EG 555 ME
Thermodynamics II

Lab 1

Title: Performance of Air Compressors
Objective:

1) To investigate the effect of delivery pressure on the performance of a reciprocating air compressor
2) To investigate the effect of two stage compression on energy consumption compared to single stage compression

Introduction

Compressed air is an important method of transmission of energy in industries. It has particular advantages in hazardous areas, where there is an explosion risk such as in chemical plants, and it is often safer than electricity for powering small hand tools in general engineering workshops. Compressed air is widely used in industries for pneumatic operated equipment, for instrumentation, for conveying material, as a direct input to a chemical process, as raw material, for pressure testing of vessels, etc.

Components of Compressed Air

i. A compressed air system is composed of:
ii. Air compressor with suction filters
iii. Motor and drive transmission
iv. Intercoolers, after coolers with cooling water system
v. Dryers
vi. Air receivers with safety valve and instrumentation
vii. Distribution lines/system, and
viii. End use equipment

Air compressors: The compressors commonly used in compressed air systems are usually reciprocating, screw, and centrifugal types. Centrifugal compressors are used when large amount of compressed air at not very high pressures is required. Reciprocating compressors are used for relatively not large amount of compressed air but at high pressures. Screw type compressors are used for moderate pressures and capacities. Since reciprocating compressors have very good energy performance at no-load conditions, they are widely used.

Motor and drive transmissions: Centrifugal and screw compressors are usually driven through gear mechanism (between compressor and electric motor) where as reciprocating compressors are motor driven through V- belt, flat belt.

Inter cooler/after cooler: These are used to cool the compressed air in order to reduce the power consumption (in case of multistage compression) and to have the compressed air at acceptable temperature.

Dryers: Dryers are used to remove moisture from the compressed air. It is usually accomplished by the use of a small refrigeration system.

Air receivers: The main function of an air receiver in a compressed air plant is to provide a storage capacity for the compressed air delivered by the compressors which will even cut short time

p_0 = suction pressure

Multistage Compressors

Multistage compressors with intercooling between the stages have a number of advantages as compared to using a single stage compressor. Consider a two stage compressor in which air is first compressed from pressure p1, temperature T1 to pressure p2 and temperature T2 and is then exhausted into an inter cooler where the air is cooled at constant pressure to its original temperature T1. The volume of the air is now the same as if it had been compressed isothermally. The air is now drawn into a smaller cylinder and compressed to its final volume p3. These processes are illustrated in figure below.

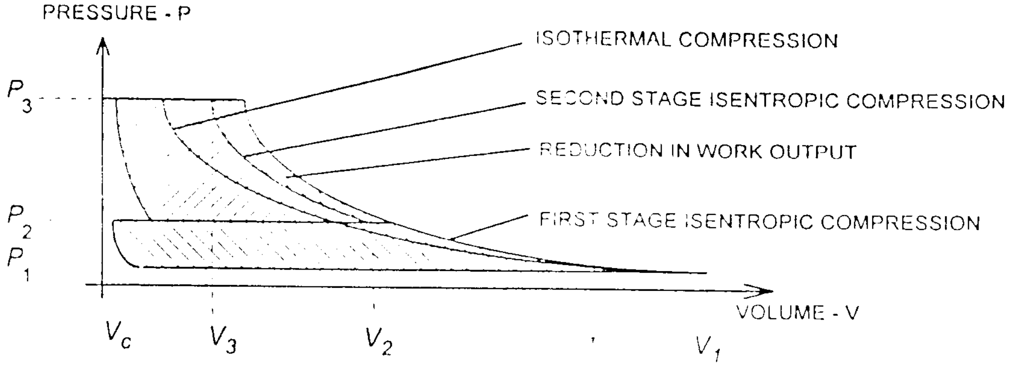

Fig 1-2 *Performance of Multi-stage compressor*

The shaded area shows the resultant reduction in work input (power). The volumetric efficiency of a multistage compressor is higher than a single stage compressor of the same pressure ratio.

