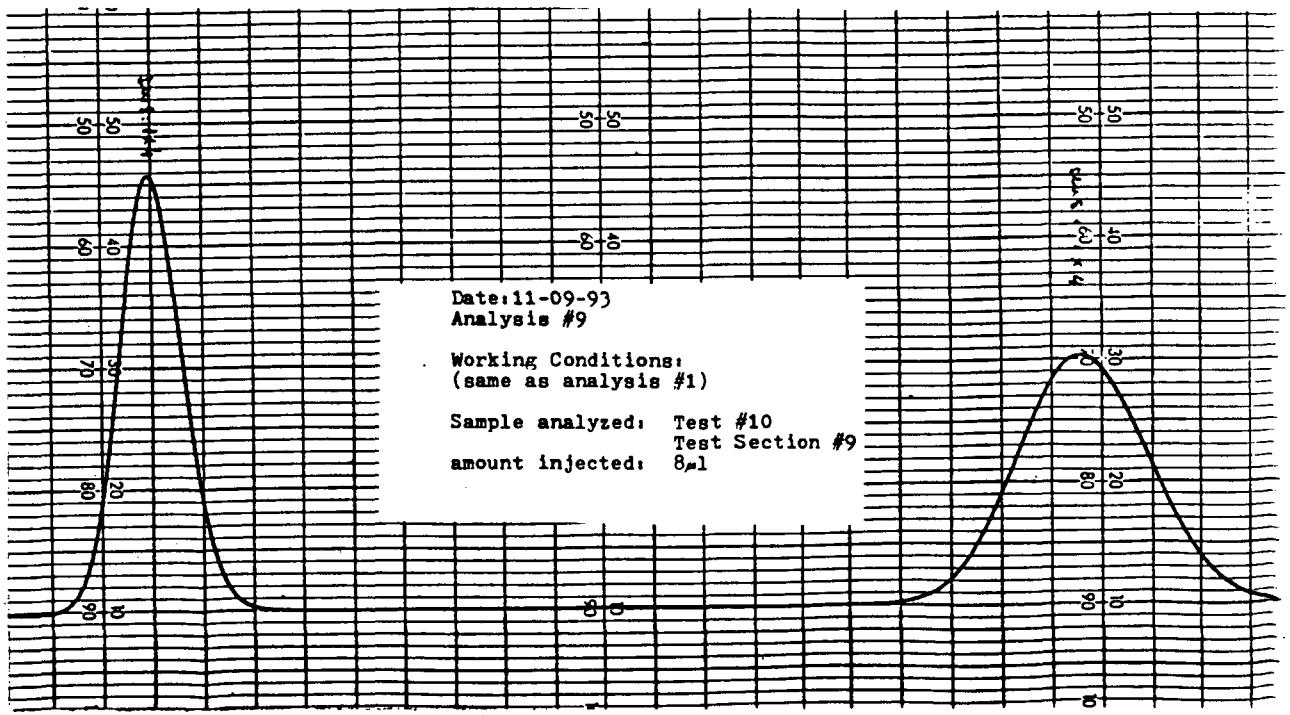


Figure 4.4 Gas Chromatograph Analysis of a Sample Containing Refrigerants 12 and 114

about 3.2 minutes. The areas under these two curves are found using a polar planimeter. For better precision, each curve was integrated five times. The area corresponding to each refrigerant was taken as the sum of all five integrations. The precision of the planimeter is better than 0.5 percent.

The gas chromatograph is more sensitive to one refrigerant than the other, therefore comparing the two peak areas will not give the true weight concentration of either component. A known standard must be prepared and analyzed in order to determine the relative sensitivity of the chromatograph with respect to the two refrigerants. Once the peak areas of the standard and unknown are found, there are two methods (Method A and Method B) of calculating the concentration of the refrigerants in the unknown sample. Each method assumes that the solubilities of the two refrigerants in hexane are the same.

Method A is based on a standard prepared with known volumes of each refrigerant. It is known that each peak area is proportional to the mass of the corresponding refrigerant. Therefore we can state that

$$A_{114} = (m_{114})\ (e_{114}) \tag{4.1}$$

and

$$A_{12} = (m_{12})\ (e_{12}) \tag{4.2}$$

where

A = peak area

e = sensitivity of the detector

m = mass

M = molecular weight

x = unknown concentration

s = standard

Dividing Eq. (4.1) by Eq. (4.2) we get

$$\left(\frac{m_{114}}{m_{12}}\right)\left(\frac{e_{114}}{e_{12}}\right) = \frac{A_{114s}}{A_{12s}} \tag{4.3}$$

It is assumed that each refrigerant behaves as an ideal gas at room temperature and pressure. If the standard is prepared with equal volumes of each refrigerant, then the mass ratio of the two refrigerants is equal to the molecular weight ratio. There,

$$\left(\frac{M_{114}}{M_{12}}\right)\left(\frac{e_{114}}{e_{12}}\right) = \frac{A_{114}}{A_{12}} \tag{4.4}$$

or

$$\frac{e_{114}}{e_{12}} = \left(\frac{A_{114s}}{A_{12s}}\right)\left(\frac{M_{12}}{M_{114}}\right) \tag{4.5}$$

Substituting Eq. (4.5) into Eq. (4.3) we get

$$\frac{m_{114x}}{m_{12x}} = \left(\frac{A_{114x}}{A_{12x}}\right)\left(\frac{M_{114}}{M_{12}}\right)\left(\frac{A_{12s}}{A_{114s}}\right)$$

If the volume ratio of the two refrigerants used in preparing the standard is not one-to-one then,

$$\frac{m_{114x}}{m_{12x}} = \left(\frac{V_{114s}}{V_{12s}}\right)\left(\frac{A_{114x}}{A_{12x}}\right)\left(\frac{M_{114}}{M_{12}}\right)\left(\frac{A_{12s}}{A_{114s}}\right)$$

where V_{114}/V_{12} is the volume ratio. Given the peak area for the standard and unknown, the concentration of R-114 and R-12 in the unknown sample can be calculated as follows:

$$\text{percent R-114} = \frac{\dfrac{m_{114x}}{m_{12x}}}{1 + \dfrac{m_{114x}}{m_{12x}}} \quad (100)$$

$$\text{percent R-12} = 100 - \text{percent of R-114}$$

Method B used for calculating the concentrations is based on carefully measuring the weights of each refrigerant used in preparing the standard [13]. This formula is given as:

$$\text{mass percent R-12} = 100 \cdot [(A_{12})(F_{12})]/[(A_{12x})(F_{12}) + (A_{114x})(F_{114x})]$$

$$\text{mass percent R-114} = 100 - \text{percent R-12}$$

where

F_{12} = response factor in weight/peak area for R-12 in the prepared standard

A_{12} = peak area of R-12 in the unknown sample.

5. EXPERIMENTAL DATA

5.1 Overview

Three series of tests were conducted as described in Section 3.1. A summary of the test conditions are shown in Table 3.1. The data collected from each test includes temperatures, pressures, chromatographic analyses, and photographs of the flow regimes. A summary of pressure and temperature data is shown in APPENDIX A. This chapter interprets some of the experimental data and strengthens the theories presented in Chapter 6 regarding the decrease in the heat-transfer coefficients. However, the results presented in this chapter should be considered as preliminary and will act as a guide in improving the procedures for further studies.

5.2 Temperature Profiles

Figures 5.1, 5.2, and 5.3 show the longitudinal temperature profiles in the condenser for selected tests in each series. As expected, the temperature of the refrigerant progressively drops when a mixture is employed.

For each test the entrance temperature of the refrigerant to the condenser was maintained at 45.0°C which represents 9 to 16°C superheat depending on the concentration. The existence of only a few small vapor bubbles was the criteria set for the exit condition. As shown in Figs. 5.1 and 5.2, the slope of temperature profile becomes steeper with increasing concentrations of R-114.

In test series 1 and 2, the tips of the thermocouple probes were located in the center of the condenser tube. Figures 5.1 and 5.2 show that the temperatures after thermocouple No. 17 (refer back to Fig. 2.9 for thermocouple locations) begin to decline sharply from the linear trend. The reason for the sharp decline in temperature after thermocouple No. 17 is that the thermo-

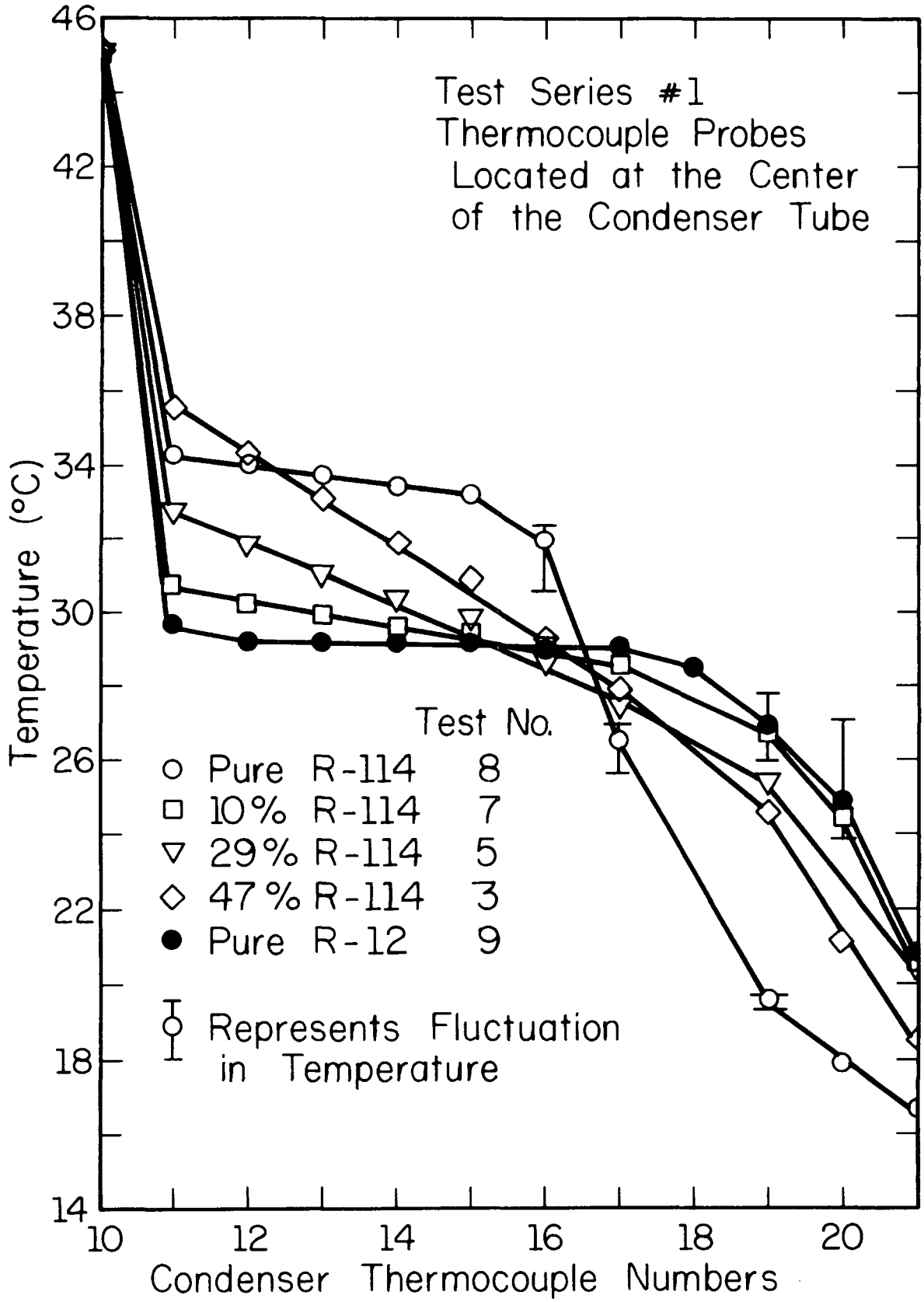


Figure 5.1 Refrigerant Temperature Profiles along the Condenser from Selected Tests in Series 1

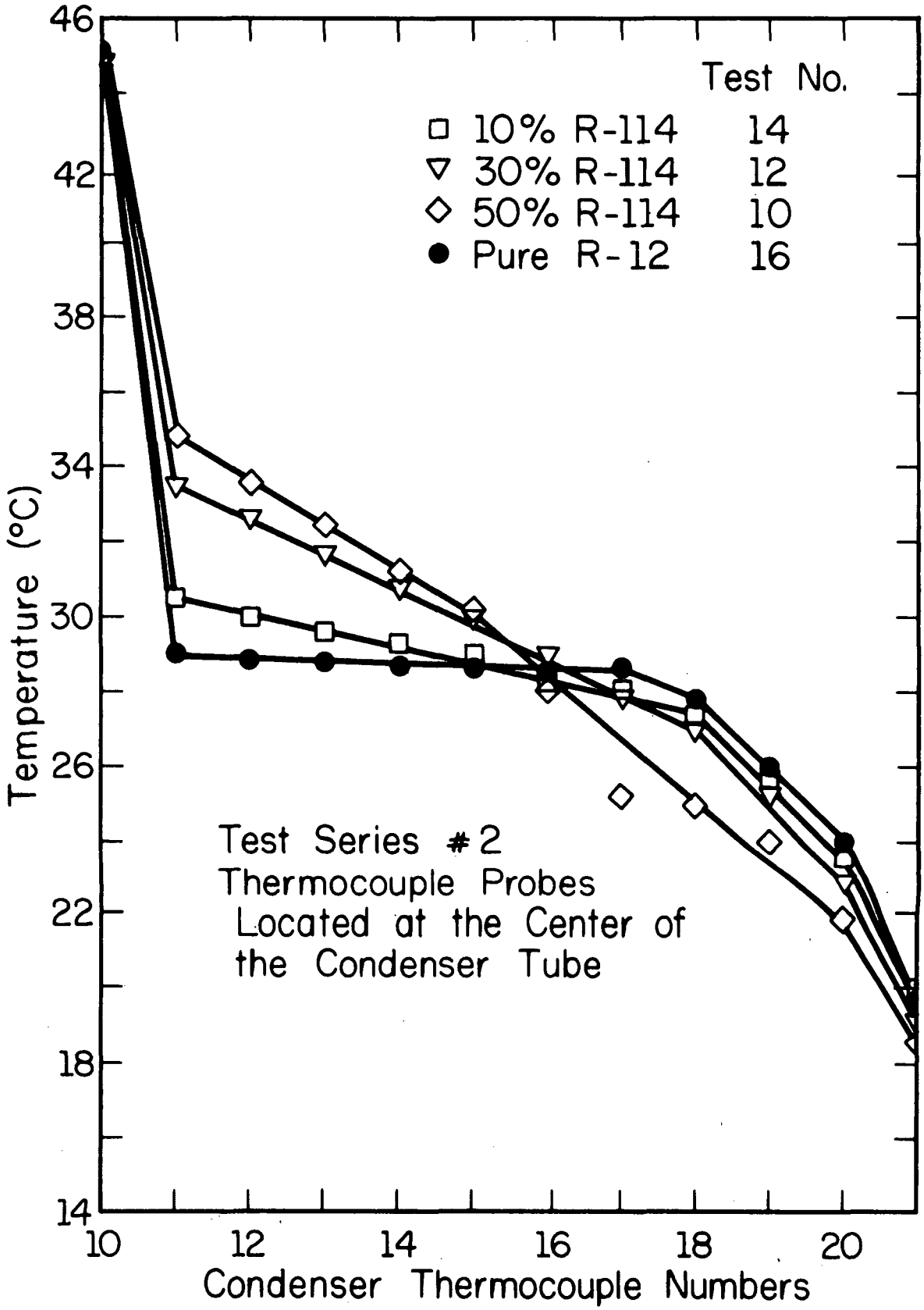


Figure 5.2 Refrigerant Temperature Profiles along the Condenser from Selected Tests in Series 2

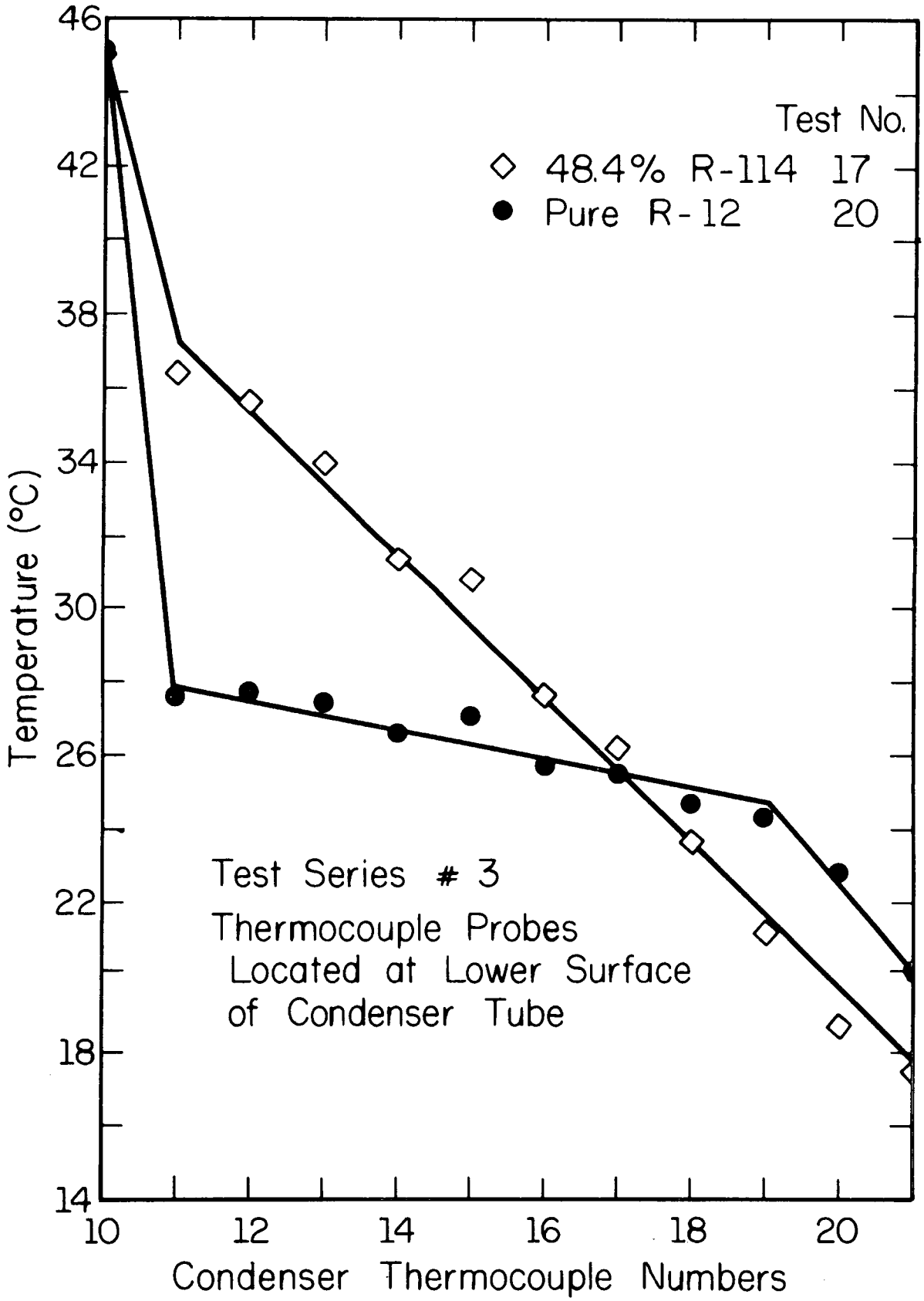


Figure 5.3 Refrigerant Lower Surface Temperature Profiles along the Condenser from Selected Tests in Series 3

couple probe is immersed in liquid which is subcooled, even while in contact with saturated vapor.

