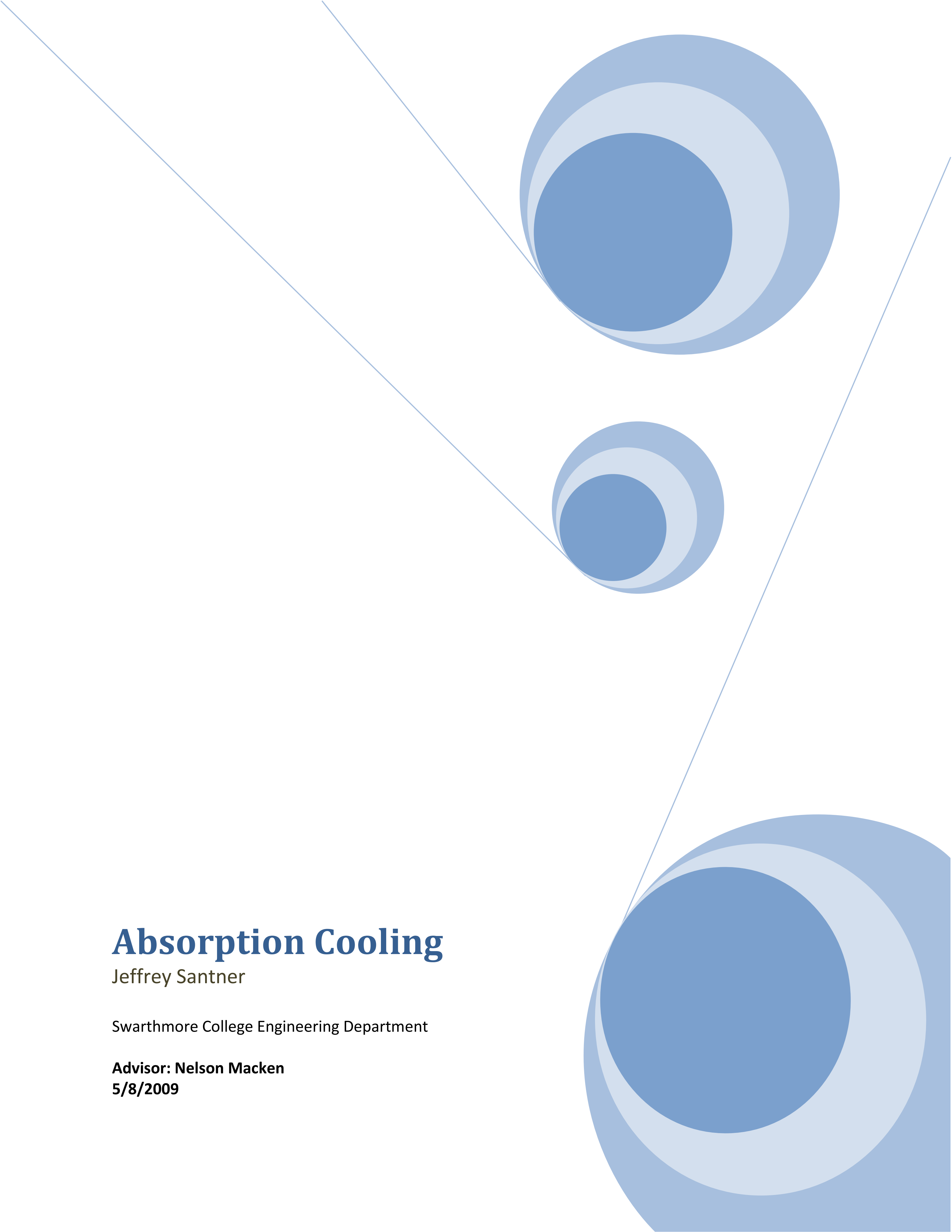

Absorption Cooling

Jeffrey Santner

Swarthmore College Engineering Department

Advisor: Nelson Macken
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Abstract

This project determines the parameters of an absorption cooling system. Pressures, temperatures, mass flows, concentrations, and heat flows were calculated. The COP was calculated as 0.225. The absorption chiller, run on electric heat with an air heat exchanger on the evaporator, can be used as a learning tool in future Swarthmore labs for students studying thermal energy. The chiller can also be a future E90, where a student could run the system on solar thermal energy.

Introduction

Vapor-Compression Refrigeration

For many years, the standard form of refrigeration and air conditioning has been the vapor-compression refrigeration cycle. (see Figure 1)

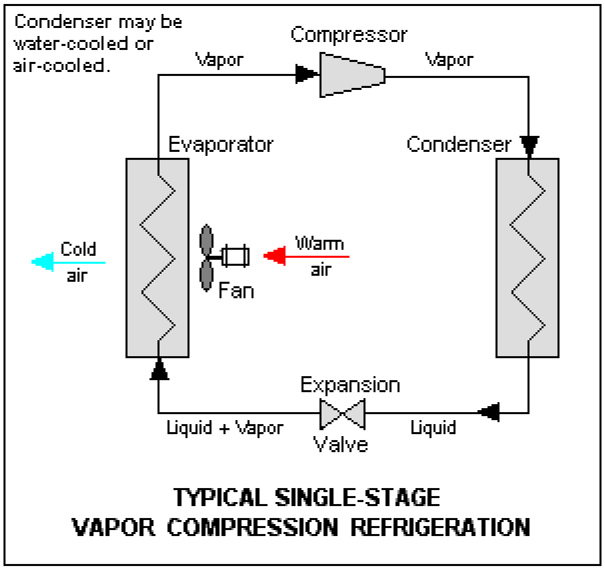


Figure 1: Vapor Compression refrigeration. Image fromhttp://en.citizendium.org/images/8/8e/Vapor_Compression_Refrigeration.png

In this cycle, refrigerant vapor is compressed. This hot compressed vapor loses heat to the environment in the condenser, where the vapor becomes a liquid. This liquid passes through the expansion valve, lowering the liquid to a pressure so that it will evaporate at a desired cold temperature. This evaporation occurs in the evaporator, cooling down air in the cooled space. Afterwards, the refrigerant is compressed again, completing the cycle. This system is very common, and has a COP that can be as high as 4. This means that the energy removed in cooling is four times the useful energy into the system (the compressor work).

Absorption Refrigeration

The absorption refrigeration cycle operates on a similar principle as the vapor-compression system. In both systems, a hot refrigerant is condensed in one location at a higher pressure, and then the pressure is lowered in the evaporator, causing the refrigerant to evaporate. But, the methods used to achieve these goals are different from those in a vapor-compression cycle. The differences cause an absorption system to use little to no work input, but energy must be supplied in the form of heat. This makes the system very attractive when there is a cheap source of heat, such as solar heat or waste heat from electricity or heat generation. This system is also used when electricity is expensive, unreliable, or unavailable, and it is easier to achieve heat input with a flame than with electricity. So, absorption cooling is often used in cogeneration systems, where waste heat from electricity generation is used to achieve cooling. Absorption is also used in refrigerators used in Recreational Vehicles (RVs) because electricity is often unreliable or unavailable, so a propane flame is used as the heat source.

In a two-fluid absorption cycle (Figure 2), the hot, gaseous refrigerant condenses by exchanging heat with the air. The pressure of the liquid refrigerant is lowered when it passes through a throttling valve to the evaporator, where it will evaporate at a lower temperature. The method of returning from a low pressure vapor to a high pressure vapor is the difference between this system and the vapor compression system. The refrigerant vapor is absorbed by a liquid after evaporating. This liquid is pumped through a regenerator to preheat it, and then to the generator, where heat is added, causing the refrigerant to come out of the absorber. Then, the gaseous refrigerant passes through the rectifier, a simple liquid/vapor separator, which removes the absorbent. A key to the two-fluid absorption cycle is that a liquid pump, not a vapor compressor, is used to create the pressure rise between evaporator and condenser. Pumping a liquid is much easier and cheaper than compressing a gas, so the system takes less work input. However, there is a large heat input in the generator. So, the system basically replaces the work input of a vapor-compression cycle with a heat input. Figure 2 shows a two-fluid absorption system with ammonia as the refrigerant and water as the absorber. The heat input is provided by solar energy, and there is a regenerator to preheat the aqueous ammonia.

