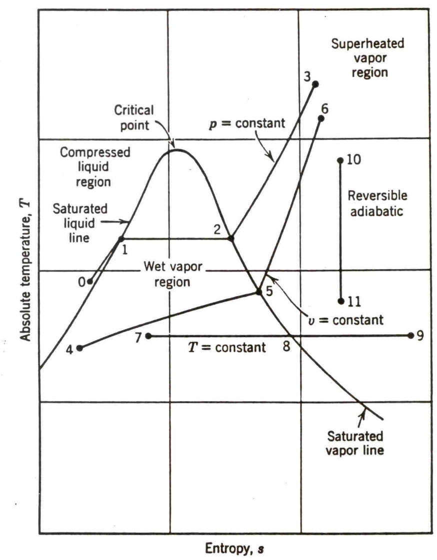
ETME 3252 , Fall 2004

Thermodynamics and Heat Transfer Laboratory Manual – 11th edition



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UNC CHARLOTTE

Preface

This manual is prepared for the class of ETME 3252 Thermodynamics and Heat Transfer Laboratory.

Over the years many fine Professors have contributed to the development of the laboratory manual. Also providing valuable assistance, are many technical staff members:

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Bomb Calorimeter Experiment

The purpose of this experiment is:

a. To ‘earn the principles operation of the Parr Bomb Calorimeter.

b. To determine the heating value of unknown samples.

Introduction

The heating value of a fuel is defined as the heat that must be removed from the products of a complete combustion in order to cool the products down to the temperature of the original air-fuel mixture.

The methods for determining heating value depend on the type of fuel, solid and liquid fuels are usually tested in a bomb calorimeter. Fig. 1 is a cross sectional sketch of a bomb calorimeter.

The operations of a bomb calorimeter are explained in the procedure section.

By burning a small sample of the study material in an oxygen rich environment and indirectly measuring the heat produced the heating value is determined (estimated).

The heating value of test sample can be calculated by the following equation:

(Heating Value) = (tW - e) / m

t = temperature rise in degree Celsius

W = energy equivalent of calorimeter in Calories/degree Celsius

(From manufacture information W = 2420 Calories/degree C)

e = heat of combustion of fuse wire in calories

The value of W (energy capacitance equivalent of calorimeter) can be determined through a process called standardization (or provided by the manufacturer of the bomb calorimeter).

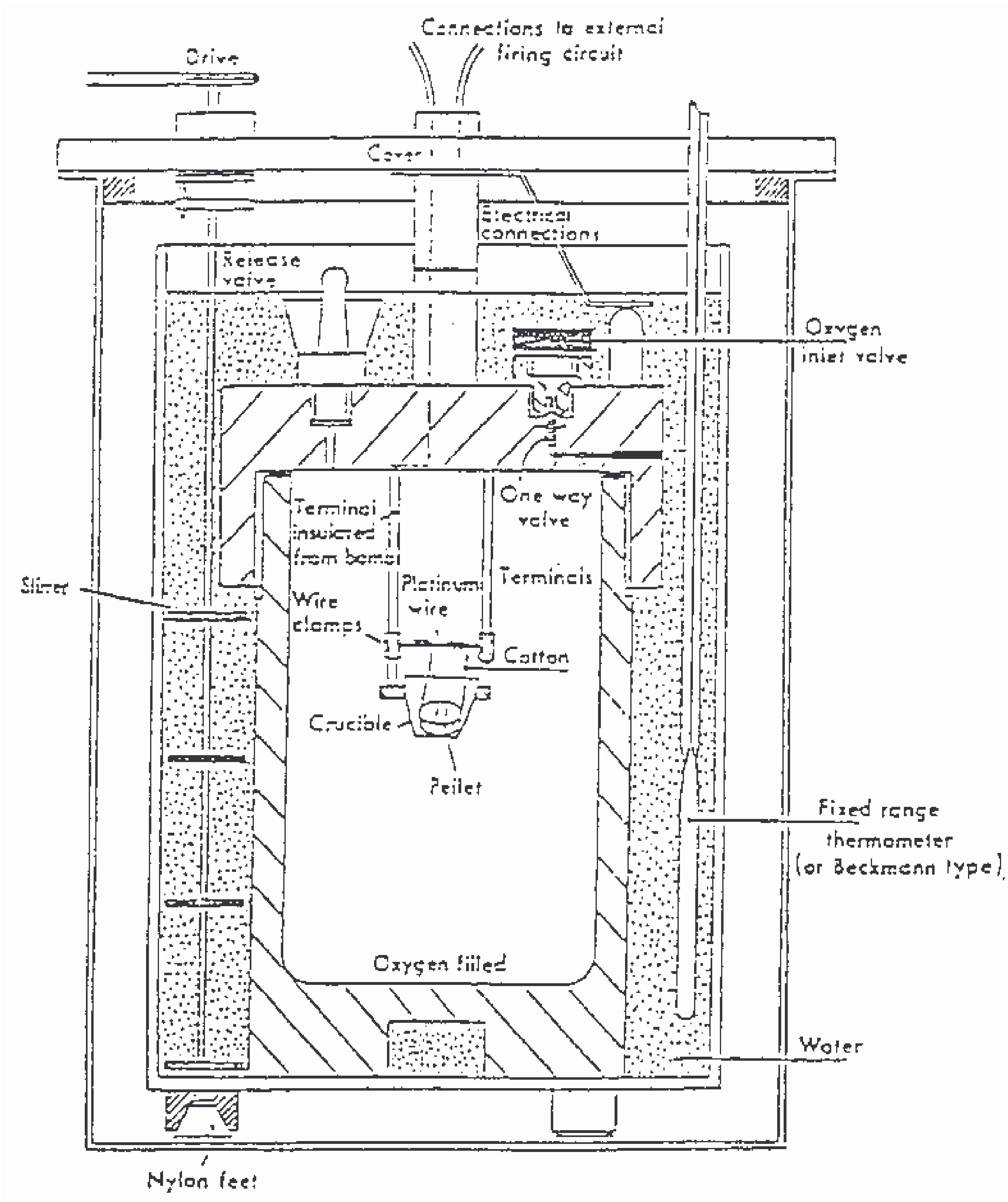


Figure 1 Cross-sectional Sketch of Bomb Calorimeter 1

Supplies

1. Oxygen bomb calorimeter
2. Oxygen combustion bomb
3. Calorimeter controller

4. Oxygen auto charger

5. Oxygen supply tank
6. Scale or balance
7. Fuel samples: Gasoline (Three different grades)
8. Fuse wire

9. Eyedropper
10. Grade cylinder and beaker

11. Thermometer or digital temperature device

12. Wire cutter and tweezers
13. Deionized water
14. Stop watch

Procedure

Use 0.5 to 0.7 gm of gasoline as your sample.

A. Manual Operation

1. Open the hot and cold-water valves that supply the calorimeter.
   Check to see that water is running out of the drain hose into the sink.

Turn the controller off.
Turn the main power to the calorimeter on.

2. Fill the calorimeter bucket by first weighing the dry bucket on the balance; then add

   2,000 (+/- 1.0) grams of water. Distilled/ deionized water is preferred but tap water is satisfactory. The water temperature should be 25 to 27 °C. Set the bucket in the calorimeter.

   Align the three indentations with the three mating protrusions.

3. Set the Oxygen Bomb:

Precautions:

a. Do not overcharge the bomb with too much sample or with a sample which might react with explosive violence.

b. Do not overcharge the bomb with too much oxygen. The auto charger is pre-set to charge to 450 psig. Never exceed 600 psig (40 atm.).

c. Do not fire the bomb alone on an open bench. The bomb should be completely submerged in water during firing.

d. Do not fire the bomb if gas bubbles are released from any point on the bomb when submerged in water.

e. Stand away from the bomb during firing and do not handle the bomb for at least 20 seconds after firing.

The Bomb:

The bomb for this laboratory experiment can be identified by its head number, cap identification, 108

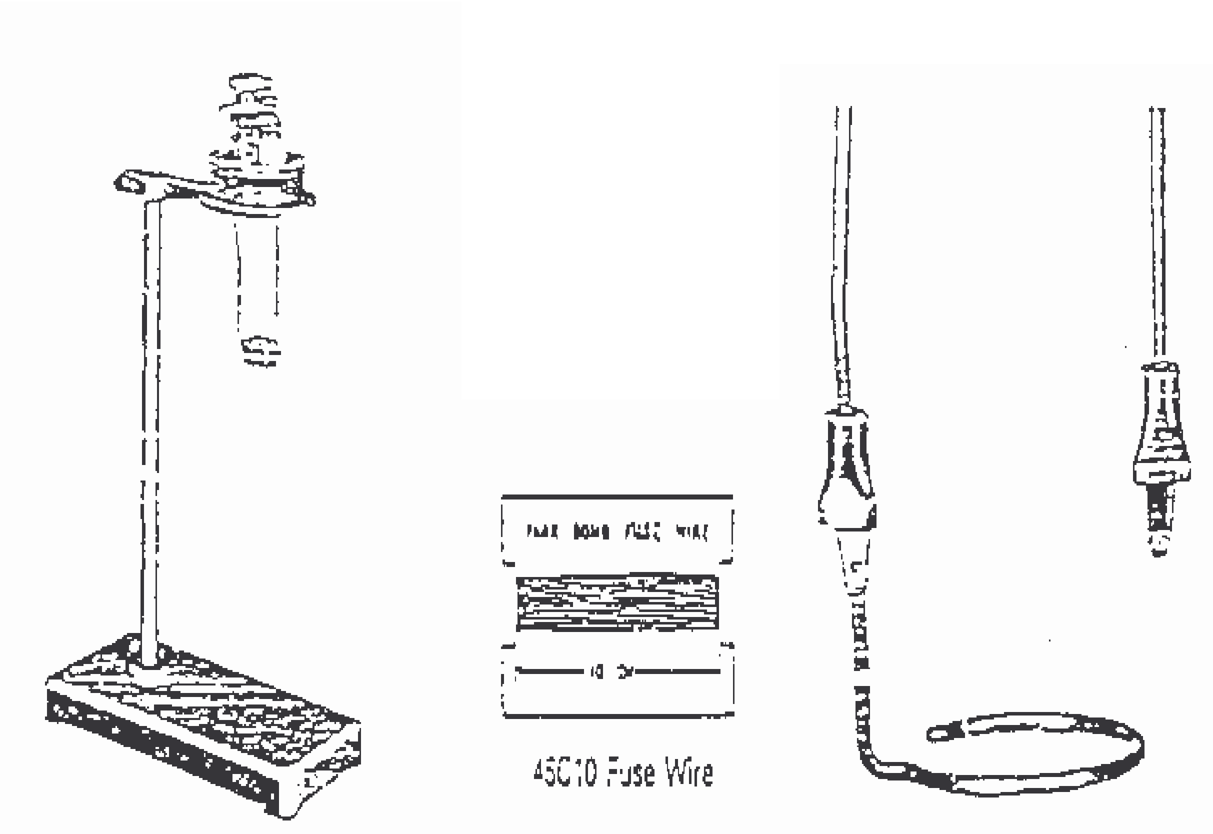
Sample size: The bomb should never be charged with a sample which will release more than 8,000 calories when burned in oxygen. This generally limits the mass of the combustible charge (sample plus benzoic acid, gelatin, firing oil or any combustion aid) to not more than 1.1 grams.

Note: Never charge the bomb with more than 1.5 grams of combustible material. When starting test with new or unfamiliar materials it is always best to use samples of less than one gram.

Attaching the Fuse: Set the bomb head on the support stand and fasten a 10 cm length of fuse wire between the two electrodes. Nickel alloy wire is used for most tests. This wire is furnished on a card from which uniform 10 cm lengths can be cut without further measurement. To attach the fuse to the quick grip electrodes insert the ends of the wire into the eyelets at the end of each stem and push the cap downward to pinch the wire into place. Refer to Fig. 2.

Place the fuel capsule with its weighed sample in the electrode loop and bend the wire downward toward the surface of the sample. It is not necessary to submerge the wire into the sample. In fact, better combustion will usually be obtained if the loop of the fuse is set slightly above the surface. When using pellet samples, bend the wire so that the lop bears against the top of the pellet firmly enough to keep it from sliding against the side of the sample capsule.

If a sample material used evaporates easily. It may be necessary to estimate the amount lost during bomb assembly.



45C10 Fuse Wire

A36A Bomb Head Support Stand

Closing the bomb:

Care must be taken not to disturb the sample when moving the bomb head from the support stand to the bomb cylinder. Check the sealing ring to be sure that it is in good condition and moisten it with a bit of water so that it will slide freely into the cylinder; then slide the head into the cylinder and push it down as far as it will go. For easy insertion, push the head straight down with out twisting and leave the gas release valve open during this operation. Set the screw cap on the cylinder and turn it down firmly by hand as far as it will go. It is important that the cap be turned down to a solid stop. Hand tightening is sufficient to secure a tight seal. It will be convenient, to hold the bomb in the bench clamp during the closing operation and while filling the bomb with oxygen. Close the gas release valve/outlet valve, prior to filling the bomb (with oxygen).

Filing the bomb:

Either an automatic or a manual operation can be used to fill the bomb. Oxygen for the bomb is drawn from a standard commercial oxygen tank. For this laboratory, use the automatic operation procedure described below.

Automatic operation, using the autocharger: The autocharger consists of an oxygen tank pressure regulator with an electronic control unit for filling an oxygen bomb to the desired operating pressure automatically without operator attention.

a. Turn on the power switch located on the rear panel. The yellow light should come on and there should be no gas flow through the hose. If any other status is indicated, reset the controller by turning the switch off and on. If any gas flow or leaks are noted they must be stopped before proceeding to use the system.

b. Check the filling pressure: The pressure regulator is preset to deliver oxygen at 450 psig. This setting should be checked before starting to use the system by observing the pressure attained during an actual filling operation. To do this, assemble an oxygen bomb without a charge and attach the filling hose to the bomb inlet valve. Then push the start button on the autocharger and observe the delivery pressure as shown on the 0-6 psi gage while oxygen is flowing into the bomb. Adjust the regulator if necessary to bring the pressure to 450 psig. If there is any uncertainty about the setting, release the gas from bomb and run a second check. Slightly higher or lower pressures can be used, + or - 10 psig, but the bomb must never be filled to more than 6(X) psig.

c. Filling the bomb: To fill the bomb, connect the hose to the bomb inlet valve and push the start button. The autocharger will then fill the bomb to the pie-set pressure and release the residual pressure in the connecting hose at the end of the filling cycle. The yellow status light will then glow, indicating that the bomb is filled and the operator can proceed with the test. If the charging pressure d not reach the range from 410-425 psig during the tilling cycle, the low charge light will glow indicating an under- fill.

Note: If the charging cycle should start inadvertently, it can be stopped immediately by turning off the power switch.

d. Attach the lifting handle to the holes in the side of the screw cap and lower the bomb in the water with its feet spanning the circular boss in the bottom of the bucket. The bomb must align with the raised circle in the bottom of the bucket.

Handle the bomb carefully during this operation so that the sample will not be disturbed. Remove the handle and shake any drops of water back into the bucket; then push the two ignition lead wires into the terminal sockets on the bomb head, being careful not to remove any water from the bucket with the fingers.

Note: If any gas leakage is indicated, no matter how slight, do not fire the bomb.

e. Close the calorimeter cover; disengage the cover roller by pulling out slightly on the black knob and pulling lever toward you. This will seat the cover snugly against the calorimeter.

Lower the thermometer bracket; lower the stiffer; adjust the reading lenses and turn on the power switch to start the molar.

f. Turn the Run/Purge switch to the run position.

g. Let the calorimeter run for 4 or 5 minutes while the controller brings the jacket temperature up to equilibrium with the bucket This may be expedited by using the hot/ cold switch. After the temperatures have equalized, vibrate the thermometer and read the bucket temperature to one-tenth of the smallest division.

h. **Firing the bomb:** Stand back from the calorimeter and press the ignition button and holding it down until the indicator light goes out. Release the button within 5 seconds regardless of the tight.

Caution: Do not have the head, hands or any parts of your body over the calorimeter when firing the bomb; and continue to stand clear for 30 s after firing.

i. The bucket temperature will start to rise within 20 seconds after firing. This rise will be rapid during the first few minutes; then it will become slower as the temperature approaches a stable maximum (1-5 minutes).

j. Start temperature readings at about 1 minute after firing, vibrating the thermometer to settle the mercury before each observation. Read the thermometer at one-minute intervals until the temperature reaches a stable maximum and remains constant for at least two minutes (three successive readings); then read and record this final temperature to one- tenth of the smallest scale division.

k. Raise the thermometers; raise the stirrer; swing the cover aside and lift the bucket out of the calorimeter, but let the motor continue to run while the calorimeter is open. Move the jacket temperature control to the purge position to lower the temperature to the starting point in preparation for another run.

l. Remove the bomb from the bucket and open the knurled valve knob on the bomb head to release the residual gas pressure before attempting to remove the cap. This release should proceed slowly over a period of not less than one minute to avoid entrainment losses. After all pressure has been released, unscrew the cap; lift the head out of the cylinder and place it on the support stand. Examine the interior of the bomb for soot or other evidence of incomplete combustion. If such evidence is found, the test will have to be discarded.

m. Wash the interior surfaces of the bomb with water and dry it afterward.

B. Automated Operation

Not covered here, at this time.

Post test:

After the tests are completed;

1. Close the oxygen valve and regulator from the oxygen tank.

2. Clean all parts and surfaces.

3. Report any malfunction to the la instructor.

Results

Mass of water = 2,000 +/- 1 gm

Pressure for bomb = 450 psig of Oxygen

Heating value of fuse wire = 2.3 cal/cm

Specific gravity of gasoline = 0.68

Mass of sample =

Evaporation rate or gasoline ($R_{evap.}$) = gm/sec

Elapsed time of exposure of gasoline = sec.

Net mass of gasoline = mass of sample - (Evaporation rate x Elapsed time) =

Uncombusted fuse wire ____________________ cal.

Calculation of heating value of gasoline sample:

Heating Value = (tW - e) / m (cal/gm)

Where $t = t_f - t_a$

e = (2.3 cailcm)(1O.O cm) - Uncombusted fuse wire in cal.

t_f = final maximum temperature (℃)

t_a = temperature at time of tiring (℃)

W = 2420 Cal./ degree C

Conversion of heating value from cal/gm to Btu/lb (1 cal/gm = 1.8 Btu/Ib)

Reference Information:

Gasoline: Bodansky, on page 3:5 of the Course Notes, tells us the heating value of gasoline is 5.253 x 10^6 BTUs per barrel, which is equal to 5.542 x 10^6 kJ/barrel.

Refrigeration System Controlled with a Capillary Tube©

The purpose of this experiment is to familiar with the function of a capillary tube in a refrigeration system and to properly charge the system.

Introduction:

The capillary tube is the most commonly used metering device for household refrigeration system. The capillary tube or cap tube is nothing more than a length of copper tubing with a small inside diameter wrapped into a coil. Its size ranges from 0.026 inch ID for a 200 Btu/hr compressor to *0.085* inch ID for a 20,000 Btu/hr compressor. The cap tube is placed between the condenser and the evaporator. A filter dryer is placed at the inlet of the cap tube in order to remove dirt and moisture from the refrigerant. The refrigerant begins to evaporate as soon it reaches the evaporator and continues throughout the evaporator. As the refrigerant evaporates, moisture in the air begins to sweat or freeze on the evaporator coils (unless the relative humidity is extremely low). As long as there is evaporation in a certain part of the evaporator, there will be evidence of sweat or frost on that part of the evaporator coil. The capillary tube system is at peak efficiency when all of the refrigerant leaving the evaporator has been evaporated. A unit with a cap tube must have a fixed charge. If frosting occurred beyond the evaporator, which is on the suction line, it is evident of over charge. The additional refrigerant would not boil off in the evaporator and liquid refrigerant would flow into the compressor and damage the compressor. Since the refrigerant charge is critical with a cap tube, the manufacturer of units usually indicates the correct amount of charge on the serial plate.

When the compressor is shut off, the capillary tube allows the pressure to balance between the high and low sides, since the cap tube is simply a restriction. It is not usually necessary, then, to use a compressor with high starting torque.

The following points are helpful to determine if a system with a cap tube is correctly charged.

1. The refrigerant temperature leaving the condenser should be approximately 30 F above the ambient temperature with an air-cooled condenser, and 105 F with a water-cooled condenser.
2. Evaporator coils should be sweating or frosting (unless extremely low relative humidity) but not beyond the evaporator
3. The temperature difference between the return elbows at the center of the evaporator and the bottom of the suction line (a few inches from the compressor) should be 15 to 25 F apart (10 F indicates an over charge, and 30 F or more indicates a low charge).

Using FIGURE C1 trace the refrigerant flow path to better understand the operation of the system.

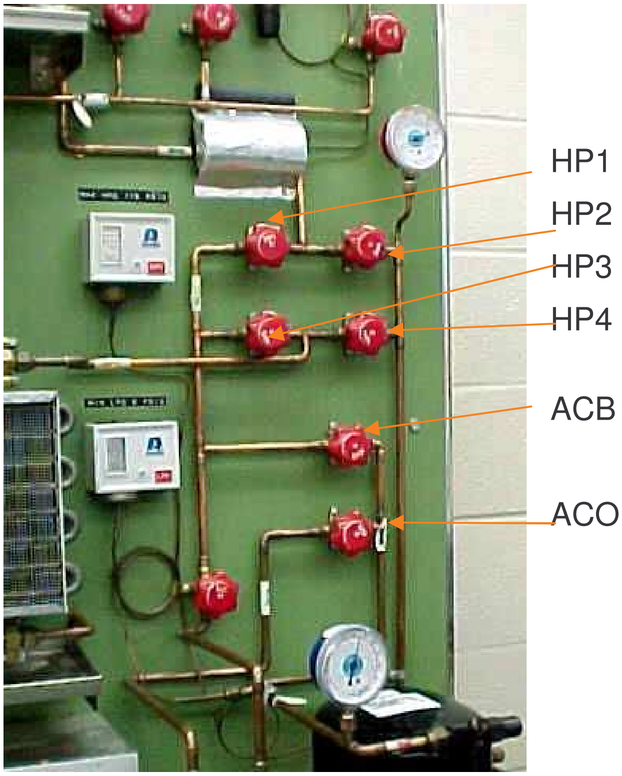
Apparatus:

- Model 9001 Brodhead-Garrett Basic Refrigeration Unit.

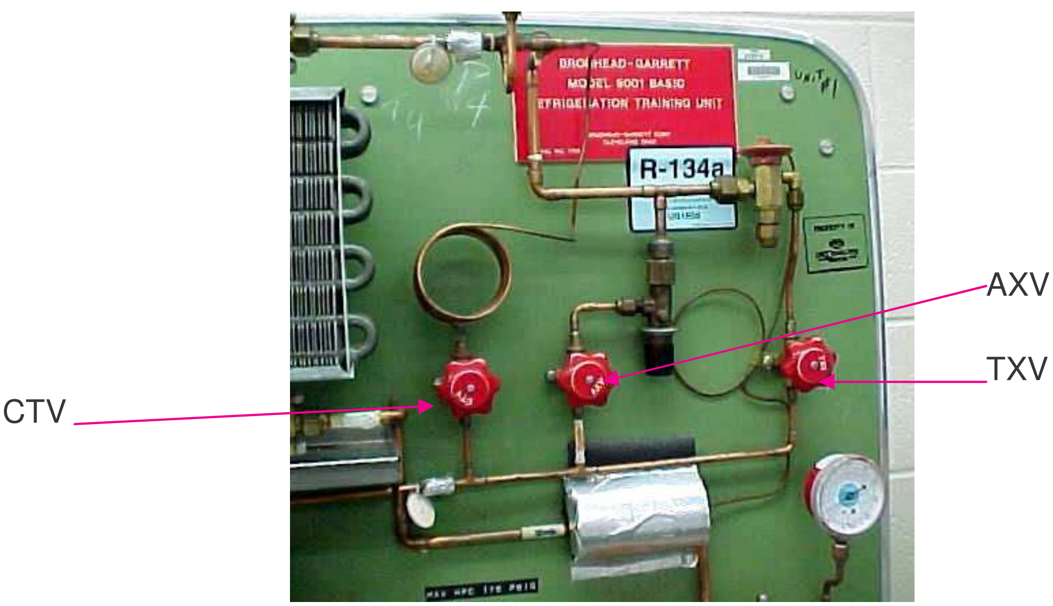
Procedure:

A. **Charge the System**

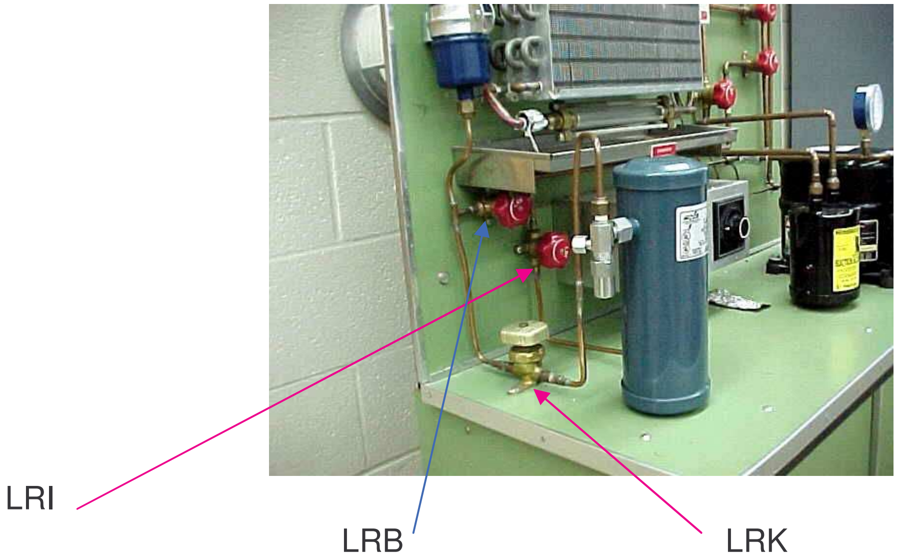
1. Set unit on the refrigeration cycle. Open valve: HP4, TXV, UP1, AC1 and ACO. Close valves: HP3, FMB, HP2, ACB, AXV, and C'TV



1. Open CTV, close TXV and AXV. With compressor off, evaporator fan on low, condenser fan on high, close valve LRB, open valve LRV.