Relevant Equations:

Inlet air flow Q_i is determined as:

$$Q_i = 2.972\,(h)^{0.5} \qquad \text{(cu.m /hr)}$$

Where, h = manometer indication in mm of H_2O

Swept Volume Vs is determined as:

$$Vs = 3.85 \times 10^{-4} \qquad (\text{m}^3) \text{ (for 70mm bore and 50mm stroke)}$$

Or,

$$Vs = 0.02309\,Nc \qquad \text{(cu.m /hr)}$$

Where, Nc = compressor RPM

Volumetric Efficiency is determined as:

$$\eta_{vol} = \frac{Q_i}{V_s} = \frac{2.972(h)^{0.5}}{0.02309N_c} = 128.71\frac{(h)^{0.5}}{N_c}$$

Dynamometer Power Output W_D is determined as:

$$W_D = 2\pi N_D T = 2\pi N_D \times 0.25\, L_D$$

Where, N_D = dynamometer RPM

T = dynamometer torque, N.m

L_D = dynamometer load, N

Compressor Air Power Input W_C is determined as:

$$W_C = W_D - 2\pi N_D T_{off\,load}$$

Where, $T_{off\,load}$ = Dynamometer torque at off load condition

Isothermal Power Input W_T is determined as

$$W_T = P_1 Q_i \ln \frac{P_2}{P_1}$$

Where P_1 = suction pressure
P_2 = discharge pressure

Isentropic Power Input W_S is determined as

$$W_s = \frac{\gamma}{\gamma - 1} P Q_i \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] = 0.972 Q_i \left[\left(\frac{P_2}{P_1} \right)^{\frac{1}{3.5}} - 1 \right]$$

Isothermal Efficiency is determined as:

$$\eta_T = \frac{W_T}{W_C}$$

Isentropic Efficiency is determined as:

$$\eta_S = \frac{W_S}{W_C}$$

Lab Setup

The equipment used for this lab is the Cussons P9050 Two Stage Reciprocating Air [illegible] Test Set which is illustrated schematically in figure 1-3 . The main components of the [illegible] are described below.

First Stage Compresssor: It is an industrial twin cylinder air cooled machine with [illegible] and 50mm stroke. The compressor is belt-driven by a dynamometer. Compressor minim[illegible] 356 RPM and maximum speed is 1300 RPM.

Second Stage compressor: It is a vertical single cylinder machine with 50mm bore [illegible] storke. Compressor minimum speed is 300 RPM and maximum speed is 1096 RPM.

Dynamometer: The dynamometer is a separately excited direct [illegible] arranged as a swinging field machine by mounting the stator on trunnion end fram[illegible] supported in pedestals fitted with self aligning bearings.Two torque arms are attache[illegible] diametrically opposite each other on a horizontal centre line. The right hand arm, vie[illegible] drive end, is attached by spherical joints to a strain gauged load cell at a radius of [illegible] measures the restraining torque that is required to prevent rotation of the dynamomete[illegible]

Belt Drive System: Each compressor is driven by a single vee wedge belt. The dr[illegible] mounted on the dynamometer shaft using taper lock bushes.

Water Cooled Intercooler: The water cooled intercooler is a shell and tube heat ex[illegible] is mounted vertically on a bracket behind the first stage compressor. The heat exchan[illegible] counter flow configuration with the water flowing upwards through the tubes with [illegible] the shell at the top and leaving at the bottom. A three port two way ball valve at [illegible] intercooler is provided to allow the intercooler to be bypassed. A moisture separator is fitted at the exit from the intercooler to provide automatic periodic discharge of the collected condensate. The moisture separator has a maximum operating temperature of 80°C.

Air Receivers: There are two horizontal air receivers of welded steel construction with a capacity of 220 liters each. Both the receivers are fitted with necessary safety devices and pressure gauge.

Speed Measurement: The dynamometer speed is measured by a magnetic pick up and is digitally displayed. ***The speed of first stage compressor is determined as 0.3841 N_d and that of second stage compressor is determined as 0.3237 N_d*** (where N_d is the dynamometer speed).

