Chamber of Mines of South Africa

MEMORANDUM

SUBJECT: **CHAMBER OF MINES OF SOUTH AFRICA – CERTIFICATE IN MINE ENVIRONMENTAL CONTROL** **PAPER 2 – THERMAL ENGINEERING** SUBJECT CODE: **COMMEC2** EXAMINATION DATE: **10 October 2018** TIME: **14:30 – 18:00**	EXAMINER**: Eugene Botha** MODERATOR: **Marco Biffi** TOTAL MARKS: **[100]** PASS MARK: **(60%)**

NUMBER OF PAGES: **17**

SPECIAL REQUIREMENTS:

THIS IS **NOT** AN **OPEN BOOK EXAMINATION**.
INSTRUCTIONS TO CANDIDATES:

1. Answer all 4 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) is recorded as marks will be deducted from answers if the incorrect unit is used. (Even if the calculated value is correct).

8. Please note that you are not allowed to contact your examiner or moderator regarding this examination.
9. Cell phones are **NOT** allowed in the examination room.

QUESTION 1. (20)

The following measurements were made during a routine check on the performance of an underground cooling plant.

Evaporator

Water flow rate	39,7 l/s
Inlet water temperature	22,8 ºC
Delivery water temperature	7,7 ºC
Evaporating pressure (absolute)	341 kPa

Condenser

Water flow rate	70,2 l/s
Inlet water temperature	37,3 ºC
Delivery water temperature	44,8 ºC
Condensing pressure (absolute)	1 201 kPa

Barometric pressure	116 kPa

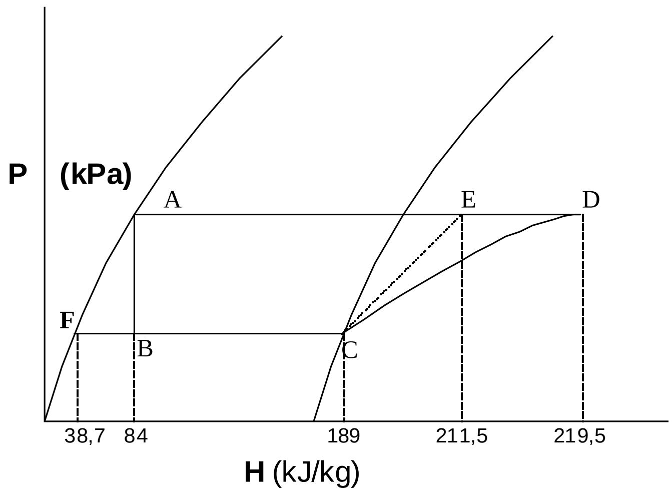
Electric input power to compressor motor	645 kW
Compressor discharge temperature	66ºC

The plant is a single stage refrigerant 12 machine. The compressor is driven via a gearbox and gearbox and motor efficiencies are 98% and 94% percent respectively. Previous measurements on this cooling plant have indicated that water flow rate measurements in the condenser and evaporator are suspect, but that the electrical input power is known to be a reliable measurement as are the condensing and evaporating pressures.

The values as plotted on a Pressure-Enthalpy diagram are as follows:

HA =84 kJ/kg	HD =219,5 kJ/kg
HB =84 kJ/kg	HE =211,5 kJ/kg

HC =189 kJ/kg HF =38,7 kJ/kg



The specific volume of the refrigerant at the compressor inlet is 0,052 m^3/kg. Using the results from the pressure-enthalpy diagram and calculate the following:

1.1 The gauge pressures for the condenser and evaporator (2)

1.2 The compressor efficiency (2)

1.3 The actual work of compression (in kW) (2)

1.4 The ideal work of compression and heat losses in compressor expressed in kW (3)

1.5 The refrigerant mass flow (1)

1.6 The refrigerant volume flow rate at the compressor inlet (1)

1.7 The plant duty (kW) (1)

1.8 The correct evaporator and condenser water flow rate expressed in litres/second (7)

1.9 The correct final heat balance with correct water flow rates (1)

Question 1 – Answer

1.1 Condenser absolute pressure = Pmeter + Patmosphere

Pmeter = Pabs - Patmosphere

= 1201 – 116 **(1)**

= 1085 kPa

Evaporator absolute pressure = Pmeter + Patmosphere

Pmeter = Pabs - Patmosphere

= 341 - 116

= 225 kPa **(1)**

1.2 The compressor efficiency:

$$\text{Compressor effciency} = \frac{H_E - H_C}{H_D - H_C} \text{x} 100\%$$

$$= \frac{211{,}5 - 189}{219{,}5 \quad 189} \text{x} 100\%$$

$$= 73{,}8\%$$

(2)

1.3 The electric motor output power = 645 x eff compressor motor

= 645 x 0,94

= 606,3 kW **(1)**

The compressor power in = 606,3 x eff compressor gearbox

= 606,3 x 0,98

= 594,2 kW (actual work of compression) **(1)**

1.4

NB: Compressor power in = ideal work of compression + heat losses

594,2 = (594,2 x 0,738) + (594,2 x 0,262) **(1)**

= 438,5 + 155,7

= 594,2 kW **(1)**

= actual work of compression **(1)**

1.5 The mass flow of the refrigerant can be determined as follows:

$$\text{massflow refrigerant} = \frac{594{,}2}{(H_D - H_C)_{\text{actualwork of compression}}}$$

$$= \frac{594{,}2}{30{,}5}$$

$$= 19{,}5 \text{ kg/s}$$

(1)

1.6 Refrigerant volume flow = VR x spec volume (<) compressor inlet

= 19,5 kg/s x 0,052 m3/kg

= 1,014 m3/s **(1)**

1.7 Plant duty = MR x (HC – HB)

= 19,5 x (189 – 84)

= 2 048 kW **(1)**

1.8 A heat balance of the measurements made in the water circuits of the condenser and the evaporator and the electrical input power confirm that the water flow measurements are suspect. This is shown below:

Condenser duty= evaporator duty + heat of compression

70,2 x 4,187 x 7,5 = 39,7 x 4,187 x 15,1 + 594,2 **(1)**

2 204kW = 3104kW **(1)**

The difference is well in excess of the 5% which is normally accepted. Therefore the water flow rates must be calculated by using the figures obtained from the P-H diagram together with the water temperatures. **(1)**

Thus:

$$\text{massflow of water condenser} = \frac{\text{kW in condenser}}{c \times \Delta t_w}$$

$$= \frac{m_R \times (H_D - H_A)}{4{,}187 \times (44{,}8 - 37{,}3)}$$

$$= \frac{19{,}5 \times (219{,}5 - 84)}{4{,}187 \times (44{,}8 - 37{,}3)}$$

$$= 84{,}1 \text{ kg/s or litres/second}$$

(2)

$$\text{massflow of water evaporator} = \frac{\text{kW in evaporator}}{c \times \Delta t_w}$$

$$= \frac{2\,048}{4{,}187 \times (22{,}8 - 7{,}7)}$$

$$= 32{,}4 \text{ kg/s}$$

$$= 32{,}4 \text{ litres/second}$$

(2)

1.9 These values differ considerably from those measured. The new heat balance will show the difference:

Condenser duty = evaporator duty + heat of compression

$84{,}1 \times 4{,}187 \times 7{,}5 = 32{,}4 \times 4{,}187 \times 15{,}1 + 594{,}2$

2 641 kW = 2 643 kW **(1)**

QUESTION 2. (25)

A base metal mine is extending its workings and you are required to determine whether acclimatisation will be necessary (a reject temperature of higher than 27.5°C will necessitate acclimatisation). Information from 12 different stope reports is summarised in the table below. The air reaches the new stoping section (which consists of 3 stopes in series) at 23.5/26.5°C, and 15 m^3/s is available. The air must ventilate these three new stopes, which each has a mean virgin rock temperature of 35.3°C, 34.3°C and 33.3°C respectively. Assume that the air leaves each stope with a dry-bulb temperature of 2°C higher than the wet-bulb temperature. Calculate the wet-bulb temperature leaving each stope on its way to the next stope and state whether acclimatisation is necessary. The barometric pressure is 95 kPa.

