Mechanical Engineering Systems Solutions

FOREWORD

HVAC Training Centers USA trains technicians to properly install refrigeration and heating systems, many of which utilize the vapor compression cycle (VCC). Your training program tests technicians on their abilities to tune the operating characteristics of the systems to deliver the best coefficient of performance (COP) for cooling and heating from a number of choices using the VCC training carts, and you have had some complaints that this test is unfair due to the uncertainties of your testbed systems. Thus, you have solicited our company's help in investigating this claim. Specifically, you have asked us to find the COP of cooling and heating for a VCC cart that you provided us with under three different compressor frequencies (30Hz, 45Hz, and 60Hz). In addition, you requested that we document the thermodynamic cycle on a temperature-entropy diagram with uncertainties at each state (using SI units). Lastly, you have asked that we report any other considerations that are important in determining the unit's ability to heat or cool efficiently and recommend whether they should be included in your testing of the technicians. We have completed these tasks. The purpose of this report is to provide you with our findings, conclusions, recommendations, and supporting documentation.

SUMMARY

We have found the COP values of cooling and heating for the compressor frequencies of 30Hz, 45Hz, and 59Hz. The COP values decrease with increasing compressor frequency (Table 1); hence, less work is needed for lower frequencies to pump a specific amount of heat into or out of the space to be heated or cooled than would be needed for higher frequencies. We have also provided temperature-entropy diagrams to show the thermodynamic cycle at each frequency (Fig. 3-5, p.4). We have found that the uncertainties of the system are small enough that each frequency has a distinct cycle and a unique COP value. Thus, we conclude that your test is fair and the complaints about the test have been unfounded. We also have also determined that the cooling and heating capacities are key considerations in determining the unit's ability to heat or cool efficiently, and suggest that you test your technicians on their ability to tune the unit to give an appropriate value of the cooling or heating capacity. The values of the cooling and heating capacities were calculated for each frequency, and were found to increase with increasing frequency (Table 1).

Table 1: Coefficient of Performance of Cooling and Heating Both Decrease with Increasing Frequency, and Cooling and Heating Capacities Both Increase with Increasing Frequency

Frequency [Hz]	COP of Cooling	Cooling Capacity [W]	COP of Heating	Heating Capacity [W]
30	3.29 ± 0.09	730 ± 20	3.29 ± 0.09	790 ± 20
45	2.15 ± 0.02	781 ± 6	2.56 ± 0.02	934 ± 7
59	1.84 ± 0.02	841 ± 7	2.15 ± 0.02	986 ± 8

PROCEDURE

Your company provided us with a VCC cart (Hamden Engineering Corporation Refrigeration Trainer, Model H-CRT-1), as well as a computer controlled data acquisition system (Labview 8.2) for recording the thermodynamic data. The VCC cart had two choices for the evaporator and several choices for the throttling valve; we utilized evaporator 1 and the capillary for these components, respectively. Schematics of the VCC cart are shown in Fig. 1 and Fig. 2. The working fluid of the apparatus was R-134a.

The data of interest for our analysis are shown in Fig. 2, where T refers to temperature, P refers to pressure, and Q refers to volume flow rate. The subscript refers to the point at which the value is measured. All the data was measured directly with Labview. However, Labview recorded gauge pressures, and therefore, we had to add the room pressure to each recorded value in order to get absolute pressure. The data of interest, for each point in the vapor-compression cycle, can be seen in Fig. 2; this data was used to find both enthalpy and entropy values at each of the points 1 through 4.