2. Open LRI for approximately 15 seconds to add refrigerant to the system.



3. When LRK is closed, close LRI and open LRB to bypass the liquid receiver. Turn on the compressor and inspect frosting of the evaporator coils. The system is properly charged when frost accumulates on all the evaporation coils, but no farther than an inch down the suction line from the end of the evaporator.

4. Record Temperatures and Pressures.

5. If it is determined that there is too little charge in the system, turn the compressor off to equalize the high and low side pressures. Close LRB and open LRI. Then open LRK for about 5 seconds. Close LRI and open LRB and turn the compressor on. Again look for symptoms of overcharge, undercharge, or correct charge.

5. If it is determined that there is too much charge in the system, some refrigerant must be reduced from the system. Close LRB and open LRI for about *5-10* seconds with the compressor running. Close LRI and open LRB and again inspect for overcharge, undercharge, or correct charge. Record temperatures and pressures for each level of charge tested.

6. Keep testing until the correct charge is reached. Record high and low side pressure and flow rate.

Flow rate ________________

High side pressure ________________Low side pressure ________________

Temp into evap________________Temp out of evap________________

Temp into cond________________Temp out of cond________________

Thermocouple Locations

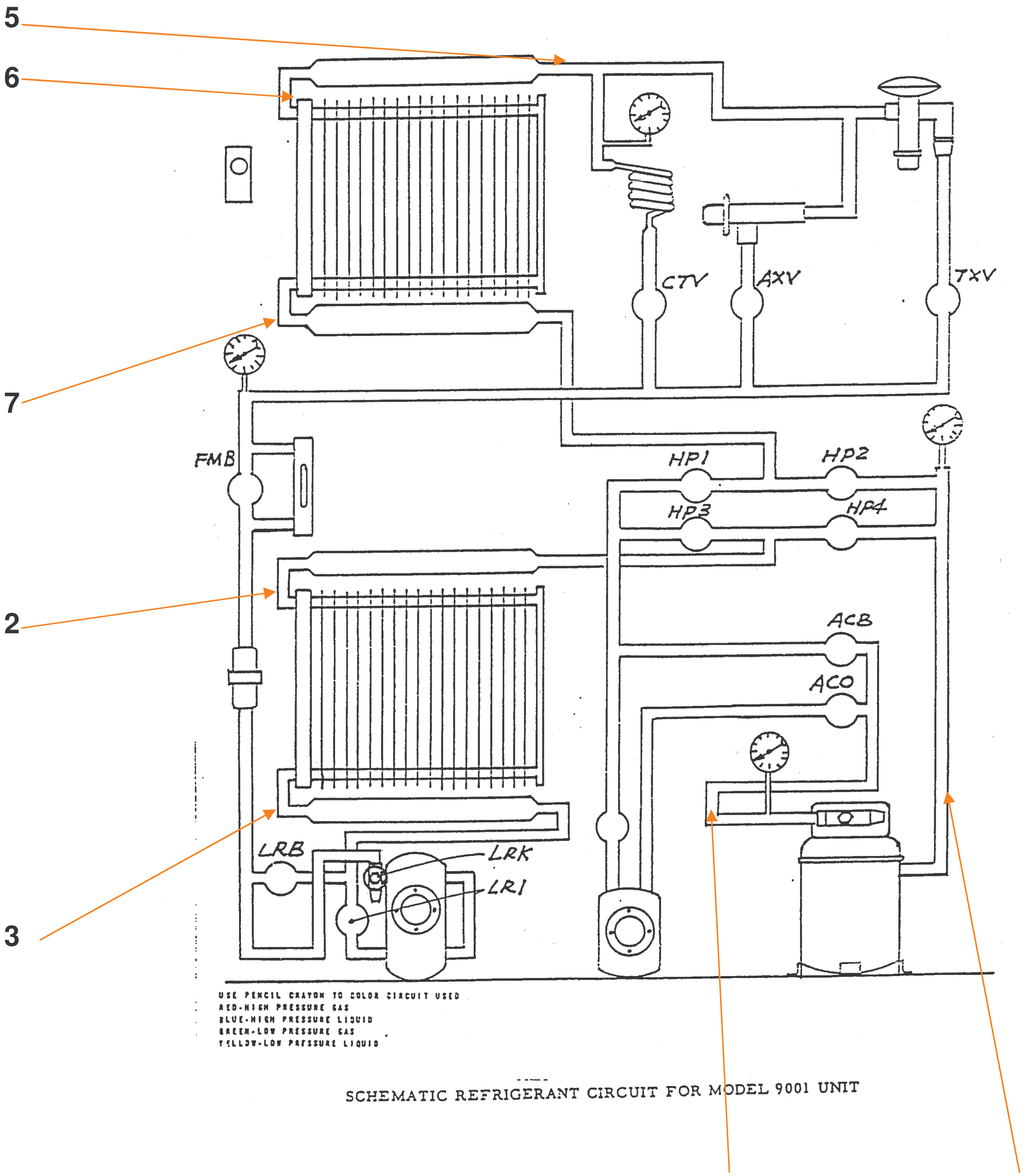


FIGURE C1

Capillary Tube Restriction

1. To simulate a restriction in the Cap Tube, turn the CTV three quarters of a turn back from the full open position. After a few minutes, record head and suction pressure and flow rate.

Head (High side) pressure _______ Flow rate ________Suction (low side) pressure. ______

2. Close the CTV completely to simulate a complete restriction. After a few minutes, record the head and suction pressure and flow rate.

Head (High side) pressure _______ Flow rate ________Suction (low side) pressure. ______

Flow Rate – PPM, pounds per minute

Shut Down

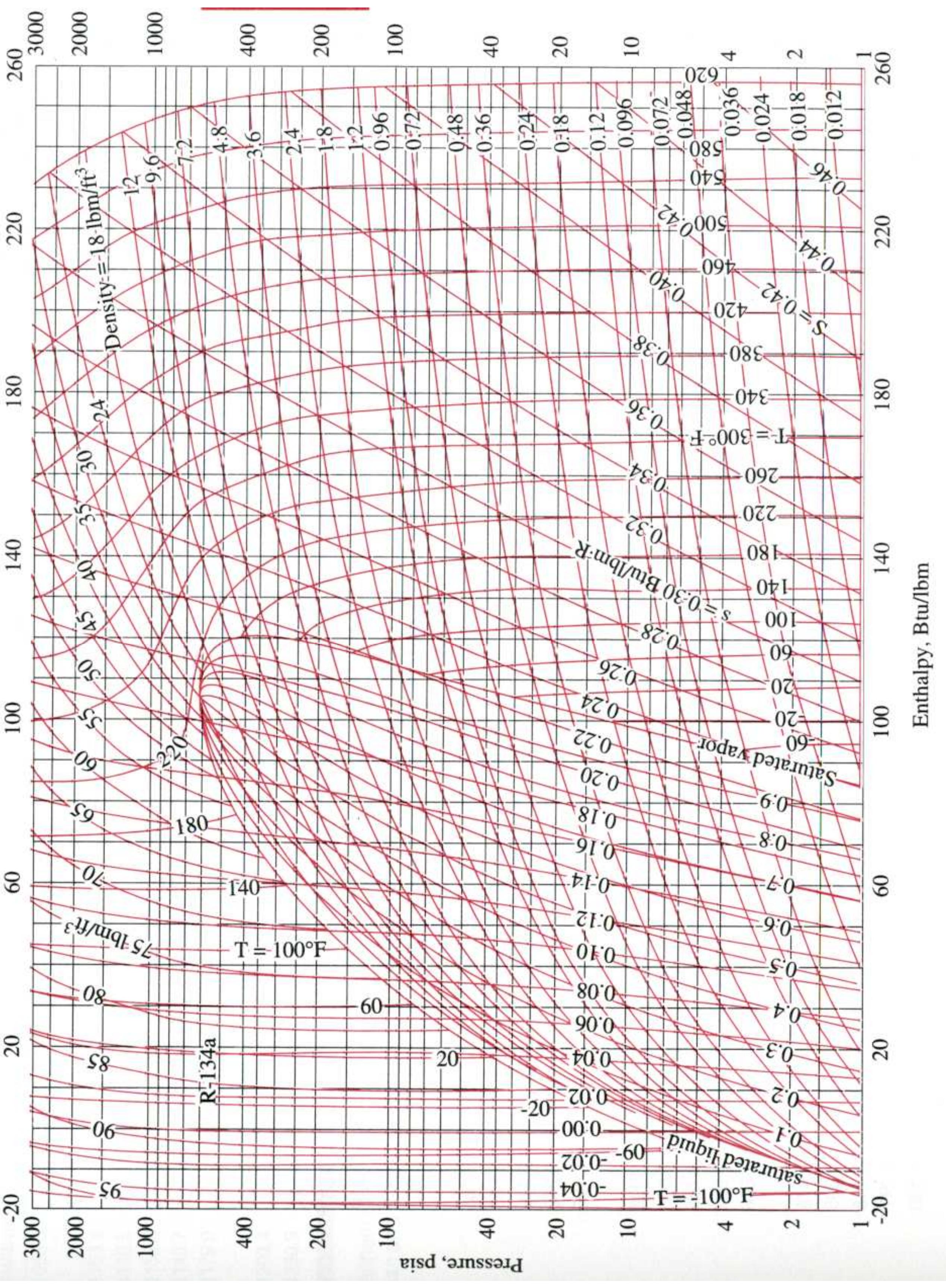
Close LRB, and open LRV and operate until the suction pressure drops to *5* lbs.

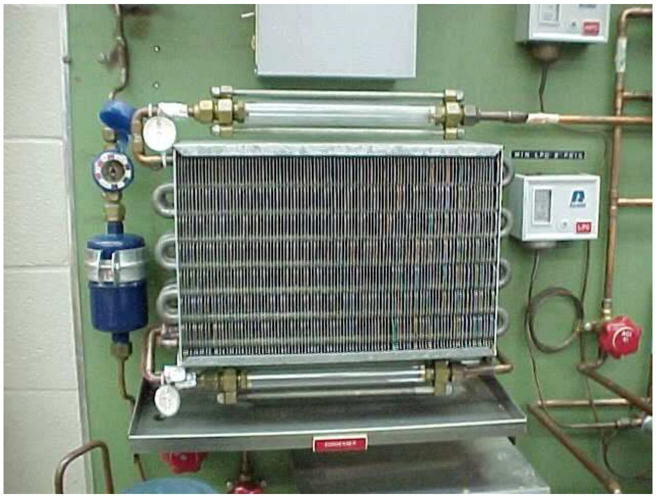
Turn the compressor off.

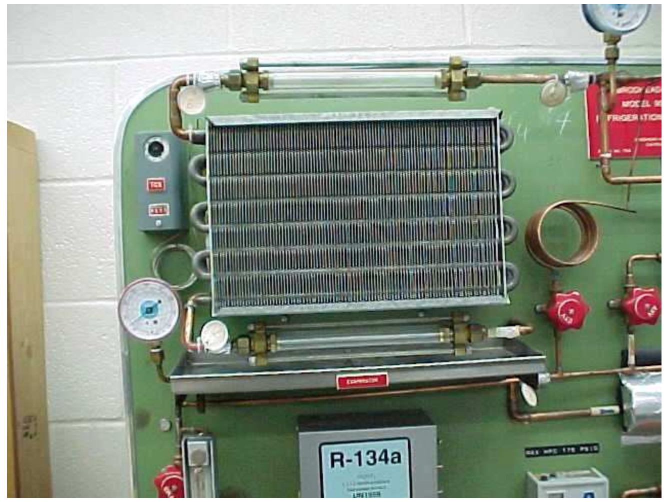
Results:

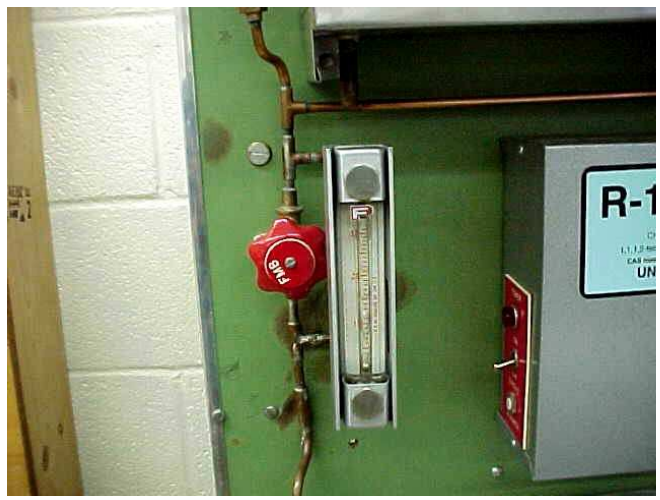
- During the experiment you will find that the liquid line is hotter than the surrounding air. Give a reason why the hot refrigerant can absorb heat into the evaporator from cooler surroundings?
- As the charge was changed show the enthalpy on the refrigerant diagram in and out of evaporator.
- What happens to the system if the cap tube is partially restricted?
- The experiment was operating with the evaporator fan on low. What would happen to the frosting on the evaporator coils if the evaporator fan were turned from low to high? Why?
- What are some of the advantages of the capillary tube type refrigerant control? What disadvantages?
- $Q_R = Q_{in}$ = [flow rate(ppm)] [Δh (Btu./Lb.)]
- Plot the cycle data on the P-h chart given for the refrigerent
- Plot the pressure drop across the expansion device vs the flow rate.

P-h diagram for refrigerant-134a. (Reprinted by permission of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.)









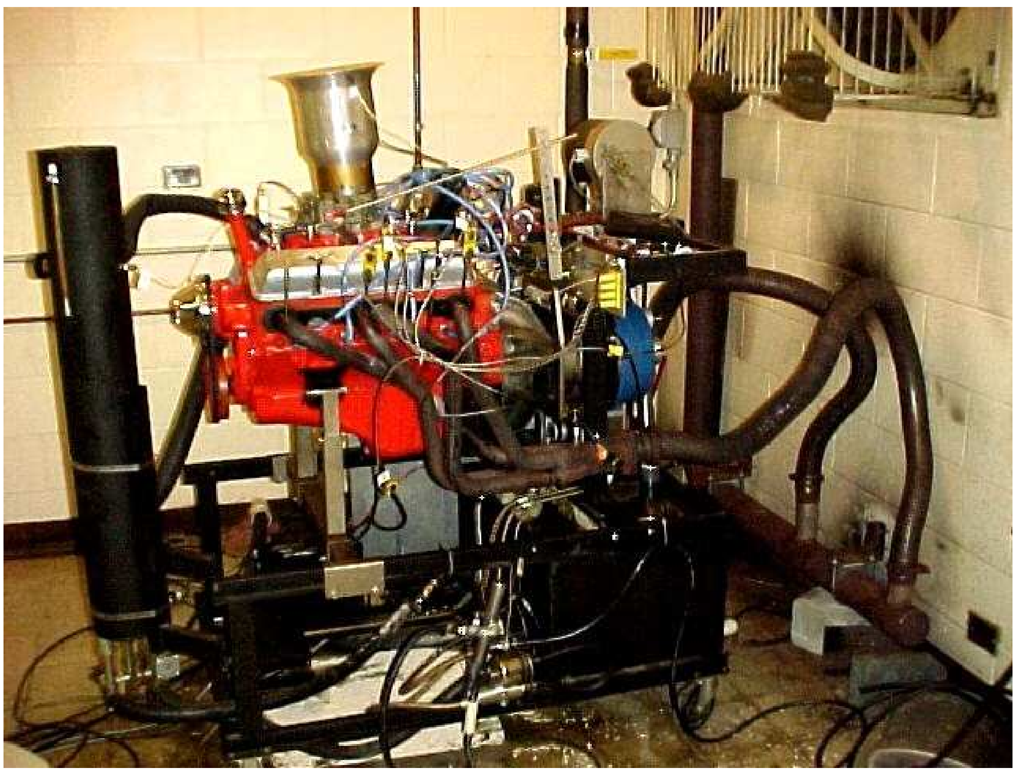
Thermodynamic property data for R134a:
http://flame.mech.gifu-u.ac.jp/TEST-j/testcenter/Test/solve/states/r134a/index.html

Absorption Dynamometer

Understanding and Using a Typical Absorption Dynamometer

Introduction

A dynamometer is a device used to measure the torque and rotational speed of a rotating machine. There are three basic types in use: absorption, driving and transmission dynamometers. Absorption dynamometers dissipate energy as torque is measured and are particularly useful for measuring the torque developed by power sources such as internal combustion engines or electric motors. Driving dynamometers are used to measure the torque required to operate such devices as pumps, compressors, or IC engines being “motored” for the purpose of measuring friction losses (e.g. Spintrons). Transmission dynamometers are used to measure the torque within or between machines.



Theory

The simplest type of absorption dynamometer is the pony brake which depends on dry friction for converting mechanical energy into thermal energy. A water brake uses fluid friction rather than dry friction for dissipating the input energy. Trunion bearings support the dynamometer housing allowing it to rotate freely except for the restraint imposed by a reaction arm. A load cell measures the force at the end of the reaction arm at a known radius r. Torque is then computed by

$$\tau = Fr$$

where τ is the torque and F is the force measured at radius r. Since the angular speed is measured, power is determined as

$$P_b = \tau\omega$$

where P_b is power and ω is rotational speed in radians per second.

This measured power can be corrected to standard pressure, temperature, and humidity with

$$P_{bc} = \left(\frac{P_{std} - P_{vstd}}{P_{means} - P_{vmeans}}\right)\sqrt{\frac{T_{means}}{T_{std}}}$$

Where P_{bc} is the corrected engine power. P_{std} and T_{std} are the pressure and temperature to which the measured values are to he corrected, P_{vstd} is the partial pressure of the water vapor in the standard

Atmosphere, P_{vmeans} is the measured partial pressure of the water vapor in the air inducted into the engine, P_{means} and T_{means} are the pressure and temperature of the air in the test cell.

An important measure of engine efficiency which can be determined using the dynamometer is brake **specific fuel consumption** (BSFC) which is given as follows

$$\text{BSFC} = \frac{m_f}{P_b}$$

Where $\dot{m}_f$ is the fuel mass flow rate.

Since the mass flow rate of the air entering the engine (m_f) is measured, an overall efficiency, η, can he calculated as

$$\eta = \frac{P_{bc}}{\dot{m}_f}\frac{1}{LHV}$$

where LHV is the lower heating value of the fuel. This is sometimes called **fuel conversion efficiency**.

The parameter used to measure the effectiveness of an engine's induction system is volumetric efficiency. The **volumetric efficiency**, e_v, of an engine is defined as the actual mass of air drawn into the displacement volume during the intake stroke divided by the mass of air that would occupy the same volume if it were at the temperature and pressure of air outside the engine. Volumetric efficiency can be calculated by

$$e_v = \frac{\dot{m}_a + \dot{m}_f}{\frac{\rho_i v_d R_s}{2}}$$

where $\dot{m}_a$ is the mass flow rate of air, V_d is the displacement volume. $R_{s,}$ is the engine rotational speed in revolutions per unit Lime and ρ_i is the density of the incoming air. The two in the above equation is present only for four stroke engines.

A parameter used to scale out the effect of engine displacement is **brake mean effective pressure**, bmep, which is defined as net work per cycle per unit displacement volume. For a four-stroke engine bmep is given by

$$\text{Bmep} = \frac{P_{bc}}{\frac{V_d R_s}{2}}$$

Apparatus

The hardware consists of a 355 in Chevrolet small block engine, a Superflow SF-901 dynamometer, and a data logging computer.

Procedure

WARNING: ***The dynamometer will be operated by our trained technician, only*.**

I. Initial Set Up Procedure

A. Determine the specific gravity of the gasoline.

1. Fill the 1000 ml flask with gasoline. Place the hygrometer in the flask and read the specific gravity (where the surface intersects the hygrometer scale.)

B. Determine the relative humidity.

1. Use the sling psychrometer to determine the wet bulb and dry bulb temperatures.

2. Use a psychrometric chart to determine the partial pressure of the atmospheric vapor.

II. Engine Room Set Up Procedure

A. Open valve V1 between the main water line and the engine's water supply tank. The valve V1 is located on the wall opposite the door (yellow handle). The engine's water supply tank ST is attached to the front of the engine; it is black and has a cylindrical shape.

B. Close drain valve DV on the engine water supply tank ST and open valve V2 between valve V1 and the supply tank ST. Valve V2 and the drain valve DV are located below the tank. The drain valve is on the right as you face the engine from the front and valve V12 is on the left.

C. Fill supply rank ST with water to a level above the engine. Use the sight glass on the side of ST to determine the water height.

D. Check the red fuel tank located on the wall opposite the window for fuel.

E. Turn the room fan on using the switch next to the fan. The fan and switch are on the wall opposite the window.

III. Dynamometer Set Up and Operating Procedure

A. Turn on the power to the dynamometer and turn on the computer and printer that are connected to the computer.

B. Set the minimum RPM setting (on the dynamometer) to 2500 rpm and the maximum RPM setting to 4500 rpm. These dial in as 250 and 450.

C. The Command Directory will appear on the screen. In order to enter the vapor pressure and fuel specific weight measured above, hit the ‘H’ key to go to the help screen. Select ‘I’ for the Data Input screen containing all of the default settings for the engine. Scroll down (using the Return key) to get to the settings for ‘water vapor pressure’ and ‘fuel specific weight’ and input the measured values. Change the other settings as necessary using this menu. Return to the Main Menu by typing ‘ctrl c’.

D. On the dynamometer, set Load Control to ‘Manual’ and turn the load dial to the lowest setting (fully clockwise). Turn on the fuel pump and set the hand throttle to its lowest setting (i.e., in the ‘back’ position).

E. Press the starter button to start the engine.

F. Visually monitor the dynamometer on the computer screen. From the Help Screen, type ‘I’ From the Command Directory hit ‘esc’. This will put you into the Input Menu which allows direct monitoring of temperatures, pressured, torques. etc., as each test is run.

G. Allow the engine to warm up until oil temperature is at least 150 F and water temperature is 150 F. These can be read from the Input Menu.

H. Procedure for performing an acceleration test.

1 Turn the Test Select knob on the dynamometer to ‘Acceleration’.

2 Turn the Auto Test Rate knob to 200.

3 Turn on the Servo.

4 Push the hand throttle to the wide open position (i.e., the up position).

5 Based on the settings chosen in step B and step H.2, the engine speed will automatically from 2500 to 4500 rpm at a rare of 200 rpm/s.

6 After the highest speed is reached, the engine will automatically throttle down. When this occurs, pull the hand throttle to the back position.

7 Once the engine has returned to idling speed, allow several minutes for cool down before turning off the engine. Turn off the fuel pump and ignition switch on the console.

8 Go to the Main Menu (hit ‘ctrl’ + ‘c’) and select ‘k’ for keep. This will save all the data from the acceleration test.