The equipment is also fitted with necessary controls and instrumentation such as stop and start control, speed control, pressure measuring devices, inlet and discharge flow measuring devices, torque measuring device, temperature measuring devices, and protective circuitry.

Safety Considerations:

1) Working with high pressures is always dangerous. Do not indent discharge pipelines, receivers etc..
2) Do not open the discharge valve full open when working with high pressures unless instructed to do so.
3) Discharge side manometer uses mercury as manometer fluid which is toxic. Handle with care when exposed to it.
4) Never try to undo the belt drives in running condition.

Laboratory Procedure:

Lab 1-1 To investigate the effect of delivery pressure on the performance of a reciprocating air compressor

1) Set up the system as a single stage air compressor operating into both air receivers by removing the drive belt from the second stage compressor, opening the bypass valves to bypass the second stage compressor, closing the bypass around the water cooler and opening the interconnecting valve to the second air receiver.
2) Make sure that discharge and drain valves are closed.
3) Connect the power cord to 3-phase power supply
4) Push the 'start' button to start the compressor
5) Adjust speed using speed controller on the front panel so that the compressor speed is 1250 RPM (it corresponds to about 3254 RPM of dynamometer on the digital display) and run at constant speed.
6) For increments of air receiver pressure of 1 bar, record air compressor discharge pressure $\mathbf{P_2}$, inlet flow orifice manometer reading **h** and dynamometer load $\mathbf{L_D}$
7) When the air receiver pressure reaches the value pre-set on the off-loading valve, both inlet valves will be held open and compressor delivery will cease. A reading of the dynamometer load in this condition can then be used as a measure of the drive belt and cylinder friction power which can then be deducted from the measurement of dynamometer power output to give a measure of the compressor air power input W_C.
8) Turn off the compressor. Discharge the air from the receiver with instructor's approval only.

Observation Sheet:

P_2, bar (abs)	2	3	4	5	6	7	8	9	10	11	12
h, mm H_2O											
L_D, N											

L_D at off load condition =

For each set of results, calculating the following parameters:
Inlet air flow, Q_I
Volumetric efficiency, η_{vol}
Dynamometer power output, W_D
Compressor power input; W_C
Isothermal power input, W_T
Isentropic power input, W_S
Isothermal efficiency, η_T
Isentropic efficiency, η_S

Plot graphs of the discharge pressure P_2 against the inlet air flow Q_I, and plot P_2 against the power outputs W_D, W_C, W_T, W_S. Finally plot the efficiencies η_{vol}, η_S, η_T against P_2.
Comment on the results.

Lab 1-2 To investigate the effect of two stage compression on energy consumption compared to single stage compression

1) Set up the system as a two-stage air compressor operating into both air receivers by putting the drive belt on the second stage compressor, closing the bypass valves to allow air to pass to the second stage compressor, opening the bypass around the water cooler and opening the interconnecting valve to the second air receiver.
2) Do not supply water to the intercooler.
3) Make sure that discharge and drain valves are closed.
4) Connect the power cord to 3-phase power supply.
5) Push the 'start' button to start the compressor.
6) Adjust speed using speed controller on the front panel so that the compressor speed is 1250 RPM (it corresponds to about 3254 RPM of dynamometer on the digital display) and run at constant speed.
7) Let the receiver pressure rise to around 10 bar.
8) Record inlet and outlet temperatures and pressures for both first-stage and second-stage compressors and receiver inlet temperature.
9) Discharge air from the receiver so that its pressure falls to about 5 bar.
10) Supply cooling water to intercooler.
11) Let the receiver pressure rise to about 10 bar again.
12) Repeat process No. 8 and record the data.
13) Turn off the compressor. Shut the water supply to intercooler and drain properly. Discharge the air from the receiver with instructor's approval only.

Observation Sheet:

Without Intercooling

1-stage P1, bar	1-stage P2, bar	2-stage P1, bar	2-stage P2, bar	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C

With Intercooling

1-stage P1, bar	1-stage P2, bar	2-stage P1, bar	2-stage P2, bar	T1, °C	T2, °C	T3, °C	T4, °C	T5, °C

Sketch the T-S diagram and show how the process of compression takes place for two-stage compression system for both cases (with and without intercooler). Using the T-S diagram supplied, find the savings in work per kg of compressed air by two-stage compression compared to single-stage compression working on same discharge pressure for both cases (with and without intercooler). Comment on the results. Which of the two systems (single stage or double stage compression) has better energy performance? What is the effect of intercooler ? What happens to savings on work when water is used in inter cooler ?