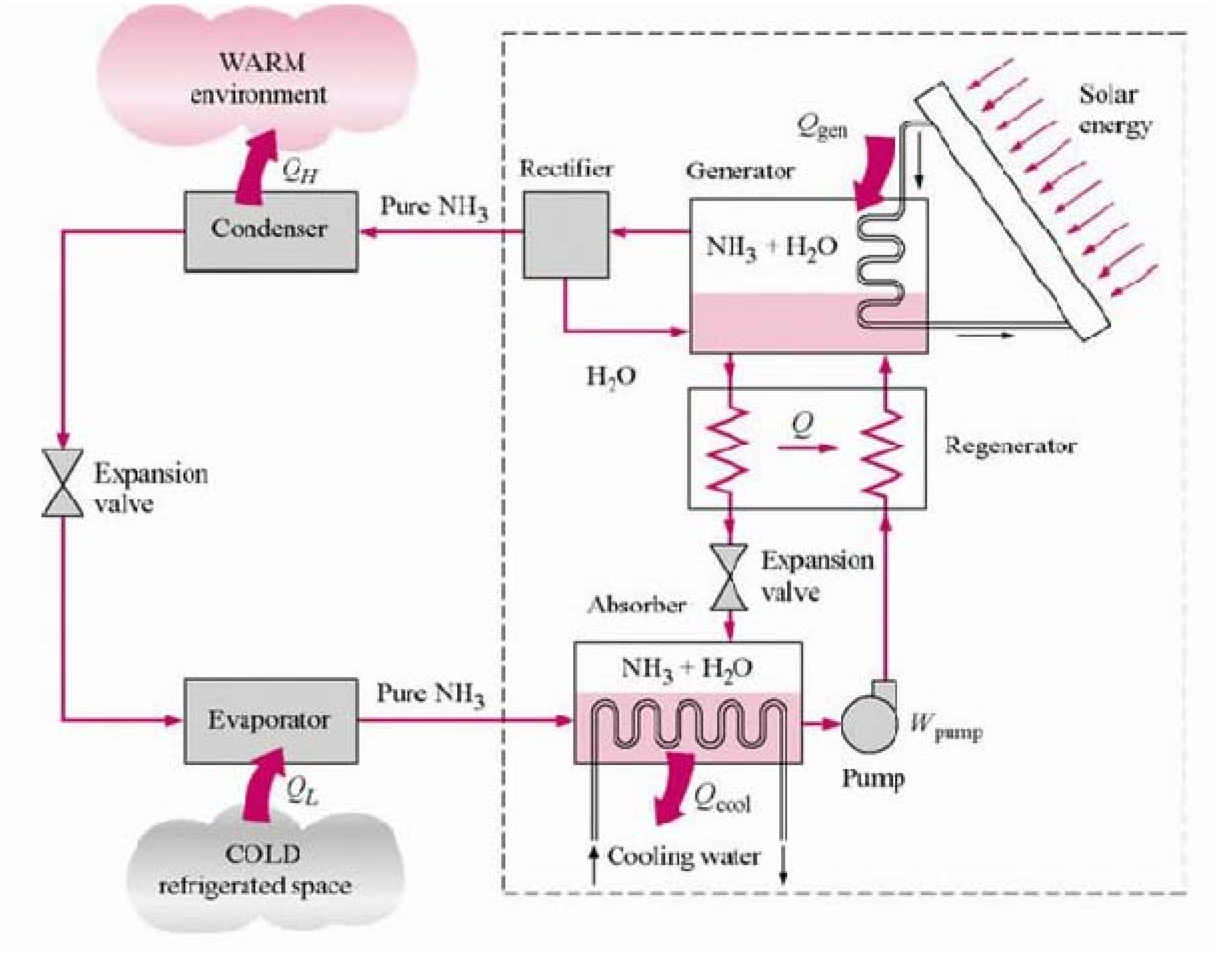


Figure 2: A two-fluid absorption system with ammonia as the refrigerant and water as the absorber. (Cengel & Boles, 2008)

In a three-fluid absorption cycle (Figure 3), the pump (the only moving part) is eliminated by keeping all elements of the system at one total pressure. So, with a non-electrical heat source, this system runs purely on heat, there is no electricity involved. To lower the pressure and cause evaporation in the previous cycles, an expansion valve was used. In the three-fluid cycle, the pressure is lowered by mixing the refrigerant with a third fluid, an inert gas. This lowers the partial pressure of the refrigerant so that it evaporates at a low temperature. Then, the absorber is chosen such that it will absorb only the refrigerant, leaving the inert gas behind. These three fluids move through the system using gravity, convection, and a two phase thermal siphon. The refrigerant moves through the system because it rises when heated as a gas, and then flows downwards as a liquid due to gravity. The inert gas moves through the system due to convection. The absorber moves using a two phase thermal siphon, also known as a bubble pump. In the generator, heat causes the refrigerant to come out of solution in a narrow vertical tube. The tube is so narrow that the liquid absorber, which now contains less refrigerant, forms slugs. These slugs are forced upwards by the hot refrigerant vapor, which rises due to its low density. At the end of the tube, the liquid absorbent flows down the outside edge of the narrow tube, building a pressure head. Twists and constrictions in the refrigerant tube release any remaining absorbent vapor that may be entrained in the refrigerant. This liquid absorber flows back downhill. In this way, the absorber is moved vertically and allowed to flow downhill, creating circulation. Figure 3 shows a three fluid absorption system with ammonia as the refrigerant, hydrogen as the inert gas, and water as the absorber.

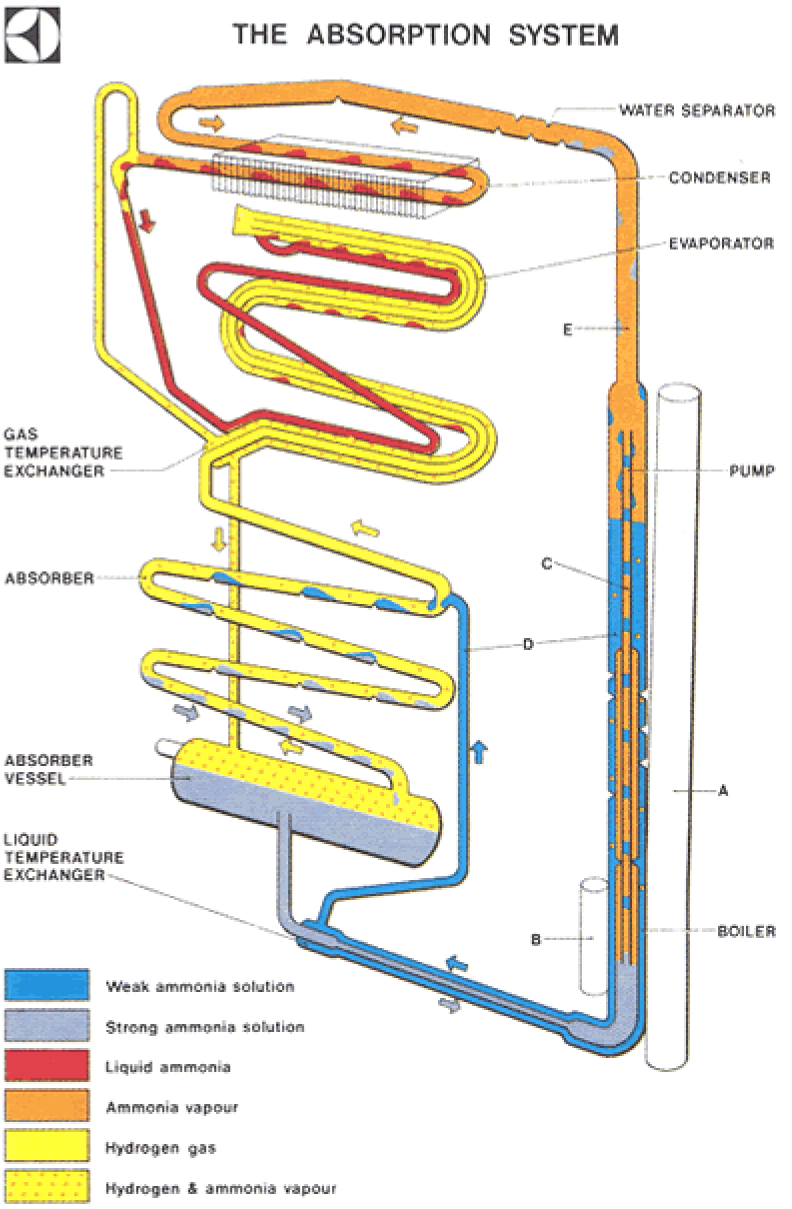


Figure 3: The 3-fluid absorption system. Image from http://www.gas-refrigerators.com/images/absorption.gif

Goals

The original goal of this project was to create a solar thermal powered absorption chiller to be used as an air conditioner in the rooftop laboratory in Hicks. Because it is powered by heat, the air conditioner would work best in the summer on days with a lot of sun. These are also the days when air conditioning is most needed. However, this goal turned out to be too ambitious. The eventual goal settled on was to purchase and instrument a three-fluid absorption system, gain as much knowledge as possible about the system, and then use it as a future lab for students studying thermal energy. The exact states of the system are a mystery; information about temperature, pressure, and concentration is patented, and I was unable to obtain this information after many frustrated emails and phone calls. So, solving for the states of the system is done in roundabout ways because the only information that can be measured is temperature. This is because measurements must be unobtrusive. The tubes cannot be opened to measure pressure or mass flow because of the hazardous, high pressure chemicals inside. So, all information must be determined from adhesive and probe thermocouples.