I. Use the Command Directory to select 'U' to retrieve the stored data files. Type in the tile name and hit enter. Select the type of analysis you want.

J. At the conclusion of the experiment, turn off the supply water to the engine, turn off the exhaust fan, turn off the dynamometer, computer and printer, drain and return to storage any unused gasoline, and properly dispose of used rags.

Report

Using a memo format (which assumes the person you're submitting the report to is familiar with the apparatus and procedure) submit a report which includes the following.

1. Calculate:
   - brake specific fuel consumption,
   - fuel conversion efficiency,
   - volumetric efficiency and
   - brake mean effective pressure

   at 2000 rpm, at the torque peak, and at the power peak.

   Show all calculations with unit's cancellation. Discuss the results.

2. Include in your report a copy of the plot of power and torque vs. engine speed and comment on any anomalies that you observe.

Active Expansion Devices©

Part I, Automatic Expansion Valve (Pressure Regulator)

The purpose of this experiment is to familiar with the function and operation of an automatic expansion valve of a refrigeration system.

Introduction:

Refrigeration works on the principle of heat absorption due to the evaporation of refrigerant. It *is* the latent heat of evaporation that gives the refrigerating effect. Liquid refrigerant is evaporated by passing it from a high-pressure region through a throttling valve to reduce its saturation pressure to a lower level, and reduce its saturation temperature. The degree of cooling can be controlled by controlling the amount of refrigerant passing into the low-pressure region. The throttling valves that control the refrigerant flow into the low-pressure region are called metering devices. Fig. 1 shows a schematic drawing of an ideal vapor-compression refrigeration cycle.

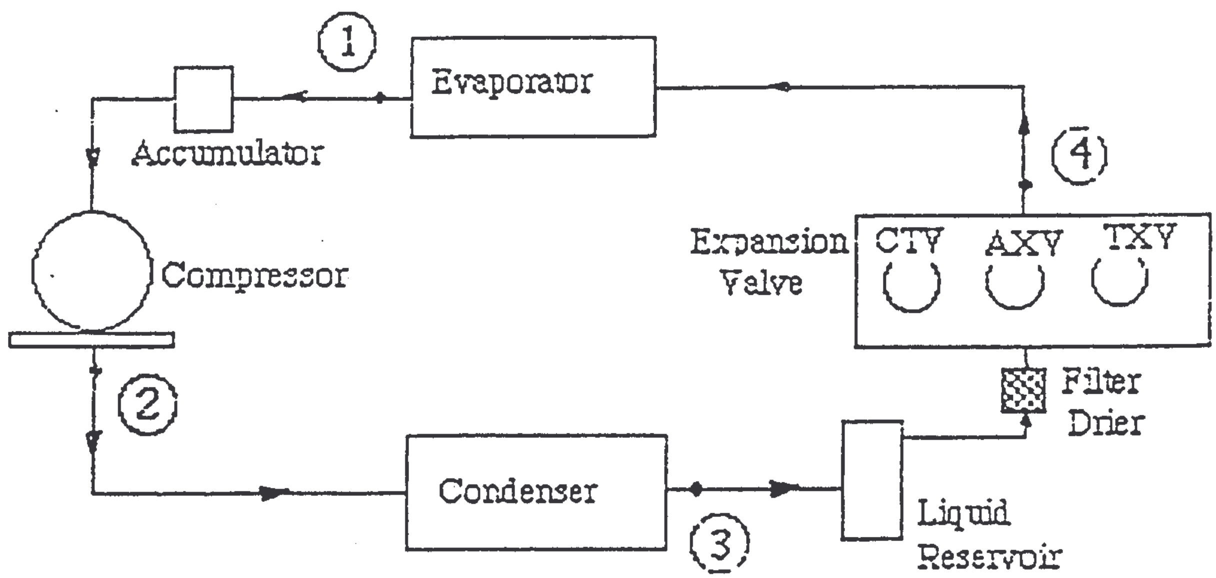


Fig. 1 Schematic Drawing of a Vapor-Compression Refrigeration cycle

The automatic expansion valve is known as a “constant pressure” valve. It implies that it holds the pressure in the evaporator at a constant level regardless of load. In this way the load on the compressor also remains about the same. Fig. 2 is a schematic drawing of an automatic expansion valve.

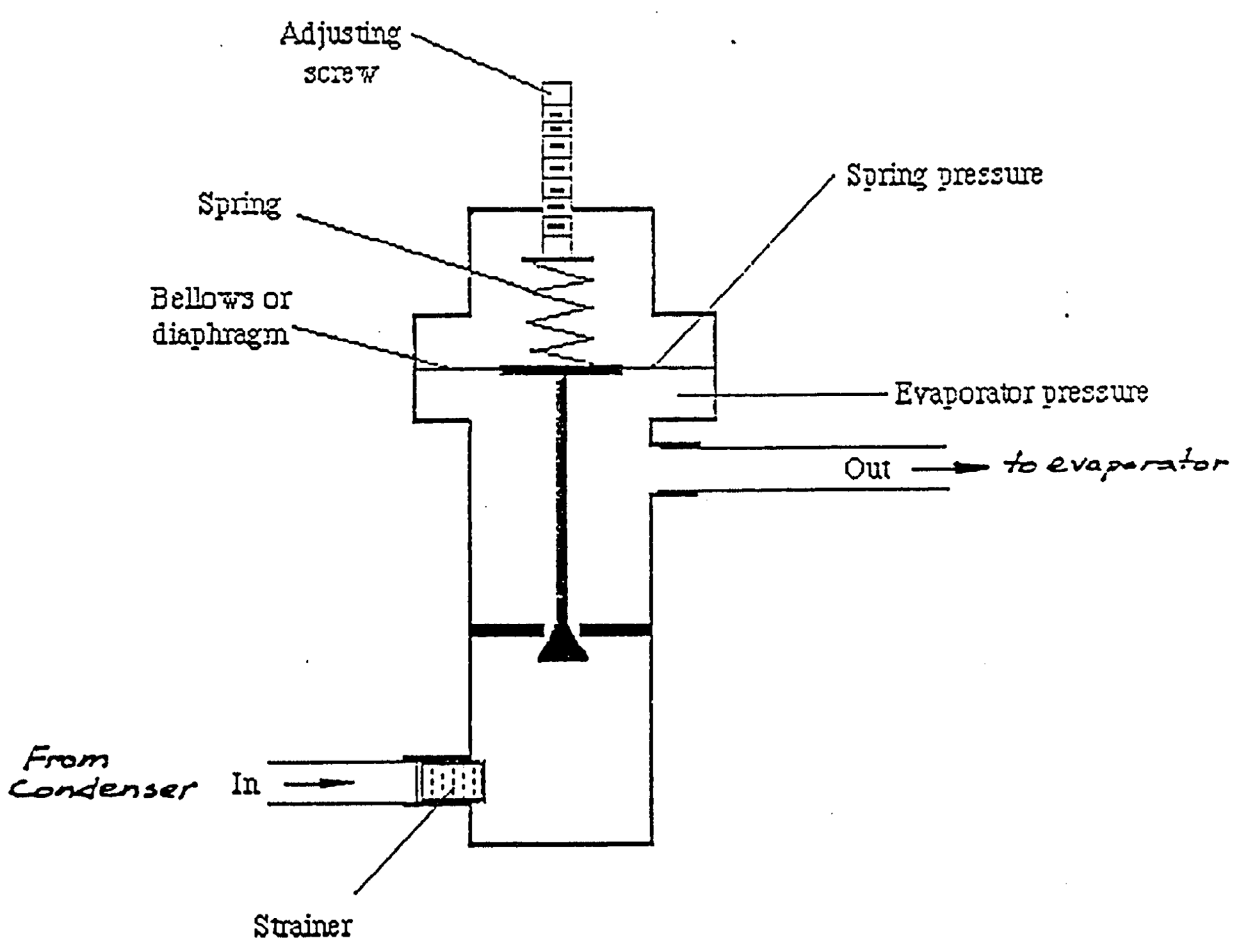


Fig. 2 Schematic diagram of automatic expansion valve

Note: Figure 2 does not precisely resemble the hardware in the lab.

The bellows of diaphragm of the AXV is actuated by the pressure in the evaporator (low side). A rise in suction pressure due to increased load causes the diaphragm to expand and reduce the opening of the valve seat; this restricts the flow of liquid refrigerant to the evaporator and brings the suction pressure back to its original state.

As the pressure in the evaporator decreases, the spring force opens the valve seat and allows more liquid refrigerant to be admitted to the evaporator. (Reducing the head pressure and increasing the suction pressure.) The control pressure is set by the adjusting screw. In this automatic expansion valve, the refrigerant flow is controlled only by the pressure in the evaporator.

<u>Apparatus</u>:

Model 9001 Brodhead-Garrett Basic Refrigeration Unit.

Refer to detailed photos in the Capillary Tube Experiment

<u>Procedure</u>:

A. Adjustment

1. Put system in cooling cycle, Open AXV with TXV and CTV closed. Close LRB, open LRI and LRK.

2. Switch main power on, set evaporator fan on low and the condenser fan on high and start the compressor.

3. Remove cap from the bottom of the AXV and turn the adjusting screw (clockwise for increase pressure and counter-clockwise for decrease pressure) until suction pressure reaches 8 psi. Allow 10 minutes for the system to stabilize before taking data.

4. Record suction pressure, head pressure, refrigerant flow rate, and refrigerant temperature before and after the evaporator. (see data sheet.)

5. Adjust the AXV by turning the adjusting screw to a suction pressure of 11 psi. Wait *5* minutes and record the suction pressure, head pressure, refrigerant flow rate, and refrigerant temperature before and after the evaporator.

6. Repeat procedure *5* for four more suction pressures.

B. Effect of Increased Load

1. Turn the evaporator fan on high. Wait five minutes and record:

    - Suction Pressure ___________
    - Head Pressure ____________
    - Flow Rate ___________

2. Turn compressor off. Wait five minutes and record:

- Suction Pressure ___________
- Head Pressure ___________

Jump to Part II

or Shut Down:

Close LRB and LRK. With LRI open, operate until the low side pressure falls to about *0* psi. Close LRV. Then, open LRB and turn the compressor and fans off.

Results:

1. Calculate cooling effect of the evaporator Qdot = Mdot refrigerant (Δh)

2. Exercises:
    a. Explain what happens in an automatic expansion valve (AXV), when the load is increased in a refrigeration system.

    b. What causes the needle valve to close in an automatic expansion valve?

    c. For each data set, what was ΔP?

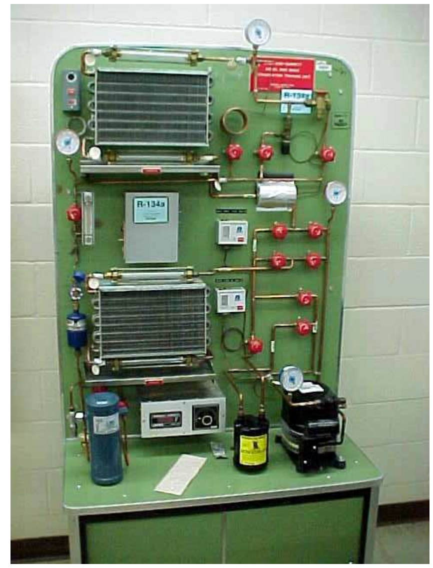
Data Sheet

Date:

Suction Pressure (psig)							
Head Pressure (psig)							
Pressure After Exp. Valve (psig)							
Refrig. Temp. Before Evaporator (F)							
Refrig. Temp. After Evaporator (F)							
Refrig. Temp. Before Condenser (F)							
Refrig. Temp. After Condenser (F)							
Refrigerant Flow Rate (PPM)							

Part II, Thermostatic Expansion Valve (TXV)

The purpose of this experiment is to familiar, with function and operation of a thermostatic expansion valve of a refrigeration system.



Introduction:

The Thermostatic Expansion Valve (TXV) is a temperature controlled expansion valve. It automatically adjusts to varying load and maintains maximum efficiency at all times. The schematic diagram illustrating the operation of a typical thermostatic expansion valve is given in Fig. 1. This valve maintains constant superheat (Ti - T_2) in the evaporator. The difference between this valve and the automatic expansion valve is that a thermal bulb connected to the valve by a small capillary tube is attached to the suction line between the evaporator and compressor. The thermal bulb is partially filled with liquid refrigerant usually the same as that used in the system. The thermal bulb is attached to the suction line so that any change in load will change in temperature of the suction line and also the temperature of the thermal bulb. Under an increased load, the refrigerant boils away more rapidly in the evaporator. This in turn will cause a greater superheat at the evaporator outlet. The higher temperature produces a higher pressure within the thermal bulb, and causes the diaphragm to expand and force the needle valve seat to open. As a result more liquid refrigerant is allowed to enter the evaporator.

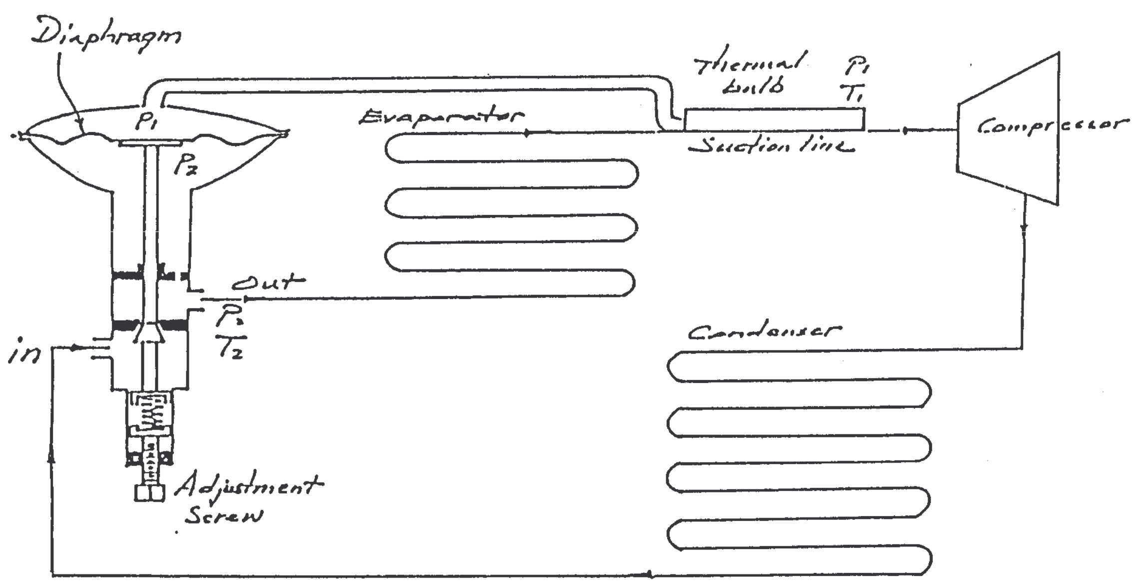


Fig.1 Operation of a thermostatic expansion valve

Apparatus:
Model 9001 Brodhead-Garrett Basic Refrigeration Unit.

Procedure:
1. To operate the TXV: close LRB, open LRI and LRK , open TXV, close AXV and CTV.

2. Put both the condenser fan and evaporator fan on high, turn compressor to "on" position and switch main power on.

3. After letting the system run for *5* minutes, measure and record suction pressure, head pressure, refrigerant flow rate, and refrigerant temperature before and after evaporator Make a preliminary determination of the superheat, which is (T_1 - T_2).

TXV

Where:
T_1 = suction line temperature at thermal bulb (TC #7)

T_2 = saturation temp. of low side pressure. (TC #6)

4. Turn the evaporator fan to low and wait for 10 min. before recording the information listed in step 3.

5. Turn the evaporator fan off and wait about 10 min. and record the same information as in step 3.

6. Shut the compressor off and record suction and head pressure after waiting *5* minutes

Shut Down:

Close LRB and LRK. With LRI open, operate until the low side pressure falls to about *0* psi. Close LRV. Then, open LRB and turn the compressor and fans off.

.

Result:

1. Calculate cooling effect of the evaporator:

   Qdot = Mdot refrigerant (Δ h)

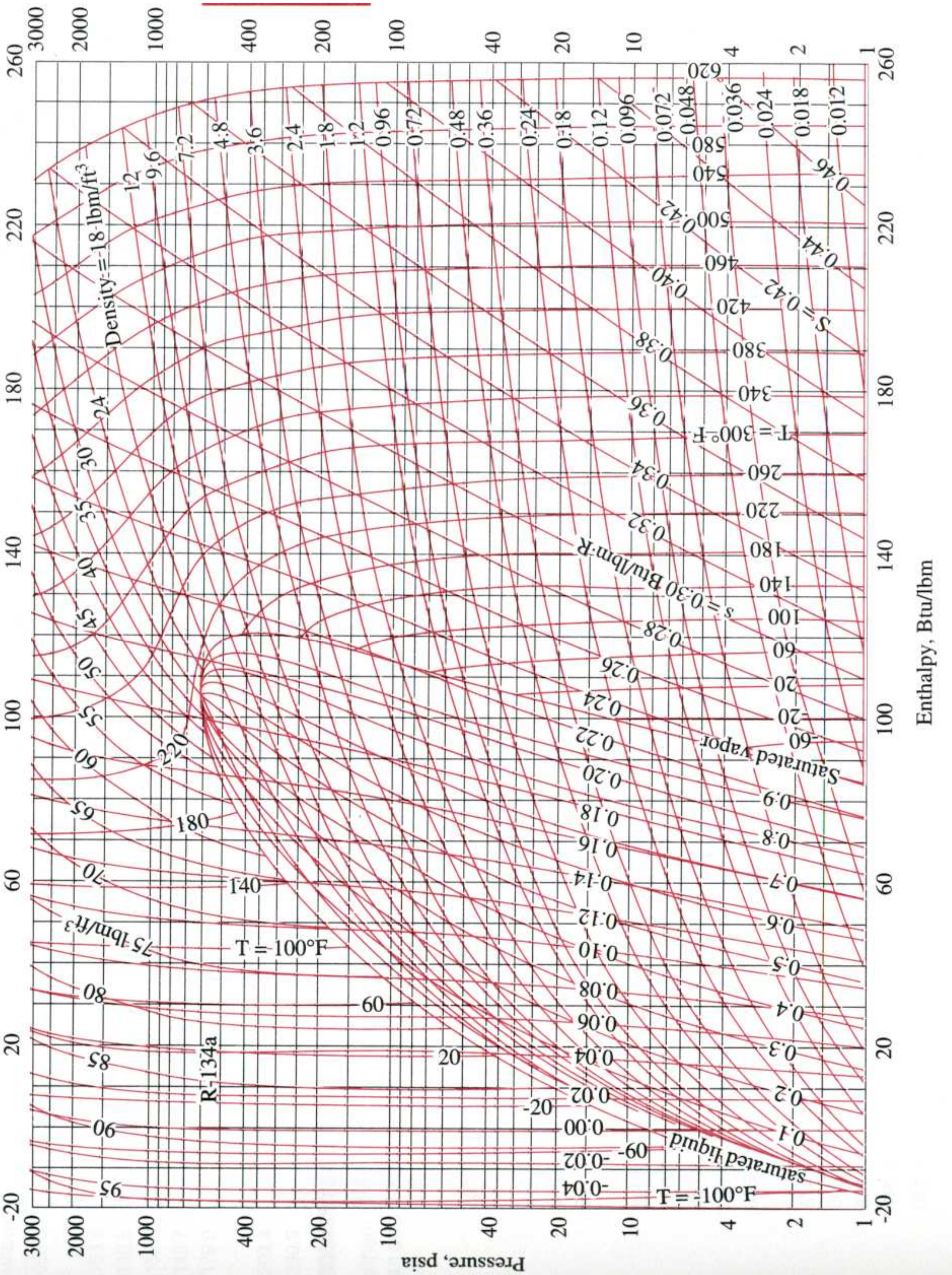
2. Exercises:
   a. Discuss what happens in the evaporator when the load is decreased and how the TXV would compensate.
   b. What happens to the pressure across the TXV when the compressor is turned off?
   c. Determine the superheat of the TXV for evaporator fan on high and low.
   d. Are the superheats the same? Should they be same? Why?
   e. What happened to the suction pressure, head pressure, refrigerant flow rate, and the air temperature when the load was increased? Why?

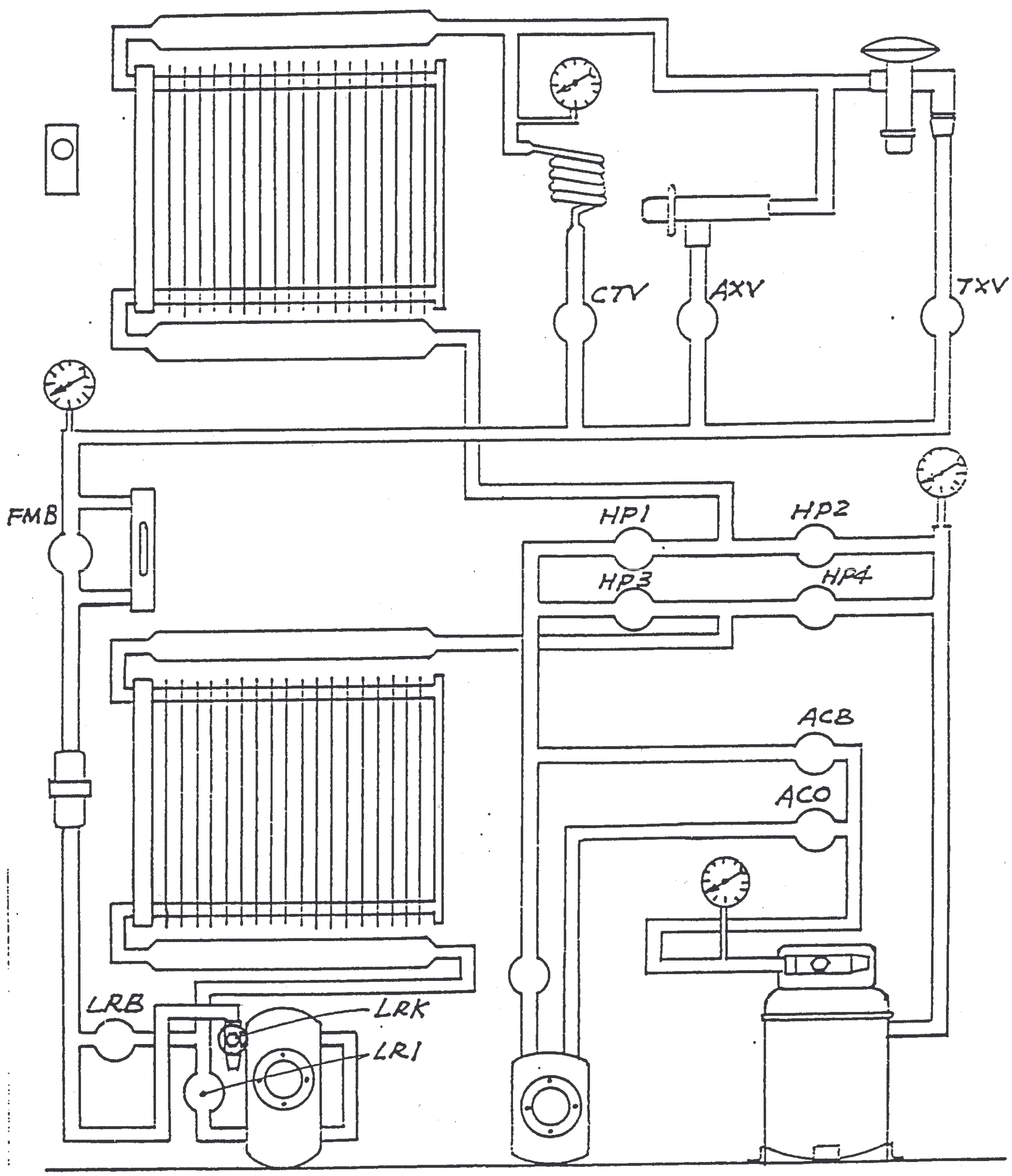
Data Sheet

Date:

Suction Pressure (psig)							
Head Pressure (psig)							
Pressure After Exp. Valve (psig)							
Refrig. Temp. Before Evaporator (F)							
Refrig. Temp. After Evaporator (F)							
Refrig. Temp. Before Condenser (F)							
Refrig. Temp. After Condenser (F)							
Refrigerant Flow Rate (PPM)							

P-h diagram for refrigerant-134a. (Reprinted by permission of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.)





