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EXPERIMENTAL ANALYSIS OF CAPILLARY TUBES FOR CFC-12 AND HFC-134a

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ABSTRACT

This work presents experimental data for capillary tubes of the type commonly used as expansion devices in domestic appliances, employing CFC-12 and HFC-134a as working fluids. Capillary tubes of 0.7, 0.8 and 1.0 millimeter internal diameter with lengths of 3 and 2 meters were tested. Condensing pressures of 18, 14, 11 and 9 bar, and subcooling ranging from 14 to 2 °C were chosen as the operating conditions. Choked conditions prevailed in all runs. The test rig and the experimental procedures are described in detail, being the uncertainties of all the measurements also given.

INTRODUCTION

An expansion device in common use in almost all small refrigeration systems is the capillary tube. This consists of a long hollow tube of drawn copper with an inside diameter ranging from 0.5 to 2.0 mm and a length from 1 to 6 m.

In spite of its strong influence on the refrigeration system performance [1] most of the capillary tubes are still selected by a trial-and-error process. The ASHRAE rating charts for capillary tubes [2], which are based on the work of Hopkins [3] and Whitesel [4,5] are the only available alternative to this procedure. Unfortunately these charts tend to underpredict the refrigerant mass flow rate [6] and are only available for refrigerants 12 and 22, which will be phased out in the near future due to the ozone depletion concern. Therefore a definite need exists for more accurate rating procedures which would allow sizing capillary tubes operating with any refrigerant.

In the last decade a great variety of capillary tube computer models [6,7,8] have been developed and validated against specific sets of experimental data, in an attempt to overcome this problem. During the 1992 IIR - Purdue Refrigeration Conference a paper analyzing the modeling of adiabatic capillary tubes was presented by the authors [9]. As a consequence of that work an experimental set-up was developed to generate reliable experimental data for the refrigerant flow through capillary tubes. The geometry of each capillary tube, i.e. internal diameter, length and roughness and the operating conditions, i.e. pressure, temperature and mass flow rate were evaluated with great care. The database thus obtained can be used not only to ascertain the impact of the refrigerant type on the capillary tube behaviour, but also for numerical modeling validation studies.

GEOMETRY OF THE CAPILLARY TUBES

Six capillary tubes made of copper were used in this study. They had two different lengths and three different inside diameters.

The inside diameter measurement is critical due to the strong influence of this parameter on the refrigerant flow [9]. The internal cross sectional areas of nine capillary tube samples, three of each diameter, were measured by an optical method. This method consists in amplifying each sample by 50 times and then integrating the internal area directly by a computerized process. Nine measurements were made for each sample. The equivalent inside diameters were then obtained from the averaged areas. The uncertainty associated with this process was found to be ± 0.02 mm.
The lengths of the capillary tubes were measured by a 3 m flexible scale with divisions of 1 mm. The tubes were kept as straight as possible by tensioning them between two holders. The uncertainty of this measurement was found to be ± 1.0 mm.

For the wall roughness measurements, six samples of each of the tubes were made. Each sample was prepared by first imbedding a small longitudinal section of the tube in a bakelite matrix. Then half of the tube wall was removed through a polishing process, exposing the internal surface of the tube. Observations using a microscope indicated that undesired scratches, from the polishing process, were not evident on the inside surface of the samples. The measurements were then made by a Form Talysurf 120, in accordance with the British Standard B.S. 1134 [10]. The wall roughness measurements correspond to the arithmetic mean of the absolute value of the departure of the roughness profile from the mean line. The uncertainty associated with this process was found to be ± 0.01 μm. Table I shows the geometry of the six capillary tubes under analysis.

### Table I - Geometry of the capillary tubes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal diameter (mm)</td>
<td>0.77</td>
<td>0.84</td>
<td>1.05</td>
<td>0.77</td>
<td>0.84</td>
<td>1.05</td>
</tr>
<tr>
<td>Length (m)</td>
<td>2.926</td>
<td>3.027</td>
<td>3.020</td>
<td>2.009</td>
<td>1.993</td>
<td>2.030</td>
</tr>
<tr>
<td>Wall roughness (μm)</td>
<td>0.75</td>
<td>0.59</td>
<td>0.72</td>
<td>0.75</td>
<td>0.59</td>
<td>0.72</td>
</tr>
</tbody>
</table>

**EXPERIMENTAL SET-UP**

The test facility used for the experiments is shown schematically in Figure 1. The system consists of two hermetic reciprocating compressors (1), a water-cooled condenser (2), an evaporator (3) and a test section (4). The test section is insulated with glass wool and consists of a capillary tube connected to couplers. Two oil separators (5) and an oil filter (6) are placed between the compressors and the condenser. Impurities in the refrigerant are removed by a filter (7). A subcooler (8) and an electric heater (9) are used to fine tune the refrigerant temperature at the capillary tube inlet.

