DIDACTIC EXPERIMENTAL SETUP TO MEASURE VAPOR PRESSURE AND COMPRESSIBILITY FACTOR OF THE REFRIGERANT R134A

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Abstract. In an undergraduate course of Thermodynamics, the pressure-specific volume-temperature (p-v-T) relation of a pure substance is one the first subjects taught to students. The p-v-T surface and its projections are explored and several concepts concerning it are introduced. Usually, the vapor pressure property is presented using a well-known substance to students, as water for example. It is not difficult to remind them that this substance boils around 100 ºC at atmospheric pressure around 100 kPa, because they bring this information from the high school. However, it is not much easy to make them understand that the boiling temperature increases as the pressure increases. Another difficult subject to teach is the p-v-T behavior in the superheated vapor region. It is not an easy task to show that the ideal gas equation of state is valid only in part of that region, when the compressibility factor is equal to one in certain engineering approach. The best way to teach the students those subjects is taking them to the laboratory to measure both the vapor pressure and the p-v-T relation in the superheated region. The objective of this work is to present a didactic experimental setup to allow the measurement of both the vapor pressure and the compressibility factor of the refrigerant R134a. This substance was chosen because of its favorable critical point properties (T=374.2 K and P=40.6 bar) and due to its current application in refrigeration systems. The results were obtained for temperatures between 0 and 40 ºC, and pressures ranging from 3 to 12 bar. Considering the didactic nature of the experimental setup, the obtained results agreed very well with the literature data.

Keywords: vapor pressure, compressibility factor, refrigerant R134a, didactic experimental setup

1. INTRODUCTION

The pressure-specific volume-temperature behavior of pure substances is one of the first subjects approached in teaching Thermodynamics to undergraduate students. For didactic convenience, one prefers starting by presenting the vapor-liquid phase change behavior because students are more familiar with this subject. It is not a difficult task to remind the students that the water boils around 100 ºC, the well-known saturation temperature, at the standard atmospheric pressure. However, when students are asked if water will always boil at this temperature, the first complications and understanding difficulties appears. It is not much easy to convince them that in higher pressures water boils at temperatures larger than 100 ºC. Using the pressure cooker, a familiar device, can help students to have the first insights about this issue. An alternative procedure is to take students to the laboratory in order to obtain the vapor pressure curve by themselves. As Confucius has said "I hear and I forget. I see and I remember. I do and I understand".

In this work, an experimental setup for studying vapor pressure of a pure substance was designed, built and tested aiming to make easier and more attractive to undergraduate students the Thermodynamics learning. The refrigerant R134a was chosen as the pure substance because of its appropriate critical point properties (T=374.2 K and P=40.6 bar) and its current application in refrigeration systems.

Another important issue treated in a Thermodynamics course is the dependence among pressure, specific volume and temperature for all possible states. In this context, the correct use of the ideal gas state equation, Pv=RT, is very confusing to students, who do not realize that this simple equation can not be used for any thermodynamic state. It is very common to encounter students using inappropriately the ideal gas state equation in order to solver thermodynamic problems for any state. In addition, it is not much easy to introduce the concept of compressibility factor, Z=Pv / RT, and the theory of the corresponding states. The experimental setup idealized in this work also allows accomplishing the study of the p-v-T behavior of the refrigerant R134a in the superheated vapor region and, consequently, obtaining the compressibility factor.

When students perform these experiments in the laboratory they improve the understanding and assimilation of the concepts, which provides more efficiency in the Thermodynamics teaching, an undergraduate course that demands much dedication.