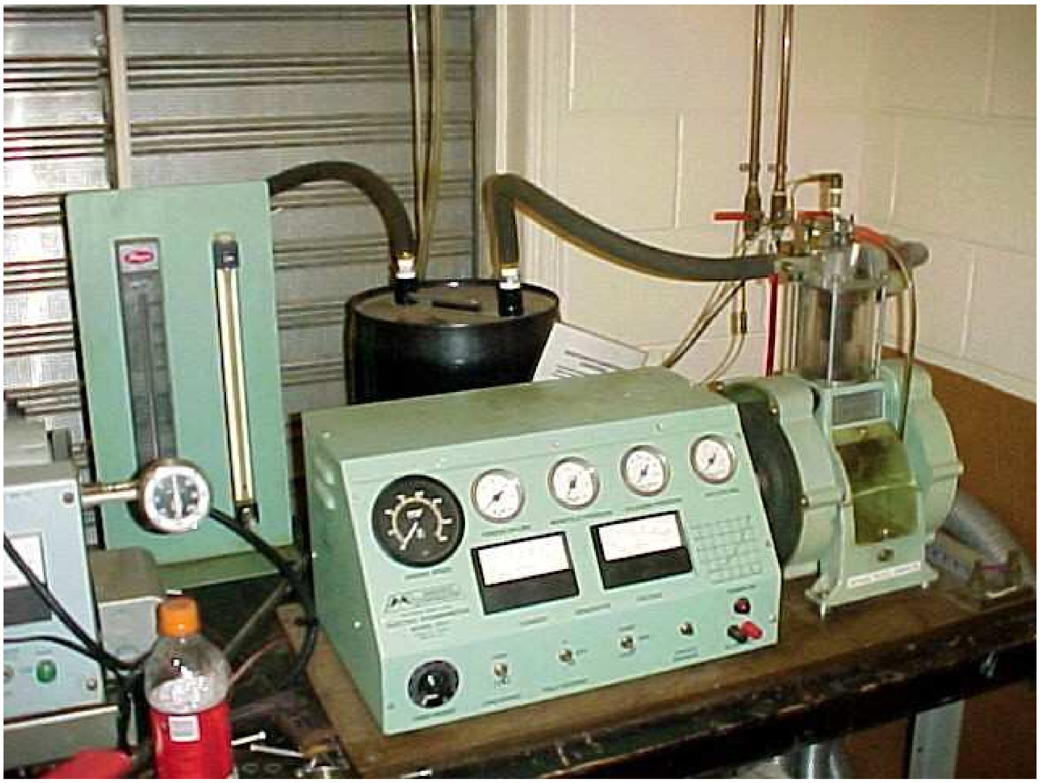
USE PENCIL CRAYON TO COLOR CIRCUIT USED
RED-HIGH PRESSURE GAS
BLUE-HIGH PRESSURE LIQUID
GREEN-LOW PRESSURE GAS
YELLOW-LOW PRESSURE LIQUID

SCHEMATIC REFRIGERANT CIRCUIT FOR MODEL 9001 UNIT

Four-Stroke Transparent Gasoline Engine Analysis

Introduction

In this experiment you will observe the construction and operation of a four-stroke, single cylinder, air-cooled, spark-ignition engine by using a Megatech -Mark III Transparent Combustion Engine. Knowledge of its construction and operating characteristics will help to provide an understanding of larger, multi-cylinder engines.



Apparatus

1. Megatech model DG-1 electric dynamometer
2. Megatech -Mark III model TE1 transparent combustion engine
3. Dayton heavy duty battery charger/booster
4. Air surge tank
5. Barometer

Procedure

Set up the air surge tank shown in Fig. 1. (For a single cylinder engine a surge tank is installed at the air intake of the engine to prevent serious fluctuations in velocity, temperature, and pressure measurement. The volume of surge tank must be at least fifty times of the cylinder volume.)

Follow instruction to start engine.

(A) **To Start the Engine**

1. Make sure the engine is connected to a suitable compressed air supply and a 12 volt DC 10 ampere (minimum) power source. For 1/2 hour or longer continuous Operation 15 psig of cooling air is required Do not operate the engine without cooling air.

2. Fill fuel supply Pipette.

3. Open fuel line needle valve on engine 1-1/2 turns. Open throttle fully and turn the ignition switch on.

4. With field reversing switch at (4-) and high-low range switch on high, turn “Load Adjust” knob to full clockwise 100% position for maximum starting torque.

5. Flip the “Load Range” switch to “High” position, otherwise the fuse will blow out.

6. Flip the “Field Reverse” switch to (+).

7. Now turn the switch to “Start”. When engine starts cranking, turn “Load adjusts” knob slightly counter-clockwise to about 70% to increase the cranking speed.

8. Choke engine slightly by holding finger over carburetor intake tube for a second. If engine fails to start, vary needle valve setting 1/4 turn and repeat

9. As soon as engine starts to run, flip the switch from “Start” position back to “GEN”., and set “Field Reverse” switch to “OFF” position (center). Adjust needle valve for smoothest operation. This will permit the engine to operate without load.

10. When engine is running smoothly and if you want to load the engine, set switch to “Load” position, set the “Field Reverse” switch to (+) and vary “Load Adjust” setting until speed is held at desired level. Readjust throttle and needle valve for best operation.

11. Take at least four load points. During this time do not adjust engine settings. Record needed data for each:
    a. RPM
    b. Torque

c. Fuel flow rate

d. Airflow rate

e. Cylinder Pressure

f.

Note: The engine is operating at a single mechanical throttle and mixture setting.

(B) **Shut Down the Engine**

1. Turn off the load by setting the “Field Reverse” switch to “OFF”
2. Turn the cooling air off
3. Let engine run at half throttle for a minute
4. Shut the engine “OFF”

Caution: If you leave the cooling air on after engine shut-off, the rapid cooling air might crack the cylinder.

Result

After recording engine rpm. dynamometer torque, fuel rate, and calculate the following:

(1) The brake horsepower

The actual work output of an engine is usually determined by a power absorption device such as the Pony brake, water brake, fan dynamometer, or an electric dynamometer, the electric dynamometer being the most satisfactory for engine test purpose. In the dynamometer a torque is measured by a force F and dynamometer arm r.

The work per minute is given by:

Work / Min. = $2\pi N T$

Where: N = Engine speed in RPM, T =Torque in lb-ft

The brake horsepower (BH) is therefore obtained by dividing the work in lb-ft/min. by 33,000 lb-ft/min.-Hp

$$BH = \frac{2\pi N T}{33,000}$$

(2) The specific fuel consumption

The specific fuel consumption is obtained by dividing the observed fuel rate by the observed brake horsepower

BSFC = Observed fuel rate (lbs/hr) / BH

(3) The brake thermal efficiency The brake thermal efficiency = Brake work / Heat of fuel

$$\text{Brake thermal efficiency } (\eta_b) = \frac{\text{Brake work } (2\pi N T) \quad (\text{Btu/min})}{\text{heating value of fuel x fuel rate} \quad (\text{Btu/min})}$$

Some conversion of units may be necessary

heating value= 19750 Btu/lb.

??(‘Which is part of energy of fuel supplied that is converted into engine shaft work)

(4) The mean effective pressure

The mean effective pressure (mep) is an indication of engine performance, and is the amount of work done per cycle in each cylinder divided by the displacement volume of the cylinder

mep = work per cycle / displacement (psi) where

_Work per cycle = BH x $\frac{33{,}000 \text{ ft-lb}}{\text{Min.}}$ x $\frac{2}{\text{RPM}}$

Displacement is the volume swept by the piston as it moves between bottom dead center and top dead center in the cylinder. The displacement of the transparent engine is 4.148 in^3

(5) Plot performance curves example shown in Fig. 2 using a spreadsheet program like EXCEL Torque, horsepower, efficiency….

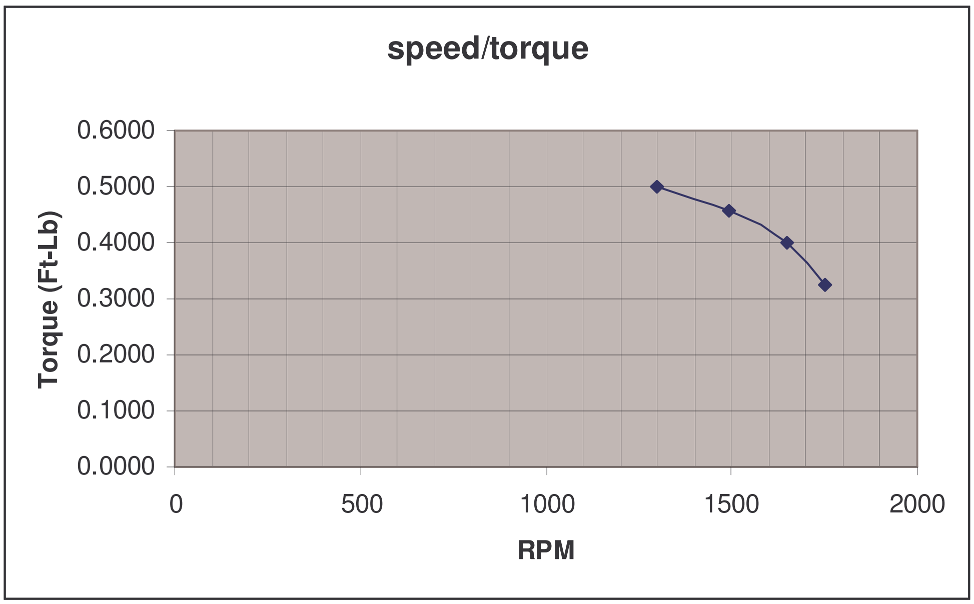


Figure 2, Sample of one possible Performance Curve

Double Pipe Heat Exchanger Experiment

Introduction:

One of the most important processes in engineering is the heat change between flowing fluids. In heat exchangers the temperature of each fluid changes as it passes through the exchanger, and hence the temperature of the dividing wall between the fluids also changes along the length of the exchanger. Examples in practice in which flowing fluids exchange heat are air intercoolers and preheaters, condensers and boilers in steam plant, condensers and evaporators in refrigeration units, and many other industrial processes in which a liquid or gas is required to be either cooled or heated.

Theory:

Consider the simple case of a fluid flowing trough a pipe and exchanging heat with a second fluid flowing through an annulus surrounding the pipe. When the fluids flow in the same direction along the pipes the system is known as parallel flow, and when the fluids flow in opposite directions to each other the system is known as counter flow. Parallel flow is shown in Fig. 1a and counter flow is shown in Fig. 1b.

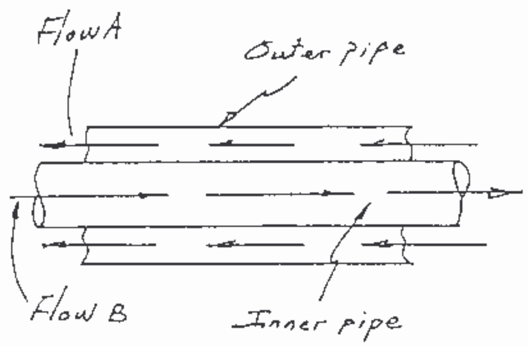


Figure 1a Counter Flow

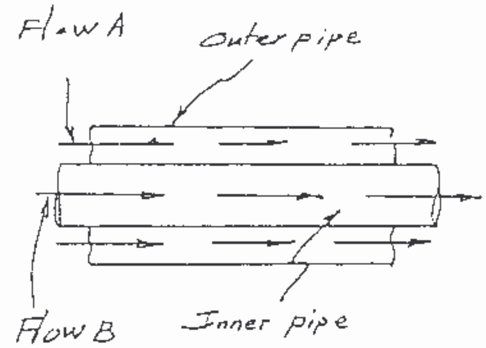


Figure 1b Parallel Flow

It should be noted for counter flow that as the flow passage is lengthened, the temperature difference between fluids A and B at any point in the flow passage becomes smaller and smaller. Thus, with a very long flow passage, the temperature of fluid B at its exit approaches that of fluid A at its entrance. Likewise the temperature of fluid A at its exit approaches that of fluid B as it enters. As the Length of flow passage increases without limit, the temperature difference between the two fluids in any point in the flow passage approaches zero and the heat transfer process approaches a reversible one.

When heat is exchanged between two fluids flowing continuously through a heat exchanger, the **local** temperature difference T, varies along the flow path. The heat transfer is calculated with the familiar rate equation:

$$Q = UA\,(\Delta T_m) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where U is the overall coefficient of heat transfer from fluid to fluid, A is an area associated with the coefficient U, and Tm is a mean temperature difference.

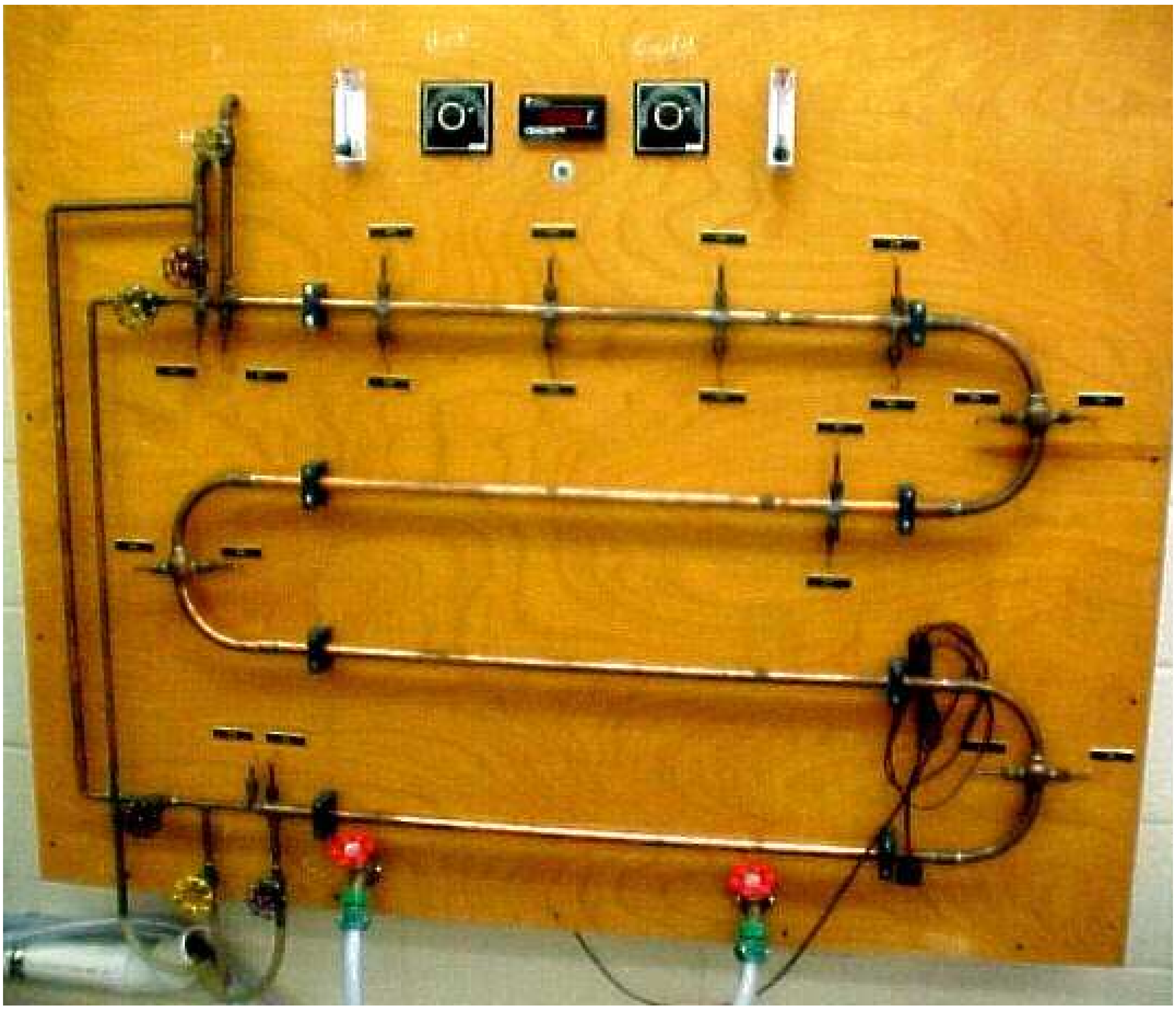
For parallel flow or counter flow heat exchangers, this **mean** temperature difference is called the log mean temperature difference (LMTD) and is defined as

$T_m = (\Delta T_1 - \Delta T_2)/ \ln(\Delta T_1/ \Delta T_2)$……………………………(2)

Where ΔT1 and Δ T2 are the differences in hot and cold fluids at the inlet and outlet, respectively.

The overall heat transfer coefficient is given:

$U = Q/A (\Delta T_m)$ ………………………………………..(3)



Experiment:

Apparatus:

1. Double pipe heat exchanger system that includes:
    a. Two concentric pipes
    b. Thermocouples located along the pipe.
    c. Flow meters
    d. Flow control valves
    e. Thermocouple selector switches.
2. Cold and hot water supplies
3. 2000 cc beaker
4. Stop watch
5. Plastic tubing
6. Flexible wire
7. Tape measure

Procedure:

1. Measure the Thermocouple locations (**X**)
2. Arrange heat exchanger for parallel flow with hot water in inner tube.
3. Turn on hot and cold water supplies to approximately same flow rate, max-range.
4. Measure volumetric flow rates for both hot water and cold water.
5. Read temperature at each thermocouple location.
6. Repeat steps 1-5 for two additional hot flow rates (3 runs total). Select flows rate, such that the exit temperatures are significantly different.
7. Repeat steps 1-6, with heat exchanger arranged for counter flow. (3 data sets minimum)

Results:

Note…If a thermocouple has an inconsistent reading, note that in your report and disregard the data.

(A) Calculations:

1. Volumetric flow rate (V)

    V = Volume/time

2. Cross-section area of inner tube (Ai)

$Ai = 3.1416(di)2 /4$

di = 0.275 inches

3. Flow velocity (V)

$V=V/Ai$

4. Reynolds Number (N_R)

$N_R = V\, di\, \rho/\mu$ or $N_R = V\, di/ v$

5. Mass flow rate (m)

$m = V\rho$

6. Heat transfer (Q)

$Q = m\, c_p(\Delta T)$

Does $Q_{hot} = Q_{cold}$?

7. Log Mean Temperature Difference (ΔT_m)

(a) Parallel flow

$T_m = [(T_H - T_C)\ out - (T_H - T_c)_{in}] / \ln[(T_H - T_c)_{out} /(T_H - T_c)_{in}]$

(b) Counter flow

$T_m = [(T_{H,out} - T_{c,in}) - (T_{H,in} - T_{c,out}] / \ln[T_{H,\ out} - T_c - T_{c,ou}t)/(TH,_{in} - T_{C,out})]$

8. Heat transfer surface area (AT)

AT 3.1416 (di)(L)

di- average diameter of inner tube

L - total length of exchanger tubing

9. Over all heat transfer coefficient (U) (Btu / hr.ft^2 °F)

$U = Q_{avg} / A_T\ (\Delta T_m)$

(B) Graphs:

1. Temperature of the hot and cold flows vs length X (consider the use of log scales). (10 graphs)
2. For Parallel flow Graph U vs Hot flow rate for a fixed cold flow rate.
3. For Counter flow Graph U vs Hot flow rate for a fixed cold flow rate.

Use a spreadsheet program like Excel to ease the graphing and calculation processes.

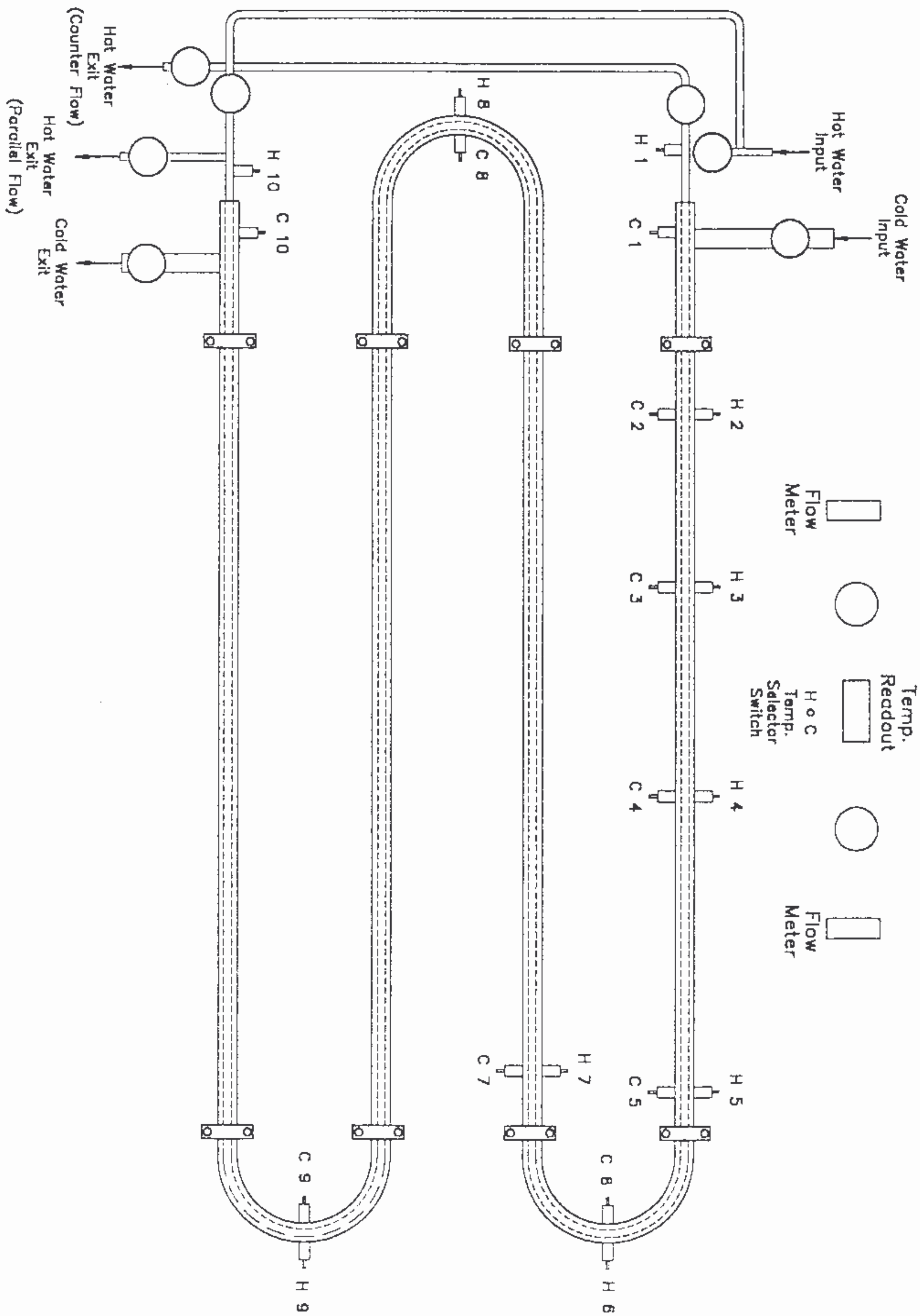
SUGGESTED DATA SHEET

Parallel Flow

Flow		Flow		Flow		Flow		Flow		Flow	
	Temp.		Temp.		Temp.		Temp.		Temp.		Temp.
C1		H1		C1		H1		C1		H1	
C2		H2		C2		H2		C2		H2	
C3		H3		C3		H3		C3		H3	
C4		H4		C4		H4		C4		H4	
C5		H5		C5		H5		C5		H5	
C6		H6		C6		H6		C6		H6	
C7		H7		C7		H7		C7		H7	
C8		H8		C8		H8		C8		H8	
C9		H9		C9		H9		C9		H9	
C10		H10		C10		H10		C10		H10	

Counter Flow

Flow		Flow		Flow		Flow		Flow		Flow	
	Temp.		Temp.		Temp.		Temp.		Temp.		Temp.
C1		H10		C1		H10		C1		H10	
C2		H9		C2		H9		C2		H9	
C3		H8		C3		H8		C3		H8	
C4		H7		C4		H7		C4		H7	
C5		H6		C5		H6		C5		H6	
C6		H5		C6		H5		C6		H5	
C7		H4		C7		H4		C7		H4	
C8		H3		C8		H3		C8		H3	
C9		H2		C9		H2		C9		H2	
C10		H1		C10		H1		C10		H1	



Graph 1: Double Pipe Heat Exchanger

Heat Pump Experiment©

The purpose of this experiment is to become familiar with the operation of a refrigerating system in the heating mode.

The objectives are:

1. To determine the enthalpies at the principle points of the cycle.
2. To determine the heating effect of the system.
3. To determine the coefficient of performance of the system.