For the pure R-12 test in Fig. 5.3, the liquid refrigerant at the bottom surface of the condenser gradually drops in temperature as it moves further downstream, therefore becoming more and more subcooled. The refrigerant near the surface at thermocouple No. 11 (Test Section No. 1) is at the saturation temperature, however by the time the liquid refrigerant has reached thermocouple No. 19 (Test Section No. 9), it has been subcooled 3.3°C. The vapor remains at the saturation temperature throughout the condenser. As a result, the local temperature gradient across the condenser tube progressively increases further downstream as the liquid becomes progressively more subcooled.

5.3 Temperature Gradient Across the Tube

Because of the local subcooling occurring at the lower surface of the condenser wall, a temperature gradient forms across the condenser tube regardless of whether a pure refrigerant or a mixture is present. However, because of the "slip" condition and its associated nonequilibrium problem with respect to temperature, one might expect the temperature gradient for a refrigerant mixture to be significantly greater. The temperature gradient may or may not play an important role in affecting the local heat-transfer coefficient, depending on how strongly the mass diffusivity of the mixture is coupled to the temperature gradient.

5.4 Temperature Fluctuations

Thermocouples No. 17 through 20 are almost always in a slug-flow regime and, therefore, experience fluctuations in temperature regardless of whether the probes are at the center or surface of the condenser tube. Figure 5.4

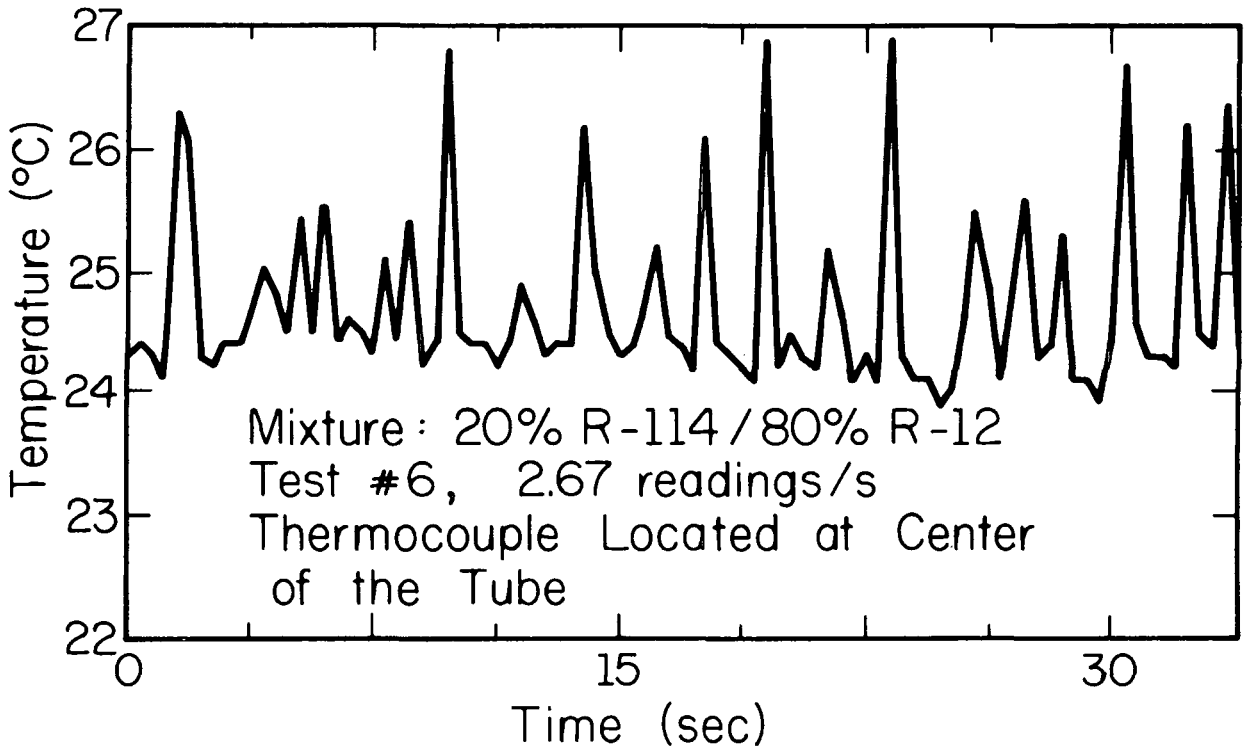


Figure 5.4 Temperature Fluctuations of Thermocouple No. 20 in Test Section No. 10

shows how thermocouple No. 20 fluctuated in temperature during a test with a 20 percent mixture of R-114. Although the fluctuations are as high as 3.0°C, there appears to be an average base temperature of about 24.3°C. The average base temperature signifies that the probe is generally in contact with the liquid refrigerant. The major peaks in temperature represent a passing vapor bubble. The temperature fluctuations recorded for three other tests with different concentrations of R-114 are presented in APPENDIX B. Note that for Test No. 8, the base temperature for thermocouple No. 16 is higher than for thermocouple No. 17. This difference indicates that the probe No. 16 is predominantly in contact with vapor and its temperature drops with a passing slug of liquid.

The extent of the temperature fluctuations can give an indication of the magnitude of the temperature gradient across the tube. However, smaller fluctuations do not necessarily imply that the temperature difference between the vapor and liquid is less at that location. The vapor bubbles may be so small that the thermocouple may not have enough time to dry off completely in the presence of the vapor. Noting any changes in fluctuations with varying concentrations of R-114 may reveal different levels of nonequilibrium. The temperature fluctuations may also prove to be characteristic to specific flow regimes. Therefore, in the future, when a metal condenser is built to better examine the heat-transfer coefficients, the temperature fluctuations will help correlate the regimes to the heat-transfer coefficients.

5.5 Pressure Drop

The R-114 vapor is less dense than the R-12 vapor, therefore, the velocity is higher for a given mass-flow rate. Because of the higher velocity, and because the R-114 liquid is more viscous that the R-12, its

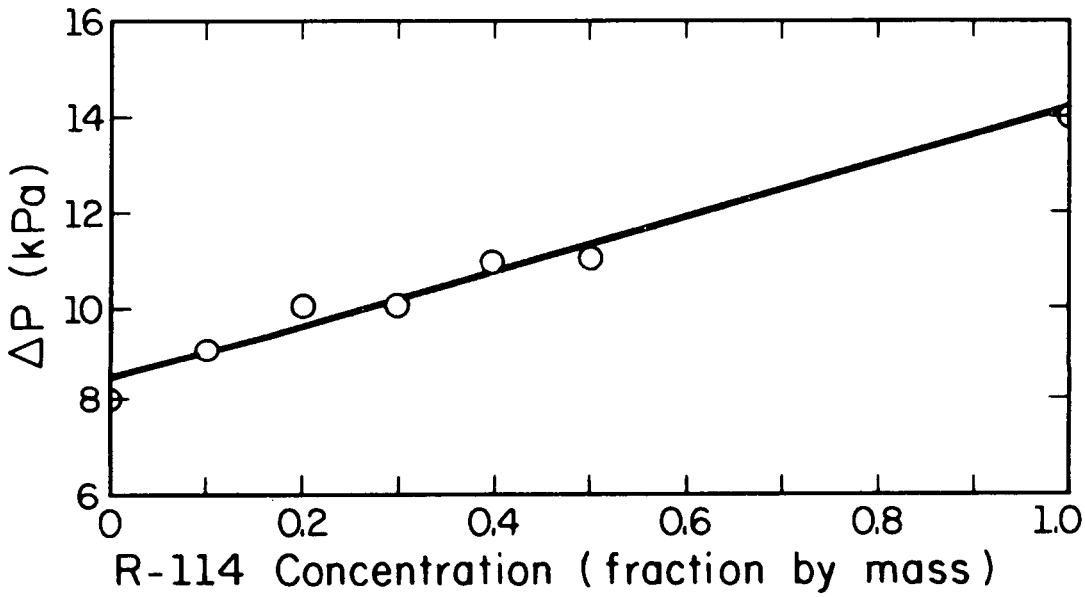


Figure 5.5 Pressure Drop across the Condenser versus R-114 Concentration

pressure drop along the condenser will be greater. Figure 5.5 shows for selected tests the measured pressure drop across the condenser as a function of concentration. The higher the concentration of R-114, the greater the pressure drop. Figure 5.1 indicates that the condensing temperature of pure R-114 drops more than does the condensing temperature of pure R-12. This difference is explainable because of the greater drop in pressure of R-114 and also that each kPa drop in pressure results in a greater drop in temperature of R-114.

5.6 Flow Regimes

An important part of the experiment was to focus on the various flow regimes occurring along the condenser during the condensation of a refrigerant mixture. Observing the flow regimes of various refrigerant mixtures is the first step in the study directed toward solving the heat transfer degradation problem. The flow regimes will be correlated to the actual heat transfer coefficients in the future. This correlation will lead to a better mathematical model that predicts the heat transfer characteristics at specific flow regimes.

Photographs were taken of the condenser tube at twelve different locations. Two sets of photographs displaying the various flow regimes have been included as data in Figs. 5.6 through 5.31. Below each photograph is the picture location number as was shown in Fig. 2.3 and, in parenthesis, the corresponding distance the picture was taken downstream from the condenser entrance. The two outside lines on the photograph are those of the 635-mm (2-3/4 in.) plastic outer tube. The two inside lines are those of the 19-mm (3/4-in.) O.D. glass condenser tube. An arrow points in the direction of the refrigerant flow. The background is a black 760-mm (3 in.) wide cardboard strip attached to white cardboard.

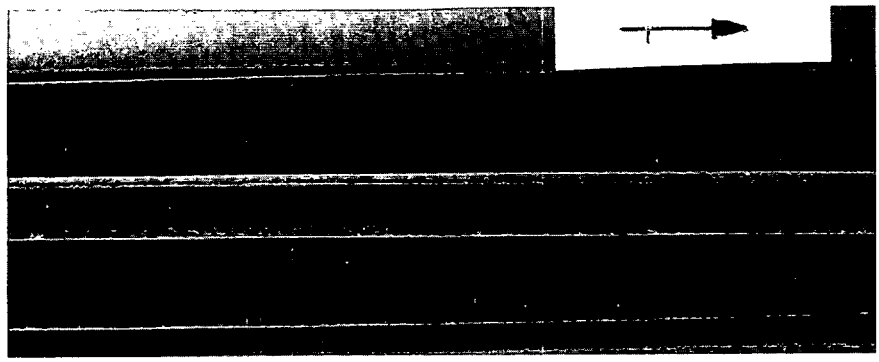


Figure 5.6 Picture Location No. 1 (1.0 m downstream) Annular Flow Regime, Very Little Liquid, 50/50 Mixture

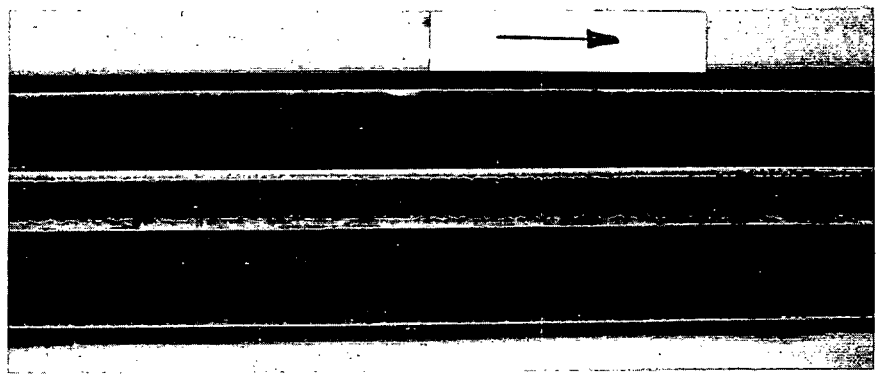


Figure 5.7 Picture Location No. 2 (2.6 m downstream) Annular Flow Regime, 50/50 Mixture

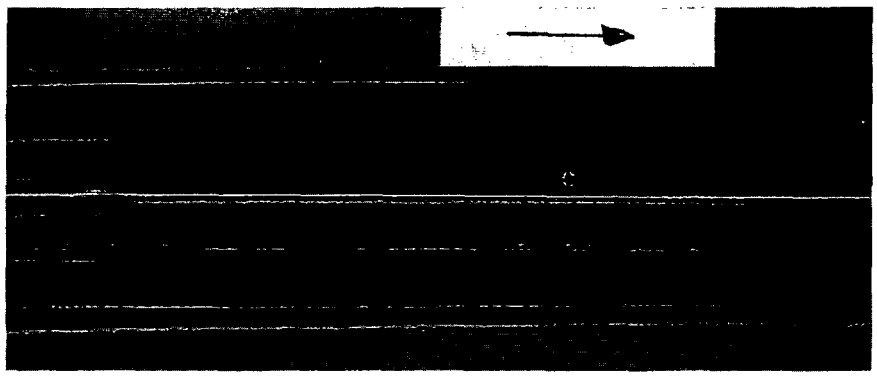


Figure 5.8 Picture Location No. 3 (4.0 m downstream) Annular Flow, 50/50 Mixture

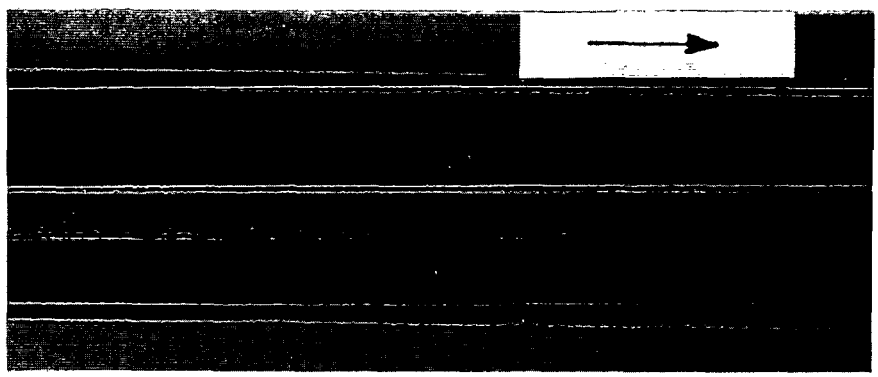


Figure 5.9 Picture Location No. 4 (5.9 m downstream) Annular Flow, Thicker Liquid Film at Bottom, 50/50 Mixture

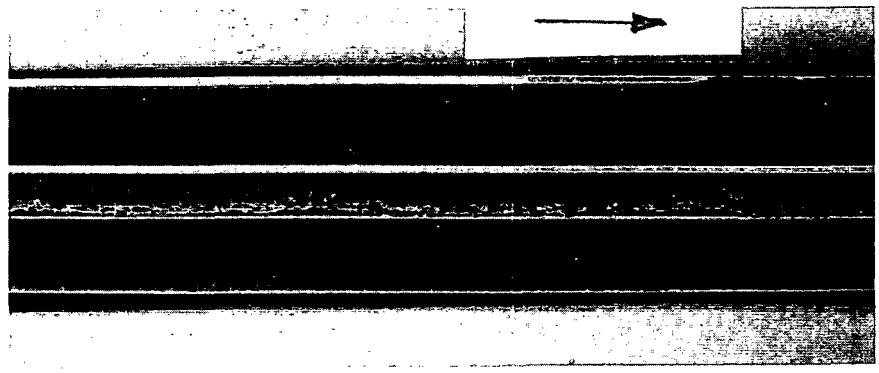


Figure 5.10 Picture Location No. 5 (7.5 m downstream)
Annular to Wavy Flow Transition, 50/50 Mixture

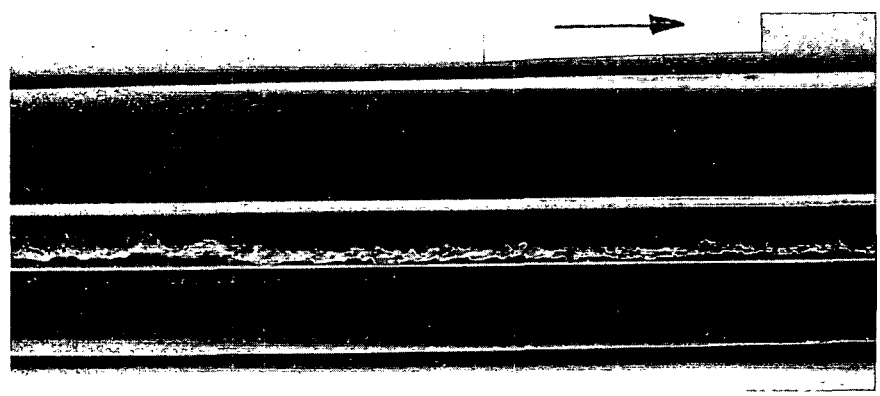


Figure 5.11 Picture Location No. 6 (9.0 m downstream)
Annular to Wavy Flow Transition, 50/50 Mixture

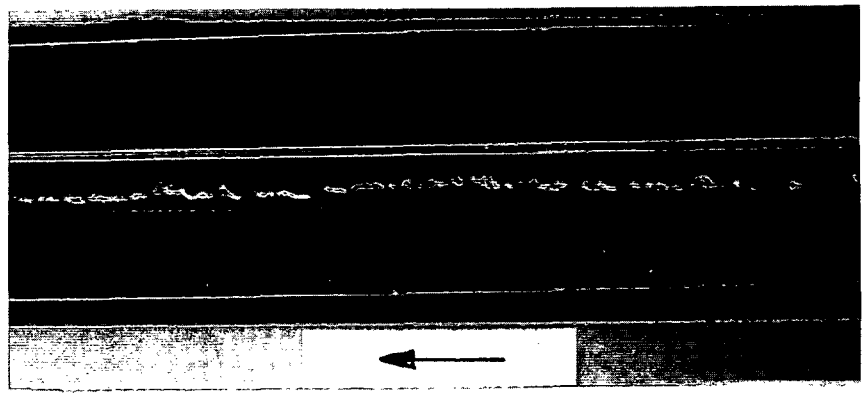


Figure 5.12 Picture Location No. 7 (12.0 m downstream)
Wavy Flow, 50/50 Mixture

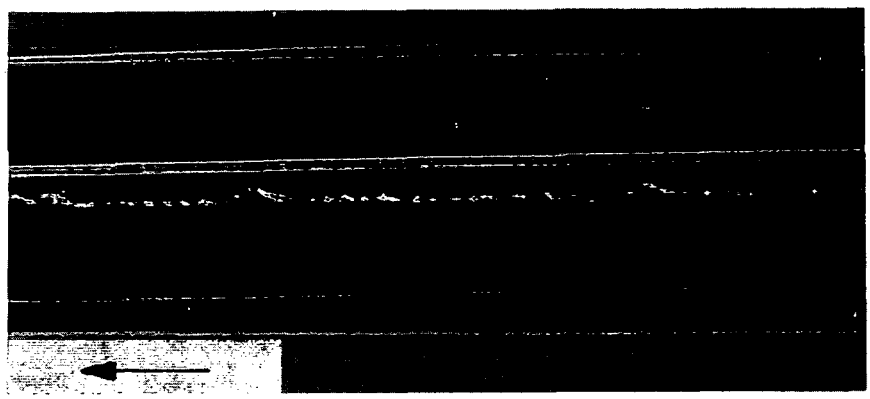


Figure 5.13 Picture Location No. 8 (13.6 m downstream)
Wavy Flow, 50/50 Mixture

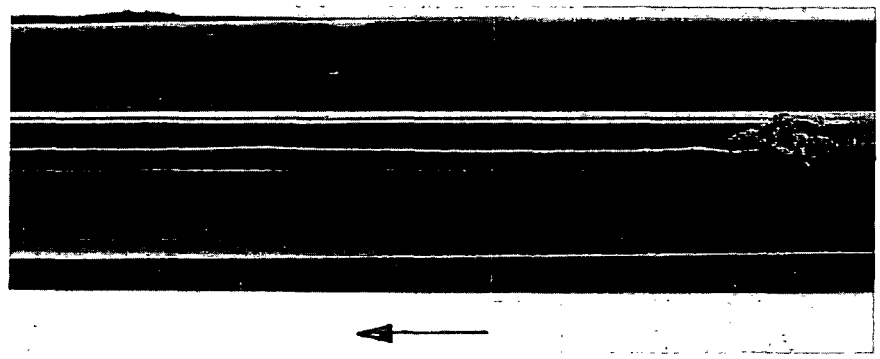


Figure 5.14 Picture Location No. 9 (15.3 m downstream)
Stratified/Slug Flow Regime, 50/50 Mixture