2. MATERIALS AND METHODS

2.1 Experimental Setup

The experimental setup was designed based on the works of Giuliani et al. (1995), Nicolau et al. (1997) and Robert (1994). Figure 1 presents a scheme of the experimental setup, which is composed basically by a commercial 13.6 kg bottle of R134a, a 350 ml cylinder test, a hermetic compressor, an oil separator, a thermostatic bath, and a scale. The R134a bottle is used as refrigerant reservoir, while the cylinder test contains the amount of refrigerant to be tested. A Bourdon tube gage is installed properly at the cylinder test exit in order to measure the gage pressure of the refrigerant during the tests. The local atmospheric pressure is measured during the tests to allow the calculation of the absolute pressure inside the cylinder test. The temperature of the refrigerant inside the cylinder test is obtained by measuring the temperature of the thermostatic bath using a type T thermocouple. The scale is used to measure the refrigerant mass inside the cylinder test in the case of the compressibility factor experiment.
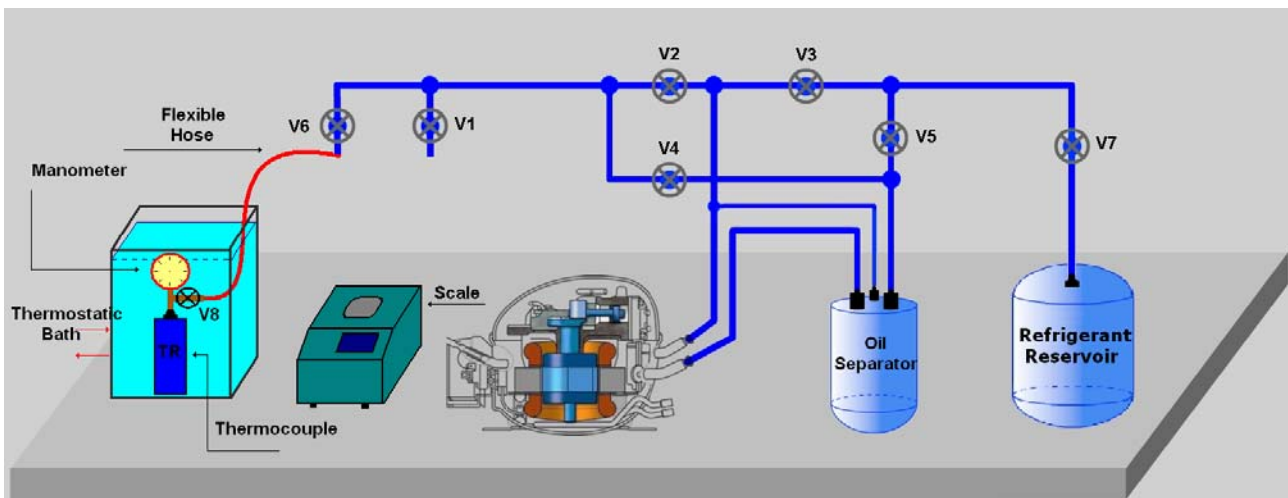

Figure 1: Visualization of the Experimental Setup.

During the tests the cylinder test is put inside the thermostatic bath which fixes the refrigerant temperature of the desired test. The cylinder test is connected to the compression-expansion station through a flexible high pressure hose. The compression-expansion station is constituted by the hermetic compressor, the refrigerant reservoir, the oil separator, valves, connections, and copper tubes. The compression-expansion station is used to provide the refrigerant mass requested for a given test. In order to reduce the refrigerant mass in the cylinder test, valves V2 and V5 must be opened and valves V4 and V3 closed when the compressed is turned on. The compressor can be used to increase the refrigerant mass inside the cylinder test when the valves V3 and V4 are opened and the valves V2 and V5 are closed. The valve V1 remains always closed during the tests and is used just to accomplish the initial vacuum in the bench. An oil separator is installed at the exit of the compressor to return the oil to the compressor, which reduces the contamination of the refrigerant inside the cylinder test and allows the appropriate compressor lubrication. Figure 2 shows a picture of the experimental setup.

Figure 2: Overview of the experimental setup.

2.2 Experimental Procedures

2.2.1 Vapor pressure curve

The procedure for obtaining the vapor pressure curve is quite simple. The cylinder test is filled by using the compressor with a fixed amount of refrigerant in such a way that a saturated liquid-vapor mixture coexists in thermodynamic equilibrium inside the cylinder. After that, the cylinder test is put in the thermostatic bath, whose temperature is set to a specific desired value. When the thermodynamic equilibrium is reached, refrigerant temperature and pressure inside the cylinder test are registered.