Introduction:

The use of the refrigerating system as a heating device or a heat pump was suggested by Lord Kelvin in 1852. It is required that the system worked as an air conditioning during the summer and operated as a heater during the winter season. When operated to remove heat from the room, it is said to operate in the cooling mode; when operated to provide heat to the room, it is said to operate in heating mode. In both the heating and cooling modes, additional energy has to be provided to drive the compressor.

Heat pumps are available in many types, shapes, and sizes, of which those operating on the vapor-compression cycle are the most commonly used.

During cooling mode, heat is absorbed from the room air into the evaporator and pumped to outdoor via the condenser. This process is reversed for the heating mode. The condenser (outdoor coil) picks up the heat, and the evaporator (indoor coil) releases the heat to the room air. Hence, the two coils switch jobs during the heating process.

To avoid confusing, the component names, evaporator and condenser, are dropped when referring to heat pumps. The two coils are referred to as the indoor coil and outdoor coil.

Heat pumps are sometimes called reversed refrigerating cycle. The term reverse is not technically correct since the cycle is not reversed. Only the evaporator (indoor coil) and condenser (outdoor coil) are interchanged. This is usually accomplished by a reversing valve.

A typical vapor-compression heat pump is shown in Fig. 1.

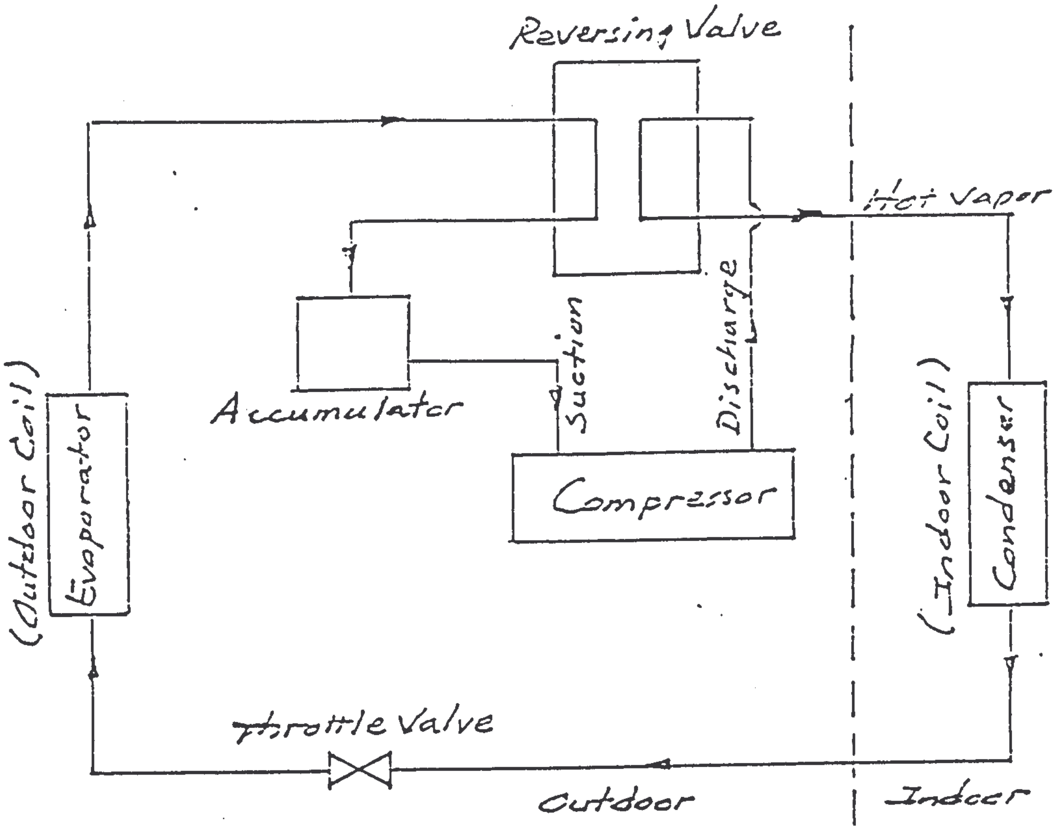


Fig. 1. Heat Pump Cycle

Apparatus:

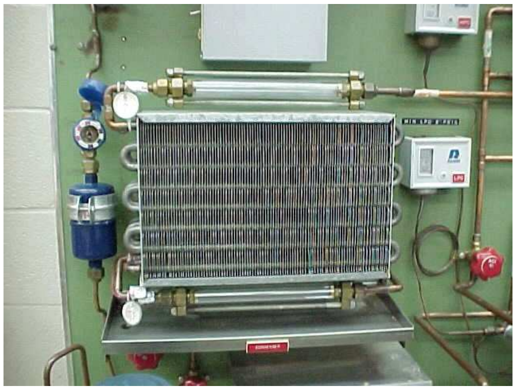
1. Model 9001 Brodhead-Garrett Basic Refrigeration Unit
2. Power measuring device (Watt meter)

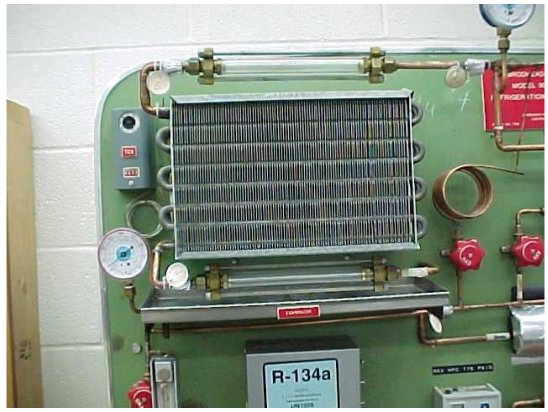
Procedure:

1. Close HP1 and HP4, open FMB, HP2 and HP3.

2. Open CIV, close AXV and TXV, open LR1, LRK, and close LRB.

3. Turn power switch on, evaporator and condenser fan on high, and start compressor.





Which Heat Exchanger is the Evaporator? Condenser?

4. Let system operate for *5* minutes or more until stabilized.

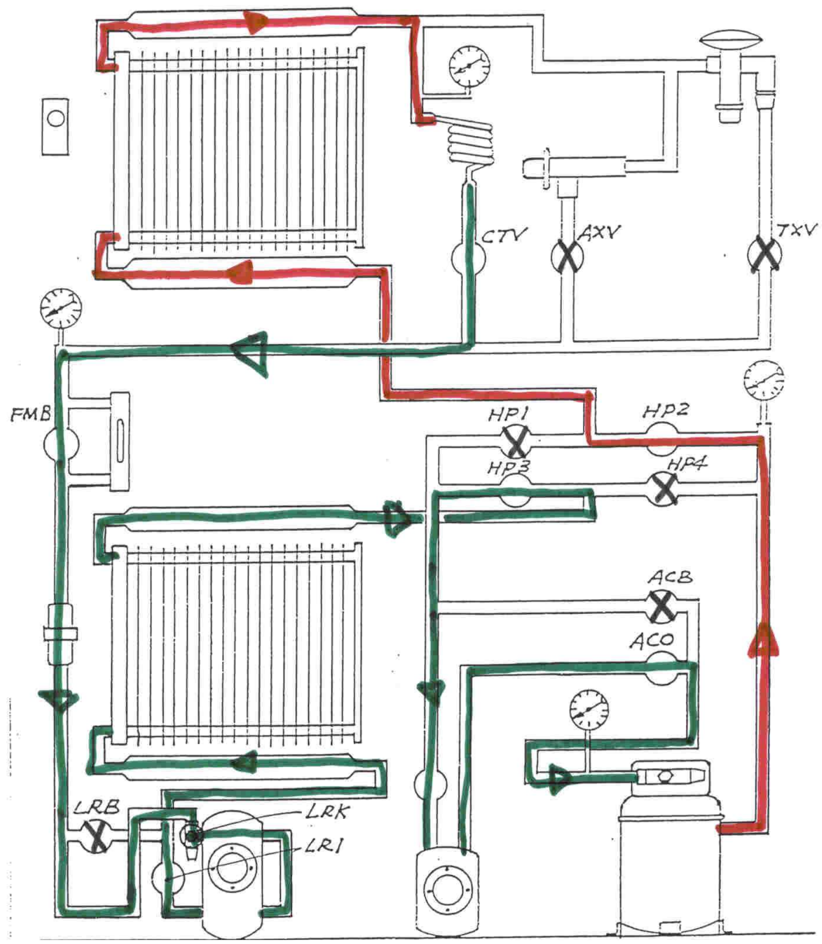
5. Record: Pressure and temperature at the principal points of the cycle, power consumed by the compressor, and refrigerant flow rate.

6. Repeat steps with different fan speeds:
   - Condenser high, Evaporator low
   - Condenser low, Evaporator low
   - Condenser low, Evaporator high

Shut Down

Close LRB, and open LRV and operate until the suction pressure drops to *5* lbs.

Turn the compressor off.



Unit Sketch with Flow Path and Direction

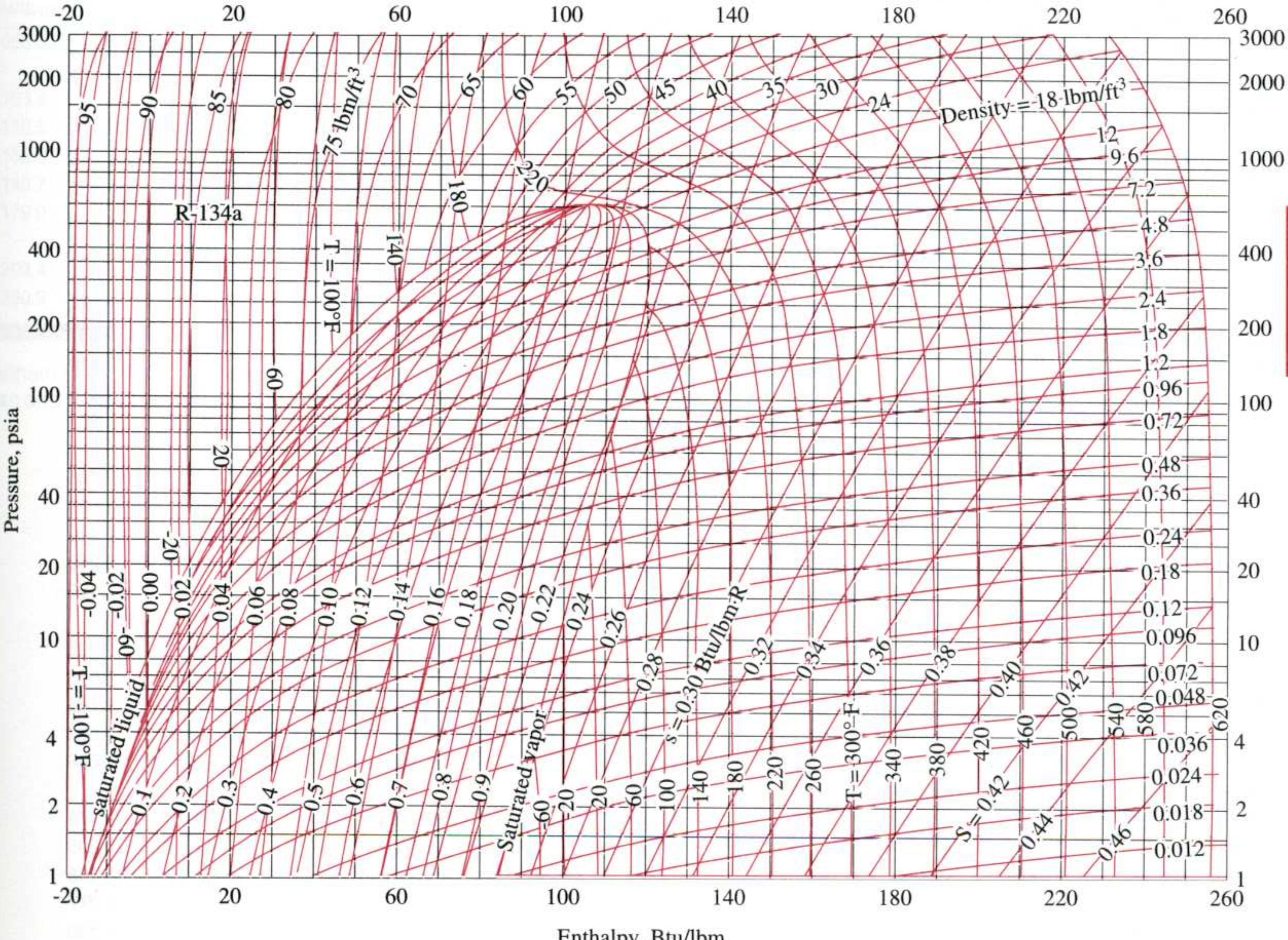
Results:

1. Determine enthalpies at the principle state points.
   Points referred to Fig. 1 in Vapor-Compression (Refrigeration Cycle) Experiment.

2. Determine the heating effect of the heat pump.
   Heating Effect = m refrigerant (h) indoor coil

3. Calculate COP of the heat pump.
   (COP)heat pump = (Heating Effect) / (Work of compressor)

P-h diagram for refrigerant-134a. (Reprinted by permission of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.)



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4. Analysis:

Show the reversed vapor compression cycle state points on the refrigerant diagram. Figure 2. Show these state points also on the unit sketch
For each of the four fan speed combinations find:

1) Enthalpy at principle points

h_1= Btu/lbm

h_2= Btu/lbm

h_3 = Btu/lbm

h_4= Btu/lbm

2) Mass flow rate of refrigerant

Mass flow rate of refrigerant can be determined from the heat balance across compressor

$M_f\ (h_2 - h_1)$ = Compressor power

Compressor power = Power consumption by compressor x compressor efficiency (1 kw = 3412.14 Btu/hr.)

3) Heating effect of heat pump

$Q = M_f\ (h_2 - h_3)$

4) COP of heat pump

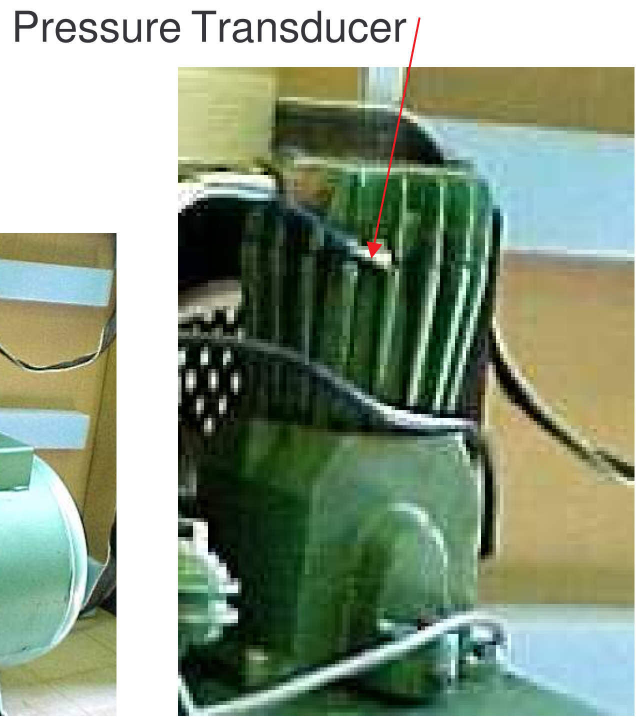
$(COP)_{heat\ pump}$ = Heating effect / Work of compressor

[Work of compressor = $M_f\ (h_2 - h_1)$]

Polytropic Process - Air Compressor Experiment

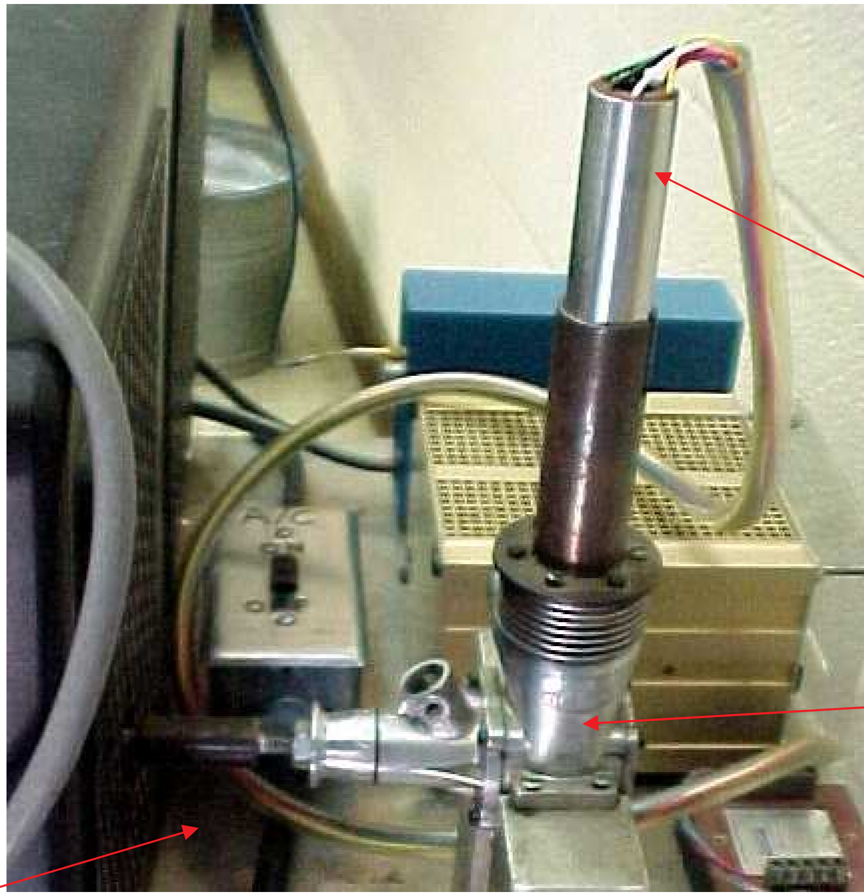
Introduction:

The position of the piston, as it travels up and down in the cylinder of the air compressor, is measured by a linear variable differential transformer (LVDT). The LVDT is attached to an external crank shaft which rotates at the same speed as the compressor. The external crank is coupled to an auxillasry cylinder, so that the LVDT output is maximum when the piston is at bottom dead center and minimum when the piston is at top dead center. Thus, maximum output corresponds to maximum displacement and minimum output corresponds to minimum displacement. The output from the LVDT signal conditioner is measured by a digital storage oscilloscope.



Pressure in the cylinder of the air compressor is measured by a piezoelectric pressure transducer. The pressure transducer consists of a quartz block and electrodes that are attached to a diaphragm. Compressing the diaphragm causes an electric charge at the electrodes that is proportional to the force that has been exerted on the quartz block. The charge is converted to an analog voltage by the signal conditioner. Thus, electrical output of the signal conditioner is proportional to pressure. Pressure will be measured by a digital storage oscilloscope which is connected to the signal conditioner.

The scope can display position vs time and pressure vs time. More interesting is to use the scope to factor time out and plot pressure vs position. Knowing that position is proportional to volume, this becomes a PV diagram.



Apparatus

1. Sears model 106-17012 piston-type air compressor
2. Digital storage oscilloscope
3. X-Y recorder with pen and chart paper
4. Trans-Tek 0216-0000) LVDT
5. Trans-Tek 1000-0012 LVDT signal conditioner
6. PCB H111A26 pressure transducer
7. PCB 482A signal conditioner for pressure transducer
8. Acopian 24GT50D/24GT50D power supply
9. Wattmeter
10. Stroboscope

Procedure

1. **Operating the Air Compressor**

- Adjust the wattmeter range to 1000 Watts and voltage to 125 Volts.
- Open the receiver discharge valve; the receiver may be pressurized, so stand to one side of the valve and do not place hands in front of the air discharge.
- Pressure in the receiver should be limited to 70 psig
- The air compressor should be plugged into the wattmeter. Plug the wattmeter into an ac receptacle to start the air compressor.

2. **Using the digital Storage Oscilloscope (DSO)**

- Properly adjust controls on the DSO
- With the air compressor running and the LVDT signal conditioner energized, adjust Channel A Range and Multiplier until a sine wave is displayed with peak-to-peak amplitude that occupies 20% to 50% of the screen. Rotate the DC Level control until the waveform is centered on the screen.
- Adjust Time Per Point until at least one complete wave, but not more than three complete waves appear.
- Turn Mode switch to NORM. Slowly rotate Threshold control until Trig light begins to glow. Adjust Threshold control so that the sine wave appearing on the screen begins half way between the maximum amplitude and the minimum amplitude.
- Switch Channel A OFF.
- Switch Channel BUN
- Adjust Channel B Range and Multiplier until the peak-to-peak amplitude of the pressure waveform occupies 20% to 50% of the screen. Rotate the DC Level control until the waveform is centered on the screen.
- Switch Channel A ON. The displacement and the pressure waveforms should be displayed. When the piston reaches top dead center and begins to travel downward, air will be drawn into the cylinder and pressure will be approximately atmospheric. As the piston moves up from bottom dead center, the pressure should increase polytropically. The discharge valve opens as displacement continues to decrease, so there will be a sudden decrease in pressure before the piston again reaches top dead center.
- Move Wave display toggle switch to X / Y. A P-V diagram should be displayed. Rotate the Y-Expansion knob, if necessary, to increase the height of the P-V diagram. If pressure vs. time was exactly the same for each power stroke of the compressor, the P-V diagram would appear as a stationary closed loop on the screen. However, because pressure vs. time differs slightly with each cycle, the display may appear as a different [for each cycle.
- Insert a disk into DISK MEMORY. Read/Write (label) side should be toward the right. Press SELECT switch until the LED is illuminated next to track 1 or other specified track for recording data Move PROTECT switch to selected track to OFF.

- Press HOLD LAST to capture the p-v diagram. Observe the rotational speed with a stroboscope and record the rotational speed. Also, record the wails input to the air compressor motor. If the p-v diagram closed on itself, indicating repeatable cycle, press STORE to record the data. If the diagram does not close on itself, press Storage Control to UVE, and when the diagram appears to be closing, press HOLD LAST once again. Repeat these steps, if necessary, until a satisfactory p-v diagram has been recorded.
- Indicated work will be determined from the p-v diagram. Indicated horsepower can then be calculated using the value of indicated work and the rotational speed of the compressor shaft. Input power is displayed by the wattmeter.
- Increase pressure in the receiver to 5 psig by partially closing the receiver discharge valve. Allow the pressure in the receiver to stabilize. Then, record the new p-v diagram and corresponding input power, following the procedure outlined above. Data should be obtained at additional receiver pressures so that everyone has a different set of data to analyze.

3. Determination of the Indicated Horsepower

- The p-v diagrams that have been recorded with the DSO can be plotted on an x-y recorder. The plots should be made on graph paper.
- To output the data from the DSO, first set the control as follows:
- Storage Control HOLD LAST
- Function PEN
- Wave Display X / Y
- Then, use the Track and Recall switches to display the desired set of stored data. The p-v diagram that is displayed can be expanded for clarity using the Vertical and Horizontal Expansion switches. It is usually possible to expand the diagram so that it occupies more than half of the screen. To transfer data to the x-y recorder, begin with the recorder pen in the lift or up position, and press Execute. The DSO will then automatically trace the p-v diagram, converting the points that make up the diagram to analog values, and passing these values on to the x-y recorder. In order to obtain a reasonably large plot of the diagram on the x-y recorder, it may be necessary to adjust the x and y gain controls on the recorder and to repeat the data transfer by pressing Execute again. When the size of the p-v diagram appears to be large enough, lower the recorder pen, press Execute, and plot the diagram.
- The length of the diagram along the x-axis represents a displacement of 9.0 cubic inches. The length of the diagram along the y-axis represents absolute pressure; the value of absolute pressure can be calculated as follows: Position the Wave Display switch to X / T. Then, use the cursor paddle switches to move the cursor to the top of the pressure waveform. Record the millivolts reading that appears on the screen. Use the cursor paddle switches to move the cursor to the bottom of the pressure waveform. Again, record the millivolts reading that appears on the screen. Calculate the difference between the millivolts readings. Multiplying the difference in millivolts readings by the transducer sensitivity results in gauge pressure, i.e.,

  Gauge Pressure = millivolts difference x (0.0335 psi) / millivolts

- Next, obtain the barometric pressure. Convert pressure from inches of mercury to psi using the relation:
  1.GXJ inch of mercury = 0.491 psi
- The largest value of absolute pressure on the p-v diagram is the sum of the barometric pressure (psi) and the gauge pressure. The smallest pressure on the p-v diagram is the barometric pressure (psia).
- The p-v diagram can now be scaled. Measure the distance (in centimeters or inches, depending on the x-y recorder and scale of the graph paper that has been selected) from the maximum value of displacement to the minimum value of displacement. The scale factor for the x-axis will be

  X-axis scale factor = (9.00) in3) / (Length of diagram along X-axis)
- Measure the distance from the maximum value of pressure to the minimum value of pressure. The scale factor for the Y-axis will be

  Y-axis scale factor = (Gauge pressure) / (length of diagram along Y-axis)
- The indicated work is indicated by the area of the p-v diagram. The area can be estimated by counting the squares on the graph paper that are contained inside the p-v diagram. It is also possible to determine area using a planimeter. To calculate indicated work,

  Indicated work = Area x X-axis scale factor x Y-a scale factor
- Note that units of work are inch pounds. Convert units of work to fool pounds.
- The amount of work indicated by the p-v diagram is performed by the compressor each time the crankshaft completes one revolution. Power is the rate at which work is produced. Therefore, the indicated horsepower can be calculated,

  Indicated HP = RPM x Indicated Work x HP / 33,000 ft-lb / min.