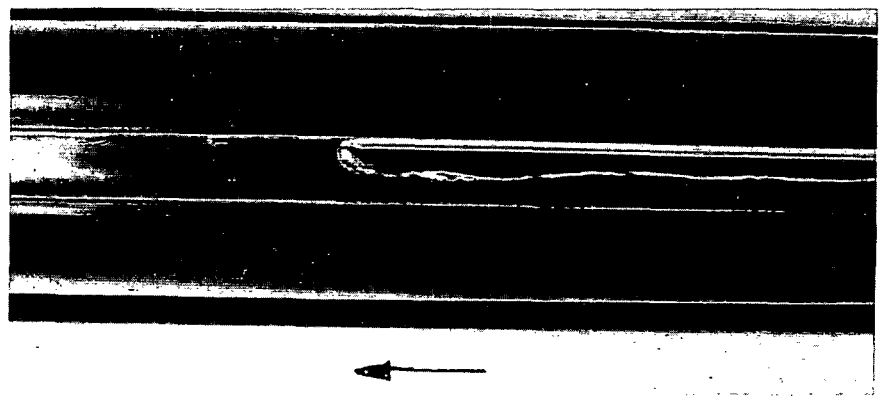


Figure 5.15 Picture Location No. 10 (17.1 m downstream)
Slug Flow, 50/50 Mixture

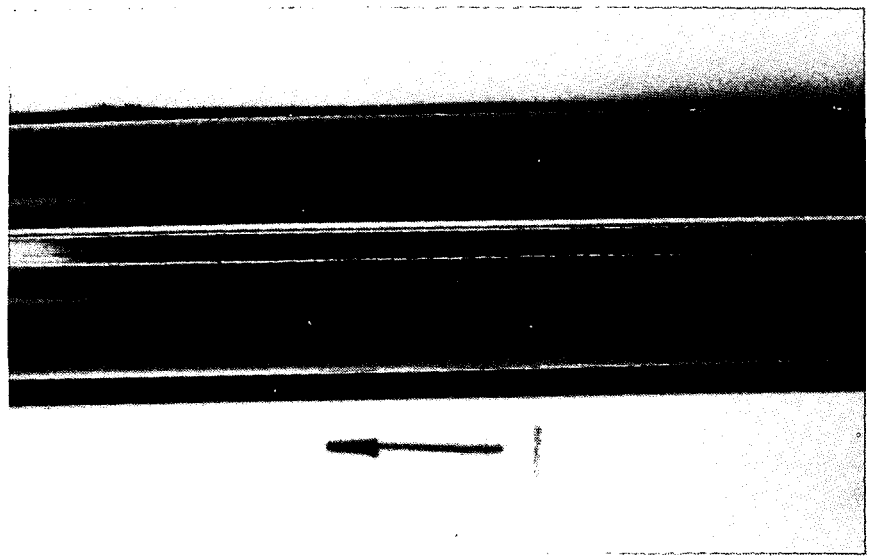


Figure 5.16 Picture Location No. 10 (17.1 m downstream) Stratified Flow (Note that this is the same location as shown in Fig. 5.17, only taken at a time just before the slug of liquid appears)

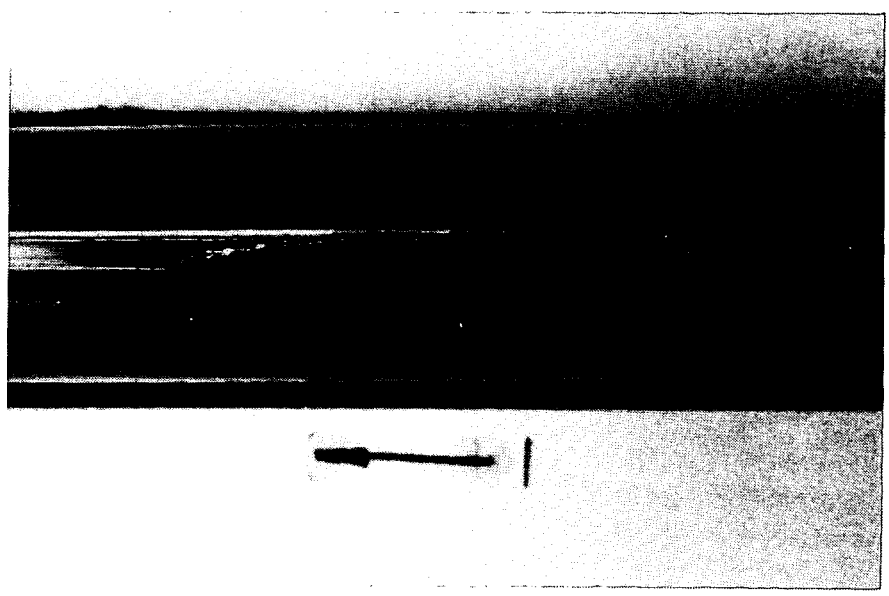


Figure 5.17 Picture Location No. 10 (17.1 m downstream) Slug Flow, 50/50 Mixture

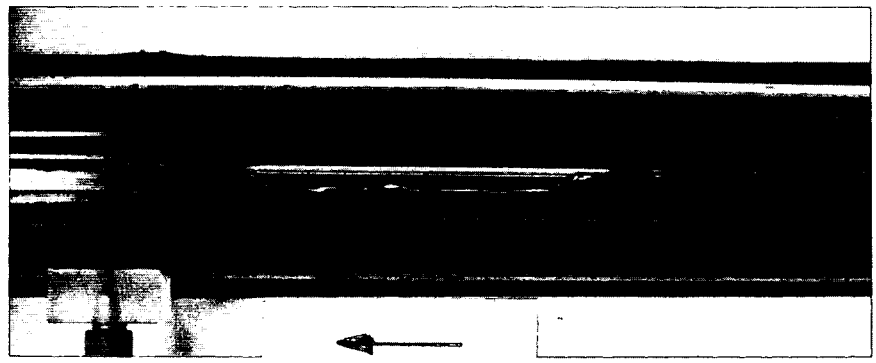


Figure 5.18 Picture Location No. 11 (18.7 m downstream)
Slug Flow, 50/50 Mixture

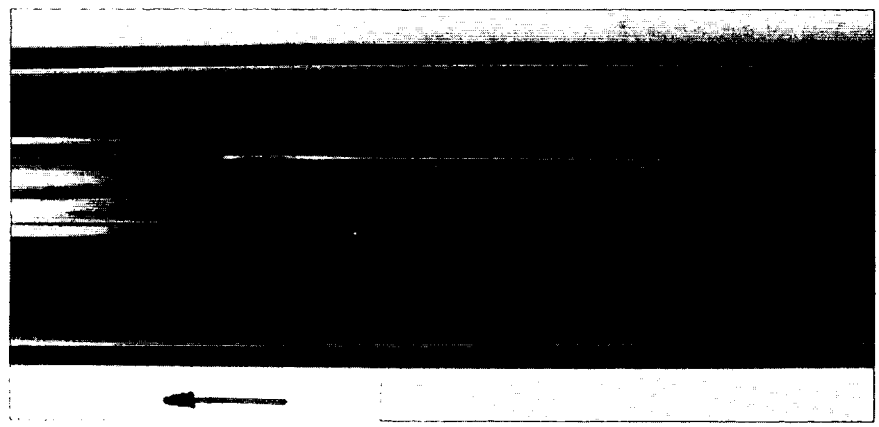


Figure 5.19 Picture Location No. 12 (20.1 m downstream)
Small Vapor Bubble, 50/50 Mixture

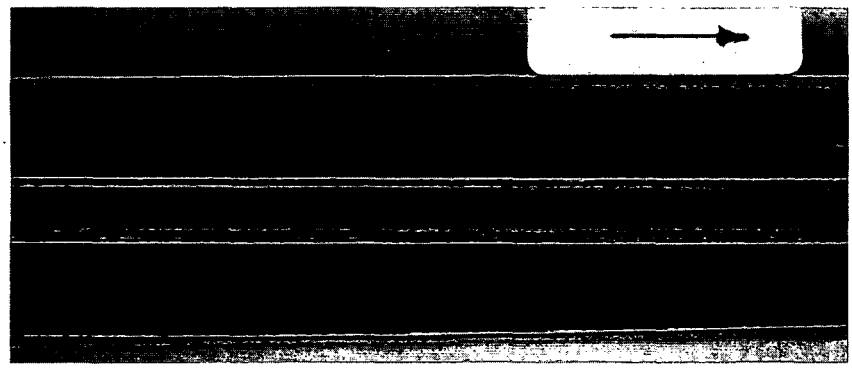


Figure 5.20 Picture Location No. 1 (1.0 m downstream)
Annular Flow, Pure R-12

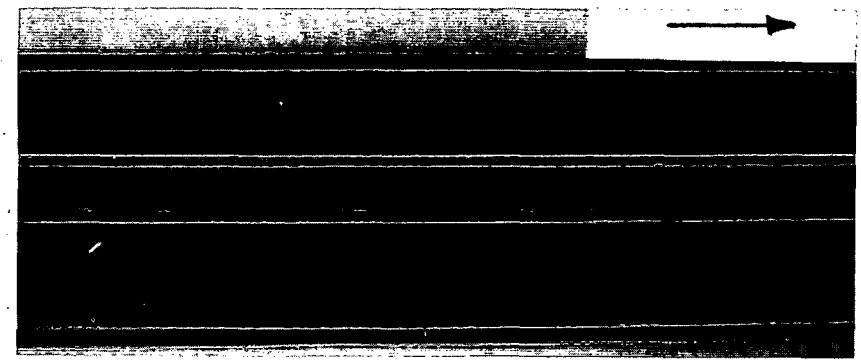


Figure 5.21 Picture Location No. 1 (2.6 m downstream)
Annular Flow, Pure R-12

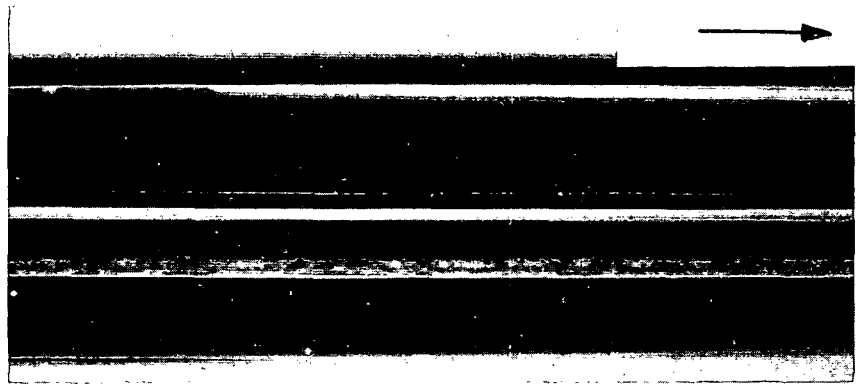


Figure 5.22 Picture Location No. 3 (4.0 m downstream) Annular Flow, Pure R-12

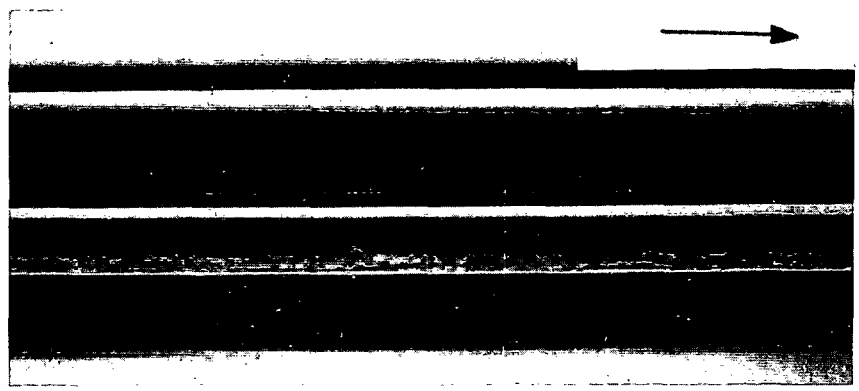


Figure 5.23 Picture Location No. 4 (5.9 m downstream) Annular Flow, Thicker Liquid Film at Bottom, Pure R-12

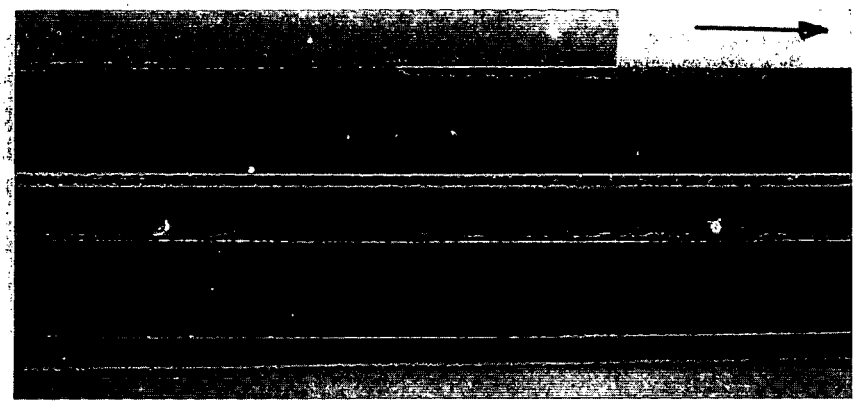


Figure 5.24 Picture Location No. 5 (7.5 m downstream)
Annular to Wavy Flow Transition, Pure R-12

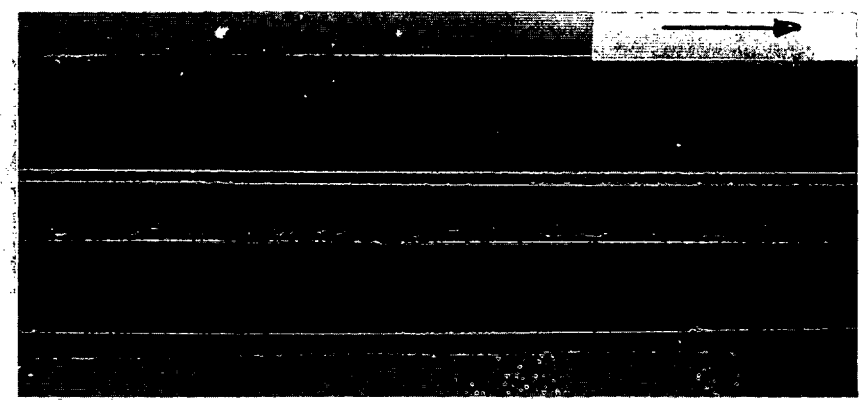


Figure 5.25 Picture Location No. 6 (9.0 m downstream)
Annular to Wavy Flow Transition, Pure R-12

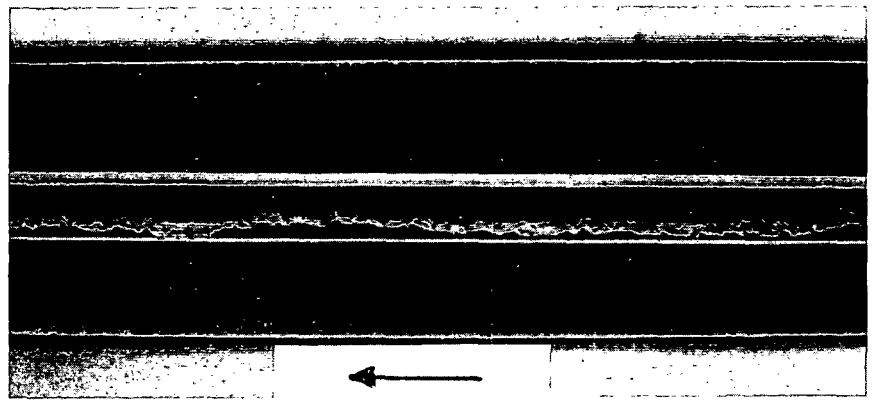


Figure 5.26 Picture Location No. 7 (12.0 m downstream)
Wavy Flow, Pure R-12

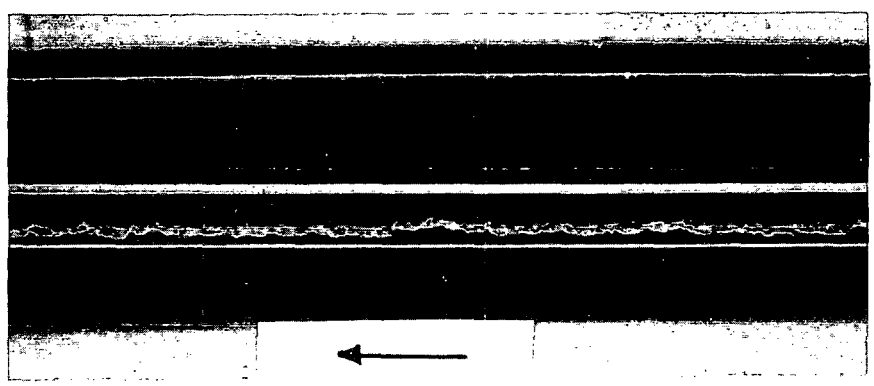


Figure 5.27 Picture Location No. 8 (13.6 m downstream)
Wavy Flow, Pure R-12

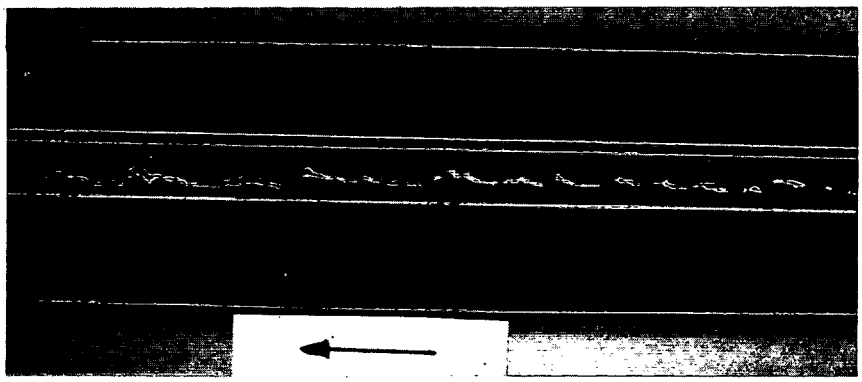


Figure 5.28 Picture Location No. 9 (15.3 m downstream)
Wavy Flow, Pure R-12

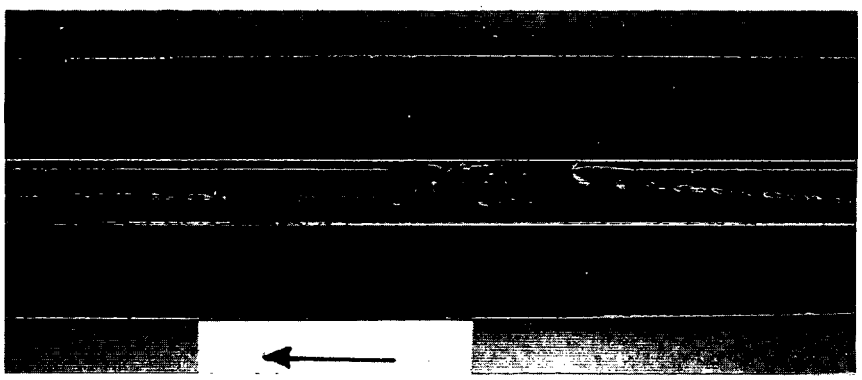


Figure 5.29 Picture Location No. 10 (17.1 m downstream)
Slug Flow, Pure R-12

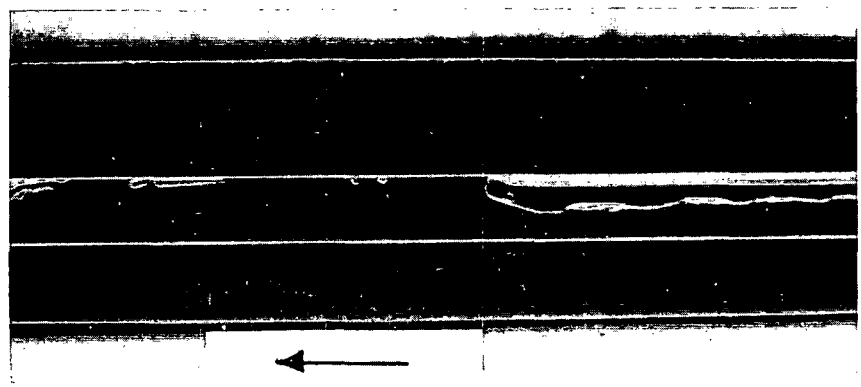


Figure 5.30 Picture Location No. 11 (18.7 m downstream)
Slug Flow, Pure R-12

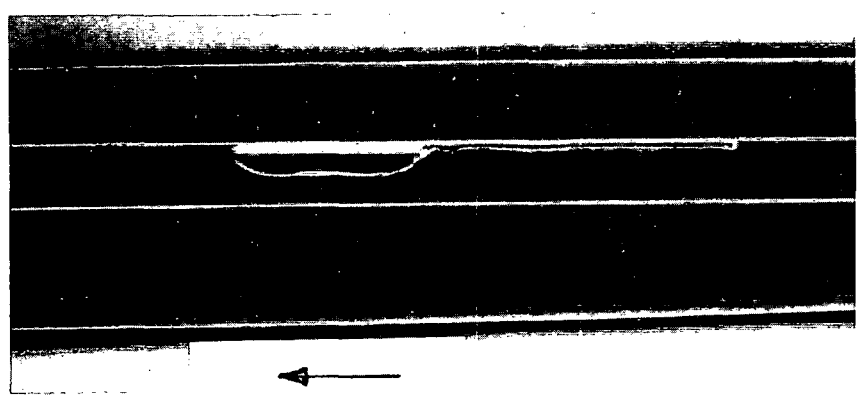


Figure 5.31 Picture Location No. 12 (20.1 m downstream)
Slug Flow, Vapor Bubble Disappearing, Pure R-12

