Chamber of Mines of South Africa

Memorandum

SUBJECT: CHAMBER OF MINES OF SOUTH AFRICA – INTERMEDIATE CERTIFICATE IN MINE ENVIRONMENTAL CONTROL PAPER 2 **SUBJECT CODE:** **EXAMINATION DATE:** **TIME**: 14:30 – 17:30	**EXAMINER:** E Botha **MODERATOR:** M Biffi **TOTAL MARKS:** [100] **PASS MARK:** (60%)

NUMBER OF PAGES:

SPECIAL REQUIREMENTS:

THIS IS NOT AN **OPEN BOOK EXAMINATION**. THERE IS NO FORMULA HANDOUT
INSTRUCTIONS TO CANDIDATES:

1. Answer all questions **legibly** in English.
2. Write your **ID number** on the outside cover of each book used and on any graph paper or other loose sheets handed in.

NB: Your name **must not** appear on any answer book or loose sheets.

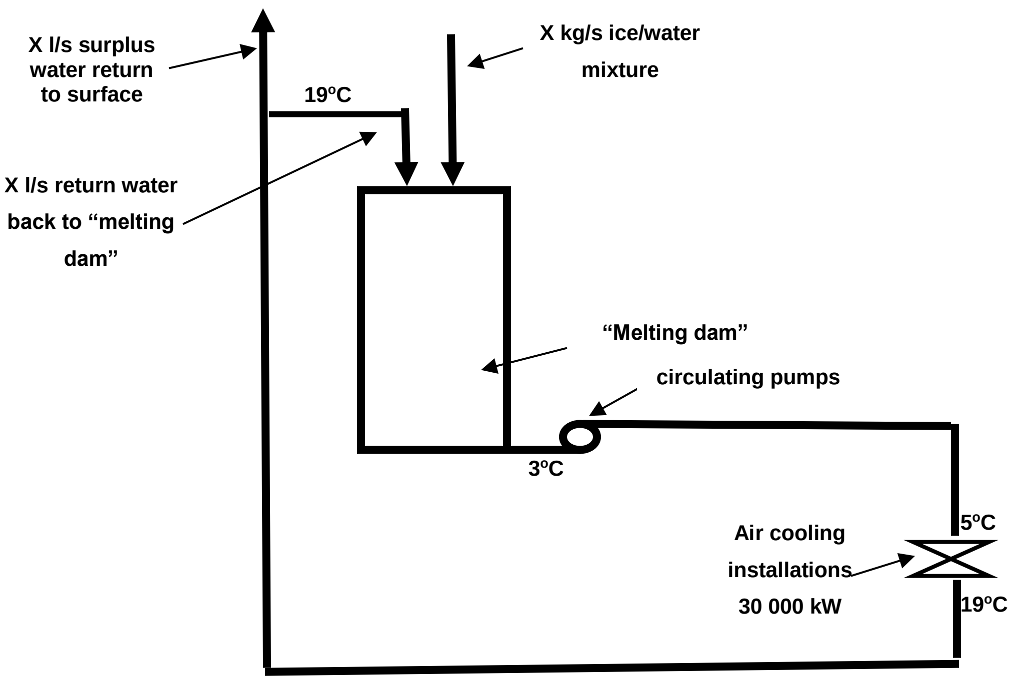
3. Show all calculations **and check calculations on which the answers are based.**
4. Hand-held electronic calculators may be used for calculations.
5. Write **legibly** in ink on the **right hand page** only – **left hand pages will not be marked**.
6. Illustrate your answers by means of sketches or diagrams wherever possible.
7. Answers must be given to an accuracy which is typical of practical conditions.

   NB Ensure that the correct unit of measure (SI unit) are recorded as marks will be deducted from answers if the incorrect unit is used. (even if the calculated value is correct).
8. In answering the questions, full advantage should be taken of your practical experience as well as data given.
9. Please note that you are not allowed to contact your examiner or moderator regarding this examination.
10. Cell phones are **NOT** allowed in the examination room.

QUESTION 1

1.1 At a deep level mine a new project is being developed, a computer simulation has confirmed the calculated additional cooling load for this project to be 30 000 kW. This is a long life project (15 years) and is deep (max depth = 3600m). The decision has been taken to use ice to supply the additional cooling load required.

