Q.1 **Question 1**

a) Sketch a typical mixed hydrocarbon gas phase envelope. Indicate the cricondenbar. What is the significance of the Cricondenbar for the operation of gas pipeline systems? **[5 marks]**

Solution:

[2/5] Cricondenbar is the horizontal tangent at top of phase envelope.✓$_2$

[1/5] Irrespective of pipeline temperature, the gas can not enter the two-phase region if the pressure is above the cricondenbar✓$_1$.

[1/5] [1/5] If liquid were to be produced, this would reduce the flow area, impacting production and could also cause troublesome slug flow✓$_1$. If a gas pipeline is operated above the cricondenbar, conditions promoting two-phase flow are prevented✓$_1$.

b) An oil/gas separator is operating at 85°C and 2.3 bara producing an oil with a True Vapour Pressure (TVP) of 0.94 bara. Why is TVP an important specification? If water is introduced with the hydrocarbons, what will happen to the TVP if the separator pressure and temperature remain unchanged? **[8 marks]**

Solution:

[2/8] It is important to maintain a TVP below atmospheric pressure to prevent vaporisation within the oil storage tanks. This could result in a loss of product and impact the safety of the storage tank by causing an over-pressure.✓$_2$

[6/8] The TVP will reduce. The introduction of water produces an additional partial pressure of water onto the gas phase. Since the separator pressure is fixed the partial pressure associated with the gaseous hydrocarbon components will reduce. This effectively "boils off" more light ends resulting in a lowering of the liquid phase (oil) TVP.✓$_6$

c) A subsea gas pipeline transports gas to a shore terminal. The seabed temperature is 4°C. The pipeline is being operated at a much higher gas throughput than normal and it is noted that the gas arrival temperature at the shore terminal is -2°C. What effect would explain a gas temperature lower than ambient temperature? **[5 marks]**

Solution:

[5/5] At high gas rates, the pressure gradient will be correspondingly higher resulting in a more pronounced Joule Thomson expansion effect. The J-T expansion is reducing the gas temperature at a rate higher than the heat transfer rate from the sea is warming the gas.✓$_5$

d) A natural gas has a calorific value of 40 MJ Nm^{-3}. If the CO_2 concentration of the gas is increased from 0 to 5% calculate the new calorific value. **[2 marks]**

Solution:

[2/2] CO_2 has no heat of combustion. Hence $4 \times 0.95 = 38$ MJ/Nm^3.✓$_2$

[Question total: 20 marks]

Q.2 **Question 2**
Flow assurance

a) Oil production from a vertical riser is enhanced by injecting gas at the riser base. A series of tests is conducted where the injected gas rate is varied. The oil production trend observed indicates an optimal gas rate which maximises oil production. If gas rates are reduced from the optimal gas rate, oil production drops, similarly if gas rates are increased above the optimal rate, oil production drops. Explain this observation and clearly state any assumptions you make. **[6 marks]**

Solution:

[2/6] Oil flowrate will be a function of the pressure drop in the riser. For vertical flow there will be two components influencing the pressure drop-friction and elevation. Acceleration will be negligible✓$_2$.

[2/6] As gas is first introduced, the oil flow rate increases as the gas lowers the density of the fluid in the column. Thus reducing the elevation pressure losses ($\rho g h$). Further increases in oil flow are seen as the gas rate is increased as the density is further reduced✓$_2$.

[2/6] Although density is reducing which is reducing the elevation losses the frictional component of the pressure loss is increasing due to the increased system velocity. There comes a point where the benefits obtained from density reduction are overcome by friction. At this point further increases in gas rate result in an increased pressure drop and reduced oil rate. Hence the opposite trend is seen with respect to oil flowrate✓$_2$.

b) Liquid and gas are flowing in a horizontal pipeline with inner diameter of 38.1 cm. The liquid rate is 0.0369 $m^3\ s^{-1}$. Using the Mandhane flow map in Fig. 1, calculate the gas rate in $m^3\ s^{-1}$ where there will be a transition from slug to annular flow. **[4 marks]**

Solution:

Calculating the pipeline cross-sectional area,

$$A = 3.141 \times 0.381^2/4 = 0.114\ \mathrm{m}^2$$

The liquid superficial velocity can then be calculated,

$$0.0369/0.114 = 0.324\ \mathrm{m\ s^{-1}} = 1.06\ \mathrm{ft\ s^{-1}}$$

[2/4] ✓$_2$ From the map we find that a transition occurs at a gas superficial velocity of approximately 50–70 ft s^{-1}, which is approximately 15.28–21.40 m s^{-1}. This is based on the thickness of the line; however, the size of the transition zone and any hysteresis it has are not well defined for such maps. The gas volumetric flow is then in the following range,

$$15.28 \times 0.114 = 1.74\ \mathrm{m^3\ s^{-1}}$$
$$21.40 \times 0.114 = 2.44\ \mathrm{m^3\ s^{-1}}$$

[2/4] ✓$_2$

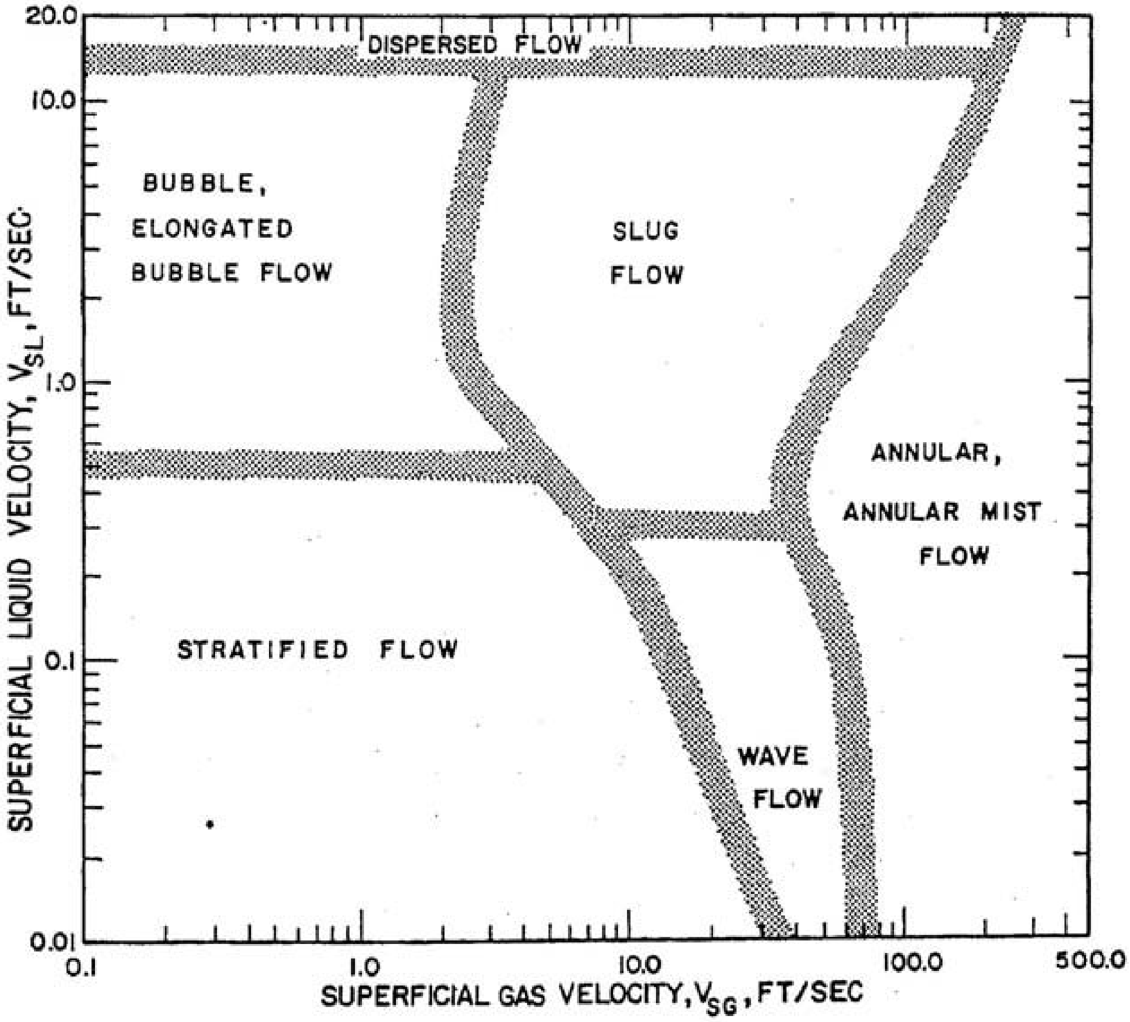


Figure 1: *The Mandhane horizontal flow pattern map.*

c) What is a hydrate and what are the conditions required for their formation? **[2 marks]**