Note: A simple method of expressing the heat gain in a stope is as a function of the difference between the virgin rock temperature and the entering dry-bulb temperature.

Air entering the stope		Air leaving the stope		Qty	VRT	Stope heat gain
wet-bulb (°C)	Dry-bulb (°C)	wet-bulb (°C)	Dry-bulb (°C)	(m3/s)	(°C)	(kW)
18.5	21.0	21.5	22.0	18.3	32.3	212
22.5	24.0	23.8	24.2	24.3	30.6	136
20.2	22.0	22.5	23.0	20.2	32.3	184
18.5	20.5	22.8	23.3	13.9	32.3	230
17.6	19.1	20.8	21.4	8.6	23.6	100
12.4	14.7	15.3	16.9	24.9	23.7	187
17.0	19.5	21.0	22.3	6.7	23.7	96
20.5	21.6	25.4	26.2	8.0	30.3	166
23.2	25.1	24.4	24.8	10.8	27.3	53
18.4	19.9	19.7	20.5	16.2	22.7	76
22.0	25.5	24.4	26.0	16.4	33.3	153
20.5	25.0	22.8	26.3	17.3	33.3	160

QUESTION 2- ANSWER

In each of the stope reports summarised in the table given the air absorbs a different amount of heat (kW), mainly because of the difference between the VRT and the entering dry-bulb temperature of the air.

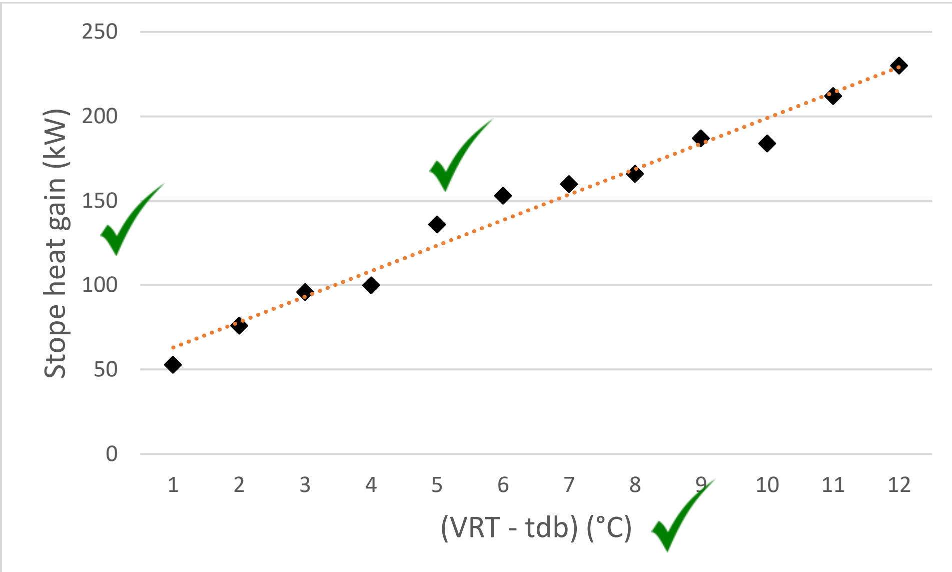
The information given can be summarised as follows;

Air entering the stope	VRT	VRT – Entering t_{db}	Stope heat gain
Dry-bulb (°C)	(°C)	(°C)	(kW)
21.0	32.3	11.3	212
24.0	30.6	6.6	136
22.0	32.3	10.3	184
20.5	32.3	11.8	230
19.1	23.6	4.5	100
14.7	23.7	9.0	187
19.5	23.7	4.2	96
21.6	30.3	8.7	166
25.1	27.3	2.2	53
19.9	22.7	2.8	76
25.5	33.3	7.8	153

25.0	33.3	8.3	160

(1)

A graph of the stope heat gain versus (VRT – entering t_{db}) can now be plotted.