1 - COMPRESSOR
2 - CONDENSER
3 - EVAPORATOR
4 - CAPILLARY TUBE
5 - OIL SEPARATOR
6 - OIL FILTER
7 - FILTER
8 - SUBCOOLER
9 - ELECTRIC HEATER
10 - SIGHT GLASS
11 - PRESSURE-REGULATING VALVE
12 - ELECTRIC AIR HEATER

![Fig. 1 - Schematic diagram of the experimental set-up](image-url)
Mounted at the capillary inlet is a sight glass (10) through which the flow can be observed, making it possible to check whether there is liquid or two-phase flow. The high pressure is established by the water flow through the condenser, which is controlled by a pressure-regulating valve (11). The evaporator pressure is controlled by the amount of bypassed refrigerant and, in some cases, by an electric air heater (12).

Two strain gage pressure transducers (P) are used to measure the capillary tube inlet and exit absolute pressures, with a maximum uncertainty of 0.016 bar. Type T thermocouples (T), 0.13 mm in diameter, with a maximum uncertainty of ±0.25 °C, are used to measure the capillary tube inlet and exit temperatures. The one at the exit is soldered on the outside surface of the tube wall, while the one at the inlet is placed inside the coupler, approximately 5 mm from the capillary tube entrance. The mass flow rate of refrigerant is measured by a Coriolis type mass flow meter (M), with an uncertainty of 0.03 kg/h. The output signals from the transducers, thermocouples and flow meter are recorded through a computerized data acquisition system.

TEST PROCEDURES

During the tests the inlet and exit pressures, the inlet temperature and the mass flow rate are plotted on the monitor screen as a function of time, to see whether the system is operating under steady state condition. After the start up of the compressors the system requires 1 to 1.5 hours to reach steady state operation, at a desired condensing pressure and inlet temperature. Thereafter the data are obtained by setting different values for the inlet temperature. When this variation is kept around 1 °C, the system requires approximately 15 minutes to return to steady state operation. Once a new steady state condition is attained, a new test is then recorded in a 20-30 minutes period, as shown in Figure 2.

As one can see the condensing pressure and the inlet temperature could never be set at an exact value. The system was then considered to be in a steady state condition when the inlet temperature and condensing pressure variations (maximum-minimum value) were kept below 0.4 °C and 0.2 bar, respectively. A data point is taken from the recorded test by selecting a time and then inferring the test parameters through graphical analysis. The errors that may arise from this process are well below the experimental uncertainties.
Tests were performed with CFC-12 and HFC-134a. Both refrigerants were 99.9% pure as verified through gas chromatography analysis. After the tests, the capillary tubes were flushed with chloroform, the solution was analyzed and no oil was detected in all the tests.

RESULTS AND DISCUSSIONS

A large number of measurements (288 data runs for CFC-12 and 245 for HFC-134a) were performed and are available in a tabular format [11], where the actual condensing pressure values are given. However, for a proper graphical display small variations in the condensing pressure were not considered, being the limit values indicated in each of the following Figures. Due to space limitations the following analysis will consider only the capillary tubes #1, 3, 4 and 6 and the 11 and 14 bar condensing pressures.

Figures 3a and 3b show the effect of the capillary tube length on the mass flow rate of CFC-12 and HFC-134a, where it can be observed that the mass flow rate, at the 8 °C subcooling, is respectively increased by approximately 26% and 31%, when the length is reduced by 31%. Similar trends are also found when the 1.05 mm internal diameter capillary tube and the 14 bar condensing pressure are considered.

Figures 4a and 4b illustrate how the capillary tube internal diameter affects the mass flow rate of CFC-12 and HFC-134a, respectively. It can be seen that for both refrigerants the mass flow rate is increased dramatically when the internal diameter is increased by only 36%. When the 14 bar condensing pressure and the 2 m long capillary tube are considered the mass flow rate of CFC-12 and HFC-134a at the 8 °C subcooling are increased by 122% and 135% as shown in Figures 4a and 4b, respectively. However small variations in these values were detected according to the refrigerant type, condensing pressure and tube length [11].

Figures 5 through 7 show the experimental results for the capillary tubes #1, 3, 4 and 6, employing CFC-12 and HFC-134a. It can be seen that both fluids generate almost the same mass flow rates at the same condensing pressure, being this trend slightly affected by the capillary tube geometry and by the operating conditions.
Fig. 4 - Effect of the internal diameter on the capillary tube mass flow rate. a) CFC-12, b) HFC-134a

Fig. 5 - Test results for the capillary tube #1 a) 11 bar, b) 14 bar

Fig. 6 - Test results for the capillary tube #4. a) 11 bar, b) 14 bar
CONCLUSIONS

Rather extensive data have been taken for flow of CFC-12 and HFC-134a through capillary tubes. The mass flow rates of both refrigerants are affected by the tube length, condensing pressure, internal diameter and subcooling. The effect of the length and of the internal diameter on the mass flow rate seems to be stronger for HFC-134a than for CFC-12.

Both fluids generate almost the same mass flow rates at the same condensing pressure and subcooling. This behavior is slightly affected by the capillary tube geometry and by the operating conditions.

The experimental apparatus has been fully tested, being able of generating reliable experimental information with adequate control of all the involved variables.

REFERENCES