This procedure is repeated for other defined temperatures by setting the temperature of the thermostatic bath. For safety reasons, the larger pressure of all tests was around 12 bar, which means saturation temperatures around 40ºC.

2.2.2 Compressibility factor

In order to calculate the compressibility factor, Z, one must measure pressure, temperature, and specific volume of the refrigerant inside of the cylinder test. For a given temperature set in the thermostatic bath, one can set up several pressures and specific volumes by varying the refrigerant mass inside the cylinder test using the compressor. The compressibility factor is then obtained by Eq. (1) (Moran and Shapiro, 2000):

$$Z = \frac{P\,v}{R\,T} \tag{1}$$

Pressure and temperature are directly measured during the experiment. However, the specific volume must be calculated by knowing the cylinder volume and the refrigerant mass. In order to determine the cylinder volume it is filled with liquid water and the volume of water utilized to fill up the cylinder is measured. This procedure is repeated 5 times and an average value is calculated. The refrigerant mass is computed by subtracting the mass of the cylinder under vacuum together with the manometer and exit valve from the mass of the cylinder filled with refrigerant together with the exit valve and manometer.

Before starting a test it is important to estimate the appropriate mass for a given temperature in order to guarantee that the initial specific volume is larger than the saturated vapor specific volume. For example, for a 40ºC test, the saturated vapor specific volume is 0.01997 m³/kg. For a 350 ml cylinder test volume, the necessary refrigerant mass is

about 17.5 g. Therefore, this is the refrigerant mass added to the cylinder to perform the 40ºC temperature test. As soon as the refrigerant mass is defined, several tests for increasing temperatures can be accomplished. For each test, temperature and pressure are registered after equilibrium is reached. This procedure is repeated for other refrigerant masses, that is, other specific volumes. Figure 3 depicts the p-v diagram of the refrigerant R134a to help defining the refrigerant mass for each constant specific volume test. The tests were accomplished for temperatures varying from 0 to 90 ºC and pressures ranging from 1 to 12 bar, depending on the selected temperature.
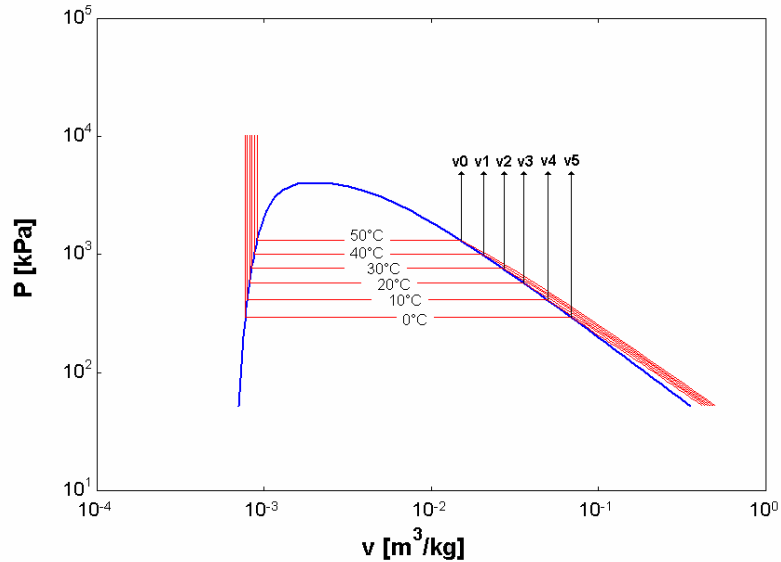

Figure 3: P-v diagram for refrigerant R134a.