(3)

A straight line can now be fitted to these points and the stope heat gain applicable for any value of (VRT – entering t_{db}) can now be read of the graph.

Stope 1

From the 95 kPa psychrometric chart at 23.5/26.5 °C read off the properties of the air:

Specific volume of air entering stope 1	=	0.933 m^3/kg	**(1)**
Specific heat of air entering stope 1	=	71.3 kJ/kg	**(1)**
Mass flow of entering stope 1	=	Q/v	
		15.0 / 0.933	
		16.1 kg/s	**(1)**
The VRT in the stope	=	35.3 °C	
Therefore (VRT – t_{db})	=	(35.3-26.5) °C	
	=	8.8 °C	**(1)**

From the graph the heat gained in the stope is **172 kW** **(1)**

The heat gained per kg as follows:

$$\text{Heat gained } (\Delta S) = \frac{\text{kW (air)}}{\text{massflow of air}} = \frac{172}{16.1} = 10.7 \text{ kJ/kg}$$ **(1)**

Therefore the Sigma heat of the air leaving the stope can be determined as follows;

Sigma heat of air leaving stope 1	=	Sin + ΔS	
	=	71.3 + 10.7	
	=	82 kJ/kg	**(1)**

From the 95 kPa psychrometric chart the wet-bulb temperature at a Sigma heat of 82 kJ/kg can be read off (keep in mind that the difference between the dry-bulb and wet-bulb temperature is given as 2 °C)

The temperature of the air leaving the first stope is 26.1 / 28.1 °C **(1)**

Stope 2

The dry-bulb temperature entering stope 2	=	28.1 °C	
Sigma heat of air into stope 2	=	82 kJ/kg	**(1)**
The VRT in the stope	=	34.3 °C	
Therefore (VRT – tdb)	=	(34.3 – 28.1) °C	
	=	6.2 °C	

From the graph the heat gained in the stope is **<u>127 kW</u>** **(1)**

The heat gained per kg as follows:

$$\text{Heat gained } (\Delta S) = \frac{\text{kW (air)}}{\text{massflow of air}} = \frac{127}{16.1} = 7.9 \text{ kJ/kg}$$ **(1)**

Therefore the Sigma heat of the air leaving the stope can be determined as follows;

Sigma heat of air leaving stope 2	=	Sin + ΔS	
	=	82 + 7.9	
	=	89.9 kJ/kg	**(1)**

From the 95 kPa psychrometric chart the wet-bulb temperature at a Sigma heat of 89.9 kJ/kg can be read off (keep in mind that the difference between the dry-bulb and wet-bulb temperature is given as 2 °C)

The temperature of the air leaving the second stope is 27.8 / 29.8 °C **(1)**

Stope 3

The dry-bulb temperature entering stope 3	=	29.8 °C	
Sigma heat of air into stope 3	=	89.9 kJ/kg	**(1)**
The VRT in the stope	=	33.3 °C	
Therefore (VRT – tdb)	=	(33.3 – 29.8) °C	
	=	3.5 °C	**(1)**

From the graph the heat gained in the stope is **80 kW** **(1)**

The heat gained per kg as follows:

$$\text{Heat gained } (\Delta S) = \frac{\text{kW (air)}}{\text{massflow of air}}$$

$$= \frac{80}{16.1}$$

$$= 5 \text{ kJ/kg}$$ **(1)**

Therefore the Sigma heat of the air leaving the stope can be determined as follows;