The water will leave the underground ice discharge dam at 3°C and arrive at arrive at the air cooling installations at 5°C and return back to the same dam at 19°C.



1.1.1 Determine how much ice must be produced at the surface ice plant.

Assume water temperature leaving air cooling installations is the same as the water temperature returning to the melting dam (i.e. 19°C)

IMF of ice = 80%

a. Determine the flow rate (MF_W) through the air cooling installations to achieve 30 000 kW. (1)

If $q = MF_w \times C_p \times dT$

Where :

q =duty of air cooling installations

MFw = mass flow of chilled water in circuit (l/s)

Cp =thermal capacity of water (kJ/kg ^{o}C)

dT =temperature difference of water across air cooling installations (^{o}C)

assume that the water temperate returning from the cooling installation to the "melting dam" remains constant (i.e. 19^{o}C)

Therefore:

MF_w $=q/(C_p x dT)$

=30 000/(4.187 x 14)

=512 l/s

b. Determine The heat energy (including line losses) that is transferred (2)

to the water circulated between the melting dam and the air cooling installations.

If q=MF_w x C_p x dT

Where :

q =heat removed from circulated water (kW)

MFw = mass flow of chilled water in circuit (l/s)

Cp =thermal capacity of water (kJ/kg ^{o}C)

dT =temperature difference of water across air cooling installations (^{o}C)

Therefore:

q =512 x 4.187 x 16

=34 300 kW

c. Determine the flow rate of the ice/water mixture transported from (2)

surface to the melting dam.

Latent heat of fusion of ice = 335kJ/kg

If q=M x {(335 x 0.8) + (dT x 4.187)}

Where :

q =heat transfer across "melting dam" (kW)

M = massflow of water/ice mixture supplied to "melting dam" (kg/s) *dT =temperature difference between ice/water inlet to "melting dam" and water out (^oC)*

Then;

M =q / {9335 x 0.8) + (dT x 4.187)

M = 34 300 / {(335 x 0.8) + (3 x 4.187)}

M =34 300/ 280.561

M =122 l/s

d. Determine the ice generation rate "ice maker". (2)

If the IMF is 80% and ice/water mixture= 122.3 kg/s

Then Ice "made" at the ice maker = 122.3 x(80/100)

Ice "made" at the ice maker = 97.8 kg/s

1.1.2 Determine how much water must be circulated underground, between the air cooling installations and the underground ice discharged dam. (2)

From the calculation above (1.1.1.a)

Flow rate is 512 l/s

1.1.3 Assuming that the surplus 'melt' water is pumped to surface from the lowest level, assuming overall pump efficiency is 68%, how much power is used to pump this surplus 'melt' water back to surface. (2)

As calculated above in (1.1.1.c) 122.3 kg/s of ice/water mixture is transported from surface to the melting dam. Calculate power (q)required to pump surplus water to surface

q_i $=MF_w \times g \times h/1000 \times P_{eff}$

Where:

q_i *= electrical input power to pumps (kW)*

MF_w = massflow of water in circuit (l/s)

h = pump head (m)

P_{eff} = pump efficiency

q_i = (122.3 x 9.79 x 3600) / (0.68 x 1000)

q_i = 6339 kW

1.1.4 If ice were not used and all cooling water was generated and pumped back to surface refrigeration systems, assuming the same pump head and efficiency, how much power would be required to pump this cooling water out of the mine? (2)

Assume that the cooling water reached the heat exchanger at 5°C

Assume 512 l/s chilled water reticulated from surface (for air cooling purposes)

Calculate power (q) required to pump 512 l/s water to surface from 3600 m

q_i = (MF_w x g x h) / 1000 x Peff)

Where

q_i = electrical input power to pumps (kW)

MF_w = massflow of water in circuit (l/s)

h =pump head (m)

P_{eff} = pump efficiency

q_i = (512 x 9.79 x 3600) / (1000 x 0.68)

q_i = 26 537 kW

1.1.5 Discuss the difference between your answers 1.1.3 and 1.1.4 (above). (2)

With 4.2 times less water in circulation, the ice option (1.1.3) requires 4.2 times less pump power than that required to pump the full 512 l/s to surface (1.1.4).