4. Input Horsepower

The input horsepower to the electric motor was measured by the wattmeter, and must be converted from watts to horsepower using the relation,

1HP = 746 watts

5. Overall Efficiency

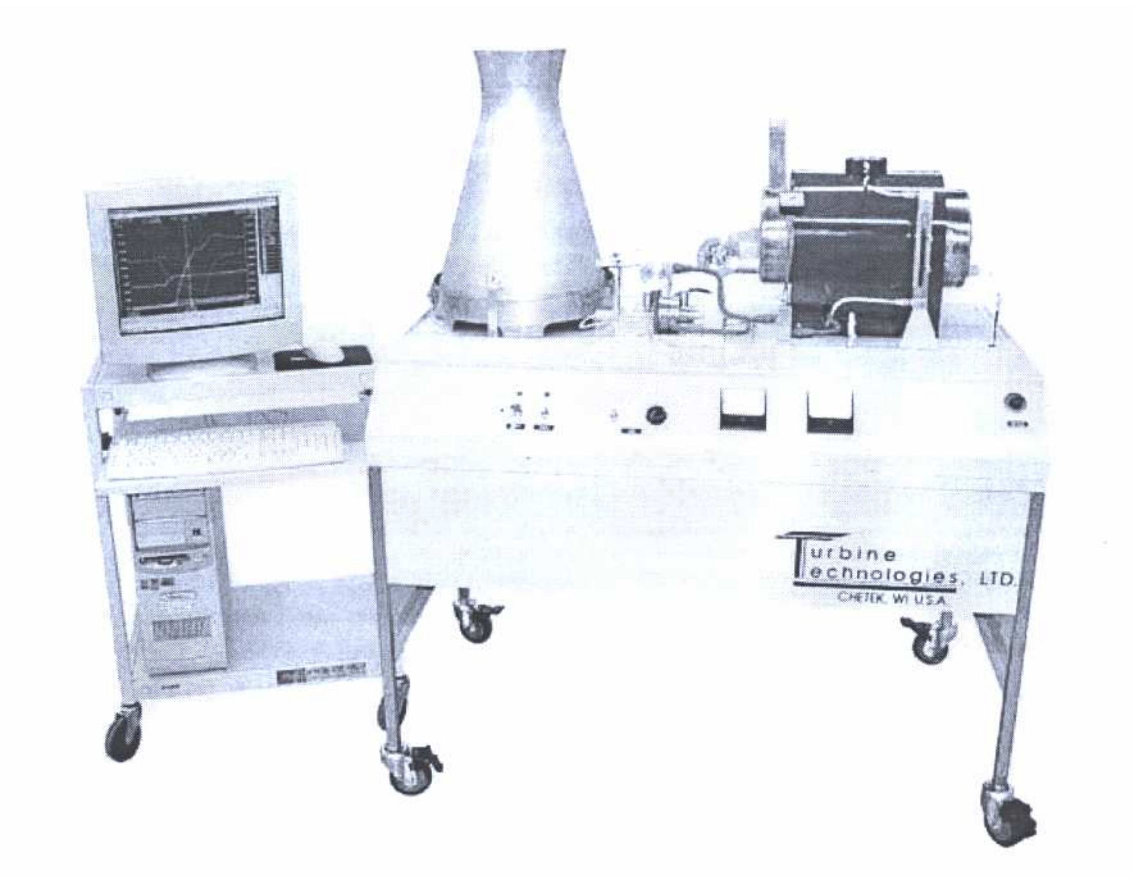
- The overall efficiency is the air compressor can be estimated,

Overall efficiency = (Indicated horsepower) / (Actual horsepower) x 100%

Turbine Technologies Ltd.

Steam Turbine Experiment

An Educational, Micro-Electric Power-Generating Station



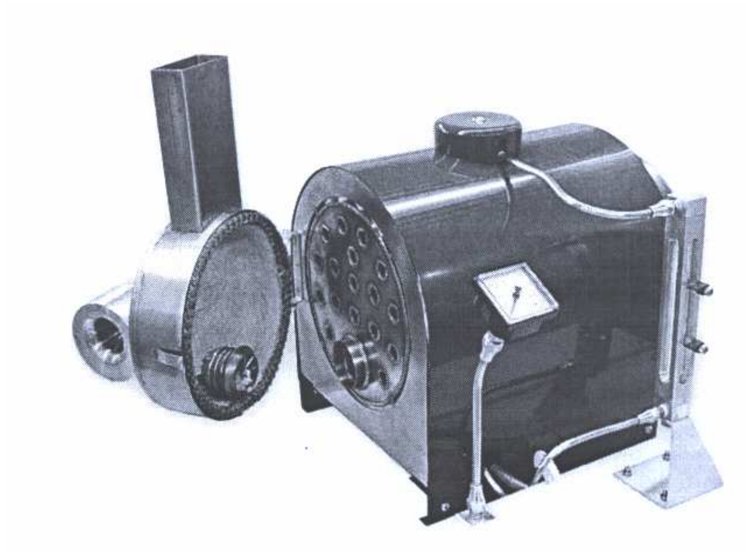
I. Objective

The objective of this laboratory is to offer students hands-on experience with the operation of a functional steam turbine power plant. A comparison of real world operating characteristics to that of the ideal Rankine power cycle will be made.

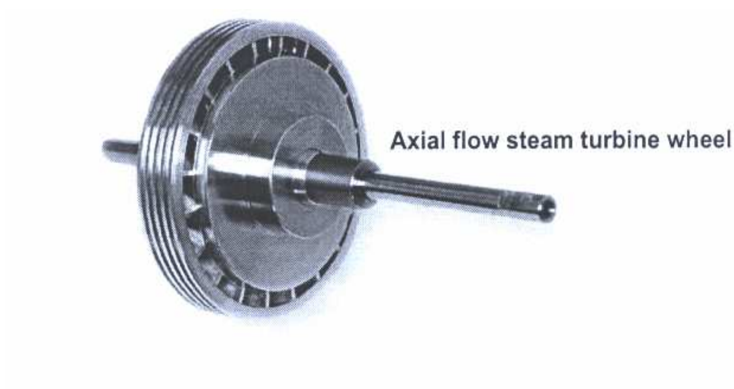
The apparatus is scaled for educational use and utilizes components and systems similar to full-scale industrial facilities. Students will be able to operate and analyze this system in detail, allowing them to determine the efficiency of the facility and suggest possible modifications for further improvement. The turnkey laboratory system carries the trade name of RankineCycler

II. Theory

The Rankine cycle is the most common of all power generation cyles and is diagrammatically depicted via Figures 1 and 2. The Rankine cycle was devised ot make use to the characteristics of water as the working fluid. The cycle begins in a boiler (State 2 in figure 1), where the water is heated until it reaches saturation-in a constant-pressure process.



Once saturation is reached, further heat transfer takes place at a constant temperature, until the working fluid reaches a quality of 100% (State 3). At this point, the high-quality vapor is expanded isentropically through an axially bladed turbine stage to produce shaft work. The steam then exits the turbine at State 4. The working fluid, at State 4, is at a low-pressure, but has a fairly high quality, so it is routed through a condenser, where the seam is condensed into liquid (State 1).



Finally, the cycle is completed via the return of the liquid to the boiler, which is normally accomplished by a mechanical pump* (See notation under Figure 3).

Figure 1 below shows a P-v diagram for a simple ideal Rankine cycle (refer to your thermodynamics text for additional details)

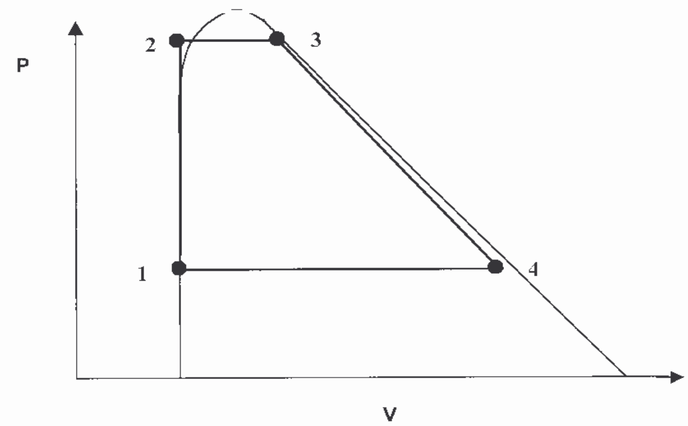


Figure 1. P-v diagram for simple ideal Rankine

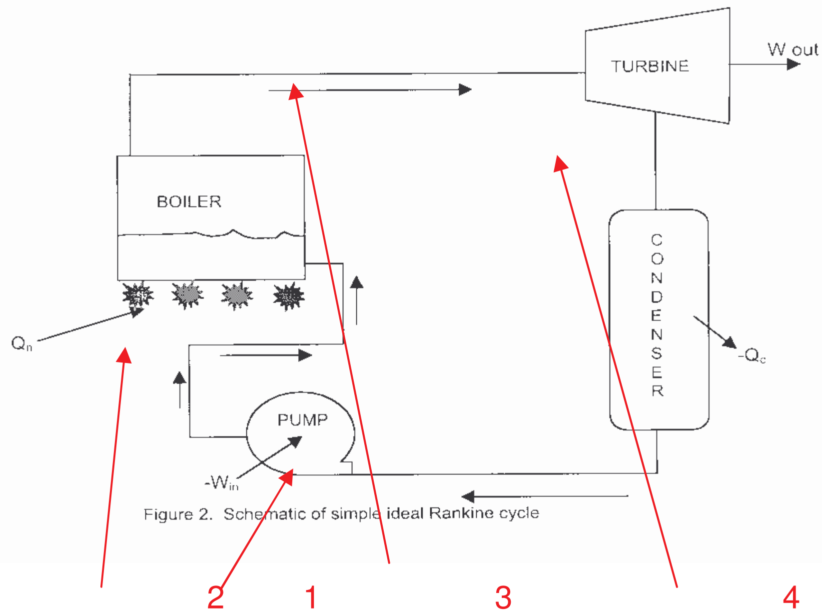


Figure 2. Schematic of simple ideal Rankine cycle

<u>Installed sensor list includes:</u>

1. Boiler pressure	2,3	
2. Boiler temperature	3	
3. Turbine inlet pressure		3
4. Turbine inlet temperature	3	
5. Turbine exit pressure		4
6. Turbine exit temperature	4	
7. Fuel flow	FF	
8. Generator voltage output	V	
9. Generator amperage output		A

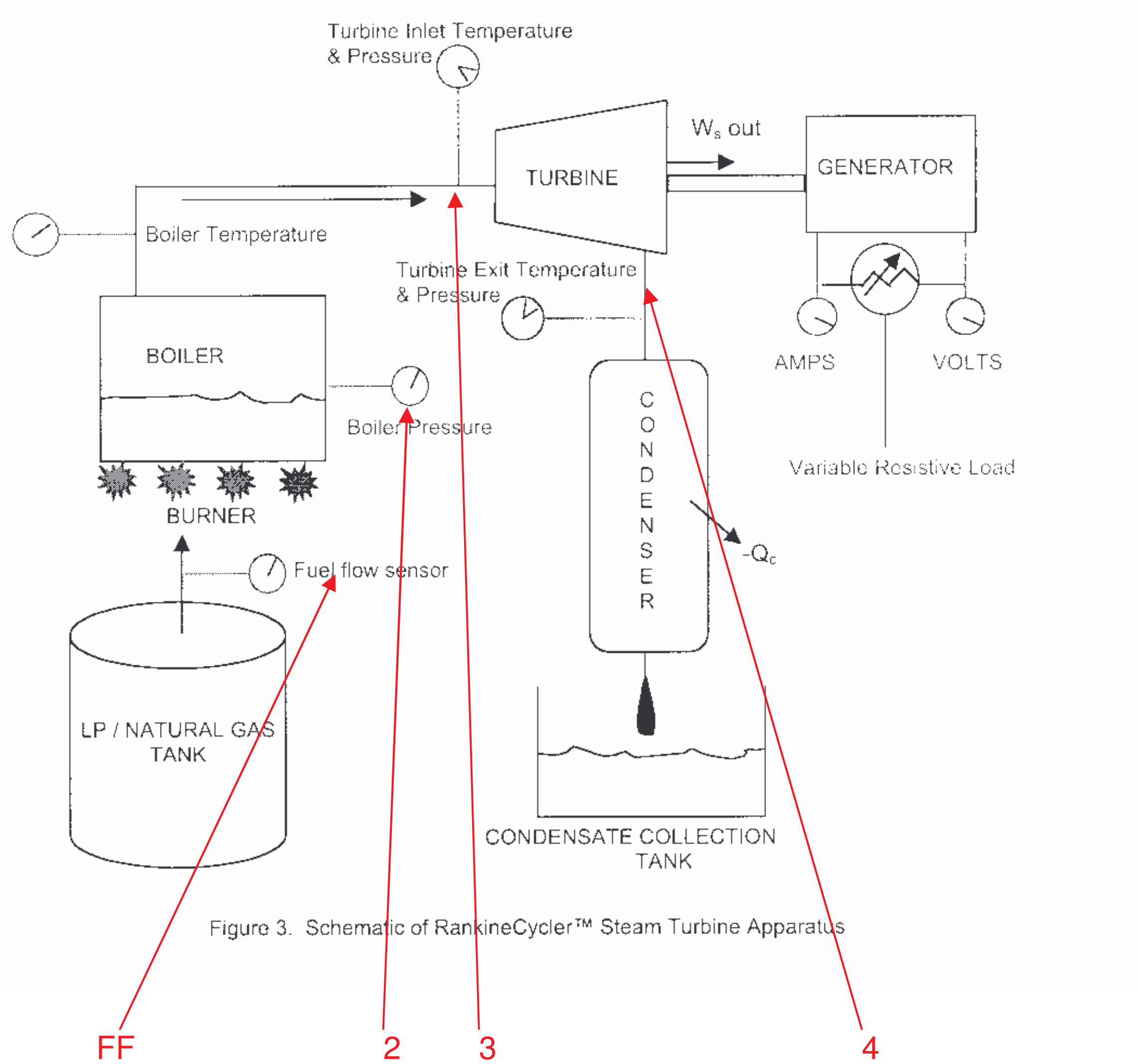


Figure 3. Schematic of RankineCycler™ Steam Turbine Apparatus

<u>Calculate</u>:

- $h_{1,2,3,4}$, Using $T_{1,2,3,4}$ and $P_{1,2,3,4}$ respectively
- Qin
- Wout of generator
- Efficiency

<u>Graph</u>:

- the cycle on a Mollier diagram to the extent possible.

III. Experimental Apparatus

The experimental hardware (RankineCycler™) consists of multiple components that make up the necessary components for electrical power generation (utilizing water as the working fluid). These components include:

Boiler

A stainless steel constructed, dual pass, flame-through tube type boiler, with super head dome, that includes front and rear doors. Both doors are insulated and open easily to reveal the gas fired burner, flame tubes, hot surface igniter and general boiler construction. The boiler walls are insulated to minimize heat loss. A side mounted sight glass indicates water level.

Combustion Burner / Blower

The custom manufactured burner is designed to operate on either LP or natural gas. A solid-state controller automatically regulates boiler pressure via the initiation and termination of burner operation. This U.L approved system controls electronic ignition, gas flow control and flame sensing.

Turbine

The axial flow steam turbine is mounted on a precision-machined stainless steel shaft, which is supported by custom manufactured bronze bearings. Two boiler ports supply lubrication to the bearings. The turbine includes a taper lock for precise mounting and is driven by steam that is directed by and axial flow, bladed nozzle ring. The turbine output shaft is coupled to an AC/DC generator.

Electric Generator

An electric generator, driven by the axial flow steam turbine, is of the brushless type. It is a custom wound, 4-pole type and exhibits a safe/low voltage and amperage output. Both AC and DC output poles are readily available for analysis (rpm output, waveform study, relationship between amperage, voltage and power). A variable resistor load is operator adjustable and allows for power output adjustments.

Condenser Tower

The seamless, metal-spun condenser tower features 4 stainless steel baffles and facilitates the collection of water vapor. The condensed steam (water) is collected in the bottom of the tower and can be easily drained for measurement/flow rate calculations.

The experimental apparatus is also equipped with an integral computer data acquisition station, which utilizes National Instruments™ data acquisition software

The fully integrated data acquisition system includes 9 sensors. The sensor outputs are conditioned and displayed in “real time”- on screen. Data can be stored and replayed. Run data can be copied off to floppy for follow-on, individual student analysis. Data can be viewed in Notepad, Excel, and MSWord (all included).

The system is test run at the factory prior to delivery and the “factory test run” is stored on the hard drive under the “My documents” folder. This file should be reviewed prior to operation as it gives the participant an overview of typical operating parameters and acquisition capability.

SENSORS

Nine (9) sensors are installed at key system locations. Each sensor output lead is routed to a centrally located terminal board. A shielded 64-pin cable routes all data to the installed data acquisition card. This card is responsible for signal conditioning and analog to digital conversion. Software and sensor calibration is accomplished at the factory prior to shipment.

Installed sensor list includes:

1. Boiler pressure
2. Boiler temperature
3. Turbine inlet pressure
4. Turbine inlet temperature
5. Turbine exit pressure
6. Turbine exit temperature
7. Fuel flow
8. Generator voltage output
9. Generator amperage output

OVER ALL SYSTEM DIMENSIONS

Length:	48.0 inches (122cm)
Width:	30.0 inches (77 cm
Height:	58.0 inches (148 cm)

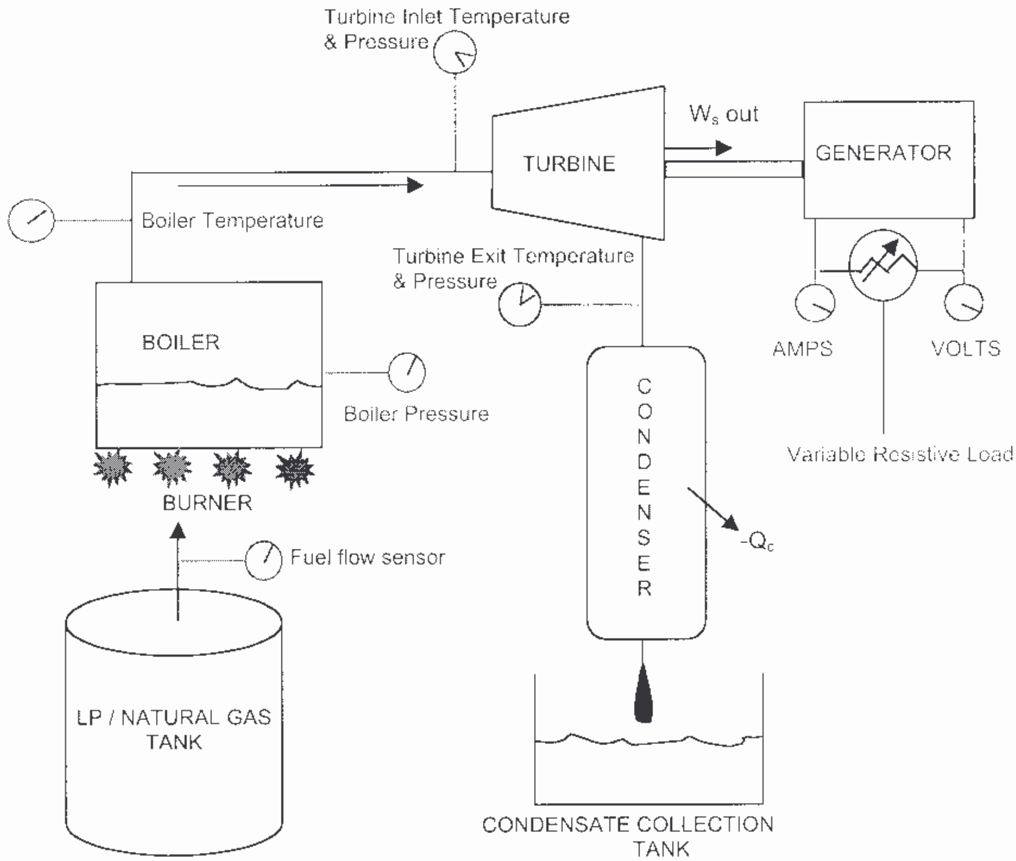


Figure 3. Schematic of RankineCycler™ Steam Turbine Apparatus

*Note: When compared to figure 2 (simple ideal Rankine cycle), the steam ejected from the RankineCyclerTM turbine condenses into liquid via the condenser tower and then exits the condenser into a collecting volume at the condensers base, rather than being pumped back to the boiler. The condensate can subsequently be weighed. This allows for measurement of the mass flow rate of the working fluid, by means of collection. This represents the main difference between the simple Rankine cylcle described in figure 2, since the liquid exiting the condensers is dispensed, rather than pumped back to the boiler.

The RankineCycler™ apparatus schematic depicted on the previous page allows students to monitor the power plant system and obtain data from the 9 installed sensors (depicted in green, Figure 3).

Thermocouples and pressure transducers located at various locations in the steam loop allow for monitoring of pressures and temperatures, which can be used to determine the state of the working fluid at appropriate locations.

IV. General Safety

The RankineCycler^{TM} apparatus exhibits hot surfaces during operation. Equipment familiarization is particularly important in order to prevent injury. Under no circumstance should anyone attempt to open boiler doors during operation, or at anytime that the boiler exhibits a positive pressure reading. The boiler has been low cycle fatigue pressure tested. Ultimate operating pressures that exceed normal operating pressures by 50% have been tested. NEVER ATTEMPT TO EXCEED MAXIMUM OPERATING PRESSURE. DO NOT ATTEMPT TO MAKE ANY ADJUSTMENTS TO SAFETY DEVICES AND OR CONTROLS TO ATTEMPT OPERATIONS OUTSIDE OF ESTABLISHED LIMITS. The boiler is not ASME rated, nor is it approved by any other test facility. IMPROPER USE MAY CAUSE DEATH OR SERIOUS INJURY. Should any questions arise regarding the safe operation of this equipment, please speak to your laboratory supervisor.

Personal protection

This plan is a sample plan of precautionary measures that should be considered to prevent injury during the use of the RankineCycler^{TM} and may or may not be more stringent than your current lab safety plan. It should be used as a guide only. Safety measures must be taken during all use of laboratory equipment. Consult your lab safety specialist for a detailed, site-specific plan.

Suggested Protection Devices:

Gloves

Eye Protection

Splash Protection

Fire Extinguisher

Posted Emergency Exit

Posted Emergency Numbers

Before developing your own personal protection plan, you first need to read and review the RankineCycler^{TM} owner's manual, as well as your facility's general lab safety plan and procedures.

Combustion is taking place and results in hot surfaces. Do not touch any surface unless familiar with the system.

Before use, the boiler should be checked to verify component integrity. DO NOT USE the RankineCycler^{TM} unless given explicit permission to do so.

During use, the following should be worn at all times: gloves, safety goggles and a splash apron. Jeans and a long sleeved shirt are much better than shorts and a t-shirt. The heavier clothing will provide some protection in the event hot surface or vapor contact.

Familiarize yourself with the location of the nearest fire extinguisher. If the RankineCycler^{TM} is running and you notice the smell of natural gas or LP (dependent upon fuel type used), quickly turn off the gas and exit the room. Notify your supervisor that a potential gas leak exists.

Assure that emergency contact numbers are posted and that you are aware of the nearest exit and phone locations. Also, be sure you know where the laboratory first aid kit is located and that it is properly stocked.

V. RankineCyclerTM Operation

Do not begin any operation without proper supervision. The operation of the equipiment will be done only by a trained lab technician or faculty member..