Sigma heat of air leaving stope 3 = Sin + ΔS

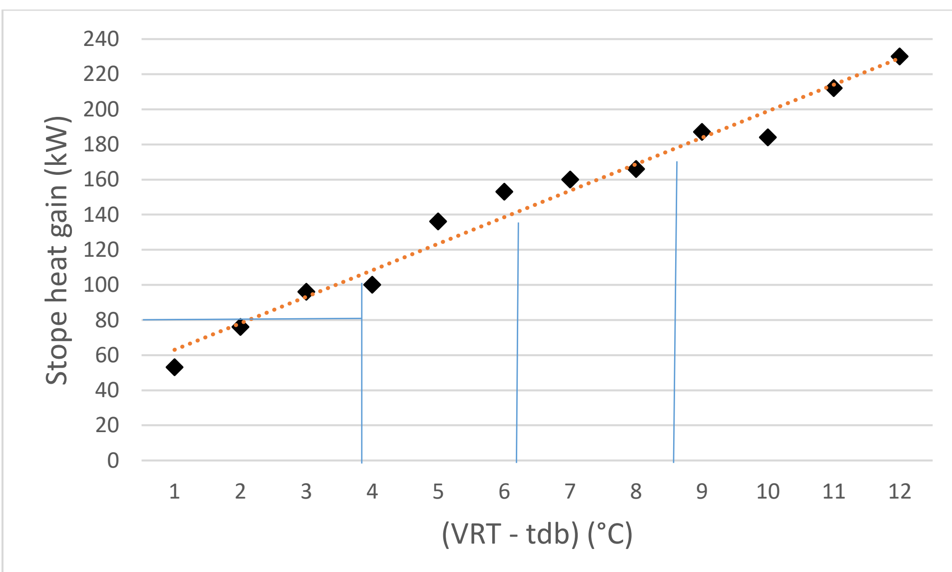
= 89.5 + 59

= 94.9 kJ/kg **(1)**

From the 95 kPa psychrometric chart the wet-bulb temperature at a Sigma heat of 94.9 kJ/kg can be read off (keep in mind that the difference between the dry-bulb and wet-bulb temperature is given as 2 °C)

The temperature of the air leaving the third stope is 28.8 / 30.8 °C **(1)**

Therefore acclimatisation would be required in stopes 2 and 3 (wet-bulb temperatures higher than 27.5 °C) **(2)**



QUESTION 3. (25)

(a) Use the Steady Flow Energy equation to discuss the heat that is added to the air by the use of electrical machinery underground, such as fans and hoists. (3)

(b) The following measurements were taken at an underground booster fan inlet: (13)

Intake air volume 236 m^3/s
Fan pressure 5 kPa
Temperature 24 / 27 °C
Barometric pressure 115 kPa
Power input to fan motor 1 775 kW
Motor efficiency 95 %

(i) Determine the condition at the fan discharge
(ii) What are the efficiency and overall efficiency of the fan

(c) The following measurements were taken at the inlet of an underground hoist chamber. (9)

Temperature	26.3 / 29.5 °C
Barometric pressure	115 kPa
Hoist motor input power	2 170 kW
Motor efficiency	87 %

How much air must be supplied to the hoist chamber to ensure that the wet-bulb temperature in the chamber does not exceed 28.5 °C wet-bulb? State any assumptions you make in giving your answer.

QUESTION 3- ANSWER

(a) If the work done by a machine is work against friction, then all of the input energy will be given off as heat. If the machine does work against gravity, that is where the energy used is converted into potential energy, then the energy not used to do work is converted to heat. Example, if a machine is 90% efficient, then 10% of the energy will be given off as heat. **(3)**

(b) (i) Using the 115 kPa psychrometric chart, the characteristics of the air can be determined

The specific volume of the air in main airway	=	0.762 m3/kg	**(1)**
The quantity of air in the main airway	=	236 m3/s	**(1)**
Sigma heat of the air entering fan	=	64.5 kJ/kg	**(1)**
Apparent specific humidity of air entering fan	=	15.3 g/kg	**(1)**

Massflow of the air $= \frac{Q}{v}$

$= \frac{236}{}$

$$= \frac{\ldots}{0.762} = 310 \text{ kg/s}$$ **(1)**

The increase in heat of the air, per kg of mass flow of air, can be determined as follows:

Unit increase in heat $= \frac{kW}{m}$ **(1)**

$= \frac{1775}{310}$

$=$ 5.73 kJ/kg **(1)**

Sigma heat of air leaving fan (S_{out}) = Sin = ΔS

= (64.5 + 5.73)

= 70.2 kJ/kg **(1)**

The barometric pressure fan outlet = 115 + 5

= 120 kPa **(1)**

The temperature of the air can be read of the 120 kPa psychrometric chart,
Sigma heat of 70.2 kJ/kg and assuming the specific humidity remains constant.
(note, 120 kPa not 115 kPa, a common mistake made by students)
Temperature of the air leaving the fan is 26.0 / 32.2 °C. **(1)**

(iii) Fan power = pQ

= 5 x 236

= 1 180 kW **(1)**

Fan motor input power = 1 775 kW (given)

Fan input power = fan motor input power x motor efficiency

= 1 775 x 0.95

= 1 686 kW **(1)**

The fan efficiency can now be determined as follows

Fan efficiency $= \frac{\text{air power}}{\text{Fan input power}} \times 100\%$

$= \frac{1180}{1686} \times 100\%$

= 70% **(1)**

The fan overall efficiency can now be determined as follows

Fan overall efficiency $= \frac{\text{air power}}{\text{Fan motor input power}} \times 100\%$

$= \frac{1180}{1775} \times 100\%$

= 66% **(1)**

(c) Using the 115 kPa psychrometric chart, the characteristics of the air can be determined

The specific volume of the air entering chamber	=	0.778 m3/kg	**(1)**
Sigma heat of the air entering chamber (26.3°C)	=	72.8 kJ/kg	**(1)**
Sigma heat of the air leaving the chamber (28.5°C)	=	83.5 kJ/kg	**(1)**
Specific humidity of air entering chamber	=	17.5 g/kg	**(1)**
The allowable increase in Sigma heat	=	83.5 – 72.8	
	=	10.7 kJ/kg	**(1)**

The waste heat given off to the air by the motor can be determined as follows:

$$\text{Waste heat of air} = \frac{(100-87)}{100} \times 2\,170$$
$$= 0.13 \times 2\,170$$
$$= 282 \text{ kW} \qquad \textbf{(1)}$$

The mass flow of air (kg/s) required can be determined as follows:

$$\text{Mass flow of air} = \frac{282}{10.7}$$
$$= 26.4 \text{ kg/s} \qquad \textbf{(1)}$$

$$\text{Air volume flow, Q} = m \times v$$
$$= 26.4 \times 0.778$$
$$= 20.5 \text{ m}^3\text{/s} \qquad \textbf{(1)}$$

Quantity required to ensure the wet bulb temperature inside the chamber does not exceed 28.5°C is 20.5 m^3/s **(1)**

QUESTION 4. (10)

4.1 In a stope the ventilation air has a speed of 1m/s. Calculate the rate at which heat is convected form a workman, assuming that his body has an average diameter of 200 mm. Assume, further, that:

a) The workman has a skin area of 1.5 m^2, and an average skin temperature of 35°C.

b) The condition of the air is 29°C wet-bulb, 31°C dry-bulb and a 100 kPa pressure. (3)

4.2 A steam pipe in a uranium plant is 26 mm in diameter and is covered with insulation 50 mm in thickness. The k-value of the insulation is 0.2 W/m°C. Calculate the heat loss per metre length of pipe if the temperatures of the inner and outer surfaces of the insulation are 300°C and 40°C.