The positional efficiency of the ice option (1.1.3) is also better than that of the water option (1.1.4)

1.2 List at least 5 advantages and disadvantages of using ice as a medium for providing underground cooling in a deep mine. (10)

Advantages	*Disadvantages*
Water for cooling can be delivered at extremely low temperatures (<5^{o}C) to cooling installations far from surface (Excellent PE)	*Very expensive capital outlay makes this technology on suitable to very deep or long lived mining operations*
Relatively low volumes of water (ice) circulated from surface – greatly reduced pumping costs	*Large excavations required for melting ice underground*
Capacity of installation virtually unlimited, modular can be expanded relatively easily	*Large piping infrastructure required to circulate cooling water*
Situated on surface – can use freely available refrigerants (ammonia)	*Relatively large plastic conveying piping required from surface through shaft infrastructure to melting dam.*
On surface, maintenance and supervision better	

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QUESTION 2

2.1 A quantity of 75m³/s of air enters a bulk cooler at 29.5/33.8°C. The barometric pressure is 112.5 kPa and the total heat removed is 3 850 kW. The water flow rate through the bulk air cooler is 80 l/s and the temperature of the water entering the cooler is 9.5 °C.

Calculate the following:

2.1.1 The temperature of the air leaving the bulk air cooler (state any assumptions) (4)

Mass flow of air entering the cooler

$M_{air\ intake} = Q/V$
$= 75 / 0.811$
$= 92.5$ kg/s

Where ASV = 0.811 m3/kg read off from the 112.5 kPa chart at 29.5/33.8 ^oC

But Total heat (kW) = Mass flow x ΔS

$\Delta S = kW / m$
$= 3850 / 92.5$
$= 41.6$ kJ/kg

Assuming that the air leaving the cooler is saturated
ΔS removed from the air = 41.6 kJ/kg

Sigma heat of the air entering the cooler = 87.4 kj/kg (read off from 112.5 kPa psychometric chart)

Sigma heat of the air leaving the cooler = 87.4- 41.6
= 45.8 kJ/kg

Assuming that the air that is leaving the cooler is saturated then the temperature read off from the 112.5 kPa chart is as follows;
17.7/17.7 ^oC (air is saturated)

2.1.2 The quantity of air leaving the bulk air cooler. (2)

Mass flow of air entering the cooler = 92.5 kg/s
Mass flow of air leaving the cooler = 92.5 kg/s – mass flow constant

ASV of air leaving the cooler at 17.7/17.7 ^oC from 112.5 kPa chart = 0.755m^3/kg
Therefore the Quantity of air leaving the cooler can be determined as follows:

$Q_{air\ exit} = m \times v$
$= 92.5 \times 0.755$
$= 69.8\ m^3/s$

2.1.3 How much water has evaporated or condensed in litres per day. (3)

Moisture content of air entering the cooler = 21.9 g/kg (from 112.5kPa chart at 29.5/33.8 ^oC)

Moisture content of air leaving the cooler = 11.4 g/kg (from 112.5kPa chart at 18.4/18.4 ^oC)

Amount of water condensed in litres per day (l/day)

Δr =21.9 – 11.4
=10.5 g/kg

The amount of water condensed can be determined as follows:

Amount of water condensed =m x Δr / 1000*(to convert k to kg)*
=92.5 x 10.5 / 1000
=0.969 l/s (assuming 1litre =1kg)

Amount of water condensed per day can be determined as follows:

Amount of water condensed per day = 0.969 x 60 x 60 x24
= 83 734.6 say 83 735 l/day

2.1.4 The temperature of the water leaving the cooler. (1)

$q = m \times C_{p\ water} \times \Delta t$
$= m \times C_{p\ water} \times (t_o - t_i)$
$t_{out} = (q / m \times C_p) + t_{in}$
$= (3850 / 80 \times 4.187) + 9.5$
$= 21.0\ ^oC$

Water leaving the cooler = 21.0 ^oC

2.2 Briefly describe the process of auto-compression which occurs when Ventilating air descends into a mine. In your description, explain why auto-compression of air is of greater significance in deep mines than in shallow mines. (5)

The law of conservation of energy states that <u>energy can never be destroyed, but it can be changed from one form of energy to another form of energy</u>. When a mass of air <u>descends into a mine, it loses potential energy</u> – as energy cannot be destroyed it stands to reason that this <u>"loss" of potential energy correlates to an increase of the heat content</u> of that air. As the <u>potential energy contained in this mass of air is directly proportional to the depth</u> to which it is to descend, the <u>deeper the mine, the greater the effect of its " auto-compression"</u> on the heat content in the mass of the air entering the intake airways of the mines.