Solution:
A hydrate is an ice like substance where water reacts with small hydrocarbon molecules
[1/2] and water✓. Conditions promoting hydrate formation are low temperatures and high
[1/2] pressures✓.

d) A pipeline is flowing with a light hydrocarbon gas and water. Given the following information, calculate the distance from the pipeline inlet to the point where hydrates will form. **[8 marks]**

- The hydrate formation temperature for the pipeline is 15 °C.
- Pipeline Overall Heat Transfer Coefficient (OHTC), U = 5 W m^{-2} °C^{-1} (based on pipe outer diameter).
- Pipeline inside diameter, D_i = 0.2 m.

- Pipeline wall thickness, W_t = 0.02 m.
- Gas/water mixture specific heat, C_p = 2.8 kJ kg^{-1} °C^{-1}.
- Gas/water mixture mass flow rate, m = 10 kg s^{-1}.
- Ambient temperature, T_a = 4°C.
- Pipeline inlet temperature, T_i = 50°C.
- You should use a log-mean temperature difference, $\Delta T_{lm} = (\Delta T_A - \Delta T_B)/\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)$ where A and B denote opposite ends of the exchanger/pipeline, when calculating the heat flux.

Solution:

The heat flux from the pipe is as follows:

$$Q = U A \Delta T_{lm} = \dot{m} C_p \Delta T_f$$

where ΔT_f is the fluid temperature change. The pipe area is a function of length:

$$A = 3.141\, D_o L = 0.754\, L \text{ m}^2$$

[2/8] $\checkmark_2$ where $D_o = 0.2 + 2 \times 0.02 = 0.24$ m. Assuming the fluid reaches 15 °C at one end, the LMTD is,

$$\Delta T_{lm} = ((50-4)-(15-4))/\ln\left(\frac{50-4}{15-4}\right) = 35/\ln(4.182) = 24.5\ ^\circ\text{C}$$

[2/8] $\checkmark_2$ The sensible heat change is,

$$\dot{m} C_p \Delta T_f = 10 \times 2800 \times (50-15) = 980000 \text{J s}^{-1}$$

[2/8] $\checkmark_2$ Equating this with the heat flux to calculate the area

$$A = 980000/(5 \times 24.5) = 8000 \text{ m}^2$$

[2/8] Thus $L = A/0.754 = 8000/0.754 = 10610$ m$\checkmark_2$.

[Question total: 20 marks]

Q.3 **Question 3**

a) Name and briefly describe four types of compressors including a description of their operating principles. **[8 marks]**

Solution:

Any four of the below are accepted:

Centrifugal compressors use a rotating disk or impeller in a shaped housing. Gas enters the impeller and is moves to the rim of the impeller, increasing the velocity of

[2/8] the gas. A diffuser (divergent duct) section converts the velocity energy to pressure energy.✓$_2$

[2/8] **Axial-flow compressors** are dynamic rotating compressors that use arrays of fan-like airfoils to progressively compress the working fluid. The arrays of airfoils are set in rows, usually as pairs: one rotating and one stationary. The rotating airfoils, also known as blades or rotors, accelerate the fluid. The stationary airfoils, also known as stators or vanes, decelerate and redirect the flow direction of the fluid, preparing it for the rotor blades of the next stage.✓$_2$

[2/8] **Reciprocating compressors** use pistons driven by a crankshaft. The piston sits within a cylinder with inlet and exhaust valves. On the down stroke the inlet valve opens allowing gas to enter the cylinder. On the upstroke the gas pressure is increased with the gas being realised at a set pressure through the exhaust valve.✓$_2$

[2/8] **Rotary process screw compressors** operate by drawing gas into the spaces between the lobes of the twin screws. As the rotors turn, the gas is forced by the profile of the screws into a continuously decreasing space until it reaches the outlet port at high pressure.✓$_2$