Experimental Apparatus

Absorption Chiller

The particular absorption refrigerator in this project uses ammonia as the refrigerant, hydrogen as the inert gas, and water as the absorber. It is from a refrigerator used in a recreational vehicle (RV). Absorption refrigerators are used in RVs because electricity is scarce and one can easily run the refrigerator with a propane flame. When electricity is available, these refrigerators typically use backup electric heaters. The unit is from Dometic, the model number is RM2310. The cooling unit was purchased without the rest of the refrigerator from an RV refrigerator repair company, RVcool.com. The system with states labeled and described is shown in Figure 4. These numbered states will be used throughout the report.

The chiller was mounted on a unistrut frame. Because the system relies on gravity, it is very important that it is vertical when in use. Otherwise, liquids could pool in undesirable places, causing decreased performance or pressure buildups. Before use, future experimenters must check that the bubble pump is vertical.

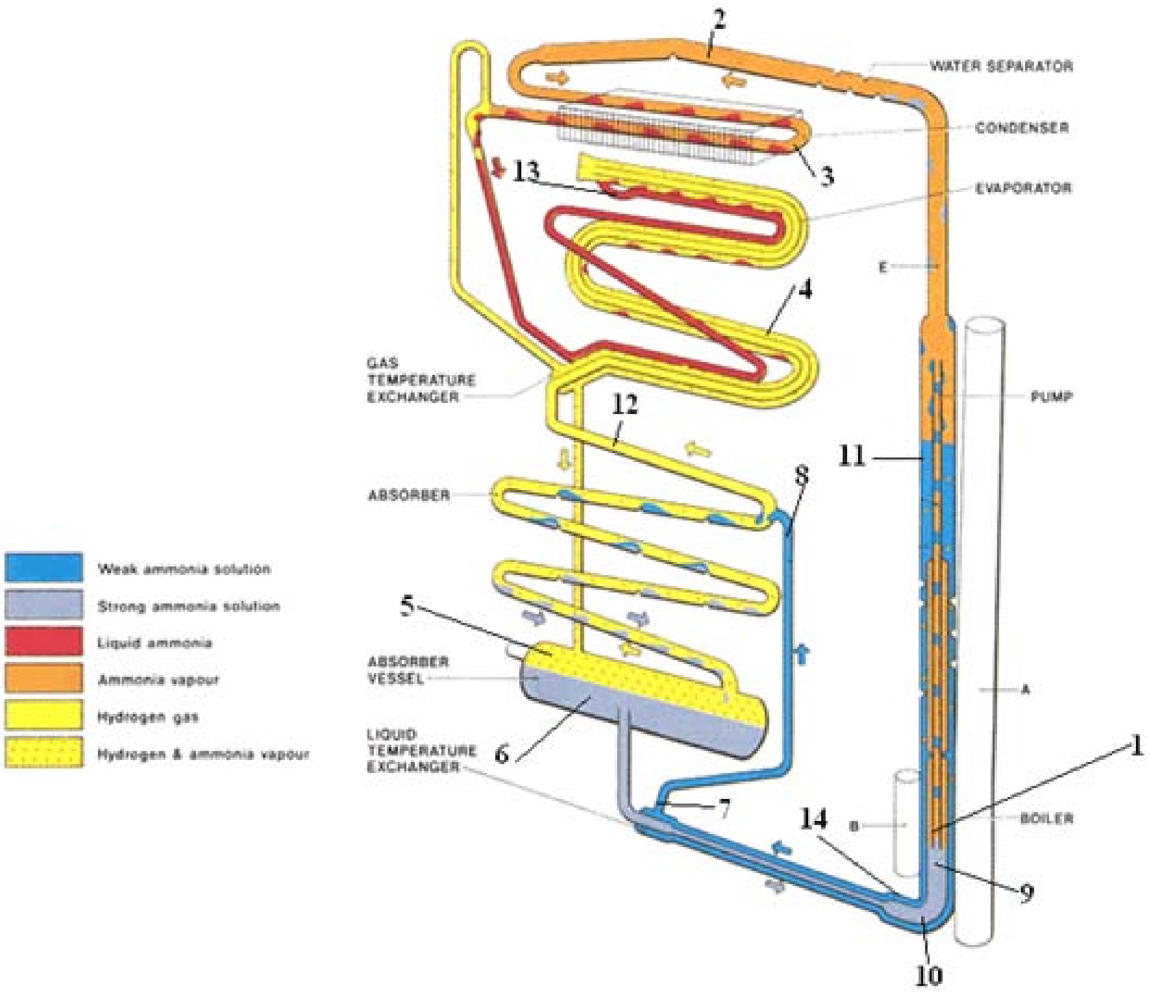


Figure 4: Absorption System with labeled states

State	Description
1	Ammonia bubbles form, moving water up in the bubble pump.
2	Ammonia after the water separator. This is pure ammonia vapor.
3	Ammonia vapor and liquid in equilibrium in the condenser. This is at saturation.
4	Ammonia and hydrogen mix in the outer tube, where ammonia evaporates, causing the cooling effect. In the inner tube, hydrogen is brought in cross flow to the evaporator entrance.
5	Ammonia vapor, hydrogen, and water vapor in equilibrium with the strong ammonia solution
6	Strong ammonia solution. The water flowing down the absorber has absorbed ammonia vapor but not hydrogen.
7	Liquid water after losing heat to the strong ammonia solution in cross-flow. This water travels up to the height determined by the bubble pump.
8	Water, after losing heat to the environment, drips into the absorber, where hydrogen and ammonia flow past it in cross-flow.
9	Aqueous ammonia in equilibrium with the vapor above it at the boiler temperature.
10	Aqueous ammonia after being preheated by water, before the boiler.
11	Water immediately after the bubble pump.
12	Hydrogen gas after the ammonia in the mixture has been absorbed by water.
13	Ammonia liquid after being precooled by the evaporator.
14	Water after passing by the boiler, before preheating the aqueous ammonia.

Evaporator Heat Exchanger

In order to measure mass flows without intrusive flow meters, the heat transferred during a portion of the cycle must be known. To do this, an air heat exchanger was built to enclose the evaporator. The duct had many ½” inlet holes near the evaporator, and a large hole with a fan. The fan (Torin TA450, 24 Volt DC) drew air from the surroundings so that the air flowed over the evaporator coil, and was then expelled. The air temperature was measured in two locations directly before being blown out of the duct, and the ambient air temperature was measured at an entrance to the duct. A hand held anemometer was used to measure the air speed out of the fan, and combining this with the area of the fan gave the volumetric flow. The duct was insulated with pink foam and sealed with duct tape.

Thermocouples

Adhesive K type thermocouples were placed at the locations labeled 3, 4, 6, 7, 11, and 12. Additional adhesive K thermocouples were placed at the inlet of the evaporator (to be known as 4A), on the vertical tube from the boiler above water level (to be known as Bout), after the condenser where there is liquid ammonia (to be known as C_out), and after the evaporator where there is hydrogen and ammonia vapor (to be known as E_out). Probe type K thermocouples were placed at the entrance to the duct to measure ambient air (state A), and two probes were placed before the duct output (AO1 and AO2).

The thermocouple data was sent to an Agilent multiplexer, which was read by a Matlab program (see Appendix A - Matlab Codes). The program saved and graphed the data.

Heat Source

In the first attempt to run the chiller, a propane torch was used. However, the torch provided a very concentrated flame, which had to be set to low heat to avoid melting the pipe. At this low flame, there was not enough heat to create the cooling effect. After this, heating tape was tried, but the tape only provided 100 W, which was not enough. Also, the tape had to overlap itself, causing it to overheat and produce smoke.

Eventually, an electric heater was purchased from an RV refrigerator parts supplier, RVmobile.com. The heater (model number AR35016) was rated at 160 W and 120 V. This heater was made for the cooling unit, and fits in the tube attached to the boiler (labeled B in the diagram). High temperature insulation was added to the boiler to decrease losses.

Results

Test with Load

There were two main types of tests. In the first, the fan in the evaporator duct was turned on, so there would be a load on the system. This load was used to calculate the heat removed in the evaporator, and the mass flows. The results of this type of test are shown below in Figure 5.