2.3 List 5 requirements of materials to be used for the insulation of chilled water piping. (5)

- *Have good protection against mechanical damage during transport, installation and while in service*

- *Must have an effective vapour barrier to exclude air and water vapour from penetrating the insulation resulting n "water-logging".*
- *Must not be a fire hazard*
- *Must be durable, provide effective insulation and cost effective*
- *Should not be labour intensive to provide, maintain and install.*

2.4 Give brief explanation of the following terms.

2.4.1 Partial pressure (1)

The pressure of each of the individual gases which makes up a sample of air. Atmospheric pressure equals the sum of the partial pressures of all the gases which make up that atmosphere.

2.4.2 Superheat (1)

The quantity of heat required to raise the temperature of a quantity of air/water vapour mixture from its wet bulb temperature to its dry bulb temperature. This heat is expressed as kilojoules per kilogram dry air (kJ/kg)

2.4.3 Wet-bulb temperature (1)

The temperature indicated by a thermometer whose bulb is covered by a wetted wick, exposed to an air velocity f at least 3m/s and shielded from radiation from the sun, furnaces, or other forms of radiant heat. The unit of measurement is degree Celsius (^oC)

2.4.4 Enthalpy (1)

This is the sum of sensible internal energy nd pressure energy of the dry air and water vapour components of an air /water vapour mixture. This energy is expressed as kilojoules per kilogram dry air (kJ/kg)

2.4.5 Isothermal process (1)

This is a process whereby the state of a substance changes without that substance undergoing any change in temperature. Isotheral compression of air is possible if enough heat can be removed to offset the temperature rise as a result of compression.

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QUESTION 3

3.1 State typically thermal conduction values (k = W/m°C)

3.1.1 Copper *380 W/m°C*

3.1.2 Steel *45 W/m°C*

3.1.3 Plastic foam pipe insulation *0.034 W/m°C*

3.1.4	Glass	*1 W/m°C*	
3.1.5	Wood	*0.17 W/m°C*	
3.1.6	UPVC	*0.14 W/m°C*	
3.1.7	HDPE	*0.34 W/m°C*	
3.1.8	Still water	*0.62 W/m°C*	(8)

3.2.1 If still air has a k-value of 0.028 W/m°C, how does this value compare to the k-value of that of pipe foam insulation. (2)

"Plastic foam insulation" has a k value of 0.034 W/m°C, this value is larger than that for still air. This infers that still air is a better insulator than tha plastic foam insulation

3.2.2 Consider your answer in 3.2.1 (above), briefly describe how thermal insulation materials work. (2)

Thermal insulation materials are designed to keep a layer of still air, in the form of large numbers of tiny bubbles "trapped" around the vessel requiring insulation.

3.3.1 Briefly describe the following heat transfer processes and list the factors which effect these processes.

3.3.1a Conduction (2)

Is a heat transfer process occurring in solid bodies such as, metal, rock, the walls of pipes or in stationary fluids. Factors which affect the rate of heat transfer are:

- *The difference in temperature (between the "hot" side and "cold" side of the body.*
- *The thickness of the body*
- *The cross sectional area of the body*
- *The conductivity value of the material from which the body is composed*

3.3.1b Convection (2)

This form of heat transfer occurs when a moving fluid flows past a solid surface at a different temperature. Factors which affect the rate of heat transfer are;

- *The difference in temperate between the surface and the fluid*
- *The cross-sectional area of heat flow*
- *The convention heat transfer co-efficient*

3.3.1c Radiation (2)

This is the transfer of heat between two surfaces by means of electro-magnetic waves, no intervening medium such as a fluid or solid body required. Factors which affect the rate of heat transfer are:

- *The difference between the fourth powers of the absolute temperatures of the two surfaces exchanging radiation*
- *The area of the smaller of the two surfaces*
- *The emissivity and view factor*