4.2.1 Using the average area (3)

4.2.2 Using the log mean area (3)

4.2.3 What is the error in % when using the different areas to calculate the heat loss(1)

Answer

4.1

(a) The convective heat transfer coefficient of the air passing over the workman is found from Figure 19.8 (diameter 200 mm, air speed 1 m/s) as h_c – 9.5 W/m^2°C **(1)**

The rate at which heat is convected away from the workman is:

$Q_c = h_cA(t_{skin} - t_{dry\text{-}bulb})$ **(1)**

= 9.5 x 1.5 x (35-31)

<u>= 57 W</u> **(1)**

4.2

Average area $A_{av} = \pi \times (r_1 + r_2) = [\pi \times (13 + 63)]/\ 1000 = 0.238\ m^2$ **(1)**

Insulation thickness b = 50 mm = 0.05 m

4.3.1 q= 0.2 x 0.238 x (300 -40)/0.05 **(1)**

=<u>248 W per metre length of pipe</u> **(1)**

4.3.2 $A1 = 2\pi r_1 = 2\pi(13/1000) = 0.08168\ m^2$

$A2 = 2\pi r_2 = 2\pi(63/1000) = 0.3958\ m^2$ **(1)**

Log mean area = $(A_2 - A_1)/\ \log_e (A_2/A_1)$

= $(0.3958 - 0.08168)/\log_e (4.846)$ **(1)**

= 0.3141/1.58

=0.199 m^2 per metre length **(1)**

4.3.3 The error is hence [(0.2388/0.199) – 1] = 0.2 or 20 % **(1)**

QUESTION 5. (20)

5.1.1 Name two commonly used refrigerants employed in underground refrigeration plant. (2)

5.1.2 Non corrosive and non-flammable are two properties of an ideal refrigerant name 3 other properties that a refrigerant should ideally have? (3)

5.2.1 Sketch a typical underground cooling tower with typical operating conditions. (6)

5.2.2 What are the limitations of such towers? (2)

5.3.1 Sketch a typical coil type cooling car with typical flow rates and temperatures. (5)

5.3.2 If a survey of such a car showed that its performance had worsened since the last survey what would you suspect? (2)

Answer Q5

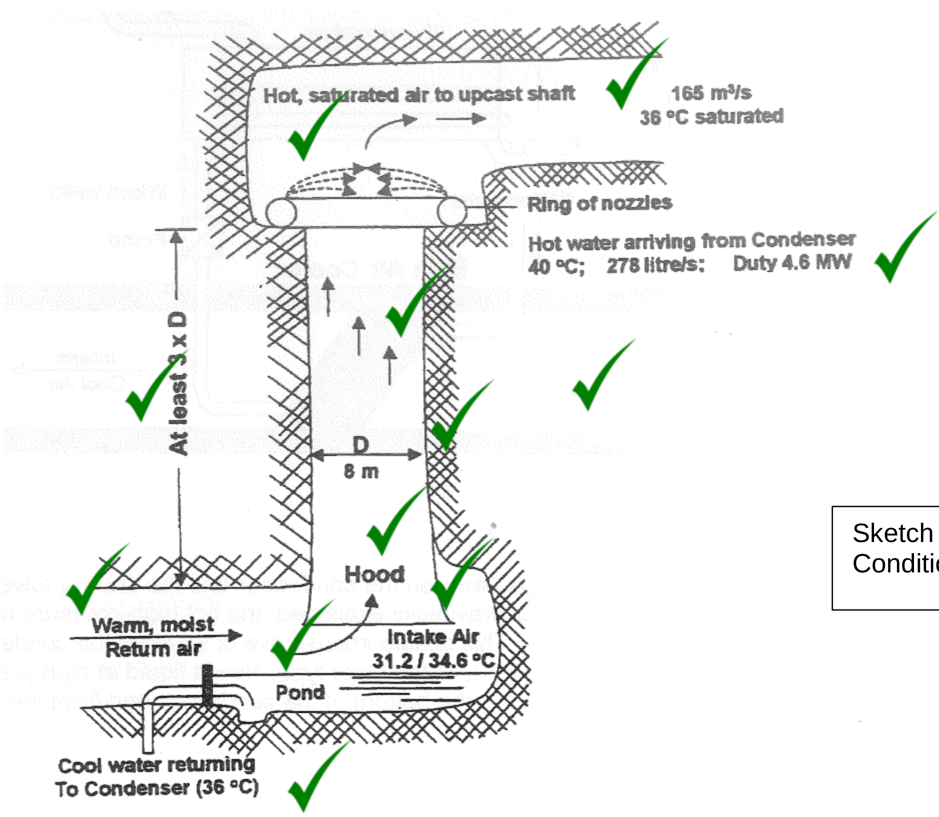
5.1.1 Freon 12 (R12) and Refrigerant 134a **(2)**