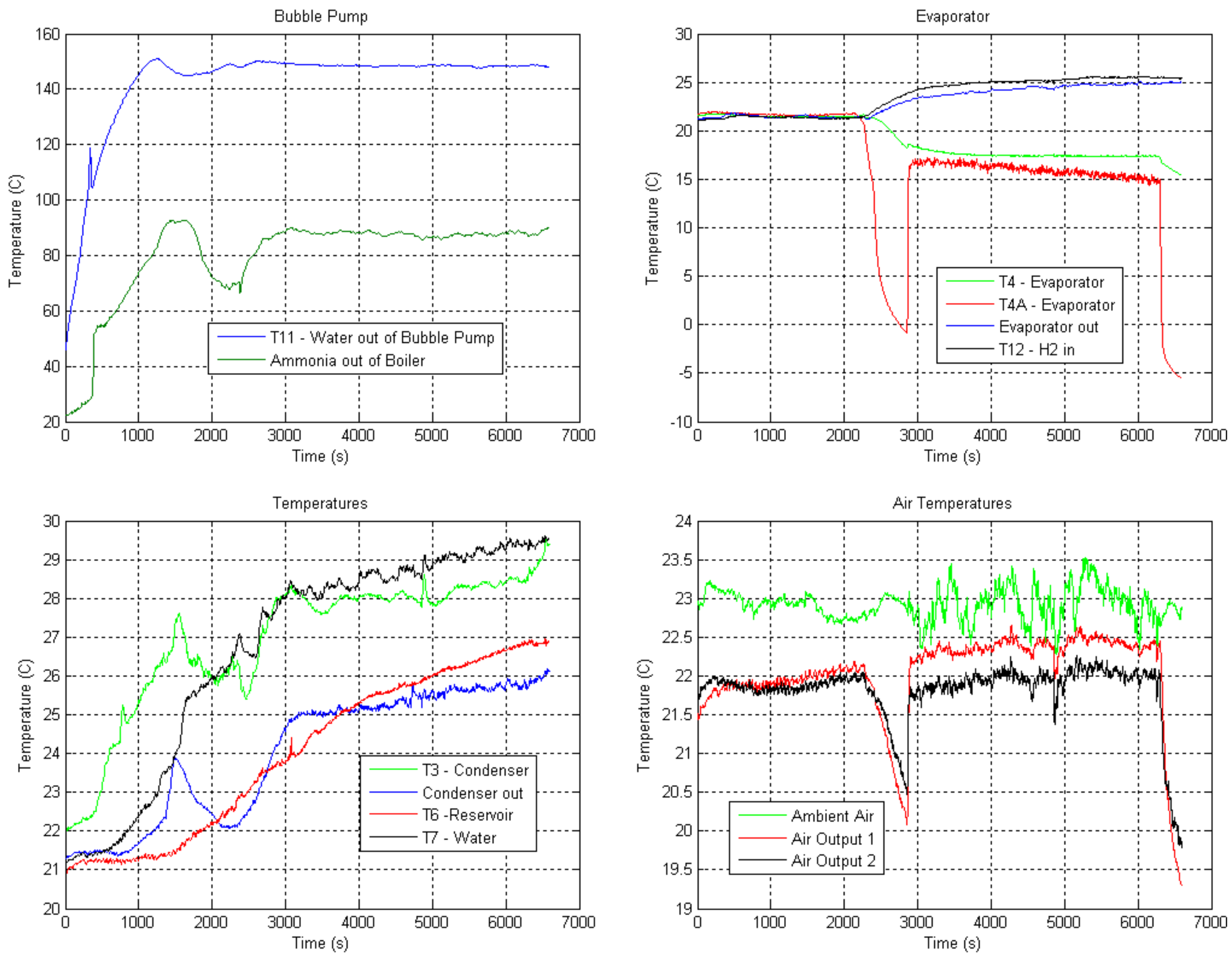


Figure 5: Test Results from April 8th

The results tell the story of what is happening in the system. At first, the only interesting information is that the temperature of water above the bubble pump is rising. This is merely due to conduction through the stationary liquid and metal pipe. Then, about 250 seconds into the test, the temperature of ammonia out of the boiler rises sharply. This temperature rose slightly at first due to conduction through the pipe, but it rises sharply at 250 s because a significant amount of ammonia gas is flowing from the generator. Shortly after the temperature rise out of the boiler, T3 rises, and then the temperature out of the condenser rises. This sequence of rising temperatures indicates a flow of ammonia. Around 1500 seconds, the experimenter put a fan on the condenser in an attempt to cause cooling to occur sooner. This lowered the condenser temperatures, but did not cause cooling to occur. There was not enough ammonia gas yet, so the pressure was not high enough to cause condensation to occur at the condenser temperature. However, at 2200 seconds, cooling begins, as shown by the drop in T4A. The temperature out of the evaporator and T12 rise at this point because the fluids have started flowing more due to the condensation in the condenser. So, liquid ammonia, in the process of being pre-cooled by the evaporator, warms the evaporator output temperature. The rise in T12 is caused by increased flow of hydrogen past the warm water in the absorber. It is also caused by the proximity of T12 and the evaporator output; there is significant conduction by the metal pipes. T4A drops much faster and farther than T4 because T4A is measured where the ammonia and hydrogen meet. By the time ammonia has reached the location of T4, it has all evaporated.

At this time (about 2250 s), cooling is occurring. The evaporator temperatures are falling, as are the air temperatures in the duct. The condenser fan was then removed at 2500 seconds, causing the rise in the condenser and ammonia vapor temperatures in Figure 5. Shortly after, at 2900 seconds, the fan in the evaporator duct was turned on, providing a cooling load. The fan expelled the cold air in the duct, and drew in fresh, warm ambient air. It also warmed the evaporator coils. The steady results from 300 to 6000 seconds will give information about the mass flows in the system. At 6250 seconds, the evaporator fan was switched off, and then the test was ended.

No Load

In the next type of test, the evaporator fan is turned off and left off for an extended period of time. This allows the evaporator to get very cold. Figure 6 shows this type of test. This shows that the evaporator temperature could be decreased significantly with a smaller load.

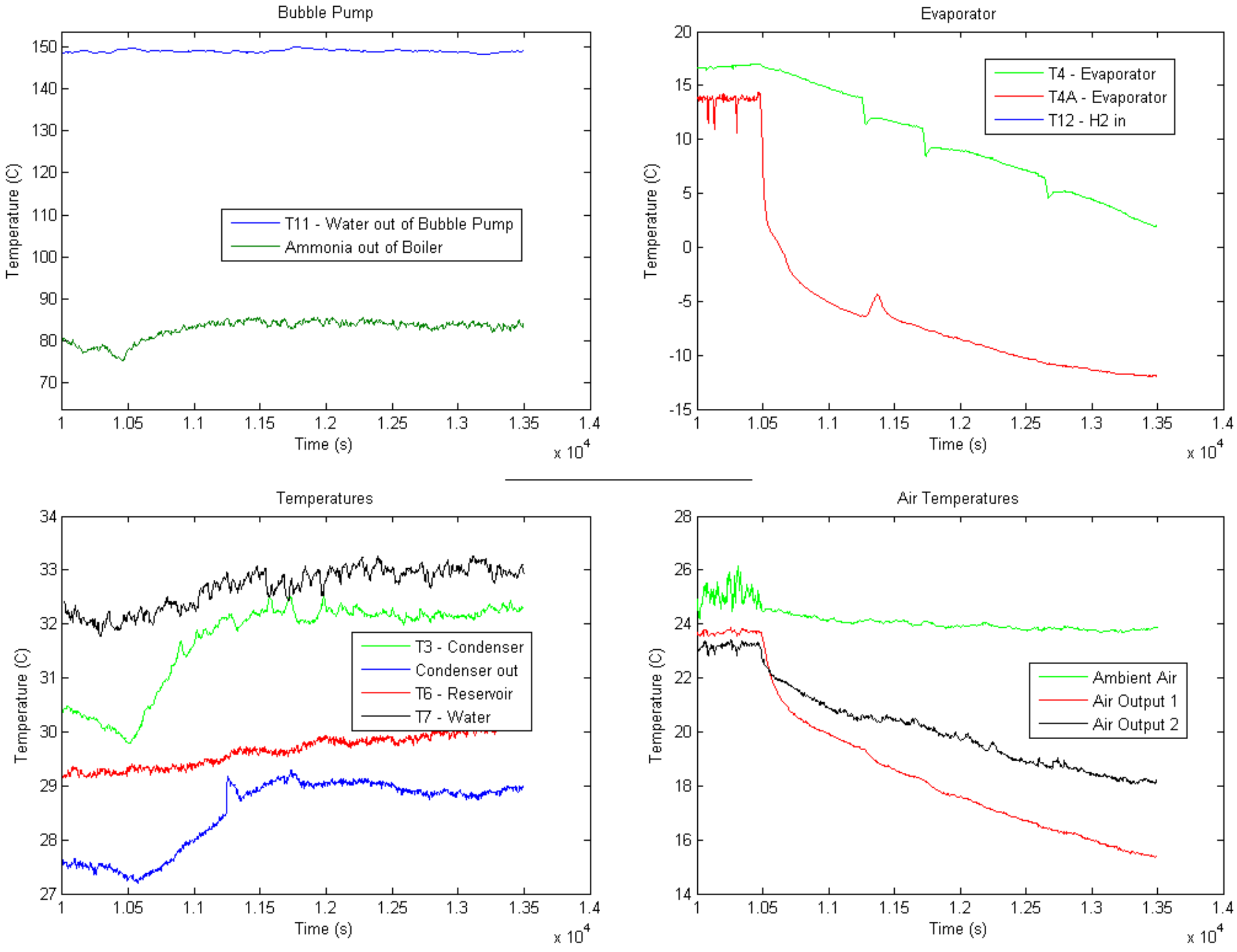


Figure 6: Truncated Test results from April 3rd

Analysis

Pressures

The total pressure in the system and the partial pressures in the evaporator can be determined from Figure 5. The condenser temperature can be used to find the temperature at which ammonia is saturated, giving the pressure in the condenser. The green line in Figure 5 represents a temperature in the condenser, where there is definitely two phase flow. So, this temperature, 28C, is the saturation temperature. This is reasonable, because the "condenser out" thermocouple is located where there must be liquid ammonia, and this temperature is slightly below 28C, at 25.5C. It is below the entrance to the evaporator, so if there was not liquid ammonia at the thermocouple location, there would be no liquid flowing to the evaporator, causing the cooling. Looking at the graph, Pressure – Temperature Relationships of Refrigerants (Carrier, Cherne, & Grant, 1941) in Appendix B – Graphs, the total pressure of the system is 160 psi or 1,103 kPa for the saturation temperature to be 28C (82.4F).