Figure 1: Schematic of VCC Cart where the Arrows Indicate Direction of Fluid Flow

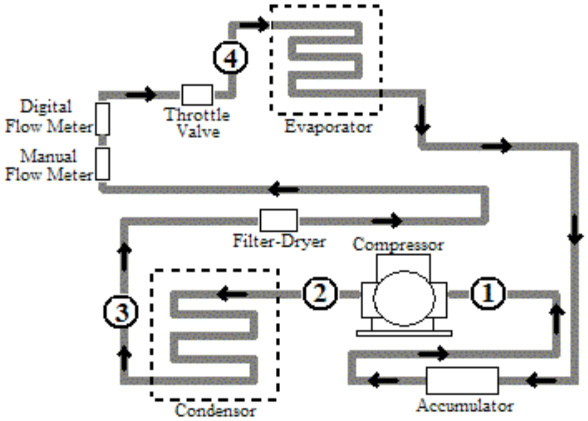
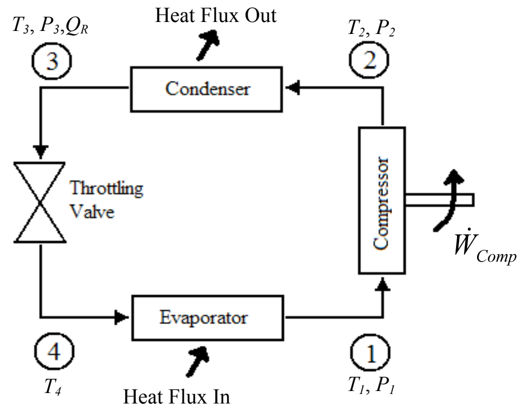


Figure 2: Simplified Schematic of VCC Cart Shows Important Measurements at Each Point



To find the COP of the VCC system, we set the compressor frequency to the desired value and waited for the system to reach steady-state. Steady-state was achieved when the computer acquisition system showed all of the measurements of interest to be constant values (straight, horizontal lines), and also, when the fluid coming out of the condenser at point 3 (Fig. 1) was completely liquid (no bubbles observed in the sight glass). We then used the Labview 8.2 software to record the data. The data was recorded ten different times for each frequency to allow us to compute the uncertainties in the data. This procedure was performed at 30 Hz, 45 Hz, and 59 Hz. 59 Hz was used instead of the requested frequency of 60 Hz, because this was as high as the compressor frequency would go for the system that you provided us with.

In our analysis of the thermodynamic properties of the VCC cart, we made several assumptions about the system. We assumed that there was no additional heat transfer apart from the heat flux in and out shown on Fig. 1 (perfectly insulation), that there were no additional pressure drops (no leaks), and that there were three reversible steps, taking place from points 1 to 2, 2 to 3, and 4 to 1 (Fig. 1). Also, oil had been added to the refrigerant to lubricate the compressor; however, we assumed that the added oil did not change the thermodynamic properties of the refrigerant.

All experimental data was taken at a room temperature of 294 ± 1°K and a room pressure of 99.13 ± 0.05 kPa. Room temperature and pressure were measured three times each with a thermometer (resolution of 1° K) and a barometer (resolution of 0.01 kPa), respectively.

In addition, as R-134a in liquid form can cause blindness, we were especially careful to wear appropriate protective eye gear.

FINDINGS

In this section we will give the coefficient of performance (COP) of the VCC system and document the thermodynamic cycle on a temperature-entropy diagram for compressor frequencies of 30Hz, 45Hz, and 59Hz. We will also discuss the heating and cooling capacities of the system and their importance in determining the system's ability to heat or cool efficiently. We will also discuss the uncertainties associated with the data.

COP of Cooling

Both the COP of cooling and the COP of heating were found to decrease with increasing compressor frequency; thus, pumping a specific quantity of heat out of or into the reservoir requires less work at a higher frequency than a lower frequency. The values for each compressor frequency (30Hz, 45Hz, and 59Hz) can be found in Table 2.