The first set of photographs presented in Figs. 5.6 through 5.19 are from Test No. 12 that was run with a 50/50 mixture by mass of R-114 and R-12. The refrigerant mixture is entering the condenser at 45°C with about ten degrees of superheat. The refrigerant mass-flow rate is 0.0239 kg/s. The first photograph was taken 1.0 m downstream from the entrance where condensation begins immediately even though the vapor is still superheated. As liquid gradually accumulates at the bottom surface of the condenser tube, a wavy flow regime develops, as seen in Figs. 5.10 through 5.13. As the waves grow larger, they can reach the top of the condenser tube and "ride" with the vapor stream which is moving at a greater velocity than the liquid, as shown in Fig. 5.14. As more vapor condenses, these surges of liquid slow down and develop into a slug-flow regime as shown in Figs. 5.15 and 5.17. Between the slugs of liquid, the flow regime is stratified, as shown in Figs. 5.14 and 5.16. The locations with stratified flow are best suited for the simultaneous removal of a liquid-only and a vapor-only sample, if that operation should be undertaken in the future. The refrigerant leaves the glass condenser with an occasional small vapor bubble existing simultaneously with the subcooled liquid as shown in Fig. 5.18.

The second set of photographs presented in Figs. 5.20 through 5.31, are from Test No. 20 run with pure R-12. The flow regimes throughout the condenser are similar to those of the mixture. The only difference is that the transitions from one regime to the next occur at different locations. For example, the transition to slug flow occurs approximately 1.5 m sooner for the mixture than for the pure R-12. When comparing Figs. 5.12 and 5.13 with Figs. 5.26 and 5.27, it is seen that this earlier transition occurs because at picture locations 7 and 8 there is more liquid present at the bottom surface of the condenser tube for the mixture than there is for the pure R-12. The

rate of condensation for the mixture in the first half of the condenser is greater due to the higher temperature of the mixture compared to the R-12 alone. In the latter portion of the condenser, the R-12 temperature is higher than that of the mixture, therefore, the vapor bubbles diminish more rapidly for the pure R-12 than for the mixture. For example, comparing Fig. 5.19 with Fig. 5.31 (picture location No. 12), we see that the vapor bubble is larger for the pure R-12 than for the mixture. However, by the time the two bubbles leave the condenser, they are of the same size. These observations compare well with the results of the energy characteristics study [13] where it was found that the heat-transfer rate for the pure refrigerant was identical in both the high- and low-temperature condensers. However, for the 50-percent R-114 mixture, over 60 percent of the energy was being transferred within the high temperature condenser. It is not apparent from the photographs, but visual observation could readily detect the difference in R-12 and mixture flow by virtue of the higher velocities of the mixture.

5.7 Gas Chromatograph Results

A gas chromatograph analysis was performed on four different tests. Table 5.1 lists these tests, the location at which the samples were removed, and the results. An "S" following the sampling location represents a second injection of the sample taken from the same hexane solution into the chromatograph. This was used as a means of checking whether the sample was being properly injected into the chromatograph. A "C" following the sampling location represents the control. This was an analysis performed with a newly formed hexane solution. The control checks whether the sample was removed properly from the canister. The refrigerant concentration of each component in the sample was calculated using both methods discussed in Section 4.5. The

Table 5.1 Chromatograph Results

Date of Analysis	Test Number	Mass % R-12 Charged	Sampling Location	Mass % R-12 A	Mass % R-12 B	Difference B-A
10-28-83	7	90	pump	91.5	1	
			Test Sec. #8	90.8		
11-08/09-83	10	50	pump	44.7	1	
			Test Sec. #6	37.8		
			Test Sec. #6S	37.4		
			Test Sec. #8	47.5		
			Test Sec. #9	55.3		
			Test Sec. #9S	55.1		
12-01/02-83	17	51.6	pump	57.6	61.7	4.1
			pump C	52.6	56.8	4.2
			Test Sec. #6	43.2	47.4	4.2
			Test Sec. #6C	41.1	45.3	4.2
			Test Sec. #9	48.7	53.0	4.3
12-07/08-83	19	90	pump #1	90.3	92.4	2.1
			pump #2[2]	90.7	92.8	2.1
			pump #2C	90.3	92.4	2.1
			pump #3	90.7	92.7	2.0
			pump #3C	90.7	92.6	1.9
			pump #4	90.5	92.6	2.1
			pump #4C	90.4	92.4	2.0

1 Not available.
2 The sample was prepared a day before the analysis.

results in column A are based on knowing the volumes of each refrigerant used in preparing the standard, while the results in column B are based on knowing the weights. It is seen that for a given test the results from these two methods differ only by a constant.

For Test Nos. 10 and 17, samples were removed from the bottom surface of Test Section Nos. 6, 8, and 9 in an attempt to remove strictly a liquid sample. Because R-114 is the less volatile component, it is expected to condense first. This means that the concentration of R-114 in the liquid phase will be the highest at the beginning of the condenser. The concentration of the R-114 in the liquid phase should decrease as the refrigerant moves further downstream. Therefore, we should expect the concentration of R-12 in the sample removed at Test Section No. 9 to be higher than the concentration of R-12 in the sample removed at Test Section No. 6 and 8. As shown in Table 5.1, the concentration of R-12 in the liquid actually did increase as it moved further downstream. APPENDIX C contains the gas chromatograph outputs for the samples analyzed for Test No. 10. Whether or not representative were removed from the condenser is unknown. Before any conclusions can be drawn, more data must be collected with the sampling techniques refined.

During Test No. 19, four samples were removed from the pump discharge at different times throughout the test. The refrigerant at the discharge is all liquid and its concentration is known. The analyzed results were consistent, hence indicating that the chromatograph analysis is repeatable and that the refrigerant mixture is homogeneous at that location. From the analysis performed on Test No. 19, method A was found to be more accurate. When using the same standard for every analysis, both methods A and B were found to be very precise with a standard deviation of only 0.17.

5.8 Sources of Error in the Chromatograph Analysis

There are several sources of error possible in the analysis of a refrigerant sample, namely (1) the gas chromatograph instrument, (2) the planimeter used in integrating the areas, (3) the solubility of the two refrigerants in hexane not being equal, (4) the nonideality of the refrigerant gases, (5) the volume and weight measurements of the standard, (6) the loss of hexane and refrigerant from the vial, and most importantly, (7) the improper removal of the sample from the condenser as well as the canister.

During the preparation of the refrigerant samples, it was important to measure the weight of the refrigerant immediately after its injection into the hexane because it was found that both the hexane and refrigerant leak from the screw-cap vial. A solution of 20 ml of hexane, 10 ml of R-12, and 10 ml of R-114 lost weight at a rate of approximately 9 mg per hour. Fortunately, when using the same standard as a reference, this leak did not affect the accuracy of the analysis. Samples prepared a day before the chromatograph analysis gave the same results as those samples that were prepared and injected immediately into the chromatograph. However, this leak may affect the accuracy of the analysis if Method B in Section 4.5 is used in calculating the refrigerant concentrations. This inaccuracy occurs during the preparation of the standard. By the time the second refrigerant sample is injected into the hexane and reweighed on the balance, the weight of the entire vial may have dropped 1 or 2 mg (refer to Section 4 regarding sample preparation). This is one advantage to using Method A.

Another advantage of Method A is that it is easier and more accurate to measure the volume of the refrigerant in a pressure-tight gas syringe than it is to measure the weight of only 10 ml of the refrigerant on an analytical balance. A test was performed to check the repeatability of measuring the

weight of a known volume of R-12. Three 10-ml samples of R-12 vapor were injected into the separate vials containing 20 ml of liquid hexane. The mass of the gas was determined by measuring the mass on the vial before and immediately after the injection. The results are shown in Table 5.2. The mass of the R-12 was different each time. Using Method A, one makes the reasonable assumption that the refrigerant gases behave ideally at room temperature and pressure. The deviation is only slight, and a correction factor can be included within the formula in the future. Based on the ideal gas law, the last column in Table 5.2 represents what the volume would be if the weights measured were correct.

This inconsistency in measuring the volume and/or weight of the refrigerant samples means that standards are difficult to reproduce. An accurate standard is needed in order to properly calculate the concentration of the refrigerants in the unknown sample. For example, two standards of identical composition were prepared on two different days for the analysis of Test No. 10. Each standard was analyzed under the same chromatograph test conditions. The result was that the peak area ratios A_{114}/A_{12} of the two standards differed by 9.5 percent. This difference will alter the calculated concentration of R-12 in the sample removed from Test Section No. 8 to 50.4 percent from 47.5 percent listed in Table 5.1. Several standards for Test No. 19 were prepared with larger volumes of refrigerant. The spread in the area ratios of these standards did not exceed 2.9 percent.

Table 5.2 Checking the Repeatability of Measuring the Volume and Weight of Refrigerant Samples

Measured Volume of R-12 (ml)	Weight of Hexane and Vial (g)	Weight of Hexane, Vial and Gas (g)	Weight of Gas (mg)	Calculated Volume (ml)
10.0	33.7749	33.8253	50.4	10.0
10.0	33.6237	33.6735	49.8	9.89
10.0	33.6397	33.6884	48.7	9.69

6. MECHANISM OF CONDENSATION OF A REFRIGERANT MIXTURE

6.1 Principal Objective of the Heat-Transfer Study

The motivation for considering the application of a refrigerant mixture is to conserve energy. However, a reduction in heat-transfer coefficient detracts from that objective. Further understanding of the process of condensation of refrigerant mixtures inside tubes is therefore important to a designer of a facility using refrigerant mixtures. This understanding can lead to approaches (choices of refrigerant velocity, heat flux, or geometric arrangements) that would inhibit the reduction in heat-transfer coefficients. A still-more significant objective at this stage in the development of refrigerant-mixture systems is to devise means of preventing the reduction in coefficient of the mixture in comparison to either component singly.

6.2 Tools Available to Explain Condensation Process

The resources available at this time to develop an explanation of the condensation process are:

1. Basic mechanisms of fluid flow and heat-and-mass transfer.
2. Experimental results from refrigerant-mixture facility (Figs. 1.4 and 1.5).
3. Improved awareness of condensation regimes from visual observations and photos.
4. Trends indicated by chromatographic tests.

The fundamental models introduce the processes of diffusion of the two vapors, slip, and gradients of temperature and concentration. The measurements of condensing heat transfer show that it is in the midrange of the condenser where the influence of the mixture is most dominant in reducing the coefficient. The observations and photos show that stratified flow is the

predominant regime in the mid-range of the condenser. Chromatographic analyses show progressive increases in the R-12 concentration in the liquid in the direction of flow through the condenser.

6.3 Idealized Condensation Inside Tubes

The first approach to explaining a reduction in condensing coefficient is to explore the existence of diffusion of the two components during the process. In particular, if it can be established that the rate of change of the concentration of one component in the vapor differs from the rate at which it condenses in the vapor, the molecules of one of the constituents must diffuse through the mixture. This selective diffusion process introduces a barrier to condensation. The first stage of the model is the idealized case where vapor and liquid move at identical velocities in a tube, and there is equilibrium between the vapor and liquid. This condition is an idealization, because there must be temperature and concentration gradients in order to establish the direction of heat and mass transfer.

The specific case to be analyzed is in the condensation of a 50%-by-mass mixture of R-12 and R-114, focusing on the condensation that takes place from 48.0 to 47.5°C, as shown in Fig. 6.1 with calculations summarized in Table 6.1. Based on a mass-flow rate of 1 kg/s of mixture, values of liquid and vapor concentrations will be computed at points A and B as shown in Fig. 6.2. It is assumed that saturated vapor at 52.2°C entered the condenser and the velocities of vapor and liquid had remained equal. When point A is reached, where the condensing temperature is 48.0°C, the R-12 concentration in the liquid is 35.96% and in the vapor is 60.765%. The fractions of liquid and vapor must proportion themselves to maintain the 50% concentration of the liquid-vapor combination, namely, 43.399% in liquid form and 56.601% in vapor

Table 6.1 Concentrations and Flow Rates in Figure 6.2

	Position A		Position B
Temperature, °C	48.0		47.5
% R-12 in Liquid	35.96		37.133
% R-12 in Vapor	60.765		62.01
Mass Fraction in Liquid Form	0.43399		0.48278
Mass Fraction in Vapor Form	0.56601		0.51722
Vapor Flow Rate of R-12, kg/s	0.34394		0.3207
Vapor Flow Rate of R-114, kg/s	0.22207		0.19649
Condensation Rate of R-12		0.02324 kg/s	
Condensation Rate of R-114		0.02558	
% R-12 in Vapor That Condenses		47.6	

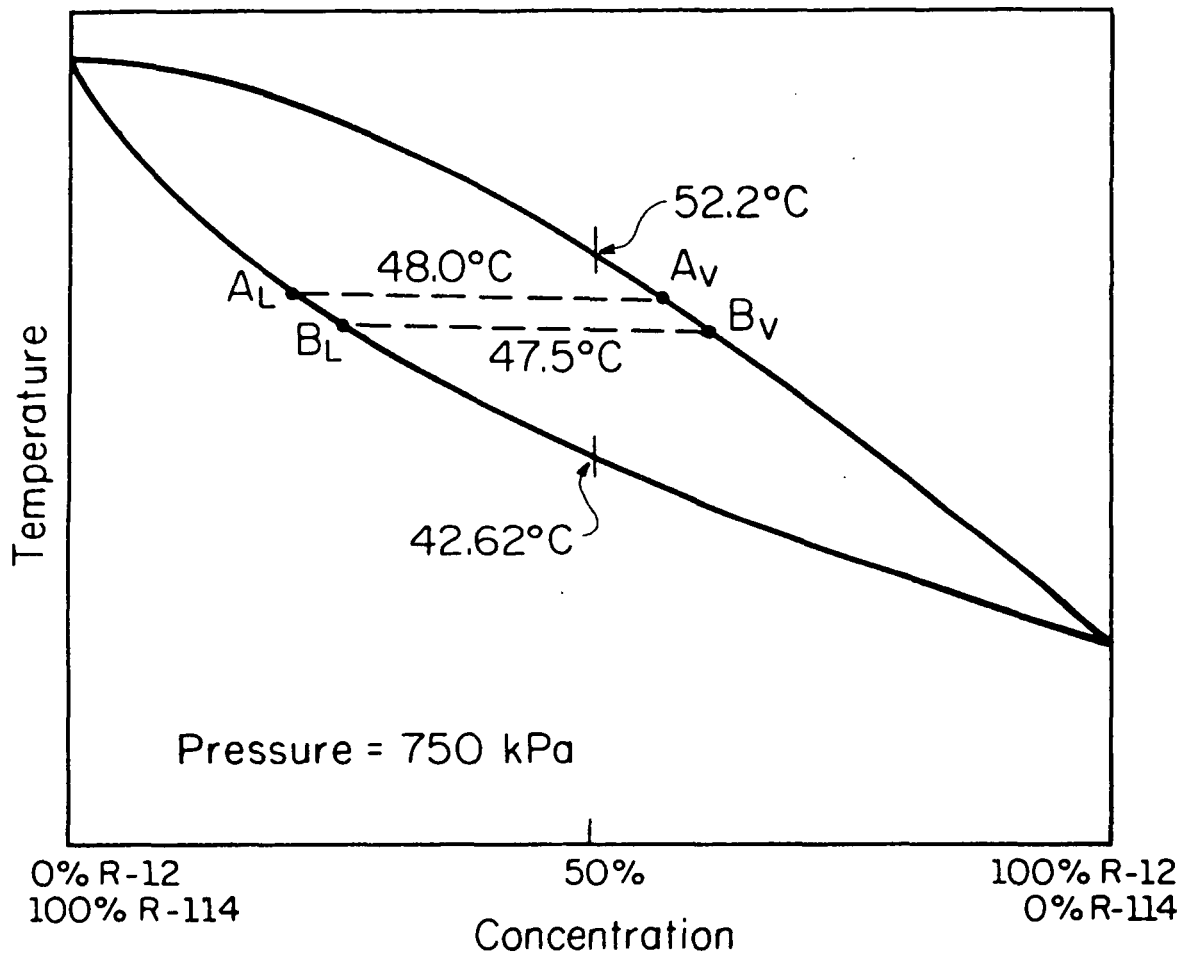


Figure 6.1 Temperature-concentration Diagram of an Idealized Concentration of a 50% by mass R-12/R-114 Mixture from 48 to 47.5°C

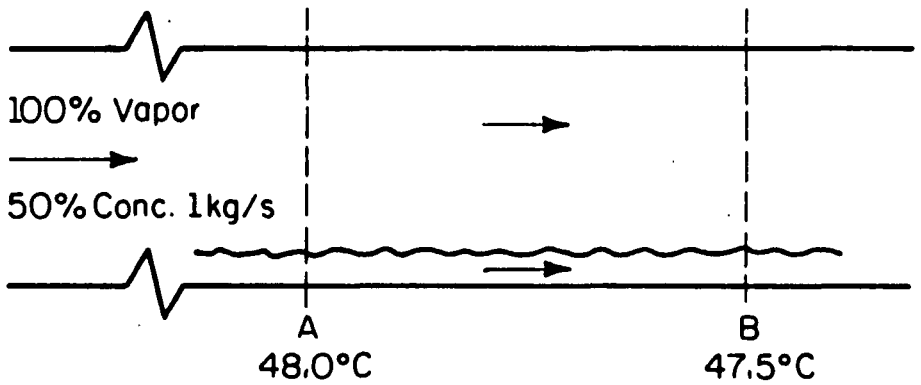


Figure 6.2 Section of a Condenser of an R-12/R-114 Mixture through which the Temperature Drops from 48.0°C to 47.5°C.

form. The flow rate of R-12 in vapor form is (0.60765)(0.56601) = 0.34394 kg/s. The flow rate of R-114 in vapor form is (1-0.60765)(0.56601) = 0.22207 kg/s. A corresponding set of values can be computed for point B where the condensing temperature is 47.5°C. The difference in the vapor flow rates of each constituent between A and B yields the flow rates condensed, 0.02324 kg/s of R-12 and 0.02558 kg/s of R-114. Thus, 47.6% of the vapor that was condensed was R-12. The concentration of R-12 in the vapor, taken as the average of 60.77% and 62.01% differs from the concentration of the vapor that condensed. In order to sustain the condensation it was necessary for R-114 to selectively diffuse through the vapor in order to provide the 47.6% R-12 for condensation.