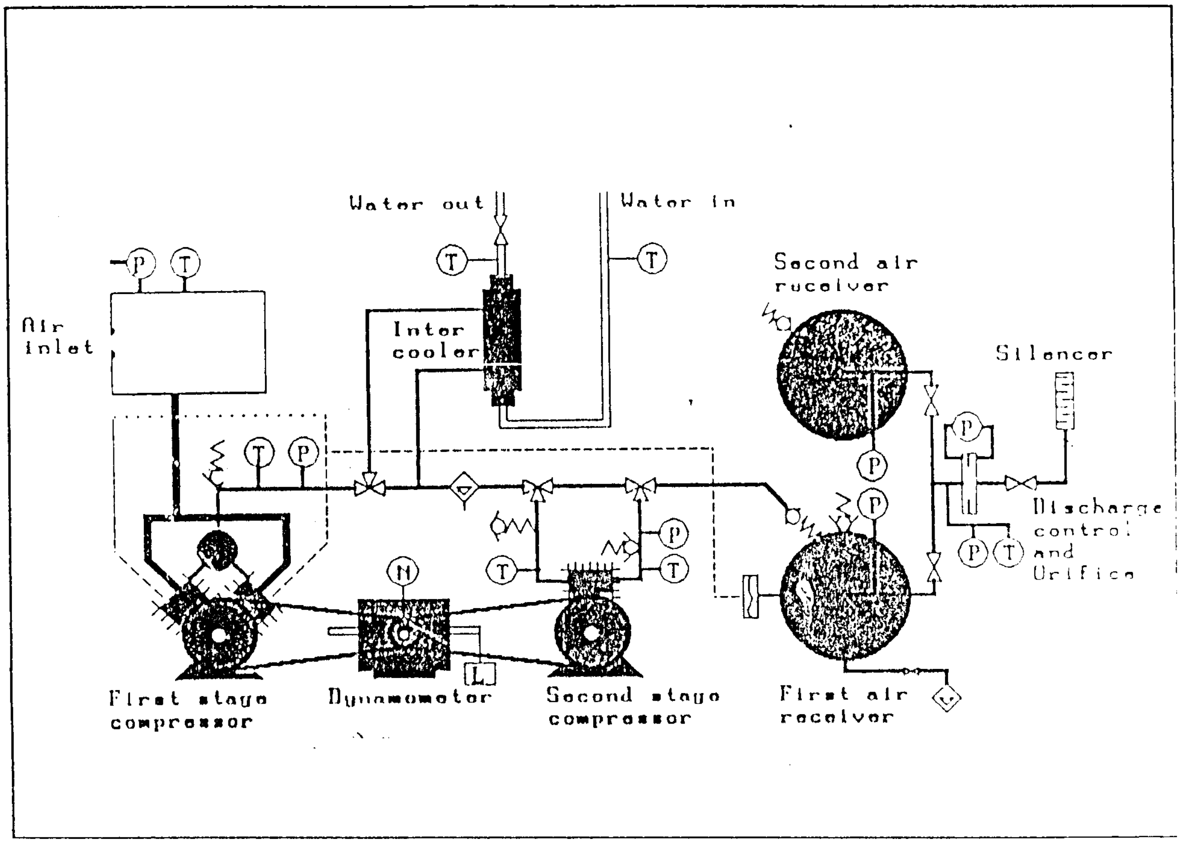

Fig 1-3 Two Stage Reciprocating Air Compressor Test Set

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Lab 2

Title: Vapour Compression refrigeration System

Objective:

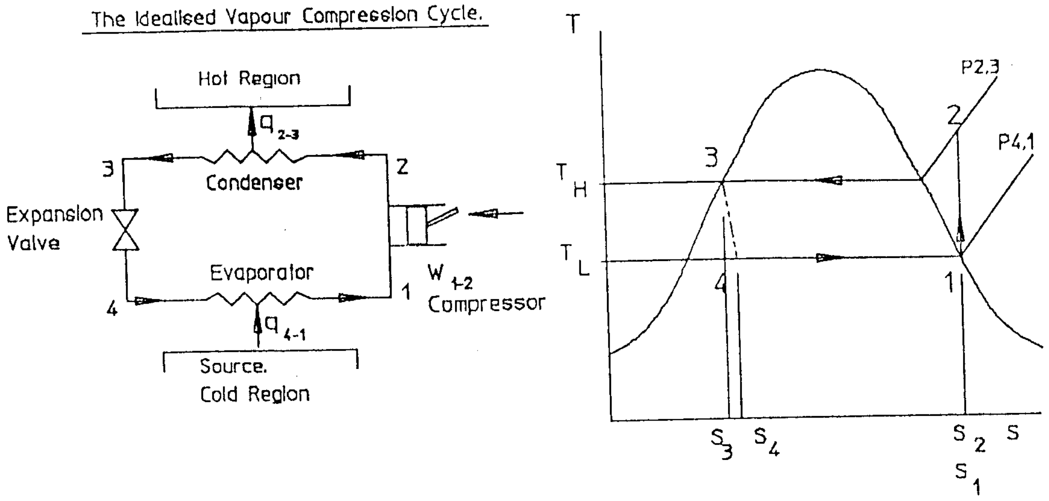
1) To introduce the students with practical vapour compression cycle
2) Draw the actual cycle in p-h diagram and compare it with the ideal cycle
3) To determine power input, heat output and COP
4) To carry out energy balance of the components and system as a whole

Introduction:

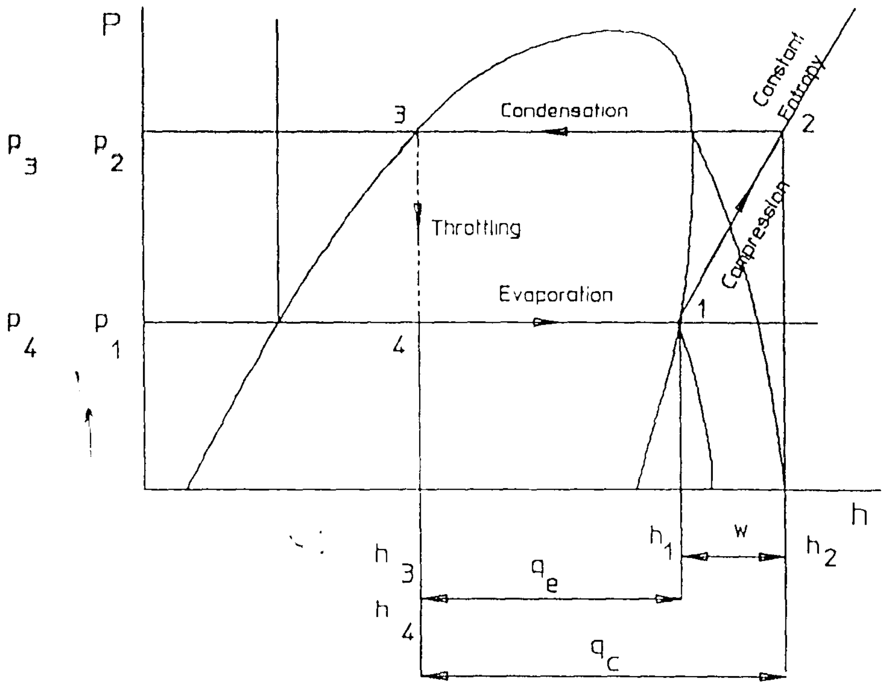
A system which transfers heat from a low temperature region to a high temperature region in known as refrigeration (or heat pump) system. In a heat pump system, external work is applied to the system and heat is delivered to a sink at a higher temperature, whereas in a refrigeration system, external work is applied to the system and heat is taken from low temperature source.