The evaporator temperature can be used to find the partial pressures in the evaporator. Figure 5 shows that the ammonia is evaporating at 16.5C (61.7F). Again, using Pressure – Temperature Relationships of Refrigerants in Appendix B – Graphs, the partial pressure of ammonia in the condenser is found to be 112 psi or 772 kPa. Applying Dalton's law gives more information about the system. It tells us that the mole fraction of ammonia in the evaporator is 772/1103=0.7. This information will be useful later on.

P-H diagram

The tests also provide the information necessary to create a P-h diagram. The four states are: superheated ammonia from the boiler at 87C, saturated liquid in the condenser at 28C, saturation in the evaporator at 16.5 C, and superheated ammonia out of the evaporator at 24 C.

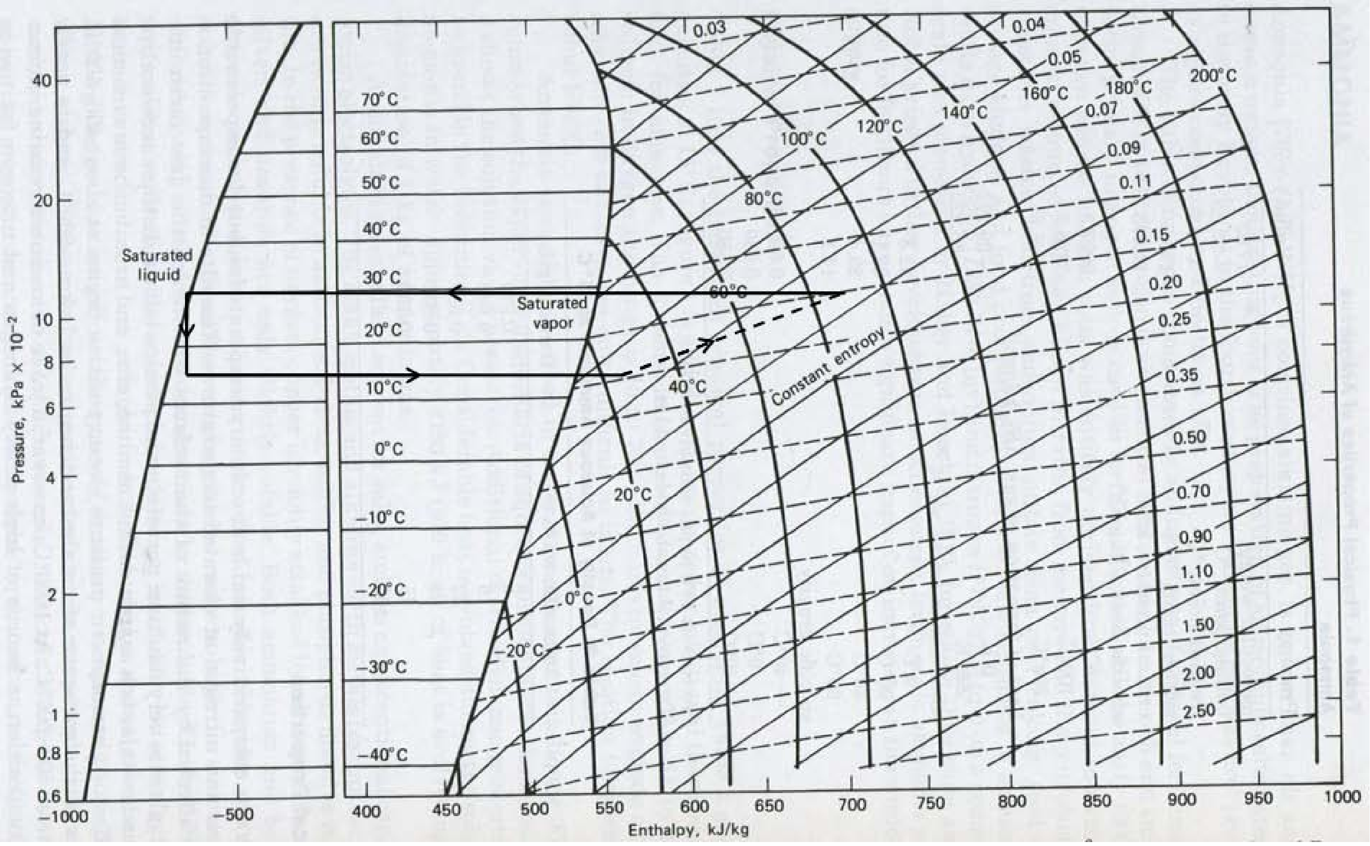


Figure 7: P-h diagram for system. Original image: (Kroschwitz, 1992)

There is a dotted line connecting the evaporator output to the boiler output to represent the states during absorption and generation. These processes are not defined in terms of a P-h diagram. Also, the vertical line connecting the two pressures may not be vertical, because the process of mixing is not necessarily constant enthalpy.

Mass Flows

To find the mass flows, an energy balance about the evaporator heat exchanger is performed. This is shown schematically in Figure 8.

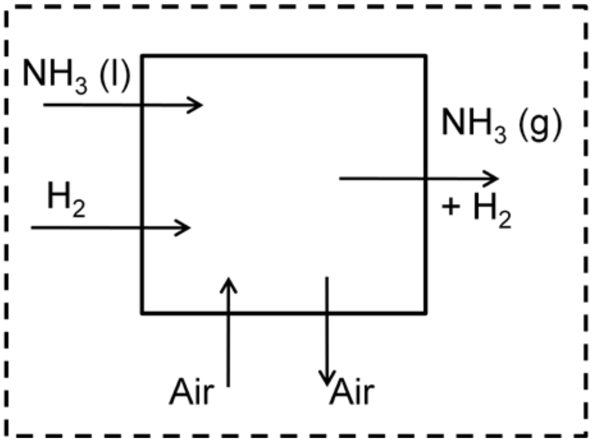


Figure 8: Flows into and out of evaporator heat exchanger

The energy balance for this control volume is given by Equation (1).

$$\dot{m}_{NH_3}[h_{C\_out} - h_{E\_out(NH_3)}] + \dot{m}_{H_2}[h_{12} - h_{E\_out(H_2)}] = \dot{m}_{air}[h_{air\_out} - h_{air\_in}] \tag{1}$$

In this equation, C_out is the outlet of the condenser, E_out is the outlet of the evaporator, and state 12 is the hydrogen into the evaporator, before mixing with ammonia. The temperature of the air out is measured before going through the fan, so the fan energy is not included in the equation. To calculate the right hand side of equation (1), a Matlab program was written (see Heat Transferred From Air in Appendix A - Matlab Codes). This code used the thermocouple data along with some extra information. The mass flow was calculated with the speed from the 24V fan, 5.1 m/s, read with a handheld anemometer. The fan had an outer diameter of 4.5” and an inner diameter of 2”, giving an area of 12.7627 square inches. So, the volumetric flow was 0.042 cubic meters per second. Using the ideal gas law, the density of air coming out of the duct was found for each data point based on the measured temperature, and atmospheric pressure. Multiplying this density by volumetric flow gave mass flow. Multiplying this by the specific heat at constant pressure and the temperature difference into and out of the duct gives the heat removed from the air. The Matlab code applied to the data from April 8th (presented in Figure 5) during the region of steady state operation produces Figure 9 below. The average value of the heat transferred is 34 watts.