RankineCycler entails the following operator controls:

GAS VALVE

The gas valve is a simple two-position valve (On or Off). It is located on the far right side of the slanted operator control panel. It will prevent gas flow to the burner when in the off position-regardless of any other control positions/settings.

KEYED MASTER SWITCH

The systems electronic master switch is key operated and is located on the left side of the operator control panel. This key switch supplies power to all electronic and electrically operated components. A green indicator light located directly above the keyed master switch, will light when the master switch is selected to the on position and power is available to the switch.

BURNER SWITCH

The burner switch is labeled as such and is located next to the keyed master switch. The burner switch powers the automatic gas valve and ignition controls. A green indicator light, located directly above the burner switch, will light when the burner switch is selected to the on position and power is available to the switch.

LOAD SWITCH

The load switch functions as a generator load d switch

LOAD RHEOSTAT CONTROL KNOB

The load rheostat control knob is connected in series with the load toggle switch and generator DC output terminals. It provides a source of variable generator load

AMP METER

The amp meter indicates generator load conditions.

VOLTMETER

The voltmeter indicates the generator voltage output.

STEAM ADMISSION VALVE

The steam admission valve controls the steam flow rate to the steam turbine

Sensors

Pressure, Temperature and Flow Sensors facilitate collection, storage and retrieval of “real time” data.

GAS FLOW

The gas flow sensor is a turbine-based flow-metering unit. It is installed inside of the operator panel and interfaced with the computer data collection station. Gas flow rates are depicted on the PC's monitor via a graphical and numerical presentation.

BOILER PRESSURE AND TEMPERATURE

Boiler pressure and temperature data is collected via transducer and thermocouple sensors, respectively. The sensor output is calibrated to read in engineering units via the PC data acquisition presentation.

STEAM TURBINE INLET & OUTLET PRESSURE & TEMPERATURE

Inlet and outlet pressure and temperature sensors for the steam turbine are installed in the steam turbines front and rear housings. Pressure transducers are located within the front operator panel enclosure. Temperature sensing thermocouples are plug connected and routed to the data acquisition terminal board. The terminal board features on board cold junction compensation.

OPERATIONAL CHECKLISTS

PRE-START

1. Determine suitability of operational location (i.e. adequate ventilation, access to 110V power)

2. Lock caster wheels

3. Perform visual inspection to check for general system condition (sight glass, piping, boiler, overall system integrity).

4. Assure front and rear boiler doors are latched

5. Open steam admission valve. Do not attempt to fill boiler while hot or under pressure.

6. Insert supplied fill/drain fitting (hose attached) into filler port located at the rear of the boiler (opposite side of instrument panel). Attach a funnel to end of hose arid hold funnel above boiler height.

7. Fill boiler with clean tap water (if the boiler doesn't appear to be accepting water, pull filler fitting out slightly until water starts to flow into boiler. If fitting is pulled out too far, water will spill onto the base cabinet).

The actual boiler diameter is equal to the door diameter. Do not fill the boiler to a higher level than to 3/4ths the height of the door height.

8. Remove filler hose.

9. Close the steam admission valve

10. Turn load switch to "off" position

11. Turn burner switch to "off" position

12. Turn load rheostat knob fully counter clockwise (minimum load).

13. Insert multi pin computer plug into terminal board on left side of RankineCycler cabinet.

14. Plug computer power cord into 115 VAC outlet

15. Plug RankineCycler power cord into 115 VAC outlet

16. Connect gas pressure regulator to LP gas tank

17 Connect low pressure gas hose from regulator exit to barbed RankineCylcler gas inlet fitting (located on the right side of the operator control panel) Assure leak free connection Allow any remaining condensate to drain from the tower by locating attached condenser drain hose and squeezing hose fitting to “un-pinch” the drain hose. Hold hose below condensate tower and drain tower water into any available container.

18. Remove knurled screw caps from steam turbine front and rear oilers.

19. Fill oilers to within 1/8th inch from the top of the oiler with turbine oil that meets Mil-L-23699C specifications.

NOTE: OIL MUST BE ADDED TO THE OILERS AFTER EACH RUN. DO NOT ATTEMPT TO START WITHOUT CHECKING OIL LEVEL. TURBINE BEARING WILL OCCUR WITHOUT PROPER LUBRICATION.

START

1. Open LP bottle gas valve

2. Turn gas valve knob CCW to “on” position

3. Turn master switch on (observe green indicator Light on)

4. Turn burner switch on (observe green indicator light on)

NOTE: *Combustion blower starts automatically. Wait for 30 seconds. This will allow the lines to purge. Then turn the burner switch to the “off” position and immediately back on (this step can be eliminated from the start procedure if the system has previously been operated using the currently attached LP source). This resets the starting cycle and assures that the lines are purged. After approximately 20 seconds, the automatic gas valve will open and the burner will light.*

5. Boiler pressure indication should be observed within 3 minutes of ignition.

NOTE: SHUT OFF BURNER SWITCH IF THE BOILER PRESSURE EXCEEDES 130 PSIG. *Automatic regulation should assure shutoff at approximately 120 psig. In the event of over pressure (exceeding 125 psig) contact Turbine Technologies Ltd.*

6. Power up data acquisition station and open “Virtual Bench” on desktop

7. Observe voltmeter and open steam admission valve. Regulate turbine speed to indicate 7-10 volts. This will pre-beat turbine components and pipes. Close valve after 20 seconds and wait for boiler pressure to rise. Very small leaks may be visible due to condensation and cold turbine bearing clearances. This is normal and will stop after normal operating temperatures are attained.

8. Open steam admission valve to read close to maximum voltage.

9. Turn load switch to “on”position.

10. Adjust load rheostat knob and steam admission valve to obtain a steady state power output. 9 volts and 0.4 amps are good values for steady state operation.

11. Mark time and set upper sight glass bezel to current water level. Fine adjust steam admission valve for steady state operation

SHUT DOWN

1. Close steam admission valve when sight glass water level reaches the pr-selected lower bezel setting

2. Move burner switch to “off” position

3. Turn gas valve off

4 Turn LP gas bottle valve off

5. Hold heat resistant measuring beaker under condenser tower drain. Drain condensate by squeezing hose pinch. Measure condensate. **CAUTION**: *Water may be hot*

6. Wait until boiler cools and pressure is below 10 PSIG. Then open steam admission valve. When boiler pressure equals atmospheric, fill a measuring beaker with clean tap water and re-fill boiler via the boiler’s drain/fill port- to the exact sight glass upper bezel level. The measured or weighted re-fill mass represents the boilers total steam production and can be correlated as steam rate by dividing the water weight by the duration of the run (found be Looking at the start and stop time of the run as measured by the data acquisition station.

EMERGENCY SHUTDOWN

1. Unplug RankineCycler power cord

2. Move to a safe distance

3. If safety is not compromised: Turn burner switch off, turn road rheostat to maximum, open steam admission valve to obtain maximum voltage.

OPERATIONAL DO’S AND DON’T’S

DO’S

Read, remember and follow operator’s manual

Watch gage readings at all times

Check oil levels on turbine oilers often

Remember the working fluid is pressurized, hot steam

Develop your own protection plan

See through operator shielding, personal protective gear! etc.

Look caster wheels

Provide good ventilation

DON’T’S

Do not tap sight glass, scratch or mark

Do not tighten or adjust fittings while boiler is under pressure

Do not touch parts that are not labeled (hot components)

Do not operate boiler with water level below 4 inches or above 6.5 inches

Do not move unit with the boiler under pressure

Do not attempt to open fill/drain valve when boiler is hot

Do not exceed scale readings on volt or amp meter

Do not allow anyone to operate the unit that is not familiar with the Operating v1anual and the systems practical usage

Do not operate unattended

VI. Data Acquisition, General Discussion

The RankineCycler^{TM} comes equipped with a turnkey data acquisition system. The PC hardware is located on a wheeled cart as depicted on the front cover of this manual. A 64-pin interface cable is routed from this station to the RankineCycler^{TM} terminal board. Nine (9) data points (pressures, temperatures, fuel flow, voltage and amperage) are collected via installed sensors.

The Sensor Parameter Chart (Table A) indicates the function, manufacturer/type, range and output value of the installed sensors. Table B depicts the physical location of the sensor on leads on the terminal board.

TABLE A
Sensor List

Function	Manufacturer/type	Range (PSIG)	Output (V)
Boiler Pressure	Setra Model 209	0-200	0.5 - 5.5
Turbine Inlet Pressure	Setra Model 209	0-200	0.5 - 5.5
Turbine Exit Pressure	Setra Model 209	0-25	0.5 - 5.5
Boiler Temperature	K-Type Thermocouple		
Turbine Inlet Temperature	K-Type Thermocouple		
Turbine Exit Temperature	K-Type Thermocouple		
Fuel flow sensor	Dwyer TF2110	2-10 liters/min	
Generator Voltage			
Generator Amperage			

TABLE B
Data Acquisition Port Illustration

Channel 8 Fuel Flow -	Channel 15 open
Channel 8 Fuel Flow +	Channel 15 open
Channel 7 Turbine Exit Temperature -	Channel 14 open
Channel 7 Turbine Exit Temperature +	Channel 14 open
Channel 6 Turbine Inlet Temperature -	Channel 13 open
Channel 6 Turbine Inlet Temperature +	Channel 13 open
Channel 5 Boiler Temperature -	Channel 12 open
Channel 5 Boiler Temperature +	Channel 12 open
Channel 4 Turbine Exit Pressure -	Channel 11 open
Channel 4 Turbine Exit Pressure +	Channel 11 open
Channel 3 Turbine Inlet Pressure -	Channel 10 Generator Amperage -
Channel 3 Turbine Inlet Pressure +	Channel 10 Generator Amperage +
Channel 2 Boiler Pressure -	Channel 9 Generator Voltage -
Channel 2 Boiler Pressure +	Channel 9 Generator Voltage +

VI. Possible Experimental Procedures

The following laboratory procedures should be used as a guide for possible student activities.

Sample labs:

The lab technician will start the facility and assist students in changing conditions. The students' primary function is to gather data at the appropriate time for each run condition. This is accomplished via the system installed software.

The condensate collection reservoir, when drained, will yield the mass flow rate (when divided by the testing interval time.

EES Power Cycle Design for Best Efficiency

Objective

The purpose of this lab is to gain insight on vapor power systems and the effectiveness of their operation. For this experiment the overall efficiency of vapor power systems will be studied. With the use of Engineering Equations Solver a power cycle will be designed. The objective is to create a power system and alter it in different ways to achieve the greatest efficiency.

Background

Vapor power systems are a type of cycle that converts energy to a useful state. The main goal of these systems is to produce a power output from a fossil fuel, nuclear, or solar energy input. In those cycles a working fluid is vaporized and then condensed. This is done using many components: however the general main components include the following:

-Heater (boiler)

-Turbine

-Condenser

-Pump

Each of these components performs a key role in creating an output from the energy input. The heater, most often a boiler, uses the energy input from burning fossil fuels, nuclear, or solar energy to heat and evaporate the working fluid. The working fluid, now a vapor, then passes through the turbine creating a work output. The condenser transfers heat from the vapor working fluid to make it sub cooled liquid. The pump uses a work input to move the liquid back through the cycle.

Equations to be used

$$\frac{\dot{W}_t}{\dot{m}} = h_2 - h_3$$

Thermal efficiency of this system is defined by the following;

$$\eta = \frac{\frac{\dot{W}_t}{\dot{m}} - \frac{\dot{W}_p}{\dot{m}}}{\frac{Q_{in}}{\dot{m}}} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$$

<u>Procedure</u> (a computer with EES software is required)

1. With EES define (within reasonable limits) the temperature and pressure at each of the stages in the cycle.

T_1=

P_l=

2. Next define that the b for each stage is the enthalpy for the working fluid at T and P
3. Use a variable, such as _, which will be the efficiency of the cycle and enter the equation that defines thermal efficiency of the cycle,
4. Solve the equation in EES to find the efficiency of the cycle with the given stage temperatures and pressures.
5. Change the temperatures and pressures ant each state to get a better efficiency.
6. Repeat the procedure until an acceptable efficiency is achieved.
7. If necessary, such things as reheat or second turbine stages may be modeled in the system.

Analysis of results

1. <u>Calculate</u>:
   a. h $_{1,2,3,4}$, Using $T_{1,2,3,4}$ and $P_{1,2,3,4}$ respectively
   b. Qin
   c. Wout of generator
   d. Efficiency

2. <u>Graph</u>:
   a. This cycle on a Mollier diagram to the extent possible.
3. Explain differences from ideal Rankine cycle.

Appendix

The following section is a general description of the Rankine Cycle as it relates to Thermodynamics, Heat Transfer, and Fluid Mechanics.

Theoretical Background of Thermodynamics

One of the most important ways to convert energy from such things as fossil fuels, nuclear, and solar potential energy is through processes known as vapor power cycles. One example of the use of vapor power cycles is electrical power plants. As engineers it is important to become familiar with these types of systems. The first step in becoming familiar with these cycles is through studying the theoretical ideal of the processes.

The ideal cycle for vapor power cycles can be modeled using the Rankine Cycle. This cycle is composed of four components: heater (boiler), turbine, condenser, and pump. To complete the system there must be some type of fluid in the cycle, which is called working fluid. Most often the working fluid is water. As the working fluid passes through each of the components it undergoes a process and ends up at a new state. Keeping in mind that the ideal Rankine cycle is physically impossible, we define each process to involve no internal irreversibility's. For the following it is necessary to number each of the states. State 1 is the state that at the boiler exit. State 2 is the turbine exit. State 3 is the condenser exit and state 4 is the pump exit.

Now the processes that the working fluid undergoes as it completes the cycle will be defined. First is the heater, which in most cases is a boiler. As the fluid ends the cycle, at state four, it is pumped into the boiler. In the boiler, the working fluid is heated from sub-cooled liquid to saturated vapor. This occurs at a constant pressure and is described in the following equation:

$$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4 \qquad \text{Equation 1}$$

Where $\frac{\dot{Q}_{in}}{\dot{m}}$, is the rate of heat addition per unit mass of working fluid passing through the boiler.

The value ($h_1 - h_4$) is the difference in outlet and inlet enthalpies of the working fluid.

Second is the turbine. Through the turbine the vapor leaving the boiler expands to the condenser pressure. This is said to be isentropic expansion so that no heat transfer to the surroundings is present. The equation that is used to describe this process is as follows

$$\frac{\dot{W}_{turbine}}{\dot{m}} = h_1 - h_2 \qquad \text{Equation 2}$$

$\frac{\dot{W}_{turbine}}{\dot{m}}$ is the rate at which work is developed per unit of mass passing through the turbine.

Again the difference in inlet and exit enthalpies of the working fluid is required. Next the working fluid enters the condenser. At this stage beat is rejected from the vapor at a constant pressure. Ideally, this continues until all of the vapor condenses to leave nothing but saturated liquid. The equation for this is seen here:

$$\frac{\dot{Q}_{out}}{\dot{m}} = h_2 - h_3$$ Equation 3

$\frac{\dot{Q}_{out}}{\dot{m}}$ is the rate at which heat is transferred from the working fluid per unit of mass. The value (h2 – h3) is the difference inlet and outlet enthalpies of the condenser.

Finally, the working fluid enters the pump. The fluid goes through an isentropic compression process to reach the boiler pressure. The equation describing this is as follows:

$$\frac{\dot{W}_{pump}}{\dot{m}} = h_4 - h_3$$ Equation 4

$\frac{\dot{W}_{pump}}{\dot{m}}$ rate of power input per unit of mass passing through the pump. Finally the difference in pump outlet enthalpy and inlet enthalpy is needed.

Theoretical Background of Heat Transfer

A heat exchanger is a device that facilitates the transfer of energy between two fluids at different temperatures while keeping them from moving. Heat exchangers allow two types of heat transfer to occur. Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion. Conduction is the interaction of particles, which transfers energy from more energetic particles to the less energetic ones. The rate of energy transfer between two fluids depends on the temperature difference between the two fluids, which varies along the length of the heat exchanger.

A heat exchanger in which one fluid condenses as it flows and gives off heat is called a condenser. A heat exchanger that involves one fluid absorbing heat and vaporizing is known as a boiler.

Newton's law of cooling allows the rate of heat transfer to be expressed as:

$$\dot{Q} = U * A * \Delta T_{lm}$$ Equation 5

A is the heat transfer area. U is the overall heat transfer coefficient. This can be determined from the equation.

$$\frac{1}{U} \approx \frac{1}{h_i} + \frac{1}{h_o}$$ Equation 6

_ T_{lm} is the logarithmic mean temperature difference:

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$ Equation 7

Theoretical Background of Fluid Mechanics

Fluid mechanics is concerned with the behavior of liquids and gases at rest and in motion. The RankineCyclerTM applies two main topics of fluid mechanics: viscous pipe flow and turbo-machinery.

Viscous pipe flow will either be completely filled or it will be partially filled open channel. It should be assumed that the steam moving through the pipe is completely filling the pipe. Determining how the flow is moving through the pipe is also important. Laminar, transitional, and turbulent flow could show up each of these cases has a different governing set of equations

$$Q = V*A \qquad \text{Equation 8}$$

If the cross-sectional area, A, and the velocity, V, is known the volumetric flow rate, Q, can be found. It is also essential to find the Reynolds Number

$$\mathrm{Re} = \frac{\rho V D}{\mu} \qquad \text{Equation 9}$$

Where: r, is the density of the working fluid, V, is the average velocity in the pipe, D, is the pipe diameter, and m, is the dynamic viscosity of the fluid. The Reynolds Number will help determine the type of flow. If the Reynolds Number in a round pipe is less than ~ 2100 the flow is laminar. If the Reynolds Number is greater than 4000 in a round pipe is determined to be turbulent. The transition region is between Reynolds Numbers of 2100 and 4000, respectively.

When a fluid enters a pipe with a near uniform velocity profile viscous effects cause the fluid to stick to the pipe wall. A boundary will form so the velocity profile changes with distance from the entrance region till the end of the entrance region, the boundary layer has completely filled the pipe. The entrance length is defined for laminar and turbulent flows as:

$$\frac{l_e}{D} = 0.06\,\mathrm{Re}\ \text{for laminar flows} \qquad \text{Equation 10}$$

$$\frac{l_e}{D} = 4.4(\mathrm{Re})^{\frac{1}{6}}\ \text{For turbulent flow} \qquad \text{Equation 11}$$

After the entrance region fully developed flow might be obtained depending upon the length of the pipe.

The pressure difference across a section of pipe:

$$\Delta p = p_1 - p_2 \qquad \text{Equation 12}$$

This is the force that moves the fluid through the pipe

Fully developed laminar horizontal pipe flow can be described as the difference in pressure acting on the end of the pipe and the shear stress acting on the walls of the pipe. Thus:

$$p_1\pi r^2 - (p_1 - \Delta p)\pi r^2 - \tau * 2\pi r l = 0$$

simplifies to:

$$\frac{\Delta p}{l} = \frac{2\tau}{r} \qquad \text{Equation 13}$$

Where r = 0 there is no shear stress acting on the fluid. Although when r = D/2 the shear stress is at a maximum, where t_w, the wall shear stress, so:

$$\tau = \frac{2\tau_w r}{D} \qquad \text{Equation 14}$$

The pressure drop if the viscosity was zero would be:

$$\Delta p = \frac{4l\tau_w}{D} \qquad \text{Equation 15}$$

So a small shear stress can have a large pressure difference if the pipe is long (l/D >>1). The shear stress of a Newtonian fluid is proportional to the velocity gradient, so:

$$\tau = \mu \frac{du}{dr} \qquad \text{Equation 16}$$

The velocity profile can be written as:

$$u(r) = \frac{\Delta p D^2}{16\mu l}\left[1 - \left(\frac{2r}{D}\right)^2\right] = V\left[1 - \left(\frac{2r}{D}\right)^2\right] \qquad \text{Equation 17}$$

where

$V = \frac{\Delta p D^2}{16\mu l}$ is the centerline velocity. Equation 18

Another expression is:

$$u(r) = \frac{\tau_w D}{4\mu}\left[1 - \left(\frac{r}{R}\right)^2\right]$$ Equation 19

The flow rate can also be expressed as:

$$Q = \frac{\pi D^4 \Delta p}{128 \mu l}$$ Equation 20

The change in pressure is often written as:

$$\Delta p = f \frac{l}{D} \frac{\rho V^2}{2}$$ Equation 21

where f is the friction factor. For fully developed laminar pipe flow:

$$f = \frac{64}{\mathrm{Re}}$$ Equation 22

It also essential to consider energy losses in the pipe:

$$\frac{p_1}{\gamma} + \alpha_1 \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} = \alpha_2 \frac{V_2^2}{2g} + z_2 + h_L$$ Equation 23

For uniform velocity profiles _ = 1 and fro nonuniform velocity profiles _ > 1. The head loss, h_L, in a pipe is a result of the viscous shear stress on the wall.

$$h_L = \frac{2\tau l}{\gamma r} = \frac{4 l \tau_w}{\gamma D}$$ Equation 24

When the pipe flow is considered to be turbulent, which probably will not occur, it is difficult to accurately predict the effects of the fluid being transported in the pipe. Consultation of the Moody chart is recommended.

The Rankine Cylcler operates on the idea of using steam to drive a turbine turning a shaft connected to a generator; thus creating electrical energy from work energy. The Rankine Cycler operates using an axial flow turbine. When the flow over a turbine blade is broken down there are three components of velocity: absolute velocity, V, relative velocity, W, and blade velocity, U. The blade velocity, U, is in the direction of the moving blade. The relative velocity, W, is in the linear direction of the curve of the blade at a specified point on the blade. The absolute velocity can be expressed as:

$$V = W + U \qquad \text{Equation 18}$$

When shaft torque3 and rotation are in the opposite direction a turbine is present. Fore steady flow:

$$\Sigma(r \otimes F) = \int_{cs} (r \otimes V)\,\rho V \cdot \hat{n} dA \qquad \text{Equation}$$

and thus:

$$T_{shaft} = -\dot{m}_1 r_1 V_{\theta 1} + \dot{m}_2 r_2 V_{\theta 2} \qquad \text{Equation}$$

The shaft poweris related to the torque and the angular velocity by:

$$\dot{W}_{shaft} = T_{shaft}\,\omega \qquad \text{Equation}$$

with U = wr:

$$\dot{W}_{shaft} = -m_1 U_1 V_{\theta 1} + m_2 U_2 V_{\theta 2} \qquad \text{Equation}$$

and $w_{shaft} = \dot{W}_{shaft} / \dot{m}$:

$$w_{shaft} = -U_1 V_{\theta 1} + U_2 V_{\theta 2} \qquad \text{Equation}$$

or:

$$w_{shaft} = \frac{V_2^2 - V_1^2 + U_2^2 - U_1^2 - \left(W_2^2 - W_1^2\right)}{2} \qquad \text{Equation}$$

This is a simple overview of turbo machinery. Many different reference materials on axial flow turbines and turbo machinery are available for a more in-depth detail on these subjects.