The second law of Thermodynamics states that transfer of heat from a low temperature region to a high temperature region without the aid of external work is impossible. The first law of Thermodynamics on the other hand, states that in a cycle, the net heat transfer is equal to net work transfer.

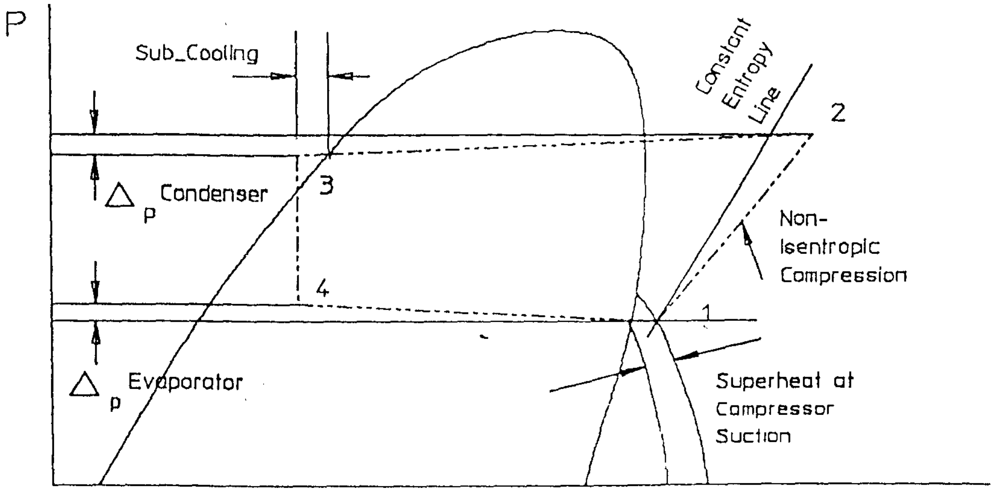
The ideal refrigeration cycle is represented by the reversed Carnot cycle in which heat is taken from a constant low temperature source T_L and rejected to a constant higher temperature sink T_H as shown in figure below.



The Idealised Vapour Compression Cycle.



The practical vapour compression cycle differs from the ideal cycle for following reasons:
The compression process is not a reversible adiabatic process
Due to friction, there will be pressure drop in both suction and discharge side
In order to prevent liquid from entering the compressor, the vapour leaving the evaporator is usually superheated
Liquid leaving the condenser is subcooled to improve COP
There is always some heat transfer between all parts of the circuit and surrounding
Because of the above irreversibilities, the cycle diagram will be as shown in figure below in p-h diagram.



Relevant Equations:

Since a theoretical Carnot cycle consists of adiabatic compression and expansion processes and isothermal heat rejection and addition processes, its COP is obtained as:

For Heat Pump $$COP_{HP} = \frac{T_H}{T_H - T_L}$$

For Refrigerator $$COP_{REF} = \frac{T_L}{T_H - T_L}$$

Heat delivered to cooling water from compressor: $Q_{comp} = m\, c_p\, \Delta t_{comp}$ (watt)

Heat delivered to condenser cooling water: $Q_{cond} = m\, c_p\, \Delta t_{cond}$ (watt)

If heat is delivered to condenser only, $$COP_{HP} = \frac{Q_{cond}}{W}$$

If heat from compressor also is considered, $$COP_{HP} = \frac{Q_{cond} + Q_{cmp}}{W}$$

Heat transfer to/from refrigerantin evaporator and condenser, $Q_r = m_r\, \Delta h$

Heat transfer to/from refrigerant in compressor, $Q_r = m_r\, \Delta h + W$

Where,

m = mass flow rate of water (kg/s)
C_p =sp. Heat of water (J/kg.K)
Δt_{comp} = difference in temperature of water entering and leaving compressor, (K)
Δt_{cond} = difference in temperature of water entering and leaving condenser, (K)
W = compressor power input (W)
Δh = difference in enthalpy of entering and leaving refrigerant, (kJ/kg.K)

Lab set-up

The equipment used for this experiment is P. A. Hilton Air and Water Heat pump. The mechanical circuit diagram is shown in fig 2-1.