5.1.2 Refrigerants should be

- Non-flammable (given)
- Non corrosive (given)
- Inexpensive
- Should not affect the lubricant used in the compressor
- Non toxic
- Non explosive
- Easily be detectable **(3)**
-

Any other 3

5.2.1



Sketch 3 marks
Conditions = 6 x0.5 = 3 marks

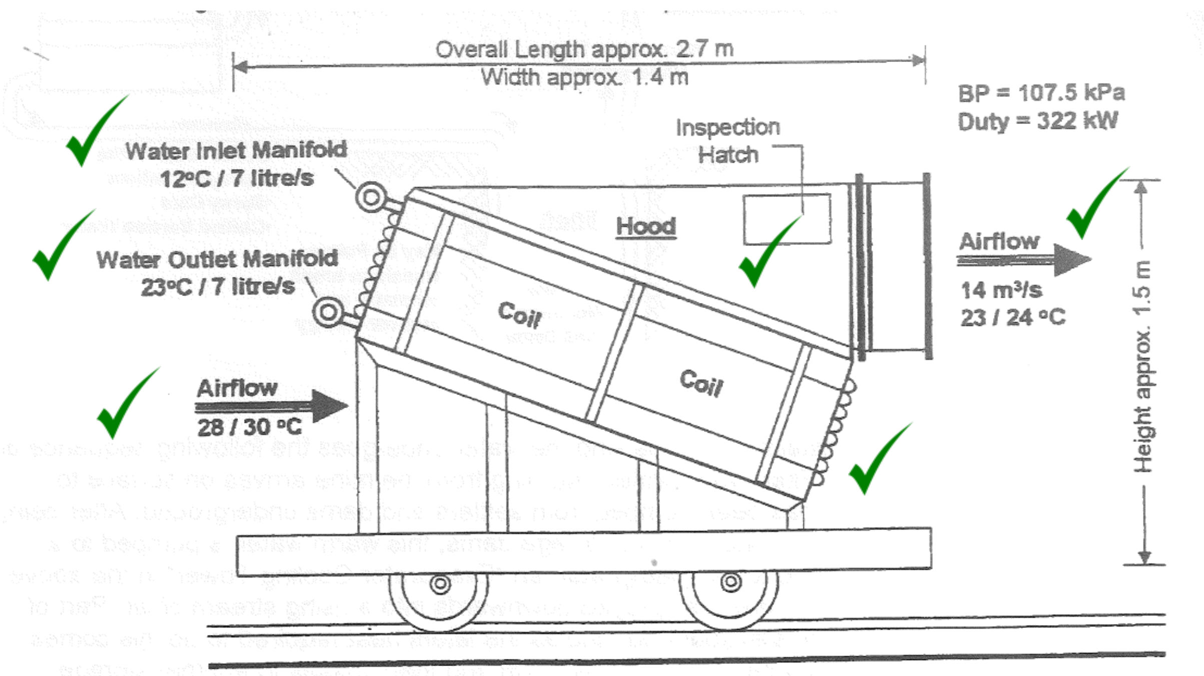
(3)

5.2.2 Heat exchange capability as this is dictated by the RAW capacity.

- Volume of air available for exchange is limited. **(1)**
- Air entering tower is already hot **(1)**

5.3.1

Sketch 2 marks
Conditions = 4 x0.5 = 2 marks any 4



(2)

5.3.2

- Fouling of coils (inside) / Water flow rate
- Outside of the coils can become blocked with dirt and mud
- Fan performance/ inward leakage after coils
- Inlet chilled water temperature
- Ambient air temperature change

Any 2

(2)