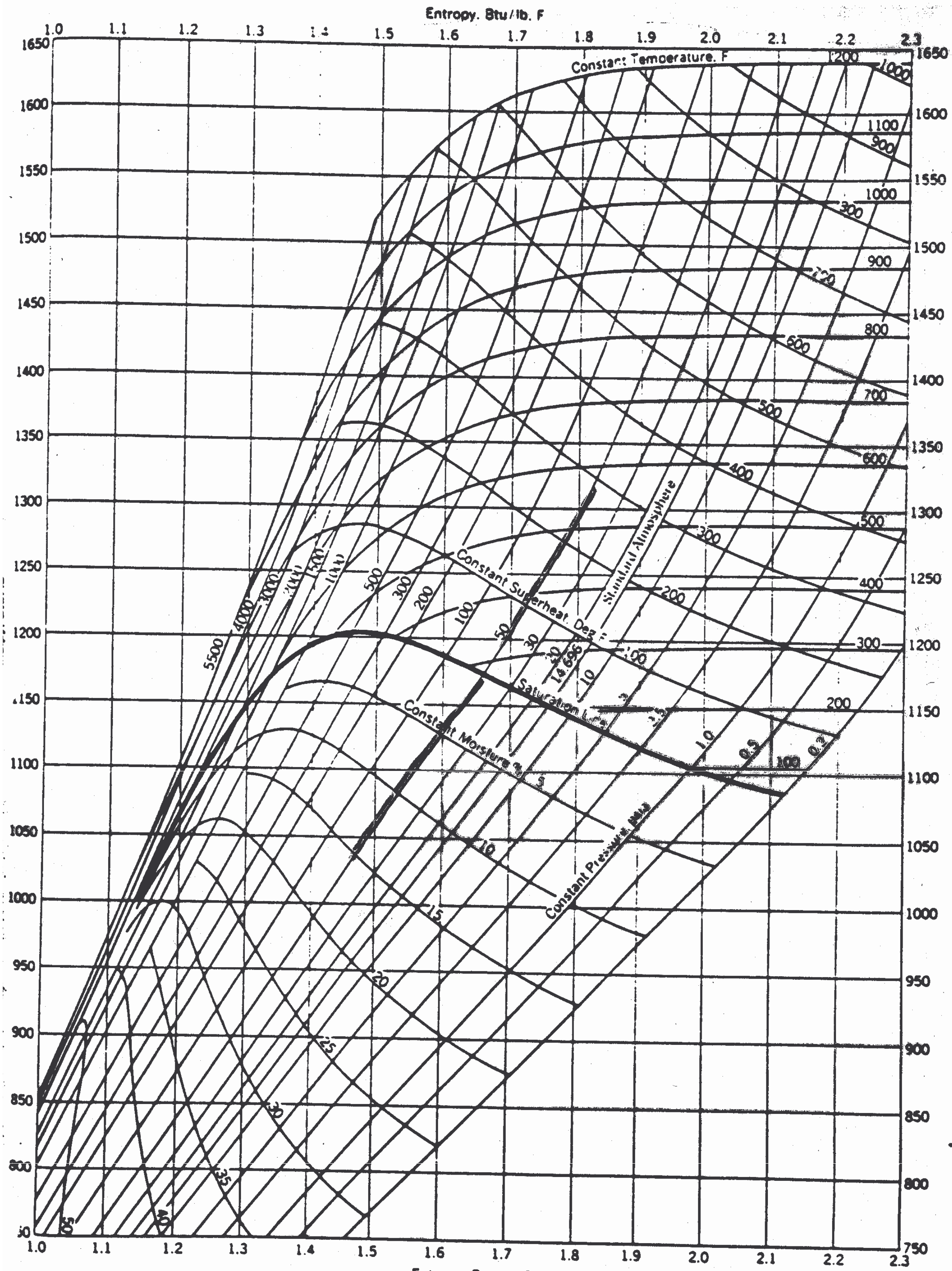


Figure 4.10 Outline of *h–s* (Mollier) diagram for steam. (Courtesy of Babcock and Wilcox Corp.)

Vapor-Compression Cycle (Refrigeration Cycle)©

The purpose of this experiment is to demonstrate and compare experimental parameters with the theory for the thermodynamic refrigeration cycle (Vapor-Compression Cycle). The student should be able to identify the individual components of the system and describe their function and performance characteristics both qualitatively and quantitatively.

Introduction:

The basic cycle for a mechanical refrigerator is the ideal vapor-compression cycle. The T-s and p-h diagrams are shown in Fig. 1.

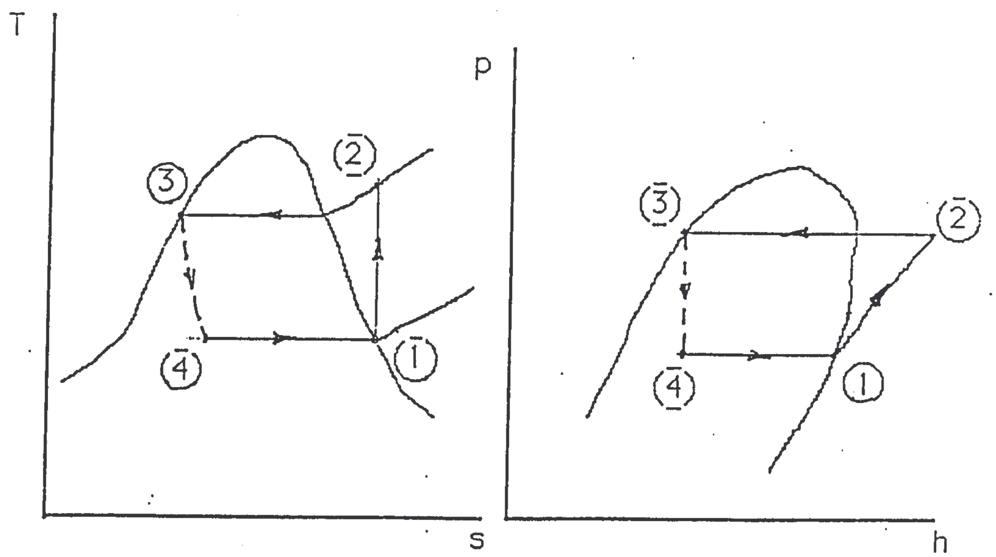


Fig. 1 T-s and p-h Diagrams of a Vapor-Compression Refrigeration Cycle

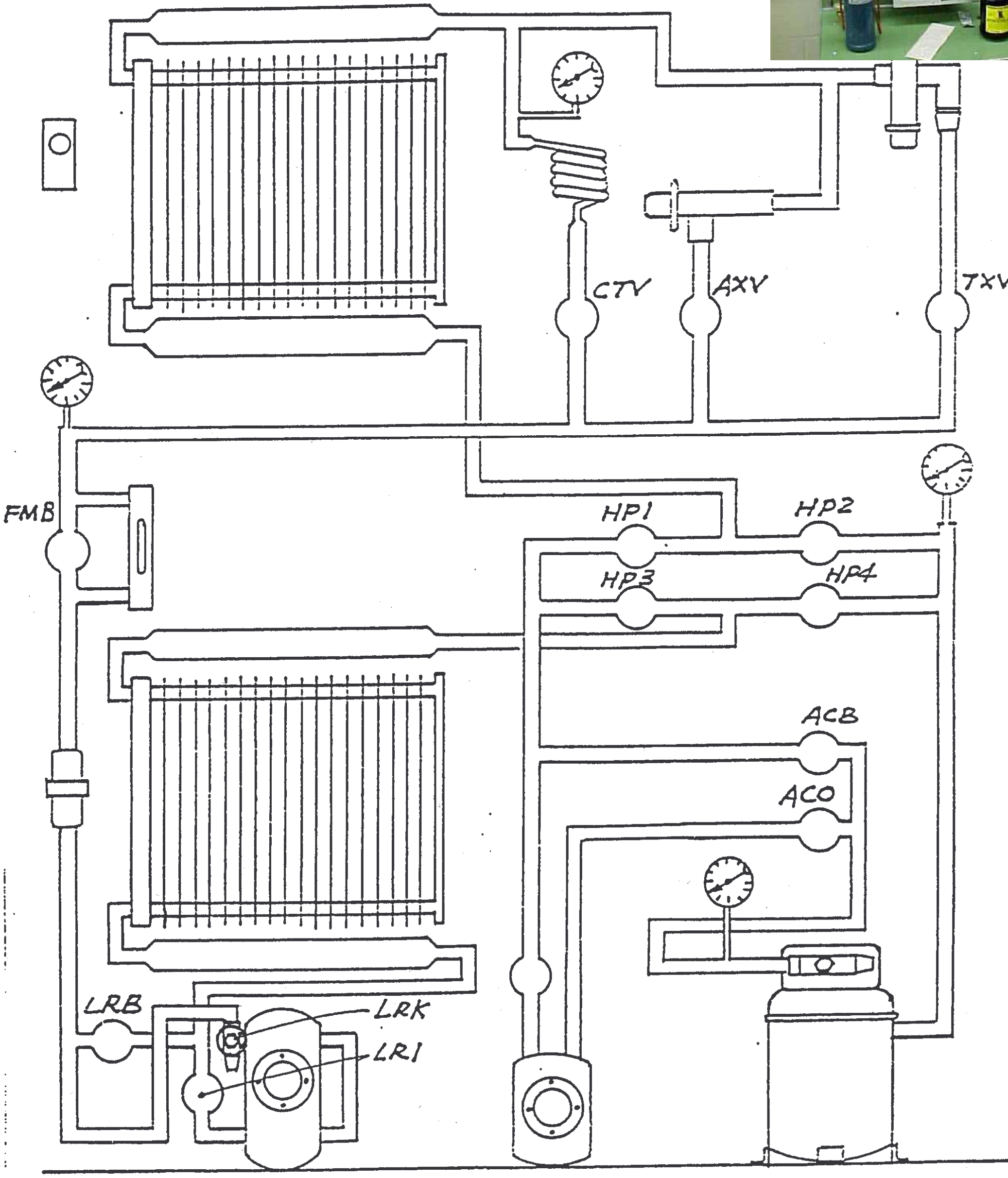
Saturated vapor is compressed isentropically to a superheated vapor (process 1-2). The heat rejection is carried out at constant pressure in the condenser (process 2-3). The fluid pressure must be reduced by expanding the refrigerant through an expansion valve (TXV, AXV, or CTV) in order to obtain a lower saturation temperature for the evaporator (process 3-4). The refrigeration effect is accomplished in the evaporator at constant pressure (process 4-1). All processes of the cycle are considered to be reversible except process 3-4, a throttling process which is an irreversible process, and $h_3 = h_4$.

Important.
Before the test, locate the location of state points 1, 2, 3, & 4 from Fig. 1, above, on the test unit.

Apparatus:

1. Model 9001 Brodhead-Garrett Basic Refrigeration Unit

2. Power measuring device (Watt meter)



USE PENCIL CRAYON TO COLOR CIRCUIT USED
RED-HIGH PRESSURE GAS
BLUE-HIGH PRESSURE LIQUID
GREEN-LOW PRESSURE GAS
YELLOW-LOW PRESSURE LIQUID

SCHEMATIC REFRIGERANT CIRCUIT FOR MODEL 9001 UNIT

Procedure:

1. Set unit on the refrigeration cycle using the thermostatic expansion valve.
   i. Open valve: HP4, TXV, HP1, AC1, and ACO
   ii. Close valves: HP3, FMB, HP2, ACB, AXV, and CTV

(See Capillary Tube Experiment Photos)

2. Open LRI, LRK, close LRB.
3. Put evaporator and condenser fan on high, and start compressor.
4. After the system has run for 5 minutes, observe, obtain and calculate the following:
   a. The pressure and temperature at the principal points (1,2,3, and 4 on the T-s and p-h diagrams. Record corresponding Thermocouple numbers.).

   b. The flow rate of refrigerant.

   c. Input power into compressor.

5. Repeat procedure 4 with evaporator fan on low.

Shut Down

Close LRB, and open LRV and operate until the suction pressure drops to *5* lbs.

Turn the compressor off.

Results:

1. Determine the enthalpy at each principal point by using a refrigerant table or chart.

2. Calculate:

   a. Cooling Effect

   Cooling Effect = $m_{refrigerant}$ $(h_1 - h_4)$

   b. Compressor power

   $P_{comp.} = m_{refngerant} (h_2 - h_1)$ (Btu/min) (60min/hr)(1 Kw-hr/3412.2 Btu) = Watt

   c. Efficiency of compressor

= $P_{comp.}$(Watt) /P_{input} (Watt)

d. Coefficient of performance

$COP=(h_1 - h_4)/(h_2 - h_1)$

e. Carnot coefficient of performance

$(COP_{Carnot} = T_1 / (T_2 - T_1)$

f. Heat rejected

$Q\ rej. = M_{refrigerant}\ (h_3 - h_2)$

g. Determine horsepower required to produce 1 ton of refrigeration

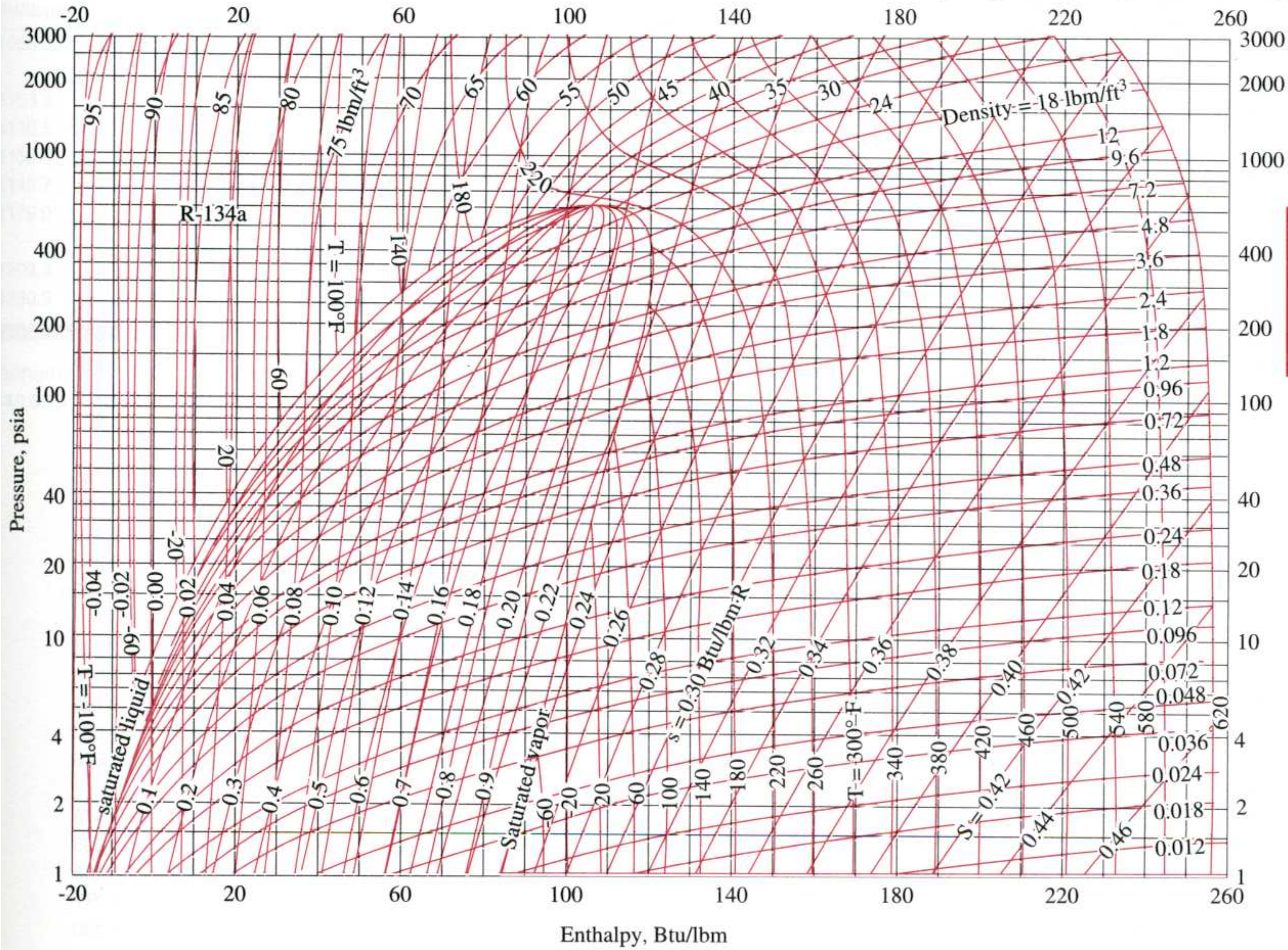
(COP) = (tons of refrigeration) (12,000 Btu / hr) / (HP input) *(2545* thu / hr)
= 4.715 / (HP/ton)
(HP / ton) = 4.715/ (COP)

h. Determine circulation rate of refrigerant for each ton of refrigeration

$m_{refrigerent}$ (lb/min) = (200 Btu/min) / (h1 - h4) Btu/lb

1 ton of refrigeration =200 Btu of refrigeration / min.

P-h diagram for refrigerant-134a. (Reprinted by permission of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA.)



VAPOR COMPRESSION REFRIGERATION CYCLE

DATA SHEET

DATE: —

ROOM TEMPERATURE ____________

BAROMETRIC PRESSURE ________IN Hg = ________ PSIA

FAN SPEED		REFRIGERANT TEMP. °F				PRESSURE PSIG			
EVAP.	COND.	PT. 1 TC#	PT.2 TC#	PT. 3 TC#	PT. 4 TC#	POINT 1	POINT 2	POINT 3	POINT 4
HIGH	HIGH								
LOW	HIGH				_				

POWER INPUT TO SYSTEM (with compressor, condenser, and evaporator fan switch ON)

EVAPORATOR FAN ON HIGH & CONDENSER FAN ON HIGH _______________Watts

EVAPORATOR FAN ON LOW & CONDENSER FAN ON HIGH _______________Watts

POWER INPUT TO FANS (with compressor switch OFF)

EVAPORATOR FAN ON HIGH & CONDENSER FAN ON HIGH _______________Watts

EVAPORATOR FAN ON LOW & CONDENSER FAN ON HIGH _______________Watts

POWER INPUT TO COMPRESSOR = POWER INPUT TO SYSTEM
- POWER INPUT TO FANS

EVAPORATOR FAN ON HIGH & CONDENSER FAN ON HIGH _______________Watts

EVAPORATOR FAN ON LOW & CONDENSER FAN ON HIGH _______________Watts

REFRIGERANT FLOW RATE

EVAPORATOR FAN ON HIGH & CONDENSER FAN ON HIGH _______________Lb./min.

EVAPORATOR FAN ON LOW & CONDENSER FAN ON HIGH _______________Lb./min.

Pre-Test Report Format

Purpose
The Propose of the Pre-Test Report is to insure the persons conducting the test are familiar with the objectives, data to be taken, and the underlying theory.

Format

The report is to be an informal memo. One page should be sufficient. Items to be included are:

- Hypothesis (what do think will be proven and or learned?)
- Simple test description
- Basic Governing equations
- Simplifying assumptions necessary.
- Expected results (i.e. data ranges)

Simple Example:

Memo

To: Professor Carnot
From: Jimmy Neutron
Date: February 30, 1672

A test will be conducted to determine the flow thru a tube for various pressures. The upstream pressure will be created by a variable speed blower. The down stream tube end will be open to the atmosphere. A pitot tube with manometer will be used to measure the velocity in the tube.

Equations:

Measured Flow = velocity X area

P = 0.5 X Rho X V^2

Flow (Q) should be proportional to the square root of the pressure.

Assumptions:
The velocity profile across the tube is uniform (no boundary layer effects)
No effects will be caused by the turbulence introduced by the blower.

All Pressures will be less than 20 inches of water.

Memo Report Format

The memo Report will be about one page of text with data sheets, simple calculations, and graphs attached if available. This report builds on the Pre Report and includes a brief discussion of what was, or was not, proven. May include data, graphs, and an example calculation. Must include a conclusion (one paragraph minimum.)

Information to include:

1. Hypothesis (what was expected to be proven?)
2. Simple test description (reference the test procedure for details.)
3. Governing equations / theory
4. Simplifying assumptions necessary.
5. Any problems incurred following the procedure.
6. What did the test prove?
7. Conclusion

1. Title Page:

University of North Carolina at Charlotte
William States Lee College of Engineering
Department of Engineering Technology

____
(Title)

Date of Test: ________________

Course Title: ________________

Course Number and Section: ________________

Report Author: ________________

Report Due Date: ________________

Lab. Partners: ____

Instructor: ________________

2. Table of Contents:

Table of Contents

3. Theory

This section includes a review of the pertinent theory relevant to the experiment. This section also is included to allow the student to investigate more fully the principles being demonstrated by the experiment. It is expected that this section will contain more than a repeat of the theory discussion in the laboratory manual. Sources from the bibliography should be used to develop the theory in detail, including relevant derivations.

4. Equipment List

All equipment used in the experiment is listed in this section, including the name or description of each piece equipment, the manufacturer, model number and serial number. It is very important to specifically identify each piece of equipment used, since any discrepancies in the data may be due to faulty equipment, which may not be discovered until the data analysis is completed. Without being able to reconstruct the experiment, it may not be possible to explain poor results.

***5.* Procedure**

The methods and operations followed in carrying out the experiment should be described in sufficient detail so that another person would be able to exactly repeat the experiment From this section, the reader should be able to obtain a clear understanding of what the experiment was and how it was done. Differences in procedure from the Lab. Manual or equipment malfunctions should definitely be recorded.

6. Results, Analysis and Discussion

This section is most important, since the interpretation of the experimental data is presented here, supported by graphs and tables, with a discussion of variations from expected results. Results should be more than presentation of graphs and tables. The results should be interpreted for the reader and thoroughly discussed since they form the basis for conclusion. Calculations required for the generation of tables and graphs should be explained and sample calculations presented. *Any assumptions in the interpretation of the data should be listed*.

Graphs and tables should be supported by the original data sheets, which should be included in the appendix of the report. When only one data sheet was taken during the experiment, copies should be made for each of the partners in the group. Neatness in original data sheets is very important for future interpretation.

Possible improvements in equipment and procedure should be discussed.

7. Conclusions

This section is the student's opportunity to show that he understands the significance of the results. Discrepancies in the results should be addressed, sources of error should be identified and explained, and recommendations for changes in equipment or procedure should presented.

8. References

Publications referred to in the final report are listed in the references section. -

The references are numbered in the order of their mention in the text, tables and figures. Only formal documents may be listed as references. If necessary, acknowledgement of other informal sources, such as private communications should be made in the text; e.g. "(private communication from John Doe, Blank Co., City, State)."

Each reference should contain the following information in the order given:

a) Author: Surname, first name, or initials as given on the reference. If anonymous, the listing is started with the title.

b) Title: Exact title as given.

c) Subtitle: If on separate line from main title, separate by a period; otherwise exactly as written. - -

d) Source:

1) Book Volume number and subtitle, if any; edition; publisher; place of publication if publisher is foreign or not well known; date (use copyright date if no other date appears); page numbers.

2) Periodical: Name of periodical; volume; number; month; year; inclusive pages. If tide of periodical has changed, give correct tide for issue cited.

9. Appendix -

An appendix presents supplementary information that does not logically fit into or might otherwise interfere with an orderly plan for the text It is material that is important, but not essential to the development of the report (such as the raw data, rough calculations and calculations that are not used as examples.

Each appendix must be referred to in the text and must have a title. Appendixes are identified by capital letter (A, B, C, etc.) in the order mentioned in the report.

Each appendix begins on a new page, with the appendix designation on the first line and the title below it.

Appendixes include:

- the original data sheet
- Calculations-other than sample calculations
- Handout materials
- Miscellaneous - published tables and charts, etc. manufacturer's instructions, copies of calibration certificates, etc.

(Original Data Sheet - readings taken during an experiments should be recorded in such a manner that all items are complete and understood by all persons conducting the experiment The heading of the sheet should indicate the date, title and number of the experiment, and the name of the observer or observers. Column headings should indicate the name of the item recorded, with units. Instrument serial numbers should be recorded. When in doubt about the amount of information to record, it is better to record more information than is thought necessary. Especially record any deviations from the recommended procedure, since these may be important in accounting for deviations in results).

General Requirements

a) Always use past tense. The only exception is in the Results section.

b) Always use third person.

c) Write complete English sentences throughout. The only exceptions are title, table, and Figure legends.

d) Reports should be typewritten on one side of white paper of good quality only and Double-spaced. When word processing program are used, the font used should be one that is easily read - no Gothic or other elaborate fonts.

e) Each new section begins double-spaced down from the previous section.

Report Layout

Each illustration or table must follow the text reference as close as possible.

Pages (8-1/2 by 11 inches) should be typed within the 6-1/2 by 8-1/2 inch dimensions. (1-inch margins on top, right and left margins; 1-1/2 inch margin on bottom)

All vertical illustrations should be within the 8-by 6-1/2 inch image area.

All horizontal illustrations should be within the 8-1/2 by 6 inch image area.

Double space to separate the text and the top of the illustration area; double space to separate the bottom of the illustration area and the figure title; and double space to separate the title from the following text.

Tables, charts, and graphs

Reference data is normally presented in tabular or chart form. Charts and graphs are assigned figure number and titles and should appear at the bottom of the chart or graph. The tide should be as descriptive as possible. The coordinate axes should be set far enough inside the margin to allow room for scale information. Scales should be selected to allow the best display of data. Unrelated curves should not appear on the same sheet. Related curves may be on the same graph, provided they are completely identified with different symbols, i.e. crossed, triangular, etc. Experimental errors are such that plotted points may not fall along a smooth line. Generally, however, smooth curves should be drawn with a French curve so as to provide a good “fit” to the data. Plotted points should be shown on the graph. The exception to this rule is a plot of a calibration graph, in which lines should be drawn from point to point. Free hand graphs are not acceptable. A table number and title should be placed above the table. Titles should be descriptive, not just “Table No. 1”. Each column should have a heading with a description of the item in the column. Each column should have units, as appropriate. Tables should be oriented so that the bottom of the table is at the bottom of the page or at the right - hand margin. No writing should be placed in the margins. Tables should be complete on one page, where possible.