3. RESULTS

3.1 Results for vapor pressure curve

Five tests were accomplished for temperatures ranging from about 3 to 40 ºC. The experimental results were compared with data obtained by the software Catt2, which accompanies the book of Van Wylen et al. (1995). Figures 4 to 6 show the vapor pressure curves for all five tests. Considering the didactic character of the experimental setup, the results are in excellent agreement. The larger difference was about 12% for the lower temperature of Test 2.
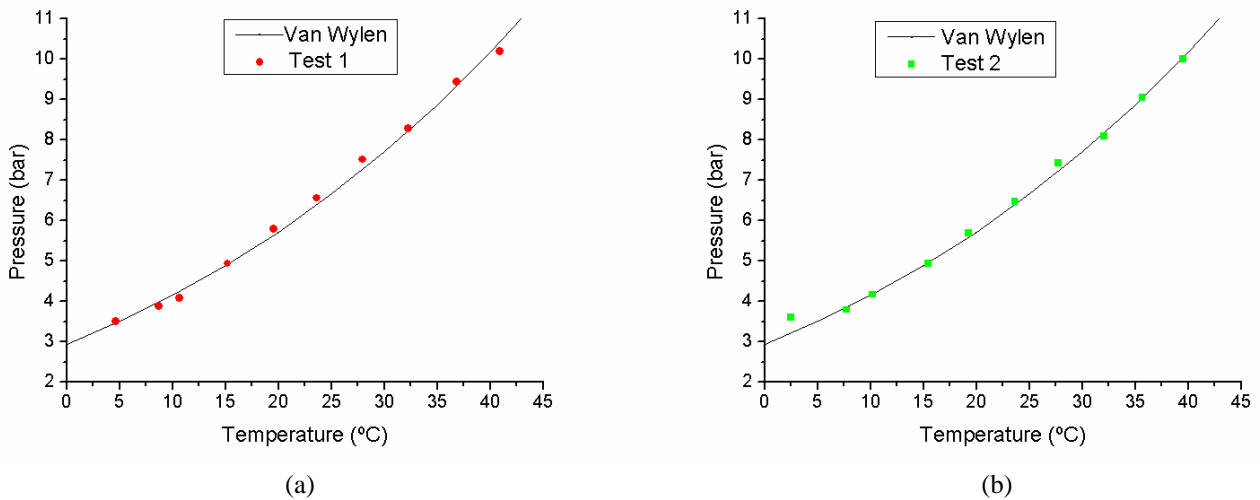

(a)

(b)

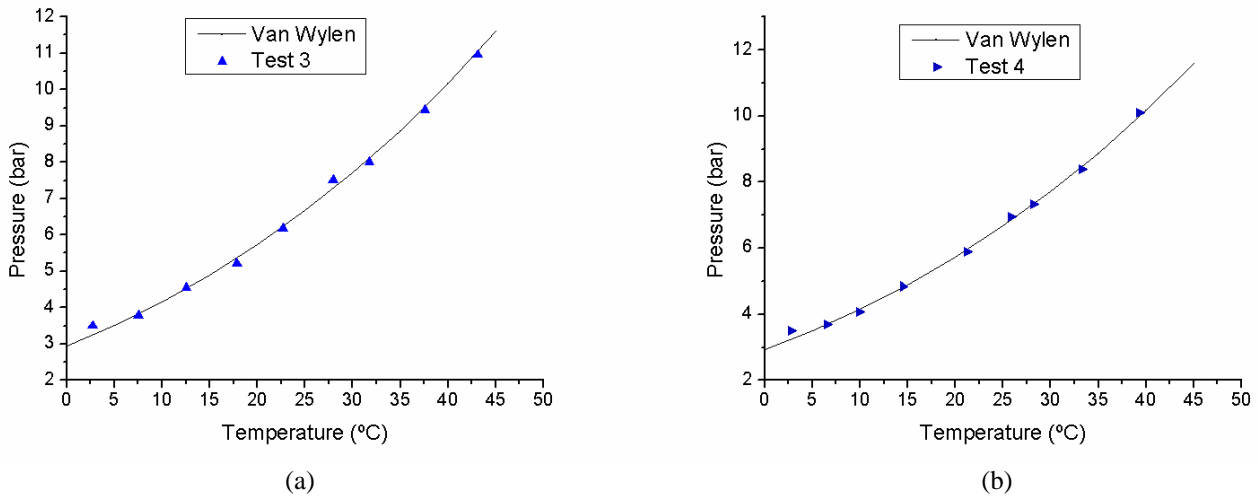Figure 4: Vapor pressure curves for (a) Test 1 and (b) Test 2.