3.4 It takes a natural gas burner 30 minutes to heat 10kg of ice to water at 50°C. If the calorific heat value of the natural gas is 38.302GJ/m³ assuming all the heat produced by the gas burner is used to heat the ice / water, calculate the volumetric flow rate, in cubic centimetres per minute (cm³/min) of the natural gas to the gas burner. (5)

Latent heat of fusion for ice = 335 kJ/kg

To heat 10kg of ice (at 0°C) at 10kg water (at 0°C) = 10 x 335 kJ = 3350 kJ

To heat 10kg of water from 0°C to 50°C) = 10 x 4.187 x (50-0) = 2093.5kJ

Total heat required to heat 10kg ice (at 0°C) to 10kg water (at 50°C) = 5443.5 kJ

If 1m³ of natural gas has a calorific heat content of 38.302 GJ (38.302 x 10^6 kJ)

Calculate amount of gas required to heat 10kg ice (at 0°C) to 10kg water (at 50°C)

Amount of gas required = (5443.5/ 38.302 x 10^6) m³

Amount of gas required = 0.000142 m³

Amount of gas required = 142.121 cm³

This heating process occurs over 30 minutes, therefore volumetric flow rate required = 142.121/ 30

Volumetric flow rate of natural gas required = 142.121 cm^3/min (for 30 minutes)

3.5 Briefly describe an adiabatic process (2)

This is a process whereby the state of a substance changes without that substance either gaining or losing heat. For example, air is compressed so quickly in a compressor that no significant heat is transferred to the air, although at the end of compression, both the temperature and pressure increases

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QUESTION 4

4. The following measurements were made on a R134a refrigeration plant operating under full load conditions.

Evaporator

Water flow rate	75.5 l/s
Water temperature in	17.7°C
Water temperature out	3.5 °C
Evaporator temperature	0.5 °C

Condenser

Water flow rate	128 l/s
Water temperature in	42.8 °C
Water temperature out	54.5 °C
Condenser temperature	58.5 °C