Table 2: Coefficient of Performance of Both Cooling and Heating Decreases with Increasing Compressor Frequency

	30 Hz	45 Hz	59 Hz
COP of Cooling:	3.29 ± 0.09	2.15 ± 0.02	1.84 ± 0.02
COP of Heating:	3.58 ± 0.09	2.56 ± 0.02	2.15 ± 0.02

The COP of cooling was calculated using Eq. 1, where all of the variables refer to properties of the refrigerant, R-134a. Q_R is the volume flow rate, ρ is the density at point 3, h_1 is the enthalpy at point 1, h_4 is the enthalpy at point 4, and $\dot{W}_{Comp}$ is the power input to the compressor (Fig. 1, p. 2). $\dot{Q}_E$ and $\dot{Q}_C$ are the cooling and heating capacities of the unit, respectively. h_1 was found from the thermodynamic tables of R-134a [2], using the temperature and absolute pressure at point 1 (Fig. 1, p. 2). h_4 is known to be equal to h_3 because enthalpy remains constant though the throttling valve [1], and h_3 was found from the thermodynamic tables of R-134a [2], using the temperature and absolute pressure at point 3 (Fig. 1, p. 2).

$$COP_{cooling} = \frac{\rho Q_R (h_1 - h_4)}{\dot{W}_{Comp}} = \frac{\dot{Q}_E}{\dot{W}_{Comp}} \qquad \text{Equation 1 [1]}$$

$$COP_{heating} = \frac{\rho Q_R (h_2 - h_3)}{\dot{W}_{Comp}} = \frac{\dot{Q}_C}{\dot{W}_{Comp}} \qquad \text{Equation 2 [1]}$$

The COP of heating was calculated in the same way as the COP of cooling; however, we now make use of Eq. 2 instead of Eq. 1. h_2 is the enthalpy at point 2, and h_3 is the enthalpy at point 3 (Fig. 1, p. 2).

For the frequency of 30Hz, however, the COP of heating had to be computed in a different way, due to a malfunction of the thermocouple that measured T_2. The thermocouple recorded the temperature of point 2 (at 30Hz) to be too low (the temperature was clearly incorrect because the fluid must be a super-heated vapor at this point, but the recorded temperature tells us that it is a saturated liquid). Therefore, we instead assumed that the entropy, s, remained constant from point 1 to 2 (Fig. 1, p. 2), as it would in an ideal cycle. We then found h_2 using the thermodynamic tables of R-134a given this constant entropy, s, and pressure, P [2]. This h_2 value was then used in Eq. 2 to give the COP of heating value found in Table 3, p. 2.

The uncertainties in the COP values are due primarily to the precision errors in Q_R, ρ, h_2, h_3, and $\dot{W}_{Comp}$.

Thermodynamic Cycle Documented on Temperature-Entropy Diagram

The temperature-entropy diagrams for the compressor frequencies of 30Hz, 45Hz, and 59Hz were plotted, and can be seen, respectively, in Fig. 3 through Fig. 5. Each diagram, labeled with the 4 points of Fig. 1 (p.2), shows the expected trend for a vapor-compression cycle, where point 1 is a saturated vapor, point 2 is a super-heated vapor, point 3 is a saturated liquid, and point 4 is a saturated mixture [1].

To plot the thermodynamic cycle, we had to find the entropy values for points 1-4 (Fig. 1, p. 2). This was done by using the R-143a thermodynamic tables to find s_i (entropy at point i), using T_i and P_i at points 1-3 and using T_4 and h_4 to find s_4 [2]. This was done for the compressor frequencies of 30Hz, 45Hz, and 59Hz (Fig. 3-5). However, for the frequency of 30Hz (as mentioned in the previous section) we found that point 2 was not a super-heated vapor as it should be for a VCC, but rather a saturated liquid; we attribute this discrepancy to a malfunctioning thermocouple that recorded the temperature to be too low. Instead of using this point, which is clearly inaccurate, we assumed that the entropy, s, remained constant from point 1 to 2, as it would in an ideal cycle. We then found the temperature using the thermodynamic tables of R-134a given this constant entropy, *s*, and pressure, *P* [2]. This new point is shown in Fig. 3 as point 2'.