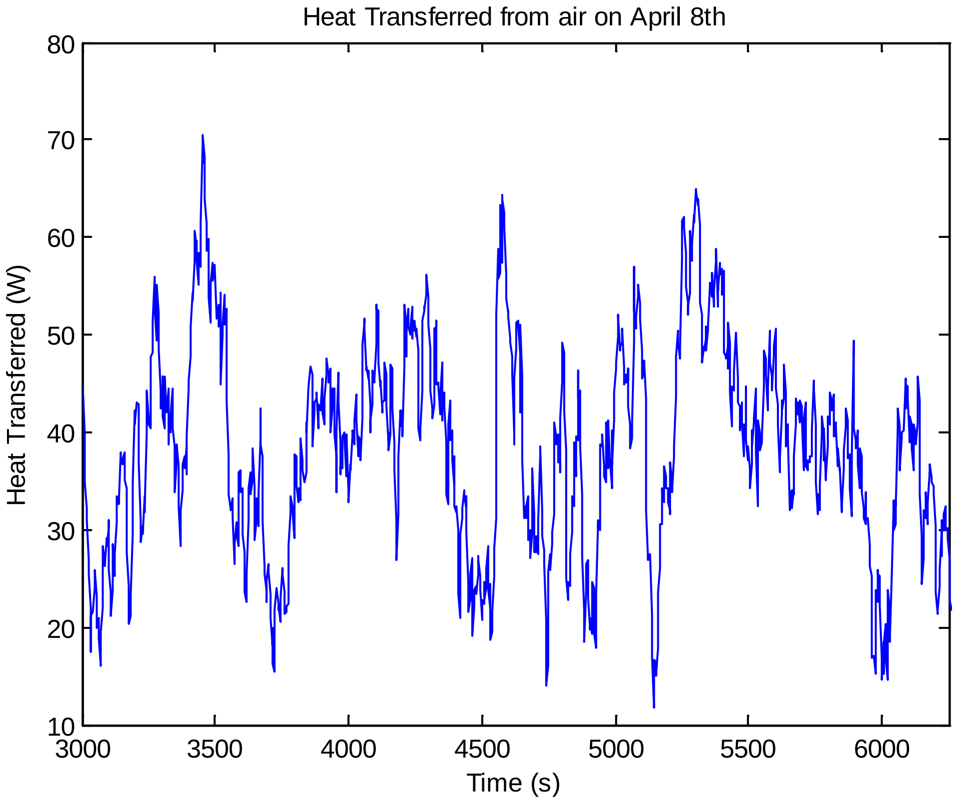


Figure 9: Heat transferred from air on April 8th

There is a large fluctuation in the heat transfer data because the air temperature data fluctuates greatly. This appears to be due to the ambient air reading, which fluctuates greatly (Figure 5). This is because the temperature was read at an inlet to the heat exchanger, which is near the condenser. Fast moving air sometimes picked up heat from the condenser, but sometimes didn't, causing fluctuation.

Now that the right hand side of Equation (1) has been taken care of, the left hand side must be dealt with. The ammonia entropies can be read from Figure 7, and the hydrogen enthalpies can be read from table A-22 in <u>Thermodynamics: An Engineering Approach</u>. This table gives values per kmol, so care must be taken in the calculations to divide by the molar mass where necessary. Now, there are the two unknowns left: the mass flows. But, the ratio of these mass flows can be determined using Dalton's law, that the ratio of partial pressure to total pressure is the ratio of moles to total number of moles.

$$\frac{P_{NH_3}}{P} = \frac{n_{NH_3}}{n} = \frac{772 \text{ kPa}}{1103 \text{ kPa}} = 0.7$$

$$0.7 = \frac{n_{NH_3}}{n_{NH_3} + n_{H_2}} = \frac{\frac{\dot{m}_{NH_3}}{M_{NH_3}}}{\frac{\dot{m}_{NH_3}}{M_{NH_3}} + \frac{\dot{m}_{H_2}}{M_{H_2}}} = \frac{\frac{\dot{m}_{NH_3}}{17.03}}{\frac{\dot{m}_{NH_3}}{17.03} + \frac{\dot{m}_{H_2}}{2.016}}$$

Solving for the mass flow ratio gives Equation (2).

$$\frac{\dot{m}_{NH_3}}{\dot{m}_{H_2}} = 19.72 \qquad (2)$$

Using this relation, the average heat removed from the air, and the enthalpy values from tables, the ammonia and hydrogen mass flows can be calculated as $\dot{m}_{NH_3}$ =27.7 mg/s and $\dot{m}_{H_2}$ =1.4 mg/s. These values seem low, but one must recall that all processes are heat drive. One must also remember that these mass flows are through the evaporator. There is a small amount of ammonia that also travels in the weak ammonia solution from the bubble pump straight to the absorber. This ammonia is not accounted for.

One can check these numbers with another energy balance. This time, the control volume will include the absorber, boiler, and pump as shown by the dotted line in Figure 10 below. The energy balance for this control volume is given by Equation (3).

$$\dot{m}_{NH_3} h_{E\_out(NH_3)} + P_{heater} + \dot{m}_{H_2} h_{E\_out(H_2)} = \dot{m}_{NH_3} h_{B\_out} + \dot{m}_{H_2} h_1 \qquad (3)$$

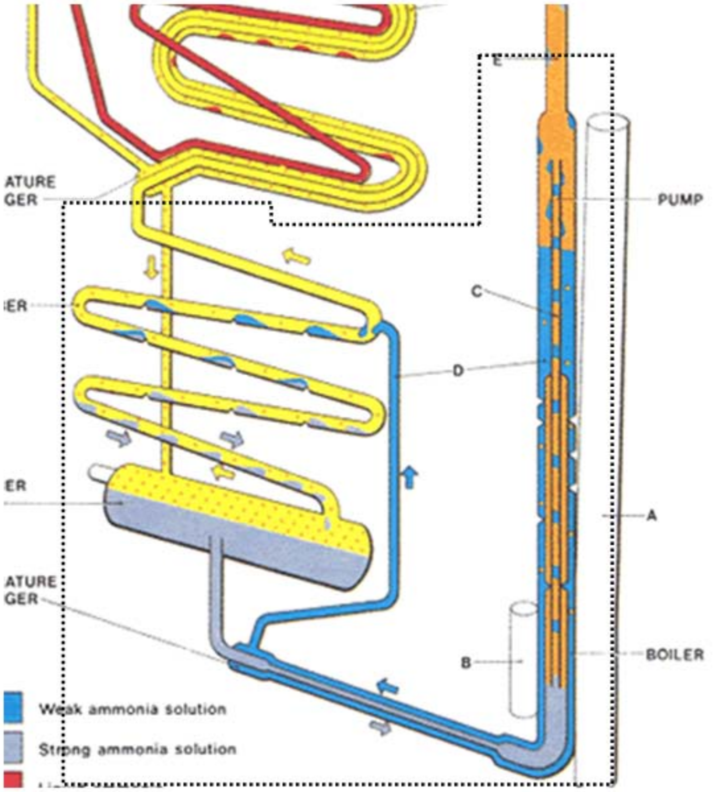


Figure 10: Control volume for check equation

As before, the enthalpies for ammonia are found from Figure 7 and the enthalpies for hydrogen are found in table A-22 of Thermodynamics: An Engineering Approach. The power in to the heater was measured as 139 watts. Plugging in these numbers, the left side of the equation is 160.9 W, and the right side is 25.3 W. This means that, if the mass flow calculated is correct, then 84% of the energy (135.6 W) into the control volume in Figure 10 is lost. This is reasonable, because there is a lot of warm uninsulated pipe in this section. The water passes the boiler, heats up, transfers some heat to the aqueous ammonia and environment in the heat exchanger, and then loses more heat to the environment (which is 5-6 degrees cooler than the water) as it travels up to the absorber. The absorber coils lose a large amount of heat as well. The process of absorption releases 2180 kJ per kg of ammonia (Kroschwitz, 1992). With the mass flow calculated earlier, this is 60.4 Watts. If this heat is dissipated to the environment and not absorbed by the fluids (a legitimate assumption) then it accounts for almost half of the heat lost from Equation (3). So, the calculated mass flows are reasonable.

Another check can be performed, this time doing an energy balance about the entire system. The energy into the system is 139 watts (electric heater) plus 34 watts (evaporator). The energy out of the system is the heat transferred from the condenser added to the losses. In the previous paragraph, the losses were calculated to be 135.6 W. To check this, one must find the energy removed from the hot ammonia vapor to condense it (Equation (4)).

$$\dot{Q}_{cond} = \dot{m}_{NH_3}(h_{B\_out} - h_{C\_out}) \tag{4}$$

Using the mass flow calculated earlier, 27.7 mg/s, and the enthalpies from Figure 7, this heat is 37.4 watts. So, the total energy into the system is 139+34-37.4-135.6=0 watts. This works out perfectly, so the mass flows are correct, and all losses are accounted for.

The mass flow of water can also be determined using the conditions in the absorber vessel. The graph of Physical Properties of Ammonia-Water Solutions (Baumeister & Marks) will provide this information. In this vessel there is aqueous ammonia below ammonia vapor, hydrogen gas, and water vapor. The temperature in the reservoir rises throughout the test, but levels off at 27 C according to Figure 5. The graph used to determine the ratio of water to ammonia does not deal with hydrogen at all; it describes an aqueous solution with ammonia and water vapor above the solution. So, the pressure in the table refers to the total pressure minus the partial pressure of hydrogen. Looking in the table at 27 C (80.6 F) and 772 kPa (112 psia, 97.3 psig) gives a concentration of 0.71 lb ammonia per lb liquid. Assuming that the liquid flowing into the evaporator contains no ammonia, so that the mass flow of ammonia into the absorber vessel is 27.7 mg/s, then the mass flow of water in the system is 11.3 mg/s.