Compressor

Motor amperage	114.6 A
Voltage	6 600 V

Power factor 0.92

No of phases 3

Calculated compressor motor efficiency 83%

Condenser cooling tower

Water flow rate 131 l/s

Water temperature in 55.8 °C

Water temperature out 43.9 °C

Pump input power rating 300 kW

Bulk air cooler

Water flow rate 106.2 l/s

Water temperature in 5.2 °C

Water temperature out 16.3 °C

Pump input power rating 230 kW

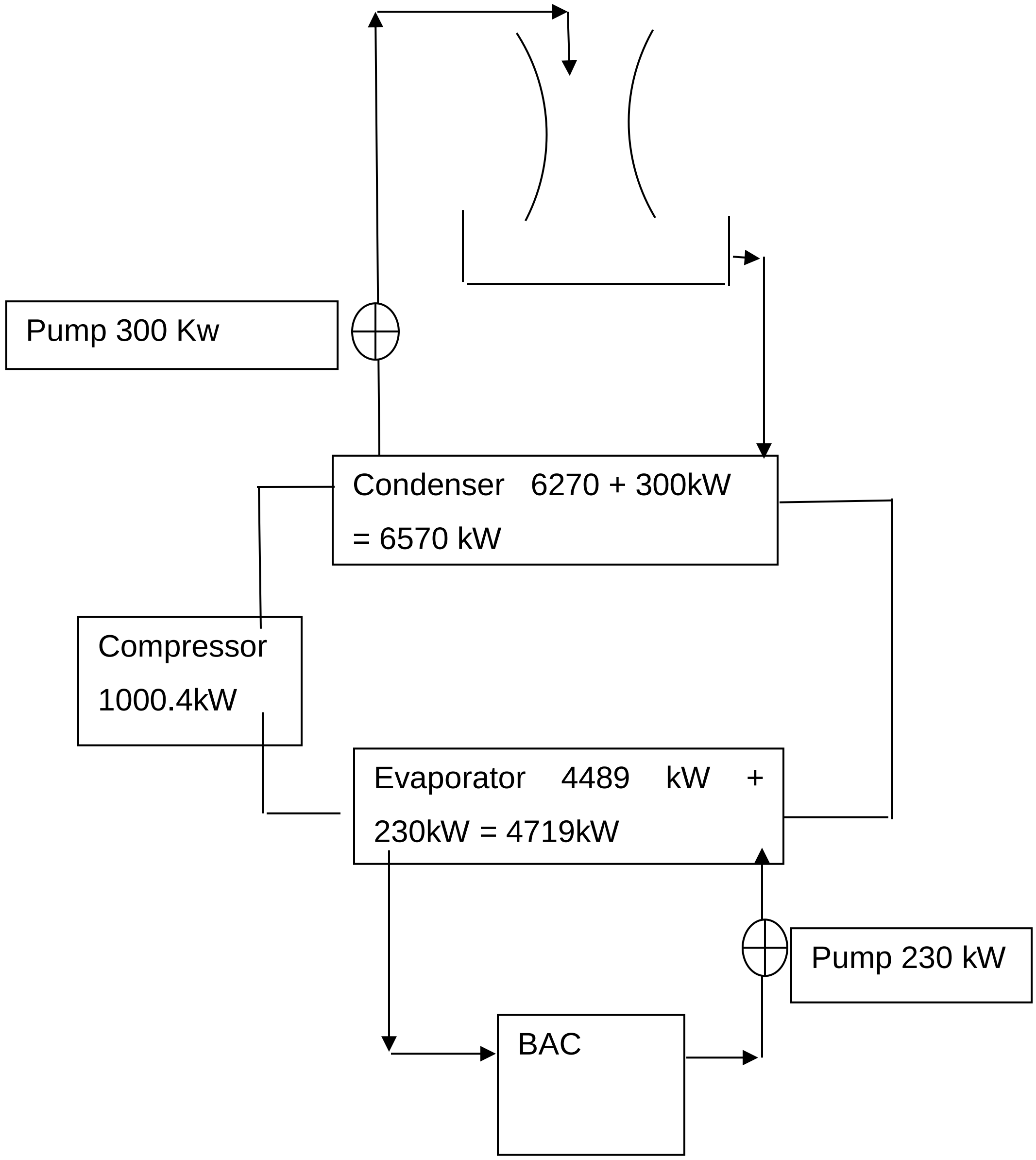
Temperature °C	Pressure MPa	Vapour Volume m^3/kg	Liquid density kg/m^3	Enthalpy Liquid kJ/kg	Enthalpy Vapour kJ/kg	Entropy Liquid kJ/kgK	Entropy Vapour kJ/kgK
-80	0,00365	4,29	1524	-1,546	248,8	0,5623	1,858
-75	0,00545	2,94	1511	4,536	251,8	0,5934	1,841
-70	0,00795	2,07	1498	10,64	254,9	0,6238	1,826
-65	0,01135	1,48	1485	16,77	258,0	0,6536	1,613
-60	0,01587	1,08	1472	22,92	261,2	0,6828	1,801
-55	0,02179	0,803	1458	29,11	264,3	0,7114	1,790
-50	0,02942	0,606	1444	35,33	267,4	0,7400	1,780
-45	0,03908	0,465	1431	41,58	270,6	0,7673	1,771
-40	0,05118	0,361	1417	47,88	273,7	0,7946	1,763
-35	0,06612	0,284	1402	54,22	276,8	0,8214	1,756
-30	0,08436	0,226	1388	60,60	280,0	0,8479	1,750
-25	0,10640	0,181	1373	67,03	283,1	0,8740	1,745
-20	0,13270	0,147	1358	73,51	286,1	0,9000	1,740
-15	0,16390	0,121	1343	80,05	289,2	0,9252	1,735
-10	0,20050	0,100	1327	86,64	292,2	0,9504	1,732
-5	0,24320	0,083	1311	93,29	295,2	0,9753	1,728
0	0,29250	0,069	1295	100,0	298,1	1,000	1,725
5	0,34920	0,058	1278	106,8	301,0	1,024	1,723
10	0,41390	0,050	1261	113,6	303,9	1,049	1,721
15	0,48740	0,042	1244	120,5	306,6	1,073	1,718
20	0,57020	0,036	1226	127,5	309,3	1,096	1,717
25	0,66340	0,031	1207	134,6	312,0	1,120	1,715
30	0,76750	0,027	1188	141,8	314,5	1,144	1,713
35	0,88350	0,023	1168	149,0	317,0	1,167	1,712
40	1,01220	0,020	1147	156,4	319,2	1,190	1,710
45	1,15450	0,017	1125	163,8	321,3	1,214	1,709
50	1,31130	0,015	1103	171,4	323,3	1,237	1,707
55	1,48370	0,013	1079	179,1	325,1	1,260	1,705
60	1,67270	0,012	1053	187,0	326,6	1,283	1,702
65	1,88000	0,010	1026	195,1	327,8	1,307	1,699
70	2,10560	0,009	996,9	203,4	328,7	1,331	1,670
75	2,35230	0,008	964,7	212,0	329,1	1,355	1,691
80	2,62130	0,007	928,7	221,1	328,9	1,380	1,685
85	2,91470	0,006	887,3	230,7	32719	1,406	1,677
90	3,23480	0,005	837,3	241,3	325,6	1,434	1,666
95	3,58530	0,004	770,8	253,7	320,7	1,467	1,649
100	3,97200	0,003	645,5	272,7	307,0	1,517	1,609
101*	4,05500	0,002	509,1	289,4	289,4	1,561	1,561