When a single-component vapor condenses the concentration in the vapor is the same as the concentration condensing. The illustration applies to the case where diffusion is a dominant mechanism of mass transfer. In the turbulence existing at the entrance to the condenser there is likely to be enough mixing that the diffusion process is not prominent. Perhaps the barrier attributable to selective diffusion can explain the reduction in the midrange of the condenser, but another phenomenon must also be considered--slip.

6.4 Description of Slip

When modeling two phase flow at low vapor velocities, the liquid and vapor are assumed to have the same velocity at the liquid/vapor interface. This is referred to as the "no slip" boundary condition needed to solve the representative differential equation. At higher vapor velocities, the velocity of the vapor at the liquid-vapor interface may exceed that of the liquid. This is referred to as the "slip" condition. When refrigerant-mixtures condense, this slip condition creates a local nonequilibrium state

between the two phases with respect to temperature and concentration. Although a temperature gradient exists across the condenser for a pure refrigerant, a mixture would increase the gradient even more so because of the nonconstant temperature profile of the mixture along the condenser.

Figure 6.3(a) represents a section of a condenser in which condensation is taking place without "slip." The liquid and vapor are at equilibrium with each other at the interface as represented on the temperature versus concentration diagram in Fig. 6.3(c).

In Fig. 6.3(b), condensation is taking place with "slip." The vapor that does not condense at point A moves at a faster velocity than its liquid counterpart, hence coming into contact with the liquid at point B. The difference between the bulk velocities of the liquid and vapor is referred to as the magnitude of the slip. At the liquid/vapor interface, the concentration of refrigerants in the vapor, A_V, are not at equilibrium with the concentration of refrigerants in the liquid B_L. In order to reach equilibrium, the result is a locally induced temperature and concentration gradient.

6.5 Effects of Slip on the Heat-Transfer Coefficients

In order for the liquid and vapor to reach equilibrium with respect to concentration at point B in Fig. 6.3(b), the R-12 concentration must decrease in the liquid phase and increase in the vapor phase. These directions in which the concentrations must shift are represented by the arrows on the dew and bubble curves in Fig. 6.3(c). In order to achieve equilibrium, either the liquid must evaporate some refrigerant with a higher concentration of R-12, or the vapor must condense some additional refrigerant with a higher concentration of R-114 than would normally be condensing. Because the vapor is at a higher temperature, the additional condensation of R-114 is not

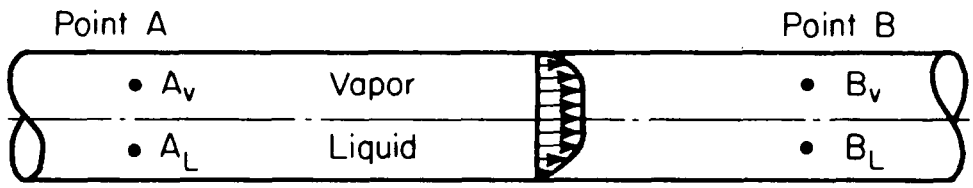


Figure 6.3(a) Condensation with No Slip, an Ideal Boundary Condition where the Velocities of the Vapor and Liquid are Equal at the Liquid/Vapor Interface

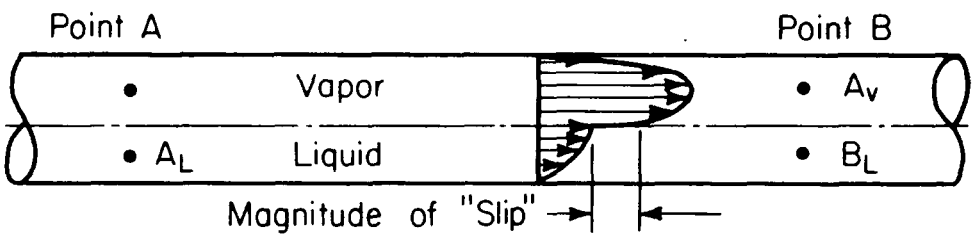


Figure 6.3(b) Condensation with Slip where the Vapor is Moving much Faster than the Liquid

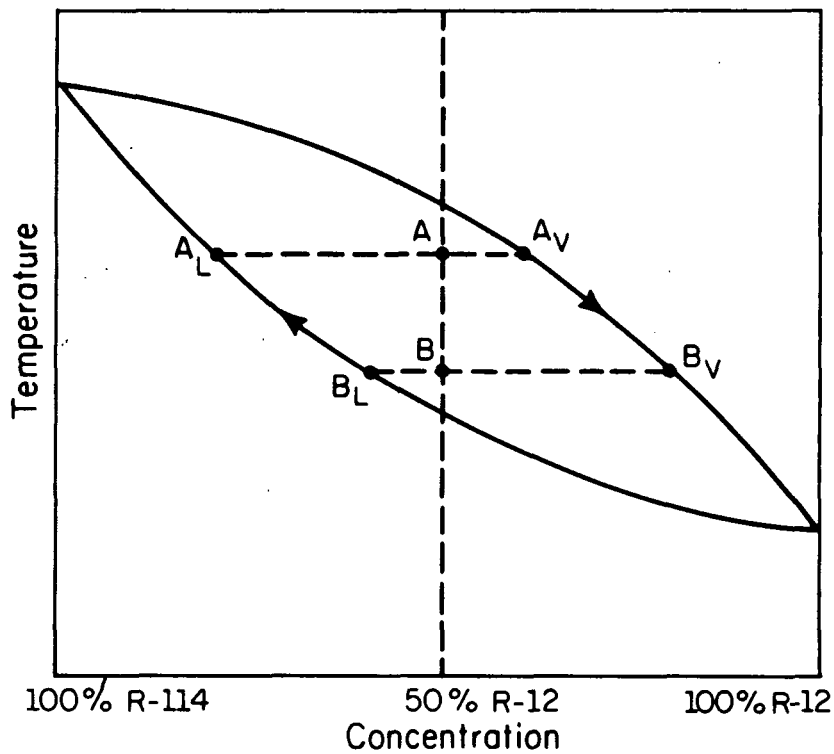


Figure 6.3c Temperature Versus Concentration Diagram Showing Effects of Slip on Points A and B

expected. Therefore, if the former case is indeed true, then the energy needed for the counterdiffusion of R-12 from the liquid phase to the vapor phase will be supplied from the higher temperature vapor. This irreversibility creates an additional resistance barrier to heat transfer that does not exist in the condensation of a pure component.

Because of the higher specific volume of R-114, the velocity of the vapor stream increases with greater concentrations of R-114. In addition, the difference between the concentration of refrigerants in the liquid and vapor phases increase as the concentration of R-114 approaches 50 percent (the envelope on the Temperature versus Concentration diagram is widest at a 50 percent mixture). The higher vapor velocity increases the magnitude of the slip. The increase in slip, and the increase in the temperature and concentration differences between the two phases results in a greater driving potential for the re-evaporation of the refrigerant mixture, hence, lowering the heat-transfer coefficients even further. Although slip occurs during the condensation of a pure refrigerant, there is no formation of a concentration gradient that would induce the re-evaporation of the liquid phase.

Because the vapor velocity is greatest near the condenser inlet, one would expect the slip, and, therefore, the reduction in the condensing coefficients to be the greatest near this location. However, the magnitude of the slip is greatest near the middle of the condenser or within the wavy flow regime. There is very little liquid in the annular regime and much of the liquid travels quite rapidly along with the vapor, thus establishing an equilibrium. It is not until further downstream when the condensate film thickens and the liquid velocity slows down that a more distinct liquid/vapor interface forms, namely in the wavy and slug flow regions. The difference in the velocities between the phases is greatest in these regimes. In addition,

the concentration of R-12 in the liquid phase of the annular regime is very low. The very first drop that condenses is rich in R-114. Therefore, there is not very much R-12 that can re-evaporate, which is the expected cause of the degradation in the first place.

The theories behind the effects of slip on the heat-transfer coefficients are based upon the results presented by McCarthy [6]. The results show that tests run with higher concentrations of R-114 had lower heat-transfer coefficients in the condenser. The decreases were most noticeable in the middle portions of the condenser, namely after the second pass of the high-temperature condenser (refer to Figs. 1.4 and 1.5). There were no apparent decreases in the condensing coefficients nearest the inlet. If a comparison of the flow regimes in the glass condenser are made to the heat-transfer coefficients recorded along the condenser of the energy characteristics test facility presented by McCarthy, the degradation of the heat-transfer coefficients can be said to begin somewhere within the annular/wavy flow transition.

6.6. Refrigerant Mixture Properties

Table 6.2 compares the properties of R-12 and R-114. The refrigerants, both nonpolar, are assumed to mix ideally and therefore the properties of the mixture can be easily calculated.

Reduction in the heat-transfer coefficients toward the end of the condenser, where only a few vapor bubbles remain, can in part be attributed to the increase in density and viscosity of the mixture compared to the R-12 alone. If the assumption is made that one can linearly interpolate between the property values of the pure components listed in Table 6.2 in order to determine the properties of mixtures, then based on the Nusselt film correlation for a condensing liquid along a vertical wall, the increase in the

Table 6.2 Comparing Refrigerant Properties

property	R-12	R-114	% difference
sat. liquid density @ 37°C (kg/m^3)	1266	1417	11.9
specific vapor volume @ 37°C (m^3/kg)	0.020	0.044	120.0
surface tension @ 26.7°C (mN/m^2)	8.9	12.0	34.8
Viscosity, sat. liquid @ 37°C (Pa · s)	199	302	51.8
conductivity, sat liquid @ 37°C (mW/m·K)	65.0	61.4	-5.5

viscosity of a 50/50 mixture would decrease the heat-transfer coefficients by nearly 6 percent. The increase in the liquid density of the mixture would reduce the velocity of the liquid by approximately 5 percent.

6.7 Condensate Film

Mixing R-114 with R-12 will increase the specific volume of the resultant vapor over that of R-12 above. This increase results in a higher vapor velocity which exerts a greater shear force at the liquid/vapor interface, hence increasing the liquid velocity. This increase in liquid velocity will cause a decrease in the liquid depth, and, therefore lower the film resistance to heat transfer. The decrease in the liquid depth was evident in the annular regime of the glass condenser. However, throughout the wavy flow regime it was observed that for the same mass flow rates the condensate film was thicker for the mixture than for the pure R-12. Again, these observations compare well with the heat transfer results presented in the University of Illinois energy characteristics study [6]. As discussed in Section 5.6, the thicker liquid depth is due to the greater rate of condensation of the mixture as compared to the pure R-12 within the first half of the condenser. The thicker the liquid film, the greater the resistance to heat transfer.

An increase in mass-flow rate will produce the same effect as an increase in the specific volume. The increased viscosity of the mixture should contribute toward increasing the liquid depth.

6.8 Refrigerant-Oil Solution

Unlike the energy-characteristics test facility [6] and refrigerant systems in general, the refrigerant in the glass condenser is oil-free. The introduction of oil affects the flow patterns by increasing the fraction of

the wall that is wetted [14]. Moreover, the oil gives rise to a rather heavy increase in pressure drop which can affect the performance of a refrigerant mixture. It is also important to note that the solubility and the viscosity-reducing effects of the two refrigerants are different in oil [15]. The oil generally travels along with the refrigerant as an annular film within the tube. Whether the higher concentration of one refrigerant in the oil film acts as a resistance barrier to heat transfer is unknown. However, the effects of the oil-refrigerant solution should not be overlooked in the future studies of the heat transfer coefficients.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary of Accomplishments

The three principal accomplishments of this study have been: (1) the visual observation and identification of the flow regimes in the glass condenser for tests run with various R-12/R-114 mixture concentrations, (2) the knowledge gained about the chromatographic techniques and sampling procedures, and (3) the contribution to the understanding of how to prevent degradation of condensing coefficients when using mixtures.

The next phase of the study is to further investigate the actual heat-transfer coefficients in a metal tube condenser of a similar configuration. The photographs taken of the glass condenser will be useful in this phase when attempts are made to correlate the regimes to the heat transfer coefficients.

Much has been learned about the chromatographic techniques and sampling procedures. The results from numerous analyses show excellent repeatability. Samples analyzed from the pump discharge show excellent agreement with the measured charge. Due to the method of sample removal, the results from the liquid samples removed from the condenser are not certain to be true representations of the refrigerant concentrations in the liquid phase. For a better quantitative indication of nonequilibrium problem associated with the "slip" condition at the liquid/vapor interface, further improvement in sampling methods is needed.

7.2 Further Directions

7.2.1 Further Testing

In the three series of tests that were conducted, the refrigerant mass-flow rate and the average heat flux along the condenser were held constant. These are two important factors influencing the heat-transfer

coefficients. In future studies it may be desirable to conduct tests with varying mass-flow rates and heat fluxes while holding the refrigerant concentrations in the mixture constant from test to test. In order to regulate the heat flux, it will be necessary to redesign the condenser cooling water circuit so that the inlet cooling water temperature may be adjusted to the appropriate level. Currently, the cooling water is directly fed from the city main.

7.2.2 Improving the Sampling Techniques

The results from the chromatograph analyses have been encouraging and the techniques in analyzing the refrigerant samples are continually being refined. Although the repeatability has been found to be excellent, the accuracy is yet to be determined, since it is not certain that the samples are being removed exactly at the position intended. When a refrigerant sample is removed, a sufficient amount of refrigerant is released from the system such that the flow pattern in the condenser is altered. Therefore, the next sample that is removed further downstream could not truly be compared to the previous sample. In the future, it is important that the samples taken from the condenser are either removed simultaneously or that the sample removal procedure be redesigned such that much less refrigerant is released during the extraction.

7.2.3 Modifying the Brass Test Section

Until now, only liquid samples have been removed from the lower surface of the condenser tube. This liquid sample alone does not provide enough information to determine the extent of the nonequilibrium between the two phases with respect to concentration. An examination of the flow regimes

showed that there are several locations along the condenser at which there is a chance at removing both a liquid-only and a vapor-only sample simultaneously. These locations are in the wavy and stratified flow regions as shown in Figs. 5.13 and 5.16. The simultaneous removal of both the liquid and vapor sample will require some modifications to the existing brass test section.

Brazed onto each brass test section are two quick-connect couplings in which the pressure tap, sample-removal port and the thermocouple probe are inserted. In order to extract a vapor sample and measure the temperature of the vapor stream, two additional couplings must be brazed on directly above the lower two couplings as shown in Fig. 7.1.

7.2.4 Improving Sample Removal

The purpose of attempting to remove liquid and vapor samples from the condenser is to establish the extent of nonequilibrium of concentration between the two phases. The refrigerant pressure and the temperatures of the liquid and vapor must be measured before the samples are extracted. The samples can be analyzed on the chromatograph and the concentration of refrigerants in the samples can then be computed. The results can be plotted on a temperature versus concentration diagram for the given pressure. A family of tests can be completed where either the velocity or heat flux is varied for a given refrigerant mixture. The plotted points may reveal a trend for a given refrigerant mixture (i.e., the higher the velocity, the greater the nonequilibrium). Currently, only liquid samples have been removed.

Because of the existence of a concentration and temperature gradient across the condenser tube, it may not be possible to remove a sample that truly represents the mean concentration of that location (see Sections 5.2 and

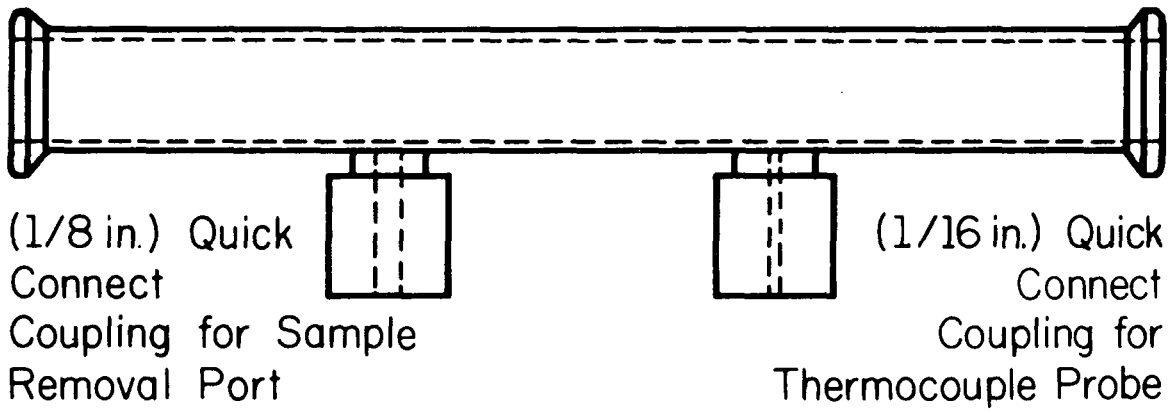


Figure 7.1(a) Existing Brass Test Section

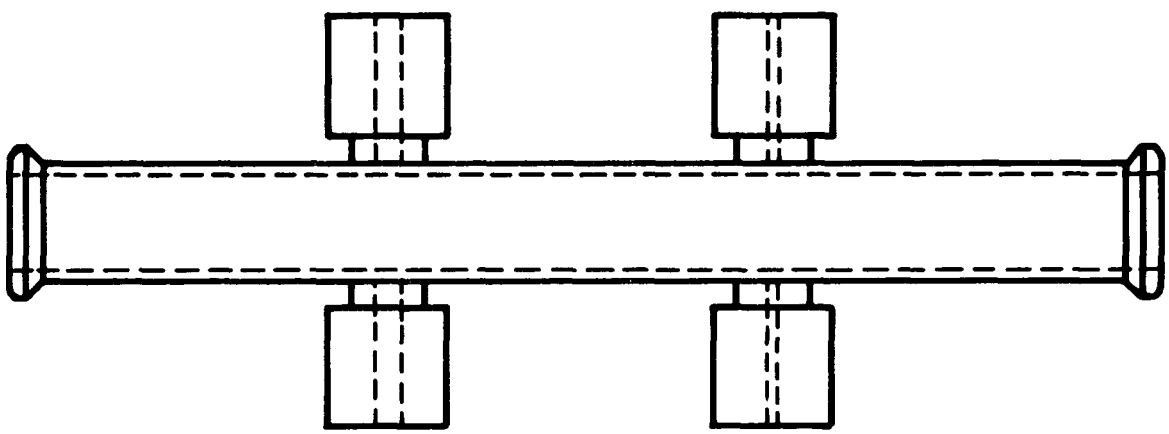


Figure 7.1(b) Modified Brass Test Section

5.3 for a discussion on the gradients). The thermocouple probe measured only the local temperature, therefore, any points plotted on the temperature versus concentration diagram may be inaccurate. In order to determine whether the liquid samples removed are true representations, the precise position from which the sample was taken must be known. Even with the position known there would still be uncertainties. Therefore, alternatives to removing the samples should be investigated.