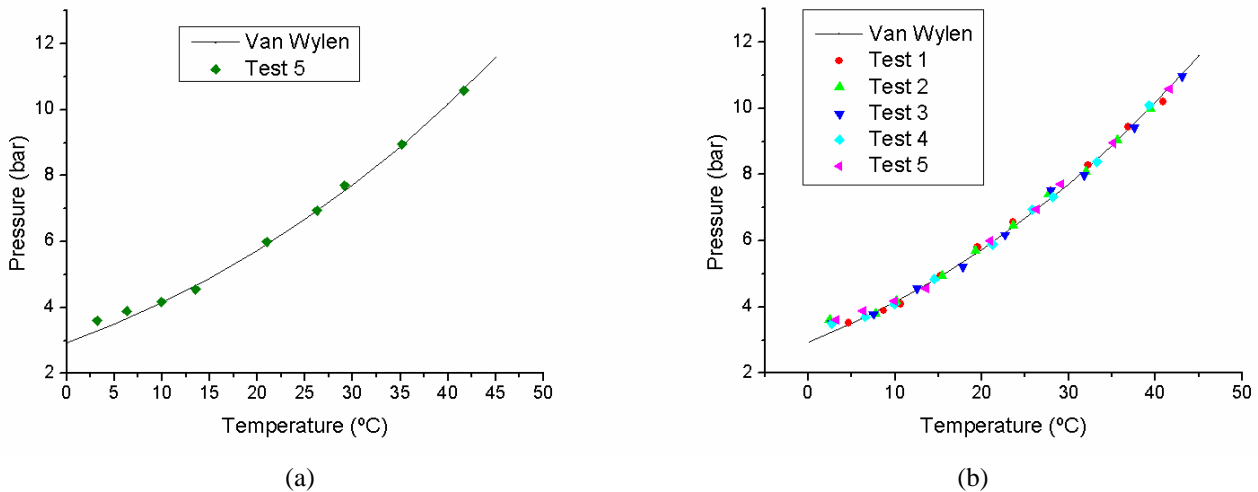Figure 5: Vapor pressure curves for (a) Test 3 and (b) Test 4.

Figure 6: Vapor pressure curves for (a) Test 5 and (b) all tests.

An experimental vapor pressure curve using all data, represented by Figure 6.a was fitted given the following equation:

$$\ln P = -2685.94 \left(1/T\right) + 10.91 \qquad (2)$$

where pressure P is in bar and temperature T is in Kelvin.

The obtained equation presented good agreement when compared with data from Moran and Shapiro, 2000, the major difference founded is 1.48%

3.2 Results for compressibility factor

Table 1 to 5 present experimental results for compressibility factor considering several reduced temperatures, Tr, and reduced pressures, Pr. In addition, the compressibility factor calculated by the correlation proposed by Lee and Kesler (1975) is also showed for comparison reason. In general one can say that the results are acceptable for didactic purposes. The average difference between experimental values and those given by the Lee-Kesler correlation is about 8%. The major difference is 17% for reduced pressure around 0.15. As expected, although reduced temperatures are too

close to each other, it is possible to notice that the compressibility factor tends to 1 as the reduced pressure decreases, except for reduced pressure around 0.10.

Table 1: Compressibility factor for Tr=0.86.

Tr=0,86			
Pr	Z (experimental)	Z (Lee-Kesler)	Difference %
0.28	0.85	0.80	6
0.22	0.90	0.85	6
0.17	0.97	0.89	9
0.14	1.05	0.91	15
0.09	0.97	0.94	3

Table 2: Compressibility factor for Tr=0.89.