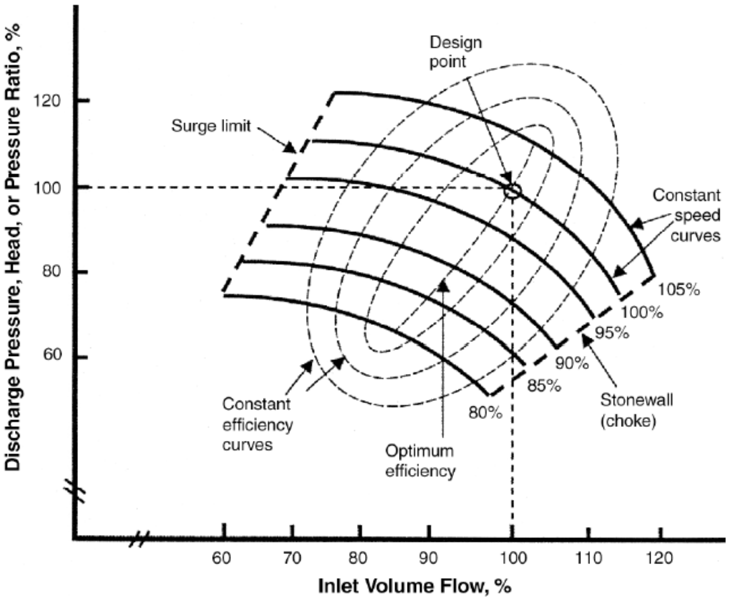
Jet pumps use a high pressure stream to generate a fast stream or jet that is injected into another stream to transfer kinetic energy which is then converted to pressure again as the two mixed streams decelerate.

Liquid ring seal compressors This is similar to a axial flow or reciprocating compressor in that it isolates a volume of gas then constricts the volume to increase the pressure before discharge, but it uses a liquid ring to provide the sealing between compressed volumes (and to provide the constriction).

b) Sketch a typical head flow characteristic for a centrifugal compressor. Indicate the effect of varying the compressor speed and the surge limit. **[4 marks]**

Solution:

[4/4] Marks are awarded based on the detail of the figure✓$_4$



c) A centrifugal gas compressor is operating with the following inlet and outlet conditions:

- Inlet pressure, p_1 = 10 bara.
- Outlet pressure, p_2 = 30 bara.
- Inlet temperature, T_1 = 30°C.
- Outlet temperature, T_2 = 110°C.

After a process upset the compressor achieves the same outlet pressure but the outlet temperature of the compressor is seen to rise by 5°C. It is suspected that the machine is losing polytropic efficiency. Calculate the percentage change in the compressor efficiency from before to after the upset.

The compression relationship is as follows;

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} \qquad\qquad \frac{n-1}{n} = \frac{k-1}{k\,\eta_{poly}}$$

where k is the ratio of specific heats for the gas and η_{poly} is the compressor polytropic efficiency. **[8 marks]**

Solution:

We use the compressor temperature relationship to calculate $(n-1)/n$ before the upset:

$$\frac{n-1}{n} = \ln(T_2/T_1)/\ln(P_2/P_1) \quad (1)$$
$$= \ln(383/303)/\ln(3/1) \quad (2)$$
$$= 0.213 \quad (3)$$

[2/8] ✓2 Calculating the value after upset,

$$\frac{n-1}{n} = \ln(T_2/T_1)/\ln(P_2/P_1) \quad (4)$$
$$= \ln(388/303)/\ln(3/1) \quad (5)$$
$$= 0.225 \quad (6)$$

[2/8] ✓2 Since the gas has not changed composition, k will remain constant, hence the change in the polytropic efficiency will be

$$0.213/0.225 = 0.947 \quad (7)$$

I.e. a 5.3% reduction in efficiency.

[Question total: 20 marks]

Q.4 **Question 4**

a) Water is to be removed from a process gas prior to pipeline entry. The pipeline entry specification is 20 mg water/Sm^3 gas. A glycol absorption unit is available with a lean glycol content of 1.5 wt% water. The absorber pressure and temperature is 50 bara and 35°C, respectively. Will the glycol absorber be capable of achieving the pipeline entry specification? Use the enclosed glycol equilibrium (Fig. 2) and water saturation (Fig. 3) charts and explain your reasoning. **[8 marks]**

Solution:

[1/8] First, it should be noted that we're discussing if a separation is possible, thus no safety factor should be used as that is just an estimate of the optimal design case (and will be adjusted through the detailed design), not the maximum achievable performance$\checkmark_1$.