One alternative method of removing the samples is to install two solenoid valves on each side of selected brass test sections, as shown in Fig. 7.2. When the test conditions have been reached and steady state has been achieved, the two valves can be triggered to close simultaneously, thus trapping the refrigerant between them. The refrigerant pump would be stopped at this instant. The condenser cooling water would remain running so that the trapped refrigerant can reach a uniform steady temperature quickly. Since the refrigerant is now motionless and at equilibrium with respect to both temperature and concentration, it should be easier to remove a more accurate liquid-only and vapor-only sample from the existing brass test section shown in Fig. 7.1(a).

If the condensation of the refrigerant mixture took place ideally, the concentration of R-12 and R-114 in the trapped refrigerant would be the same as the refrigerant composition charged into the test apparatus. Given the temperature and pressure of the trapped refrigerant and the refrigerant composition charged in to the system, the corresponding concentrations of R-12 and R-114 in the liquid and vapor phases can be found from the temperature versus concentration diagram. These points on the diagram represent the ideal condition. However, because of the "slip" phenomena discussed in Section 6.4, this ideal condition will most likely not be the case. Using gas

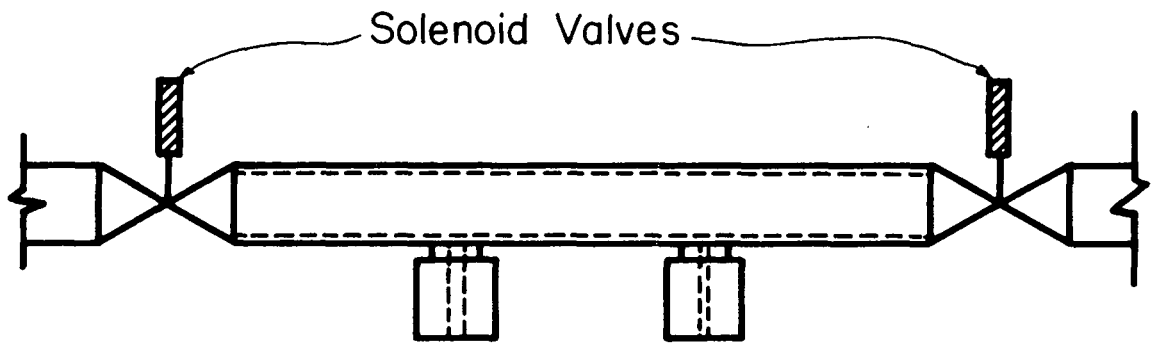


Figure 7.2 Modified Brass Test Section Showing a Solenoid Valve on Each End

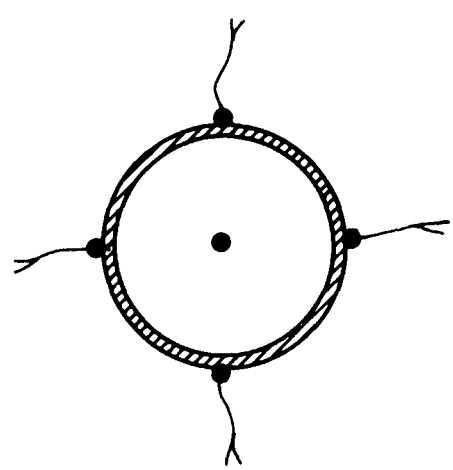


Figure 7.3 Cross Section of the Metal Refrigerant Side Condenser Tube Showing Thermocouple Locations

chromatography, the actual refrigerant concentrations in the liquid or vapor phase of the trapped refrigerant can be measured. The deviations between the values found on the temperature-versus-concentration diagram and those measured by the chromatograph can be used as a measure of the extent of the nonequilibrium at that location along the condenser.

In order to determine what variables encourage greater degrees of non-equilibrium, tests can be performed with various velocities, heat fluxes, etc. The refrigerant can be trapped at several locations along the condenser. The location with the highest deviation from the ideal condition may indicate the location of greatest slip. Although this method is more difficult to implement, it can lead to better quantitative interpretations of the chromatographic results.

7.2.5 Further Investigation of the Actual Heat-Transfer Coefficients

A planned addition to the test apparatus is a metal condenser to be fully instrumented to measure the heat-transfer coefficients. The objectives of the study using the metal condenser are two-fold:

1. To confirm the heat-transfer degradation measured in previous tests [6], and
2. To parallel the glass condenser such that the heat-transfer coefficients can be correlated more closely to the observed flow regimes.

Since the heat-transfer coefficients have been shown to vary around the circumference of a condenser tube [15], it is recommended that the refrigerant side of the condenser be instrumented with thermocouples on the top, bottom, side and center of the tube as shown in Fig. 7.3.

Because the flow regimes are not visible in the metal condenser, some form of instrumentation must be used to correlate the heat-transfer coefficients measured in the metal condenser to the flow regimes observed in the glass condenser. One possibility in correlating the data is to use the fine thermocouple probes already located in the brass test sections. As was discussed in Chapter 5, the temperature of the probes fluctuated with a certain periodicity and amplitude depending on the concentration of R-114, the location of the probe, and the position of the probe within the tube. If during the test the probes can be made to traverse the cross section of the tube at a constant rate, then the signal can be viewed on an oscilloscope and recorded with photos of the oscilloscope trace. Each flow regime observed in the glass condenser would have a corresponding signal pattern dominated by either the frequency and size of passing vapor bubbles, or the liquid depth. Similarly, thermocouple probes can then be traversed along the cross-section of the metal condenser. The signals recorded from the metal condenser can then be correlated to the flow regimes present in the glass condenser.

Another possibility for correlating the data is to use a fiber optic probe [16] similar to the one proposed in Danel and Delhaye [17] and then later developed by Galaup [18]. A fine glass fiber, approximately 40 μm in diameter and bent into a U-shaped configuration can be used to detect the presence of either vapor or liquid (see Fig. 7.4). The light signal sent into one end of the fiber is received by a phototransistor at the other end. The fiber-optic probe can be inserted into a two-phase flow stream. The intensity of the returning signal will vary depending on whether a liquid or vapor surrounds the tip of the probe. The change in intensity of the returning signal is due to the difference between the refractive indices of the liquid and vapor. When the U-bend is surrounded by vapor, more light rays are reflected back to the detector than when surrounded by liquid as shown in Fig. 7.5.

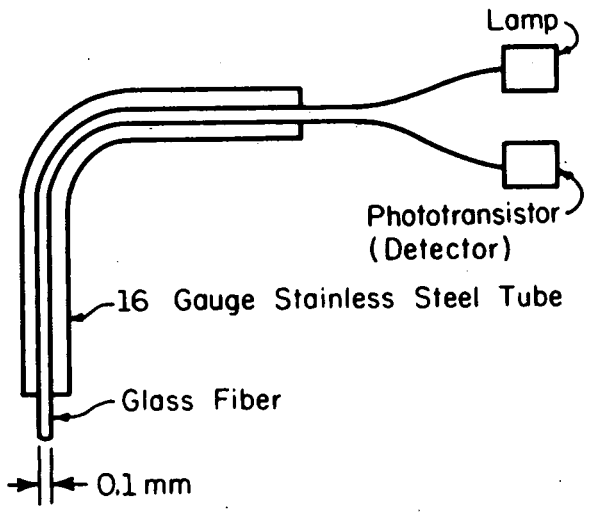


Figure 7.4 Fiber Optic Probe Proposed by Danel and Delhaye [6]

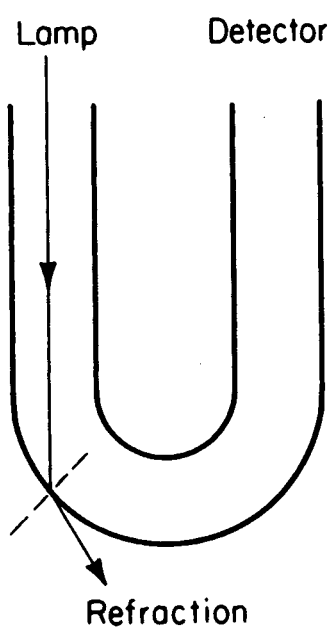


Figure 7.5(a) Glass Fiber Surrounded by Liquid

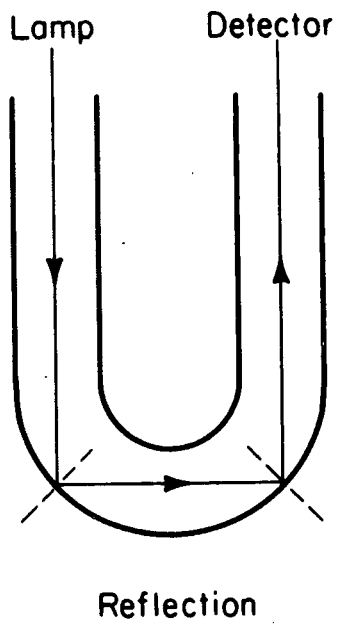


Figure 7.5(b) Glass Fiber Surrounded by Vapor

Like the thermocouple probe, the fiber optic probe can be traversed along the cross-section of both the metal and glass condensers. The signals can be recorded and correlated so that the flow regimes can be matched to the heat-transfer coefficients. The glass fiber can be inserted into the same stainless steel tube as the thermocouple. This combination probe can detect when a vapor bubble passes by as well as the temperature of the vapor. There will be a difference in the time response between the two sensors which must be taken into account when comparing the signals.

7.3 Closing Statement

To achieve the potential improvements in energy characteristics offered by refrigerant mixtures, it is necessary to prevent any significant reduction in heat-transfer coefficients when shifting from a single refrigerant to a mixture. This study has concentrated on condensing heat-transfer coefficients and used a glass-tube condenser to facilitate observations of the regimes. The region of the condenser where the use of a mixture seemed to detract most from the coefficient was in the midrange of the condenser during stratified flow where a distinct interface existed between the liquid flowing along the bottom of the tube and the vapor at the top.

Three mechanisms can be proposed as the reasons for reduction in heat-transfer coefficient: selective diffusivity of one constituent of the mixture, concentration as well as temperature gradients that exist in the liquid and vapor, and slip. It would appear that the vapor-liquid slip is occurring in the midrange of the condenser where the coefficient drops, so the prevention of this slip by such devices as turbulence promoters should be considered.

The question of heat-transfer of refrigerant mixtures is an extensive one, and it is the intent of this study to contribute to a better understanding and controlling the processes.

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APPENDIX A

TEMPERATURE AND PRESSURE READINGS, (Test Numbers 3 to 20)

Table A.1 Temperatures Recorded at Various Locations Throughout the Condenser During Tests 3 to 20

Test No.	Mixture Composition (% R-114)	Condenser Temperatures at Various Test Section Locations (°C)											
		Inlet	1	2	3	4	5	6	7	8	9	10	Outlet
3	46.7	45.1	35.5	34.2	33.1	31.9	30.9	29.1	25.9	23.1	24.6	21.1	18.6
4	38.4	45.1	36.1	35.4	33.8	32.7	32.0	30.0	27.0	22.9	24.3	21.0	18.5
5	29	45.1	32.7	31.9	31.0	30.3	29.8	28.6	27.4	24.2	25.4	25.7	20.3
6	20	44.8	32.0	31.3	30.8	30.3	29.6	29.0	28.3	24.9	26.0	24.3	20.5
7	10	45.0	30.7	30.2	29.9	29.6	29.4	29.0	28.6	24.9	26.4	24.2	20.3
8	100	45.0	34.3	34.0	33.7	33.4	33.2	31.9	26.5	19.8	19.6	18.9	18.7
9	0	45.1	29.7	29.2	29.2	29.2	29.1	29.0	29.0	28.5	26.8	24.9	20.8
10	50	45.1	34.8	33.6	32.4	31.2	30.2	28.0	26.2	25.5	25.1	21.8	18.5
11	40	45.1	34.2	33.1	32.9	31.0	30.0	29.2	26.7	25.9	24.5	22.3	18.5
12	30	45.0	33.5	32.6	31.7	30.9	30.2	29.0	27.7	26.9	25.7	22.8	19.1
13	20	45.0	31.3	30.6	30.1	29.6	29.2	28.4	28.0	27.2	26.7	23.9	20.0
14	10	45.0	30.5	30.0	29.6	29.3	29.0	28.4	28.0	27.4	25.8	24.7	19.6
15	100	44.9	32.1	31.7	31.3	31.0	30.8	30.4	28.5	25.8	21.8	18.9	17.1
16	0	45.0	29.1	28.9	28.8	28.7	28.7	28.8	28.6	27.8	26.1	23.9	19.5
17	48.4	44.9	36.4	35.6	33.9	31.3	30.7	27.7	26.0	23.4	21.3	18.9	17.4
18	29	44.9	34.0	33.4	32.8	29.9	29.6	27.2	26.0	23.0	20.5	17.9	16.4
19	10	45.1	29.9	29.6	29.0	27.7	28.1	26.3	26.1	25.2	24.2	22.4	19.2
20	0	45.1	27.6	27.7	27.4	26.6	27.1	25.7	25.5	24.7	24.2	23.1	19.8

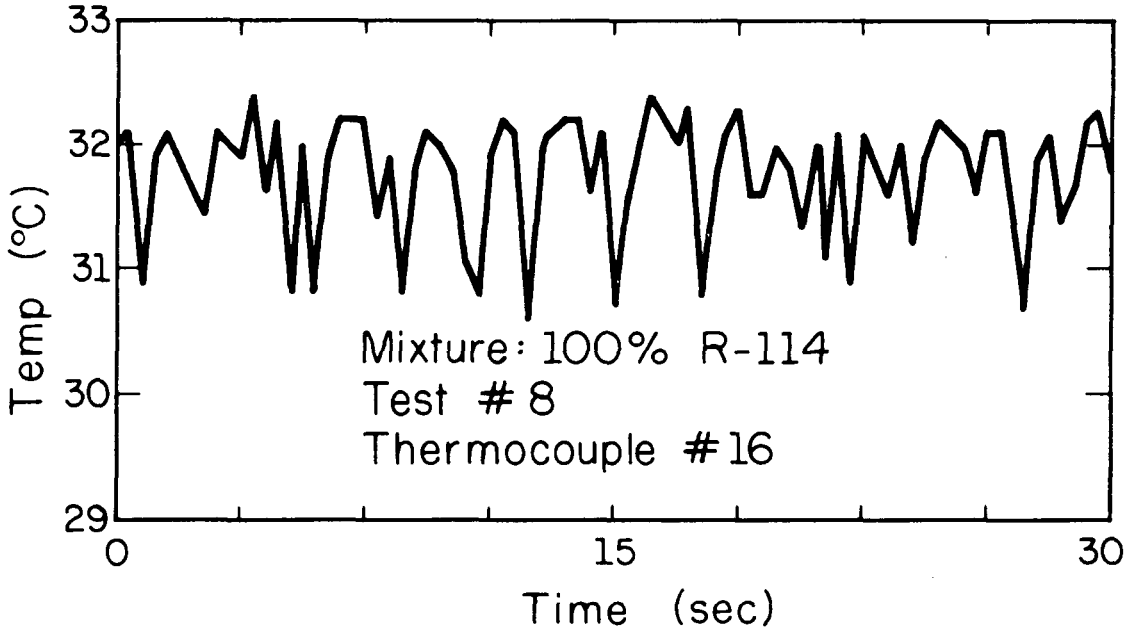
Table A.2 Pressures Recorded at Various Locations Throughout the Condenser During Tests 3 to 20.

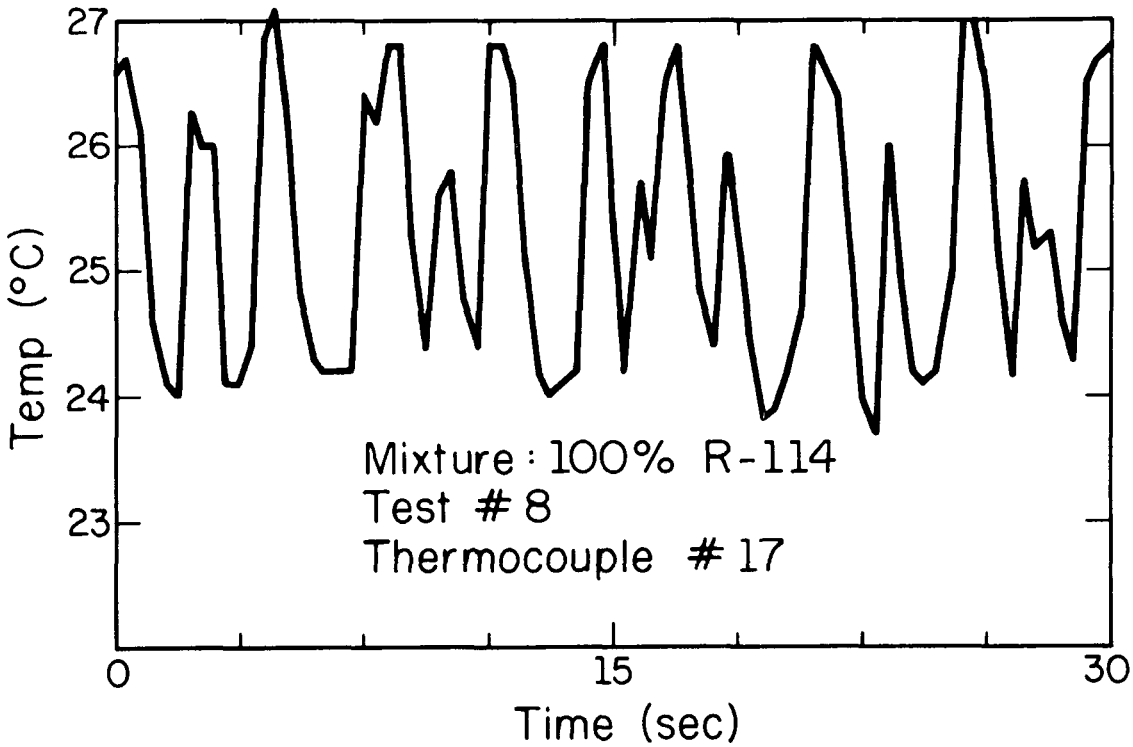
Test No.	Mixture Composition (% R-114)	Condenser Pressures at Various Test Section Locations (Kpa Gauge)							Average Heat Flux (kW/m^2)
		Inlet	2	4	6	8	10	Outlet	
3	46.7	478	480	474	---	472	472	471	4.22
4	38.4	503	509	505	500	500	500	495	4.37
5	29	543	542	540	539	536	535	532	4.24
6	20	579	587	582	578	578	578	580	4.33
7	10	610	615	613	610	609	608	600	4.24
8	100	208	198	191	191	189	188	190	4.14
9	0	639	639	637	632	632	632	629	4.32
10	50	420	425	419	416	414	414	412	4.44
11	40	475	478	473	370	468	468	466	4.44
12	30	537	535	532	529	529	528	526	4.45
13	20	575	578	575	569	569	568	565	4.25
14	10	593	598	593	589	589	589	584	4.29
15	100	193	179	177	170	170	170	170	4.23
16	0	638	638	635	628	628	627	627	4.32
17	48.4	465	455	465	461	461	461	455	4.50
18	29	562	574	571	567	565	564	555	4.50
19	10	592	597	595	587	587	587	582	4.44
20	0	609	617	614	609	609	608	600	4.35