*Critical point

MPa

Saturation points of Refrigerant 134 A

4.1 Show the different energy transfer points in the 3 circuits, clearly assign the Heat transfer to each component. (10)



4.2 With reference to the enclosed saturation point data sheet for refrigerant R134a, perform a heat balance on the refrigerant side of the circuit given that the compressor discharge refrigerant enthalpy is 320 kJ/kg. (5)

Next: Consider the data on the water circuit:

The BAC duty $= m \times c \times \Delta t$

$= 106.2 \times 4.187 \times (16.3 – 5.2)\ ^oC$

$= 4936$ *kW*

Added to which should be the (approximate) circulating pump rated power of 230 kW,

The heat balance is then calculated as follows (assuming condenser duty is correct)

6270 should = 5166+ 1000.4

6720 should = 6166.4

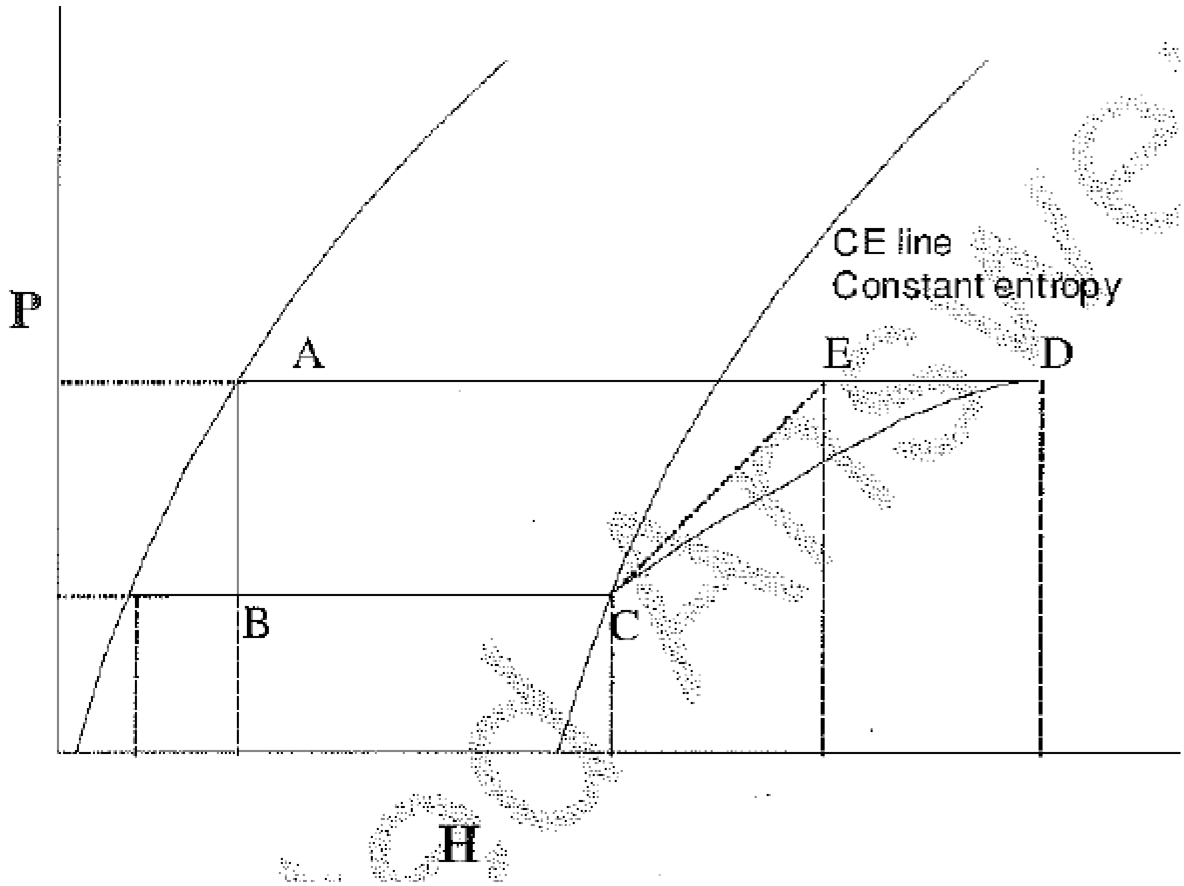
The % error must now be established:

% error = (6270 – 6166.4) / 6270 x 100 = 1.7%

This figure is well within acceptable limit of 5%

From the above, it therefore appears as if the evaporator water flow rate has been measured incorrectly (75.5 l/s is therefore wrong)

Draw a simple enthalpy diagram:



From the above P-H diagram a heat balance can be obtained:

$H_D - H_A \quad = (H_C - H_B) + (H_D - H_C)$

*From the data sheet provided, calculate (by interpolation) the enthalpy for the liquid phase A and B (which are the same, but at different temperatures) and for the vapour at point C(point D is given). The temperature is 0.5°C (given) for the line BC and 58.5°C for the line A- the saturated vapour curve line. (**Note: The point C represents the saturated vapour position of the refrigerant on the pH diagram at a temperature of 0.5°C and point A represents the saturated liquid position of the refrigerant at 58.5 °C)** Point B is a mixture of refrigerant liquid and vapour and therefore not saturated.*

$H_A \quad = H_B \quad = 179.1 + [(58.5 - 55)/5 \times (187 - 179.1)]$

$\quad\quad = 184.6$ kJ/kg

H_C = 298.1 + [(0.5 – 0)/5 x (301 – 298.1)]

=298.4 kJ/kg

And

Perform balance (point H_D given as 320 kJ/kg)

$H_D – H_A$ = $(H_C – H_B) + (H_D – H_C)$

(320 – 184.6)= (298.4 – 184.6) + (320 – 298.4)

135.4 = 135.4

Note: The above answer is obvious and will be so for any mass flow of refrigerant, we need to find out what the actual mass flow for the refrigerant in this example is.

4.3 What is the refrigerant mass flow rate at the inlet to the compressor. (5)

The refrigerant mass flow can now be determined by using the P-H diagram results as obtained for the condenser heat exchange (6270 kW)

$$\text{Massflow} = \frac{\textit{Total heat exchanged at the condenser (kW)}}{\textit{Unit heat exchange in the condenser (kJ/kg)}}$$

= 6270 / H_D - H_A

= 6270 / (320-184.6)

= 46.3 kg/s

The evaporator duty using the unit heat exchange figures and the mass flow rate determined in c, can be determined

Plant duty (using refrigerant data):

Evaporator duty = (HC – HB) x mass flow rate (of refrigerant)

= (298.4 – 184.6) x 46.3

=5269 kW

4.4 What is the plant duty based on the refrigeration side calculations and what conclusions you draw regarding errors in the measurements obtained (5)

This figure very much to the figure used in improved heat balance (5166 kW, using BAC duty and pump power input power rating). This therefore also supports the *previous argument that the evaporator flow rate is suspicious. The heat balance then calculated as follows (based on the refrigerant data);*

6270 should = 5269+ 1000.4

6720 should = 6269.4

The % error must now be established:

% error = (6270 – 6269.4) / 6270 x 100 = 0.01%

The % error must now be established, but it is obvious that the figures are the same. The heat balance is correct.

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