The refrigerant (HFC 134a) vapour generated by absorption of low grade heat in either the air or water source evaporator is drawn into the compressor. This extraction of heat from air or water reduces the temperature or air or water leaving the unit.

The work done on the gas by the compressor increases the pressure and temperature of the refrigerant vapour. This hot high-pressure gas flows to a concentric tube water-cooled condenser.

In the condenser, the gas is desuperheated and then condensed at essentially constant temperature. Before leaving the condenser the liquid refrigerant is slightly sub cooled below the saturation temperature for the condensing pressure and this liquid then flows to a liquid receiver

The liquid receiver gives a large volume into which excess refrigerant can flow during certain operating conditions. In addition the receiver ensures that liquid is always available for changes in demand due to evaporator loading.

The compressor motor has winding resistance losses, internal friction and the compression process is not isentropic. All of these conditions result in some of the electrical energy input being converted into heat. The compressor and motor are contained within the hermetically sealed steel casing and run in oil which during normal operation is warmed by circulation around the casing and collects at the base of the unit. During normal operation, some oil will be carried around the system and under certain conditions may appear in the variable area flowmeter as a discolouration to the flow. This is quite normal and will disappear during normal running.

As the compressor is designed specifically for heat pump use, a copper heat transfer coil is located at the base of the compressor within the oil reservoir. By passing the cold water from the mains supply through this coil before the water is transferred to the condenser the normally waste heat from the oil can be added to that given up to the condenser.

Sub cooled liquid HFC 134a at high pressure passes through a panel mounted flow meter to a thermostatically controlled expansion valve. On passing through the valve the pressure is reduced to that of the evaporator and the two phase mixture of liquid and vapour begins to evaporate within the selected evaporator

Control of the heat pump is by variation of the evaporation temperature by the source air or water temperature and flow rate, and by variation of the condensing temperature by the flow rate of the condenser water.

The range of source temperature can be extended by directing warmed air from a fan heater at the air intake or by supplying warmed or chilled water to the source water inlet.

Relevant system temperatures are recorded by thermocouples and a panel mounted digital temperature indicator. The thermocouples used are type K (Nickel Chrome-Nickel Aluminium).

Condenser and evaporator pressures are indicated by panel mounted pressure gauges. Water and refrigerant flow rates are indicated by panel mounted variable area flow meters. The electrical input to the compressor motor is indicated by a panel mounted analogue meter.

Safety Precaution:

1) The thermocouple wires used in the system are very thin and even a slight pressure can break it, handle with care.
2) The equipment is a table mounted unit. Take care when connecting water hose and do not spill water.

Lab Procedure:

Lab 2-1 Investigating the practical vapour compression cycle

1) Turn on the water supply to the unit (to condenser and evaporator) and turn on the main switch
2) Select water evaporator using the evaporator change-over switch
3) Set condenser water flow rate to approximately 50% of full flow and evaporator water as set by the instructor
4) After all the parameters reach a stable condition, make the observations set out in observation sheet.
5) After observation is over, turn off the unit and shut down the water supply.

Observation Sheet

HFC 134a Gage pressure at compressor suction	P1, kN/m^2 [illegible]	
HFC 134a Abs.pressure at compressor suction	P1, kN/m^2 [illegible]	
HFC 134a Gage pressure at compressor discharge	P2, kN/m^2 [illegible]	[illegible]
HFC 134a Abs. pressure at compressor discharge	P2, kN/m^2 1080	
HFC 134a temperature at compressor suction	t1, °C 15	24
HFC 134a temperature at compressor discharge	t2, °C	[illegible]
HFC 134a temperature of condensed liquid	t3, °C 30	
HFC 134a temperature at expansion valve outlet	t4, °C 9	

Draw the actual vapour-compression cycle on the p-h chart provided. Compare with the ideal vapour compression cycle and comment on the result.

Note: Make the following assumptions while plotting the cycle
a) The pressure drop through the condenser is insignificant
b) The throttling process is sensibly adiabatic, i.e. enthalpy is constant during the process