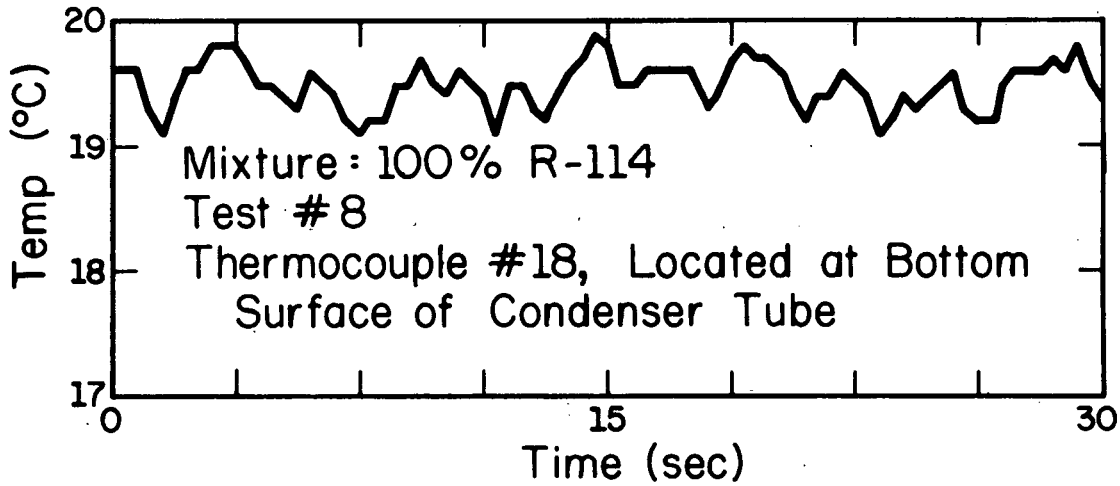
APPENDIX B

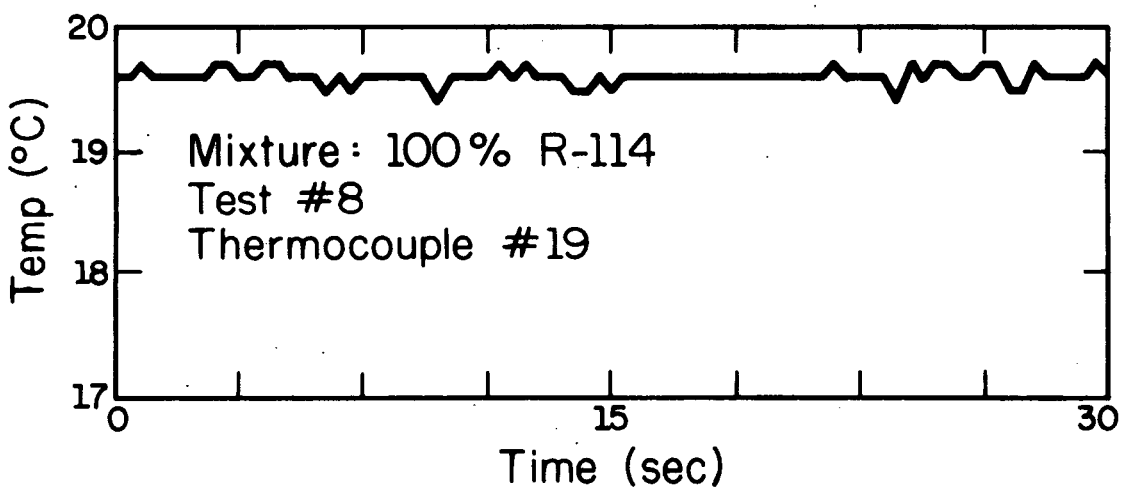
TEMPERATURE FLUCTUATIONS OF THE THERMOCOUPLE PROBES LOCATED IN THE CONDENSER FOR TEST NUMBERS 8, 9, AND 10

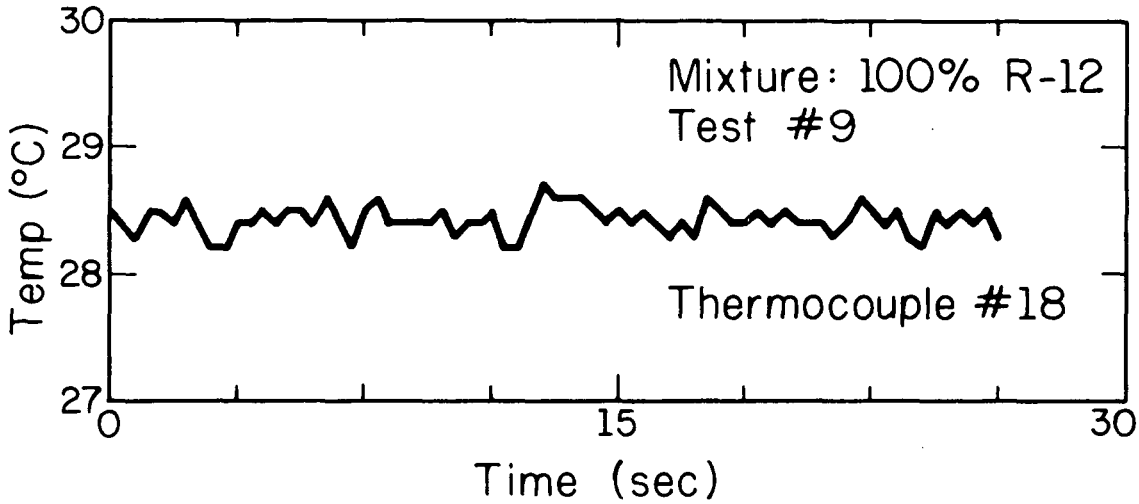
Test Number and Thermocouple Number
Shown on Each Graph

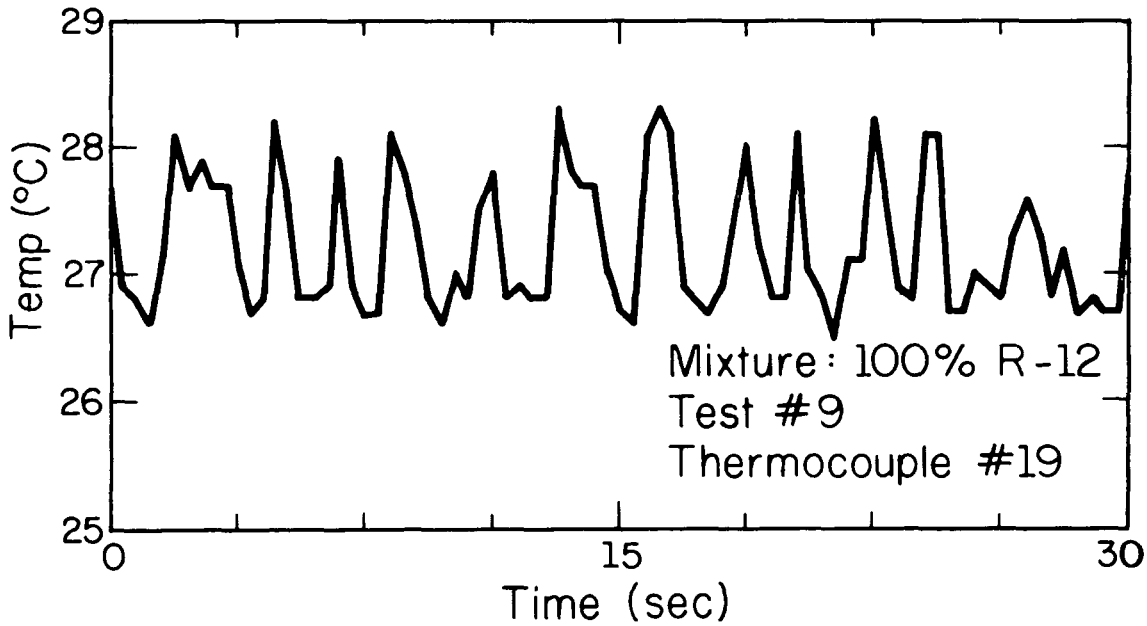

33
32
31
30
29
Temp (°C)
Mixture: 100% R-114
Test # 8
Thermocouple #16
0
15
30
Time (sec)

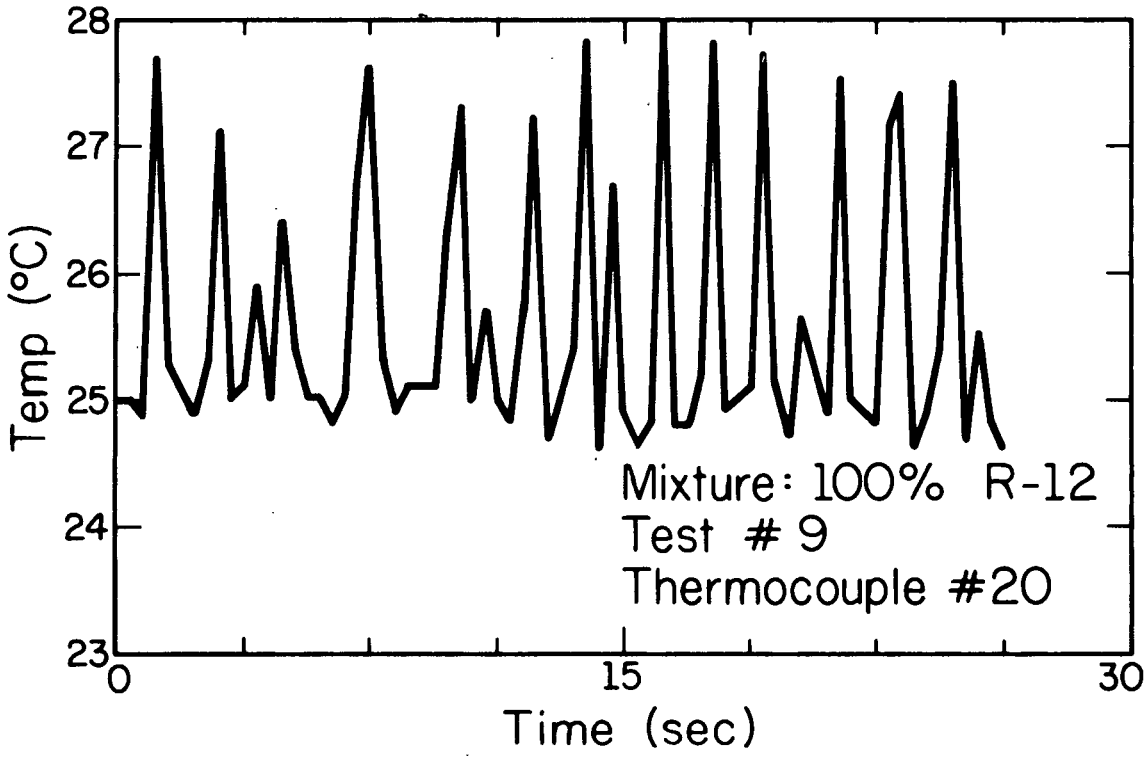

27
26
25
24
23
Temp (°C)
Mixture: 100% R-114
Test # 8
Thermocouple # 17
0
15
30
Time (sec)

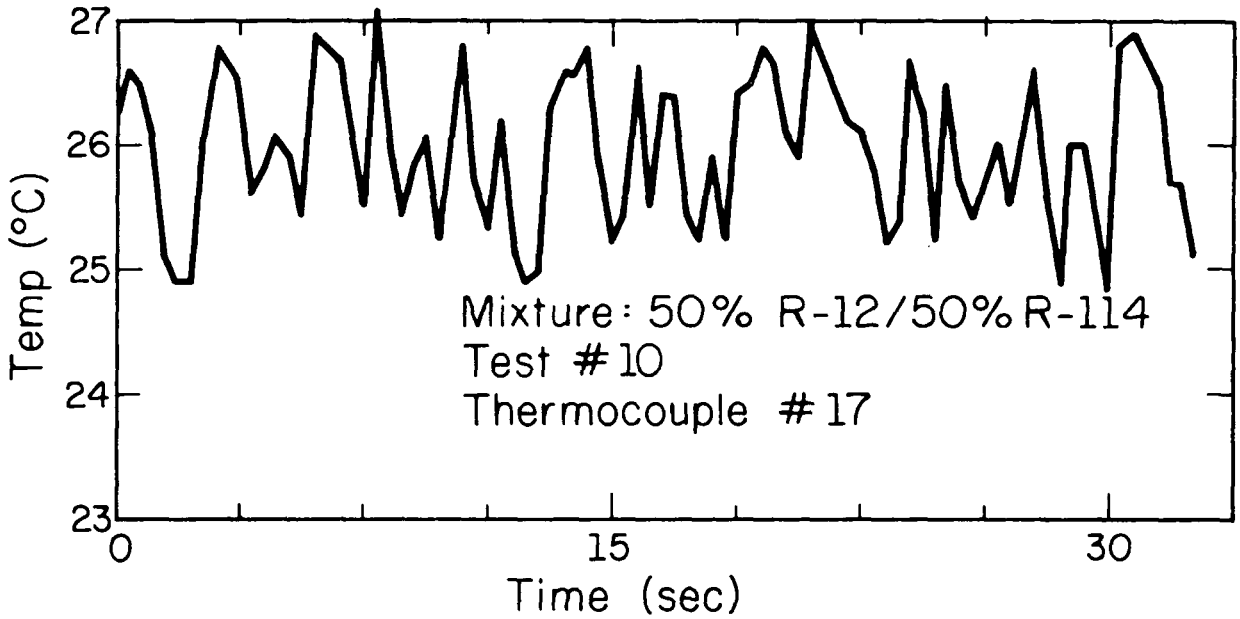

20
19
18
17
Temp (°C)
Mixture: 100% R-114
Test #8
Thermocouple #18, Located at Bottom
Surface of Condenser Tube
0
15
30
Time (sec)

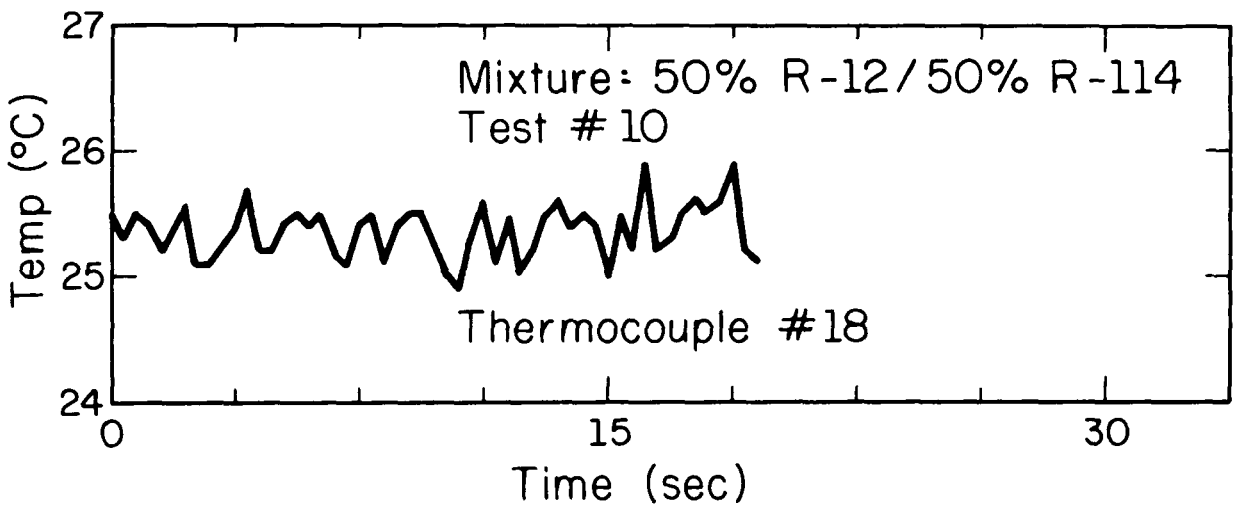

20
19
18
17
Temp (°C)
Mixture: 100% R-114
Test #8
Thermocouple #19
0
15
30
Time (sec)

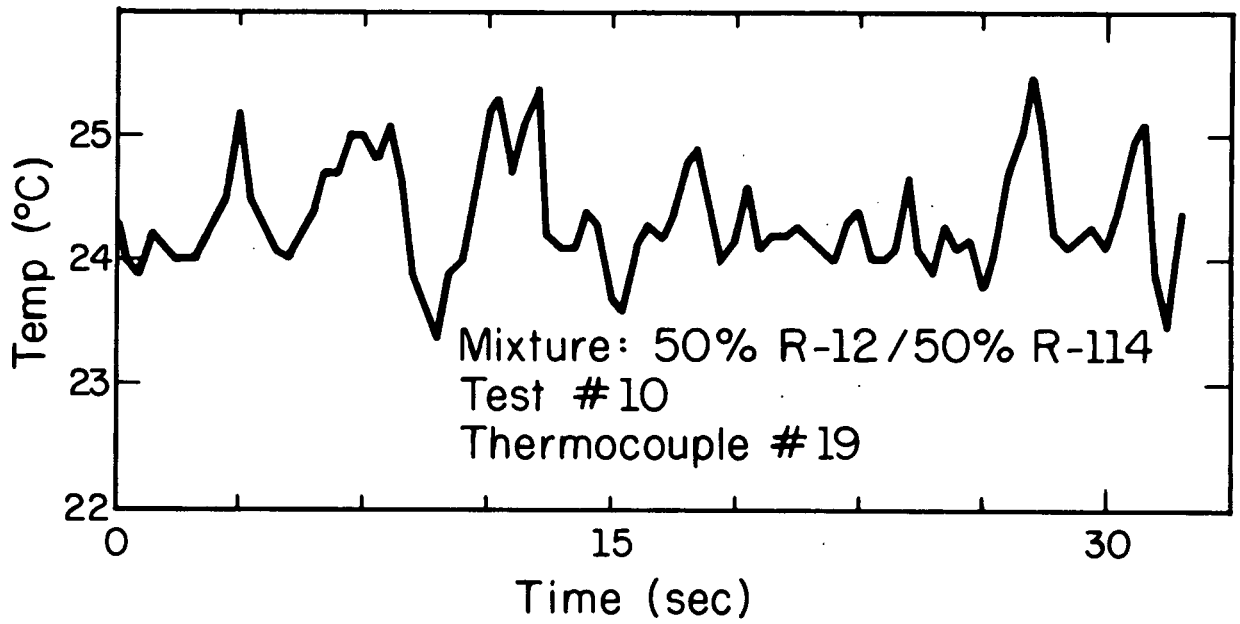

30
29
28
27
Temp (°C)
Mixture: 100% R-12
Test #9
Thermocouple #18
0
15
30
Time (sec)

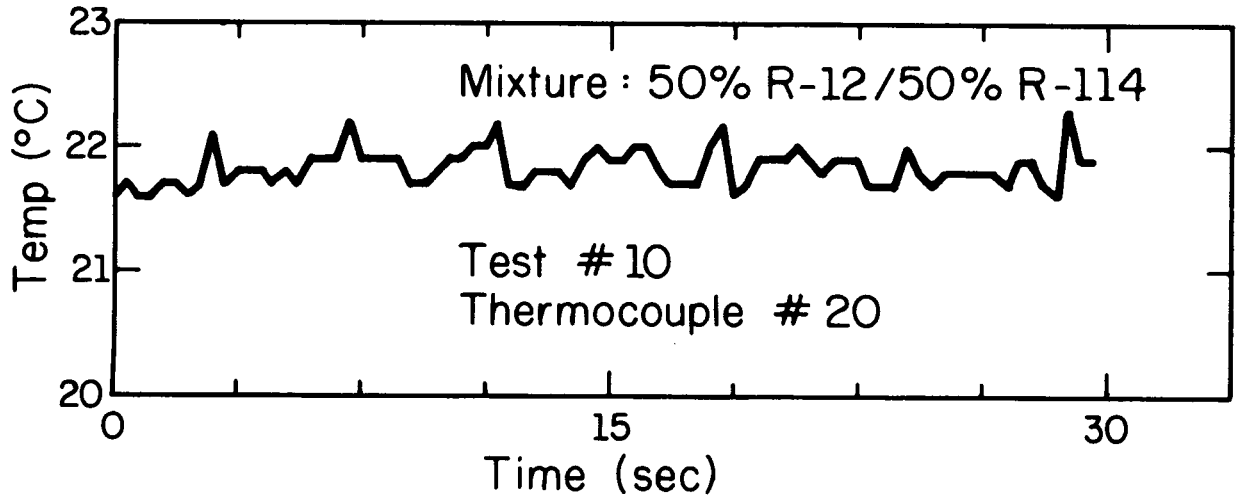

29
28
27
26
25
Temp (°C)
Mixture: 100% R-12
Test #9
Thermocouple #19
0
15
30
Time (sec)