Tr=0.89			
Pr	Z (experimental)	Z (Lee-Kesler)	Difference %
0.29	0.86	0.82	5
0.23	0.92	0.86	7
0.18	0.96	0.90	7
0.15	1.07	0.92	17
0.10	0.99	0.95	4

Table 3: Compressibility factor for Tr=0.92.

Tr=0.92			
Pr	Z (experimental)	Z (Lee-Kesler)	Difference %
0.31	0.88	0.83	5
0.24	0.93	0.87	6
0.19	0.99	0.90	9
0.15	1.07	0.92	16
0.10	0.98	0.95	3

Table 4: Compressibility factor for Tr=0.94.

Tr=0.94			
Pr	Z (experimental)	Z (Lee-Kesler)	Difference %
0.25	0.94	0.88	7
0.19	0.98	0.91	7
0.16	1.07	0.93	15
0.10	0.98	0.95	3

Table 5: Compressibility factor for Tr=0.97.

Tr=0.97			
Pr	Z (experimental)	Z (Lee-Kesler)	Difference %
0.26	0.95	0.89	6
0.20	1.00	0.91	9
0.16	1.07	0.93	15
0.10	0.99	0.96	4

There is greater error of measurement of mass of refrigerant for lesser pressures. This result is improved with the reduction of the test pressure, what it can be seen in Tables 1 to 5 when Pr diminishes. However, for Pr below of 0.10, the difference between the experimental and Lee-Kesler data diminishes unexpectedly, this behavior of experimental data can be associated with the amount of used mass in this test, which is much lesser than other tests. This result suggests that can have occurred compensation of experimental errors

The most critical property to measure in this experiment is the specific volume of the refrigerant. The larger the volume of the cylinder test the larger the necessary refrigerant mass. Therefore, in order to improve the results of these tests one suggests the use of a larger cylinder test.

Figure 7 depicts the compressibility chart for Tr=0.86. Through this chart it is easier to notice that the difference between the experimental data and the Lee-Kesler results increases as Pr decreases, that is, as the refrigerant mass needed to the test decreases, except for Pr=0.10. In this case, the refrigerant mass is the smallest one, and the difference should be the largest one if the tendency of the data continued.
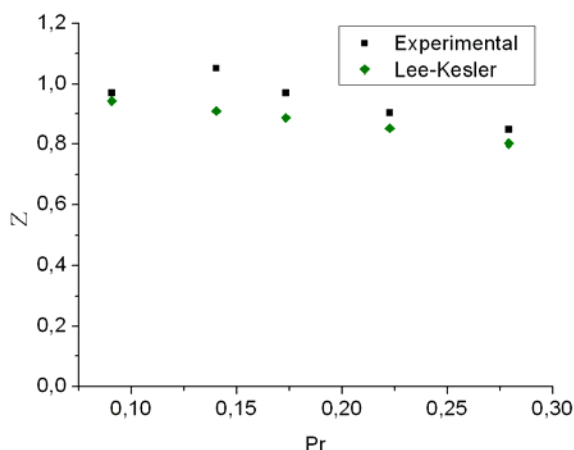

Figure 7: Compressibility factor chart for Tr=0.86.

4. CONCLUSIONS

In a Thermodynamics undergraduate course, two subjects must be taught and bring about some difficulties to students: the vapor pressure curve and the p-v-T relation of a pure substance. One can promote a substantial improvement in the learning process if students are taken to the laboratory to live an experience about those issues. The main goal of this work is to present a didactic experimental setup to allow the measurement of both the vapor pressure and the compressibility factor for the superheated region of the refrigerant R134a, a current refrigerant used in domestic refrigeration system. The results were obtained for temperatures between 0 and 40 ºC, and pressures ranging from 3 to 12 bar. Considering the didactic character of the experimental setup, the results agreed well with the literature data, mainly for the vapor pressure data.

5. ACKNOWLEDGEMENTS

6. REFERENCES

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