Figure 3: Temperature-Entropy Diagram for 30Hz Shows that Thermocouple Measured Incorrect Value for Temperature at Point 2. More Accurate Cycle Was Found By Assuming Constant Entropy from Point 1 to Point 2.

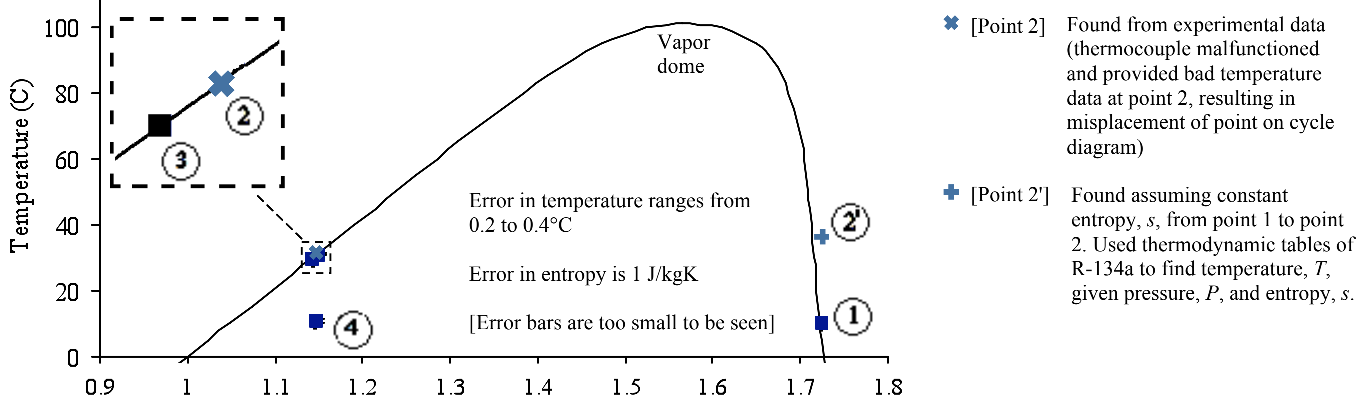


Figure 4: Temperature-Entropy Diagram for 45Hz shows typical vapor-compression cycle

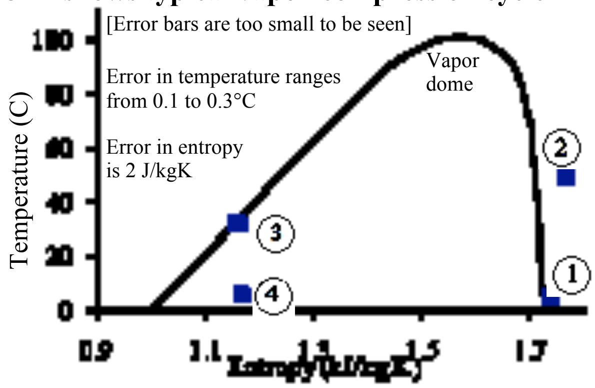
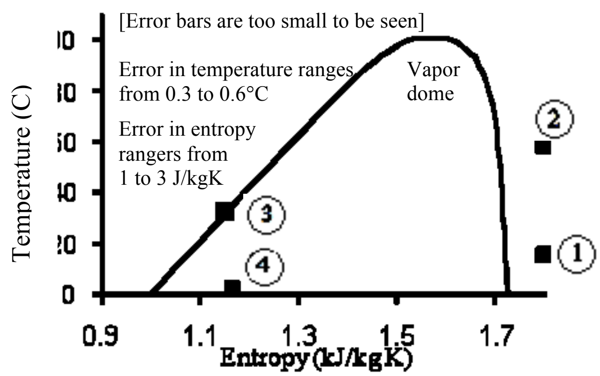


Figure 5: Temperature-Entropy Diagram 59Hz shows typical vapor-compression cycle



In the temperature-entropy diagrams (Fig. 3-5), the uncertainty in the temperature arises primarily from precision error, and the uncertainty in the entropy is due primarily to the precision errors in the temperature and pressure.