Coefficient of Performance

The coefficient of performance (COP) is defined as the cooling output divided by the energy input. For the April 8th test, cooling output was 34 watts, the heat input was 139 watts, and the fan on the evaporator used 12 watts, so the COP is 34/(139+12)=0.225. For an absorption system, a COP less than 1 is expected, but this is still very low. However, the COP can be improved easily. The cooling output would be increased by the use of fins on the evaporator coil. Other geometric methods, such as forcing air to move close to the evaporator before leaving the duct, would increase the heat transferred.

The original idea was to replace the electric heater with solar heated water. If this were achieved, the heat input would be “free”, although there would be a liquid pump. This would significantly change the COP, because the 139 watts of heat input would be removed, and replaced with the 35 watt pump used in the rooftop laboratory. This would raise the COP to 34/(35+12)=0.723.

Lab for Future Students

In future thermal energy classes, this experiment could serve as a lab similar to the refrigerator lab. Students would learn about absorption refrigeration in the classroom, and then learn hands on. They can take data similar to my data, and make some basic calculations. The students should explain their data and the process behind each temperature behavior. Also, they should calculate the COP and create a P-h diagram. To vary the data, a variable speed fan could be installed, changing the evaporator temperature. This would change the COP, P-h diagram, and mass flows. To make the lab more ambitious, students could calculate the mass flows as I have, but I do not think this is necessary.

Future Work

As stated previously, the original intention of the project was to replace the heater with solar heated liquid. The first step in this process would be to choose a liquid that will not boil at the high temperatures needed. The hottest thermocouple reads 150 C, but it is not measuring the temperature at the heater; it is in a slightly different location. To be safe, the fluid should stay liquid up to 165 C. One could pressurize a fluid to increase its boiling point, but it would be easier to create a system operating at atmospheric pressure.

The next step would be to construct a shell and tube heat exchanger around the vertical boiler pipe of the chiller. This must be constructed without damaging or cutting into the boiler. This would be the most difficult part of the process. One could cut a large diameter pipe in half, and then reattach the halves around the boiler. However, the top and bottom of the heat exchanger would have to be shaped very carefully to accommodate the odd shape of the vertical boiler pipe.

Once the heat exchanger is constructed and sealed, the system should be tested with water heated electrically. This should be done because it allows the experimenter to easily measure the heat input to the system as well as perform tests reliably. If the system works well on electric heat with a heat exchanger, the next step is to move it to the roof and connect the heat exchanger to liquid heated by the evacuated tube collectors. Next, the chiller should be installed such that the cold side (evaporator) is in the lab and the hot side (condenser, absorber, and boiler) is outside. In this way, the chiller can function as supplementary air conditioning as well as a lab for E41 or E35 students.

If the solar collector cannot provide enough heat, then auxiliary heat could be provided by electric heat applied to the fluid. Or, if a fluid with a high enough boiling point cannot be found, then auxiliary heat could be applied directly to the boiler with an electric heater.

Conclusion

An absorption chiller is an economically viable option when there is cheap heat available, or electricity is unreliable. For these reasons, they are often coupled with solar heaters, electricity or heat generation, or propane flames for remote or portable refrigeration. For this reason, I hope that the chiller is implemented in the rooftop lab in the future.

The absorption chiller is a very unique system. It takes in heat at a high temperature, rejects heat at room temperature, and takes in heat to achieve cooling at a low temperature. It is the only thermodynamic system I know of that operates at one pressure, and has no work done in any part of the cycle. Most states and properties of the system have been successfully determined throughout the report, and the COP is 0.225.

Acknowledgements

Professor Nelson Macken, my project advisor, for guiding me throughout the project, keeping me on track, and giving me good ideas

Professor Arthur McGarity, for advice on solar thermal power

Grant Smith, for help in constructing my mounting and heat exchanger, as well as telling me that absorption systems are used in RVs when I first started the project.

Edmond Jaoudi, for help with the fan and heater wiring.

Alex Bell and Andres Pacheco, for giving me their Matlab program for me to alter.

Appendix A - Matlab Codes

Data Acquisition

```
%This program was used by Alex Bell and Andres Pacheco in a heat transfer
%project involving a fuel cell motorcycle in fall 2008.  It was then
%modified by Jeff Santner for an E90 project involving an absorption
%chiller in spring 2009

clearall
fid = fopen('data.txt','at');
DSEQ = input('ENTER THE NAME OF TEST: ','s');
fprintf(fid,'\n\n');
fprintf(fid,'%s','TEST=',DSEQ);
hp = visa('agilent','GPIB0::9::INSTR');
fopen(hp);

min = input('How many minutes? ');
el = min*60; %final elapsed time
ti = [0 0];
i = 1;
t1=clock;
whileti(i)<el

%measuring temperature
fprintf(hp,'MEAS:TEMP? TC,K, (@110)\n');
T3(i)= str2num(fscanf(hp));
fprintf(hp,'MEAS:TEMP? TC,K, (@102)\n');
T6(i)= str2num(fscanf(hp));
fprintf(hp,'MEAS:TEMP? TC,K, (@104)\n');
T7(i)= str2num(fscanf(hp));
fprintf(hp,'MEAS:TEMP? TC,K, (@115)\n');
T11(i)= str2num(fscanf(hp));
fprintf(hp,'MEAS:TEMP? TC,K, (@108)\n');
T4(i)= str2num(fscanf(hp));
fprintf(hp,'MEAS:TEMP? TC,K, (@106)\n');
TA(i)= str2num(fscanf(hp));
fprintf(hp,'MEAS:TEMP? TC,K, (@105)\n');
T4A(i)= str2num(fscanf(hp));
fprintf(hp,'MEAS:TEMP? TC,K, (@101)\n');
TAO1(i)= str2num(fscanf(hp));
fprintf(hp,'MEAS:TEMP? TC,K, (@103)\n');
TAO2(i)= str2num(fscanf(hp));
fprintf(hp,'MEAS:TEMP? TC,K, (@111)\n');
TBout(i)= str2num(fscanf(hp));
fprintf(hp,'MEAS:TEMP? TC,K, (@112)\n');
TCout(i)= str2num(fscanf(hp));
fprintf(hp,'MEAS:TEMP? TC,K, (@113)\n');
TEout(i)= str2num(fscanf(hp));
fprintf(hp,'MEAS:TEMP? TC,K, (@116)\n');
T12(i)= str2num(fscanf(hp));

%graphing
    subplot(2,2,1)
```

```
    plot(ti(1:i),T11(1:i),ti(1:i),TBout(1:i)); xlabel('Time
(s)'),ylabel('Temperature (C)'),title('Bubble Pump')
    subplot(2,2,2)

plot(ti(1:i),T4(1:i),'g',ti(1:i),T4A(1:i),'r',ti(1:i),TEout(1:i),ti(1:i),T12(
1:i),'k'); xlabel('Time (s)'),ylabel('Temperature (C)'),title('Evaporator')
legend('Evaporator low','Evaporatorhigh','Evaporator out','H2 in');
subplot(2,2,3)

plot(ti(1:i),T3(1:i),'g',ti(1:i),TCout(1:i),'b',ti(1:i),T6(1:i),'r',ti(1:i),T
7(1:i),'k');
xlabel('Time (s)'),ylabel('Temperature (C)'),title('Temperatures'),
legend('Condenser in','Condenserout','Reservoir','Water')
subplot(2,2,4)
    plot(ti(1:i),TA(1:i),'g',ti(1:i),TAO1(1:i),'r',ti(1:i),TAO2(1:i),'k');
xlabel('Time (s)'),ylabel('Temperature (C)'),title('Air Temperatures')

fprintf(fid,'\n %7.1f %7.1f %7.1f %7.1f %7.1f %7.1f %7.1f %7.1f %7.1f %7.1f
%7.1f %7.1f %7.1f %7.1f',...
ti(i),T3(i),T6(i),T7(i),T11(i),T4(i),TA(i),T4A(i),TAO1(i),TAO2(i),TBout(i),TC
out(i),TEout(i),T12(i));

    pause(1.2);
    i=i+1;
    ti(i)=etime(clock,t1);
end
ti = ti(1:(i-1));
com = input('Enter any comments: ','s');
save([date '_' DSEQ]);
fprintf(fid,'/n %s',com)
h = figure(1);
saveas(h,[date '_' DSEQ]);
fclose(fid);
fclose(hp);
delete(hp);
```