28
27
26
25
24
23
Temp (°C)
0
15
30
Time (sec)
Mixture: 100% R-12
Test # 9
Thermocouple #20


27
26
25
24
23
Temp (°C)
Mixture: 50% R-12/50% R-114
Test #10
Thermocouple #17
0
15
30
Time (sec)


27
26
25
24
Temp (°C)
Mixture: 50% R-12/50% R-114
Test #10
Thermocouple #18
0
15
30
Time (sec)


Temp (°C)
25
24
23
22
0
15
30
Time (sec)
Mixture: 50% R-12/50% R-114
Test #10
Thermocouple #19

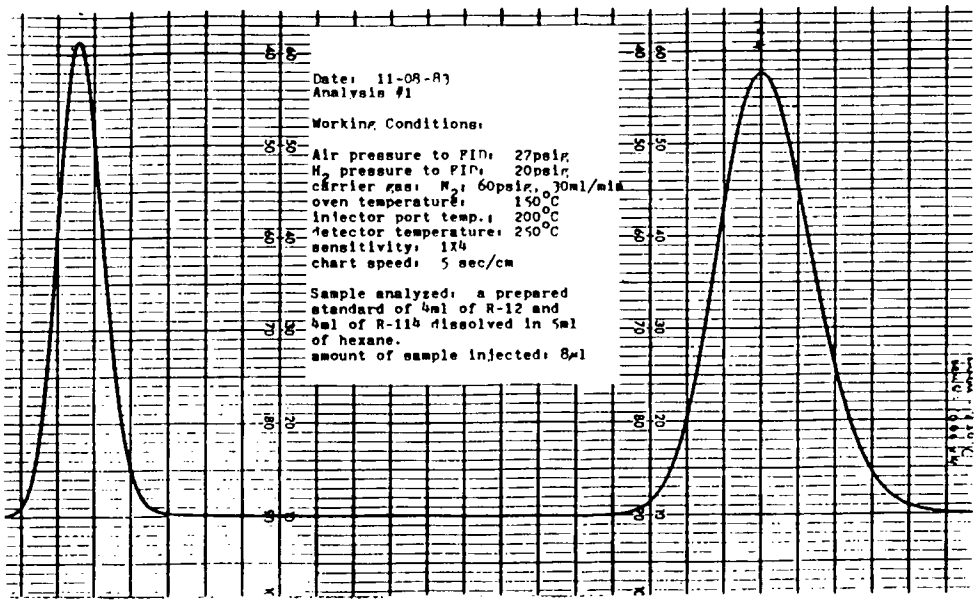

Temp (°C)
23
22
21
20
0
15
30
Time (sec)
Mixture: 50% R-12/50% R-114
Test #10
Thermocouple #20

APPENDIX C

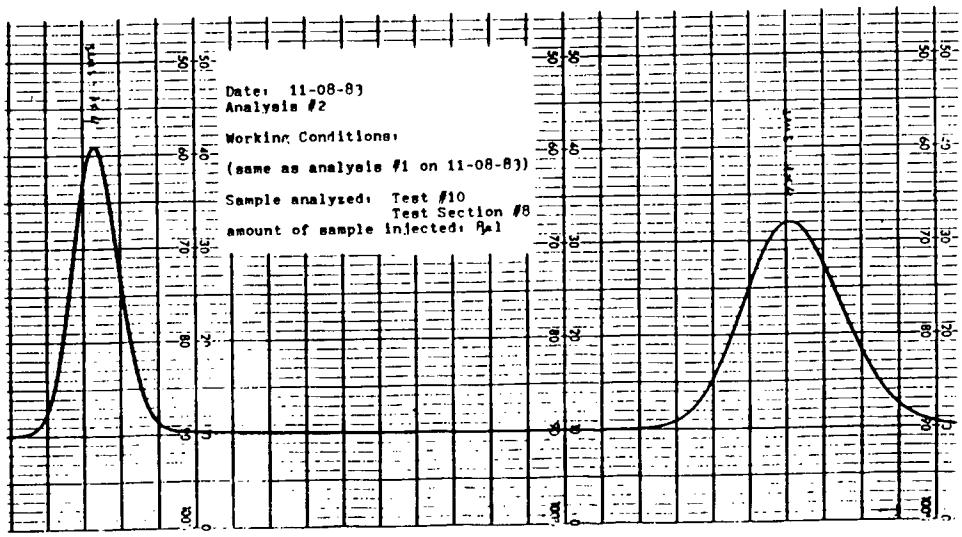
GAS CHROMATOGRAPHY RESULTS FOR SAMPLES ANALYZED FROM TEST NUMBER 10 (50% R-12)

The First Peak Corresponds to R-12
and the Second Peak Corresponds to R-114

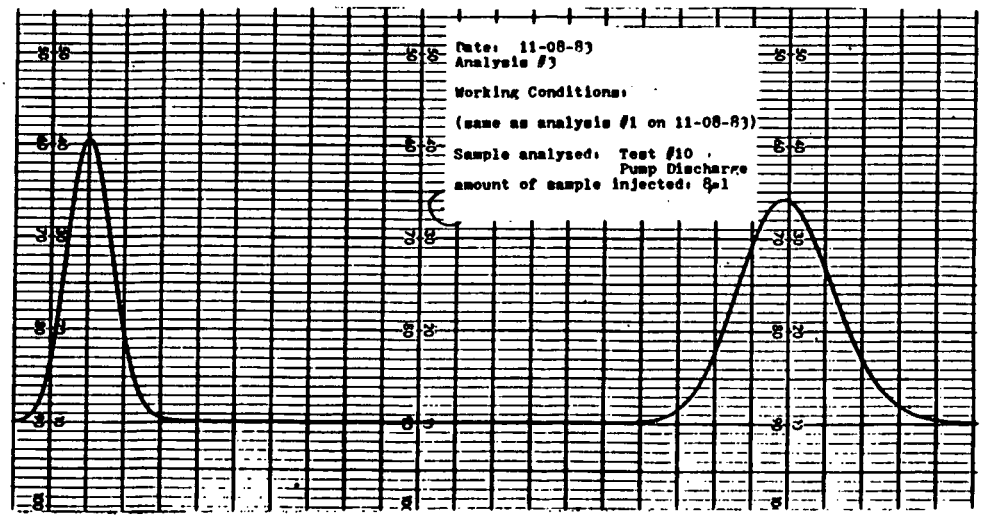
The Refrigerant Concentration Calculated
from the Outputs are Summaruzed in Table 5.1



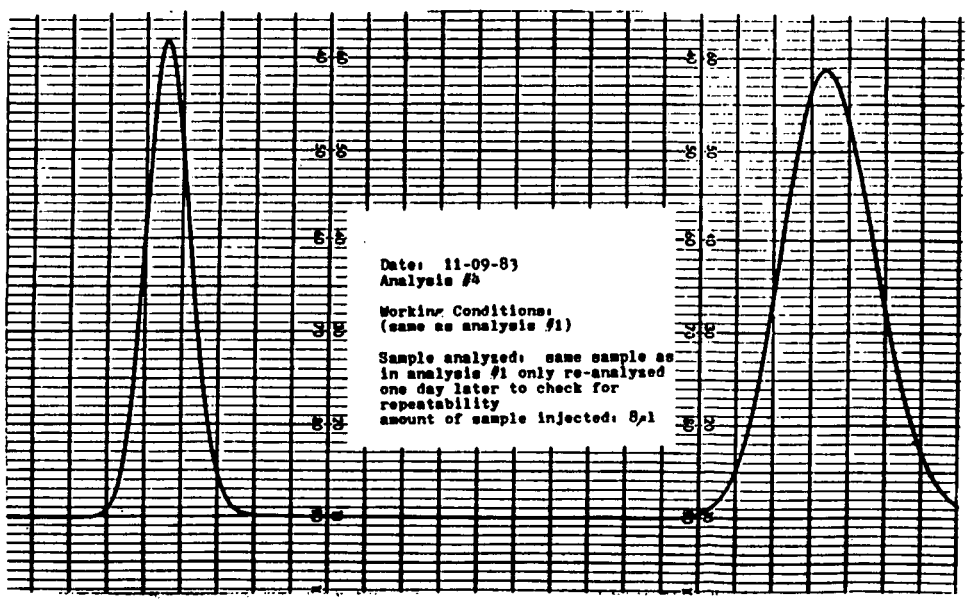
Analysis #1 Standard Prepared with Equal Volumes of R-12 and R-114



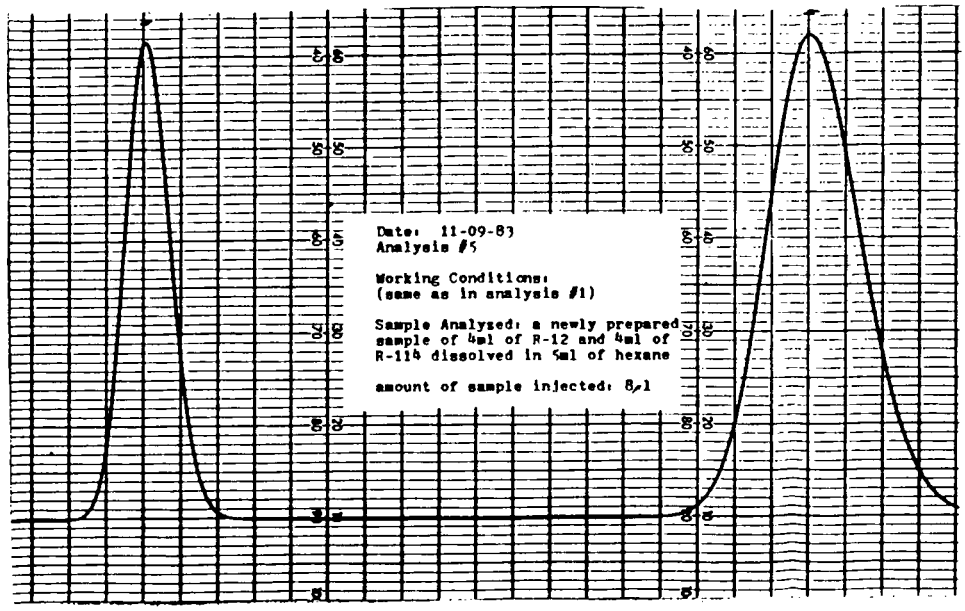
Analysis #2 Test #10, Test Section #8
Result: 47.5% R-12



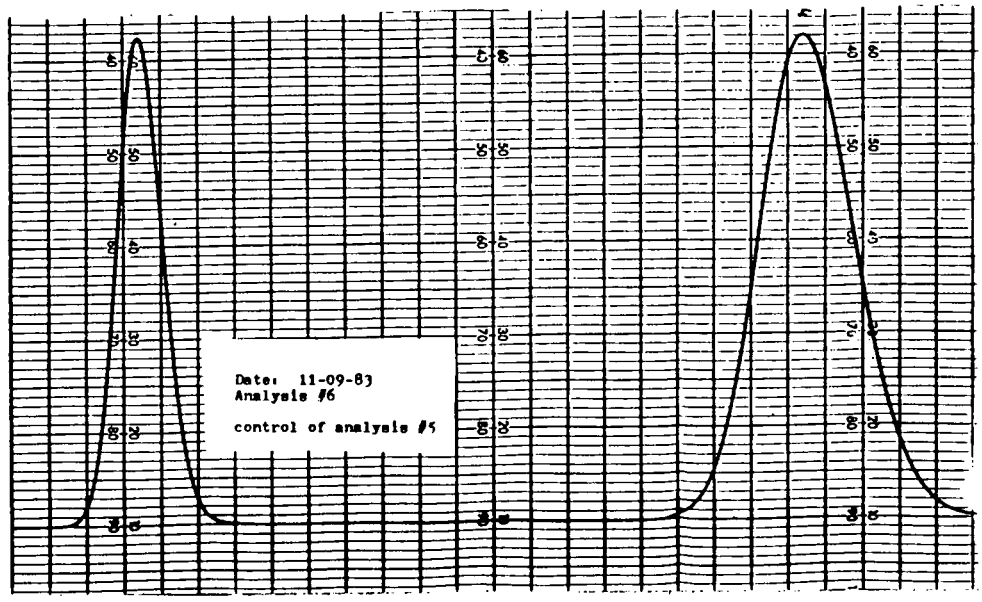
Analysis #3 Test #10, Pump Discharge
Result: 44.7% R-12



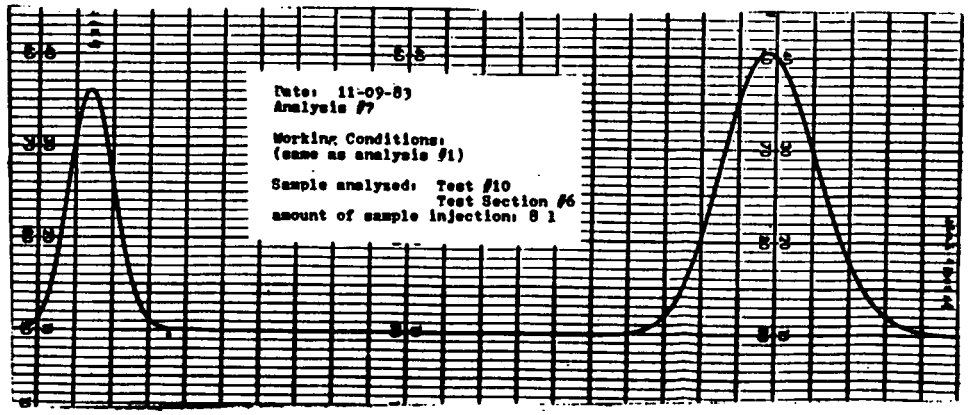
Analysis #4 Same Standard as in Analysis #1 only Re-analyzed One Day Later to Check for Repeatability



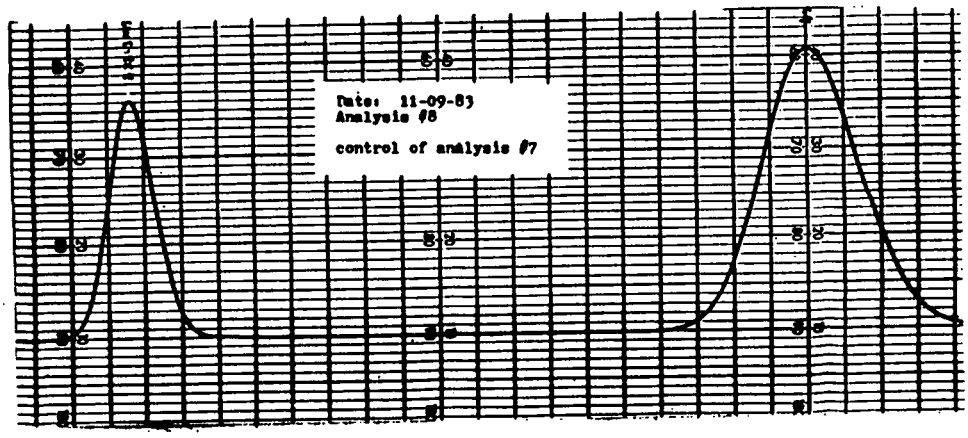
Analysis #5 Newly Prepared Standard of Equal Volumes of R-12 and R-114



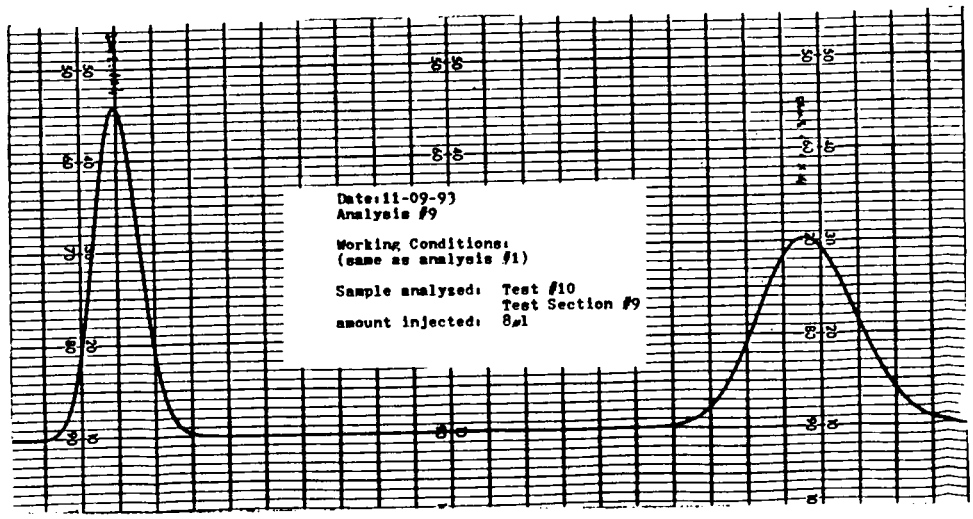
Analysis #6 Control of Analysis #5



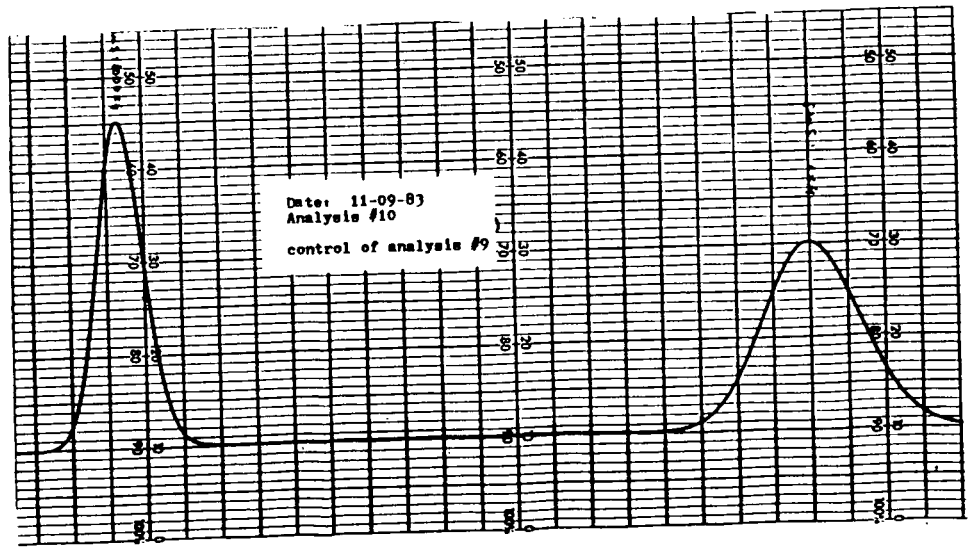
Analysis #7 Test #10, Test Section #6
Result: 43.2% R-12



Analysis #8 Control of Analysis #7



Analysis #9 Test #10, Test Section #9
Result: 48.7% R-12



Analysis #10 Control of Analysis #9