The cycles of the VCC cart (Fig. 3-5) differ slightly from the ideal vapor-compression cycle. In an ideal vapor-compression cycle, pressure should remain constant from point 2 to 3 and from point 4 to 1, and the entropy should remain constant from point 1 to 2. Because these values are not held constant between said points, we can conclude that the processes of compression (1 to 2), heat rejection (2 to 3), and heat addition (3 to 4) are not reversible. This is because of energy losses due to friction and unwanted heat transfer; for example, the pipes were not perfectly insulated and inevitably exchanged heat with the ambient.

Cooling and Heating Capacities

When determining the unit's ability to heat and cool efficiently, it is also important to consider the cooling and heating capacities of the VCC system. We have calculated the cooling capacity, $\dot{Q}_E$, and the heating capacity, $\dot{Q}_C$, for the three compressor frequencies using Eq. 1 and Eq. 2 (p. 3) and we can see that both the cooling capacity and the heating capacity increase as the compressor frequency increases(Table 3). This means that a higher frequency will be able to pump more heat into a room in a certain amount of time than a lower frequency will be able to.

Table 3: Cooling and Heating Capacities Both Increase with Increasing Compressor Frequency

	30 Hz	45 Hz	59 Hz
Cooling Capacity [W]:	730 ± 20	781 ± 6	841 ± 7
Heating Capacity [W]:	790 ± 20	934 ± 7	986 ± 8

The cooling and heating capacities are important to consider for a VCC system, because even if the operating characteristics of the system yield a large COP, the unit still won't be efficient unless the cooling or heating capacity is appropriate for the type and amount of space to be heated or cooled. If the cooling/heating capacity is too small, the system will not cool/heat the room or space adequately; however, if it is too large, the system will turn on and off too often causing the efficiency of the unit to decrease and energy bill to increase. Therefore, we suggest that you test your technicians in their ability to match the cooling/heating capacity with the necessary factors, for example, the size of room to be cooled or heated, the number of windows, and the number of people typically inside room.

CONCLUSIONS AND RECOMMENDATIONS

Through our analysis of the VCC cart that you provided us with, we have concluded that the test you give your technicians is fair, and the complaints that you have received were unfounded. With all uncertainties accounted for, each frequency gives a unique thermodynamic cycle with a distinct COP. Our analysis shows that both the COP of cooling and the COP of heating decrease with increasing compressor frequency (see Table 1, p. 1), which means that less work is needed for lower frequencies to pump a specific amount of heat into or out of the space to be heated or cooled than would be needed for higher frequencies.

In addition, we have concluded that the heating and cooling capacities are key components in determining the unit's ability to heat or cool efficiently, because if the cooling/heating capacity is too small, the system will not cool/heat the room or space adequately, but if it is too large, the system will cycle on and off too often causing the efficiency of the unit to decrease and energy bill to increase. We have provided you with the values of the heating and cooling capacities for the three compressor frequencies of 30Hz, 45Hz, and 59Hz in Table 1 (p.1), and have found that both the heating and cooling capacity increase with increasing frequency. This means that a higher frequency will be able to put more heat into or take more heat out of a space than a lower frequency will in the same amount of time.

We recommend that you test your technicians not only their ability to tune the cart to give a good value of COP, but also on their ability to choose a good value of the cooling or heating capacity, based on what type of space is to be heated or cooled. This will give your technicians the knowledge to help their clients save on energy costs.

REFERENCES

[1] Borgnakke, Claus and Richard E. Sonnatag., 2007, *Introduction to Engineering Thermodynamics*, Second Edition, John Wiley & Sons, Inc., Hoboken, NJ, p. 183-197

[2] Bhattacharjee, Subrata, 1999. Evaluating Thermodynamic States: The R-134a State Daemon, November 2007, from http://flame.mech.gifu-u.ac.jp/TEST-j/testcenter/Test/solve/states/r134a/index.html