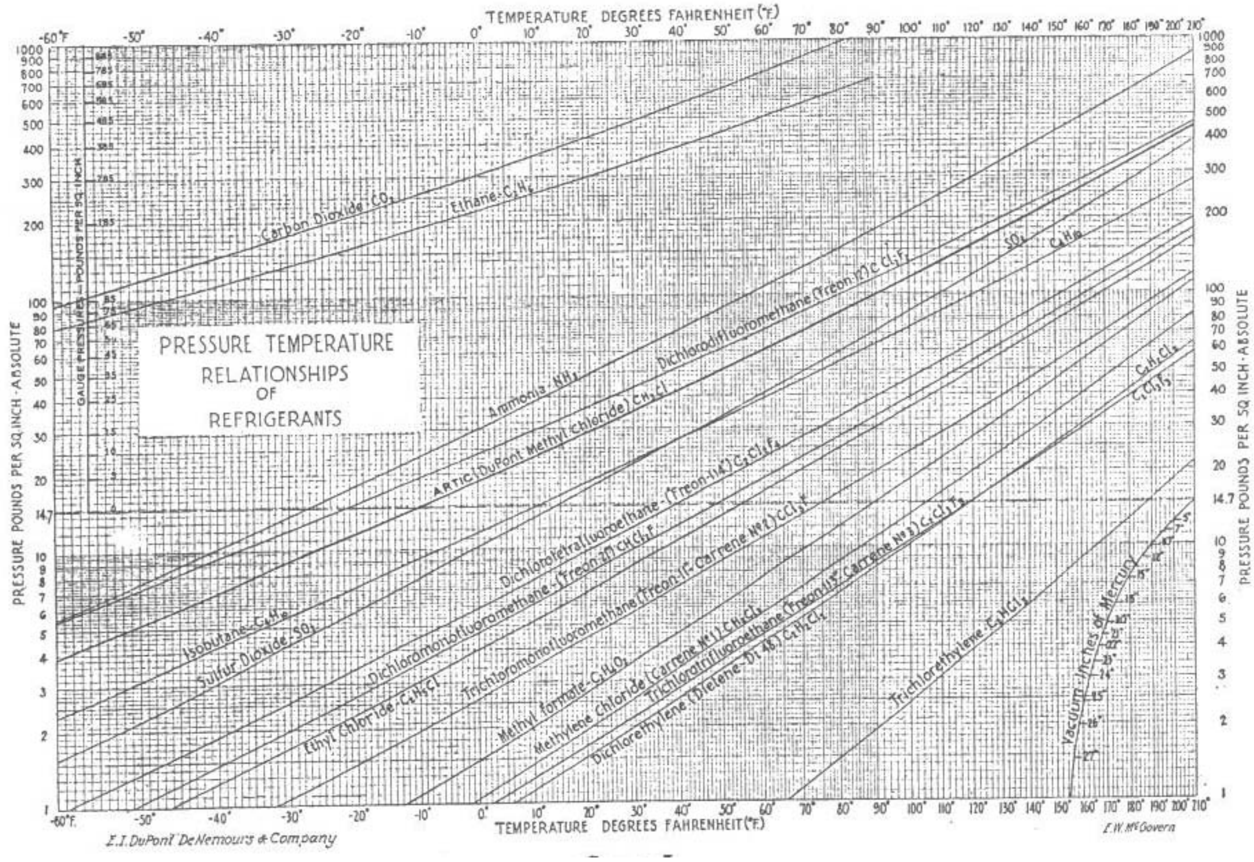
Heat Transferred From Air

```
%find heat removed by cold air
out = (TAO1+TAO2)/2+273;
dT = TA+273-out;
%vol = R*T/P, with air as an ideal gas
R = 287.05; %J/kg*K for dry air
P = 101325; %Pa atmospheric pressure
vol = R*out./P; %m^3/kg
vdot = 0.0420; %m^3/s from anemometer and fan area
mdot = vdot./vol;
q = mdot.*1003.5.*dT; %q = dH = m*cp*dT
plot(ti(1:(i-1)),q);
```

Appendix B – Graphs

Pressure – Temperature Relationships of Refrigerants

(Carrier, Cherne, & Grant, 1941)



Physical Properties of Ammonia-Water Solutions

(Baumeister & Marks)

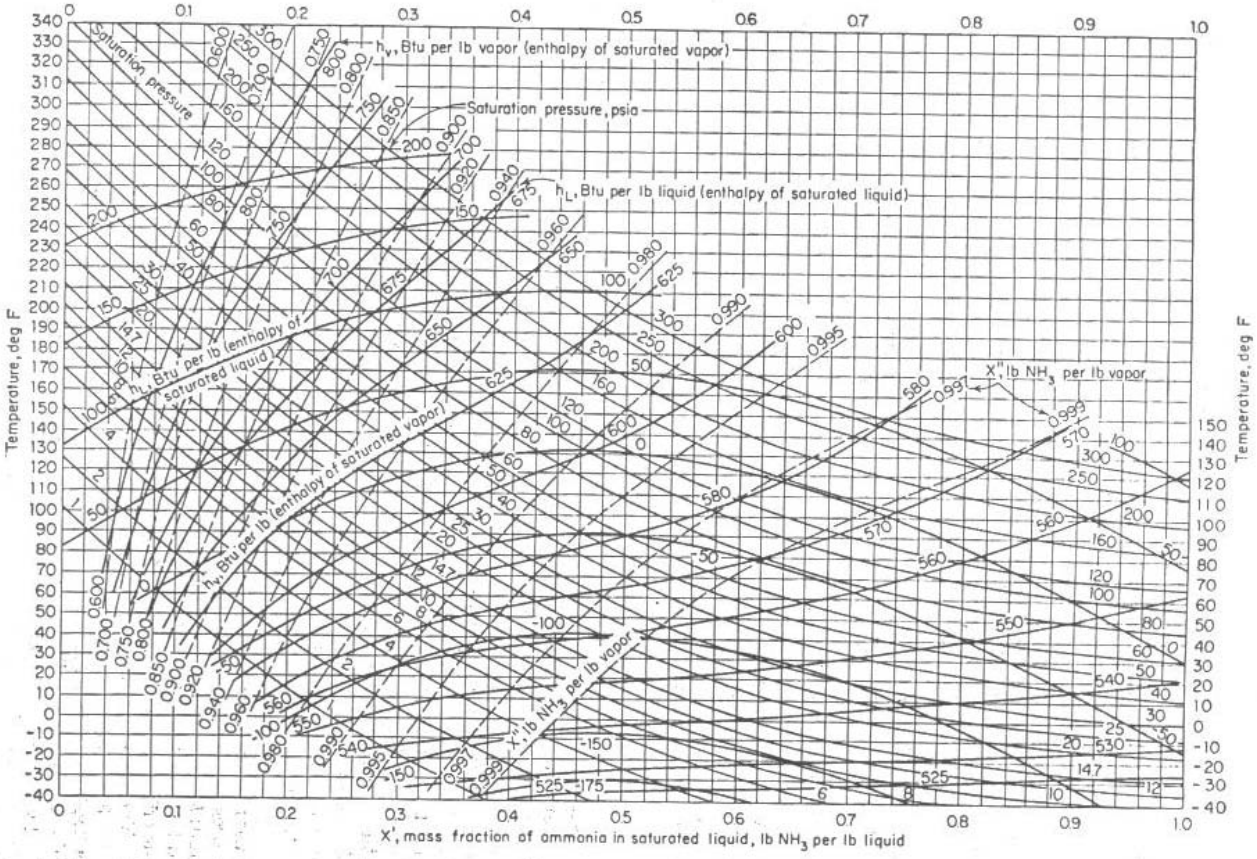


FIG. 26. Properties of aqua-ammonia. (*Kohloss and Scott, Refrig. Eng., Oct., 1950, reproduced by permission of ASHRAE.*)

Appendix C – Purchasing Information

The Cooling Unit was purchased from www.RVcool.com. It was $400, with an extra $100 fee for not returning an old cooling unit in exchange.

The electric heater was purchased from www.rvmobile.com. It was part number AR35016, and cost $45.00 including shipping.

Appendix D – Calculation Information

In the report, detailed calculations were not shown. The following are the data from tables and graphs used in calculations.

h_{C_out}=-650 kJ/kg

$h_{E\_out(Ammonia)}$=575 kJ/kg

h_{12}=8468 kJ/kmol

$h_{E\_out(Hydrogen)}$=8644 kJ/kmol

h_{B_out}=700 kJ/kg

$M_{Ammonia}$=17.03 kg/kmol

$M_{Hydrogen}$=2.016 kg/kmol

References

Baumeister, & Marks. *Standard Handbook For Mechanical Engineers* (7 ed.).

Carrier, W. H., Cherne, R. E., & Grant, W. A. (1941). *Modern Air Conditioning, Heating, and Ventilating.* New York: Pitman Publishing.

Cengel, Y. A., & Boles, M. A. (2008). *Thermodynamics: An Engineering Approach.* New York, NY: McGraw Hill.

Kroschwitz, J. I. (Ed.). (1992). Kirk Othmer Encyclopedia of Chemical Technology. *2 , 4*. New York: John Wiley & Sons.