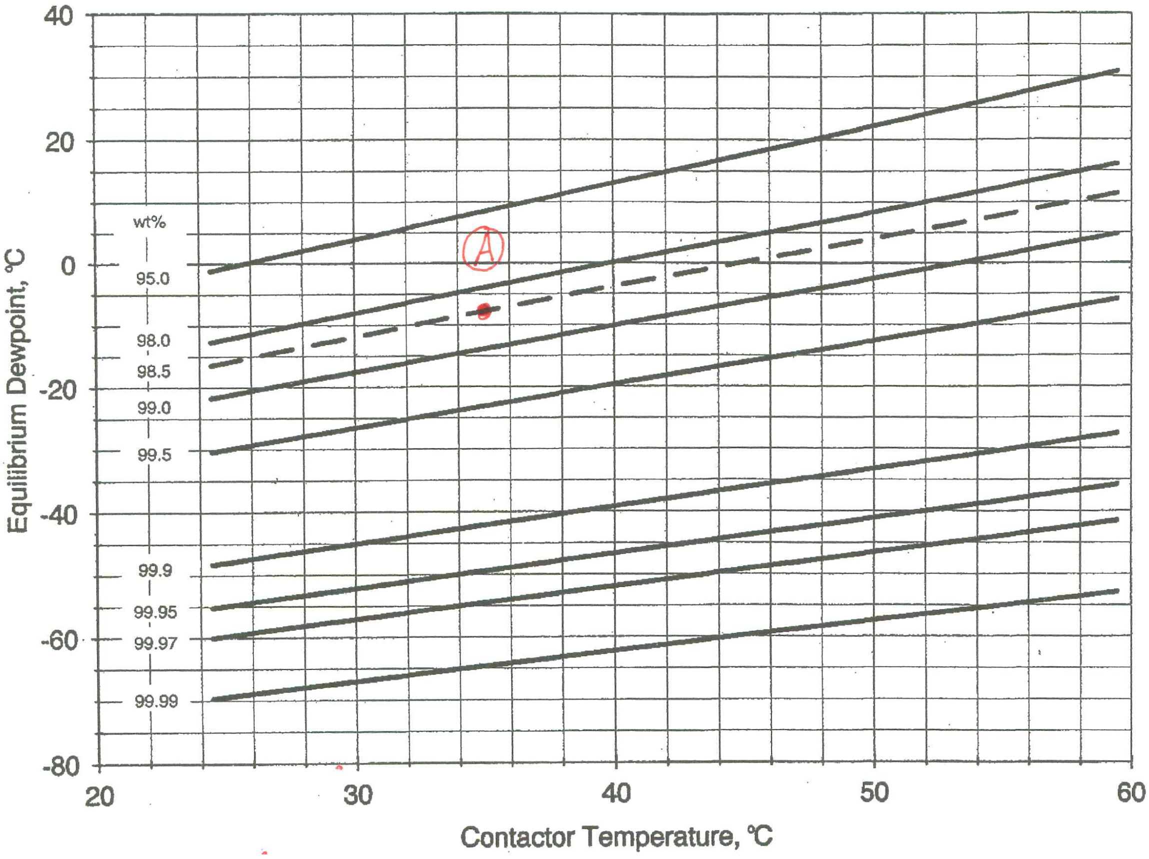
[1/8] The gas leaving the top of the glycol absorber requires to have a water content of 20mg water/Sm^3 gas. Water is removed from the gas by absorption into the counter flowing glycol hence the lowest possible water content would occur if the glycol and the water reached equilibrium.$\checkmark_1$

[3/8] The equilibrium level has to be determined for the contactor conditions. The Glycol water content is 1.5 wt% water-98.5 wt% glycol. From equilibrium chart at 35°C the equilibrium dew point is indicated by A - a dewpoint temperature of -8°C which corresponds to 80 mg Sm^{-3}.$\checkmark_3$

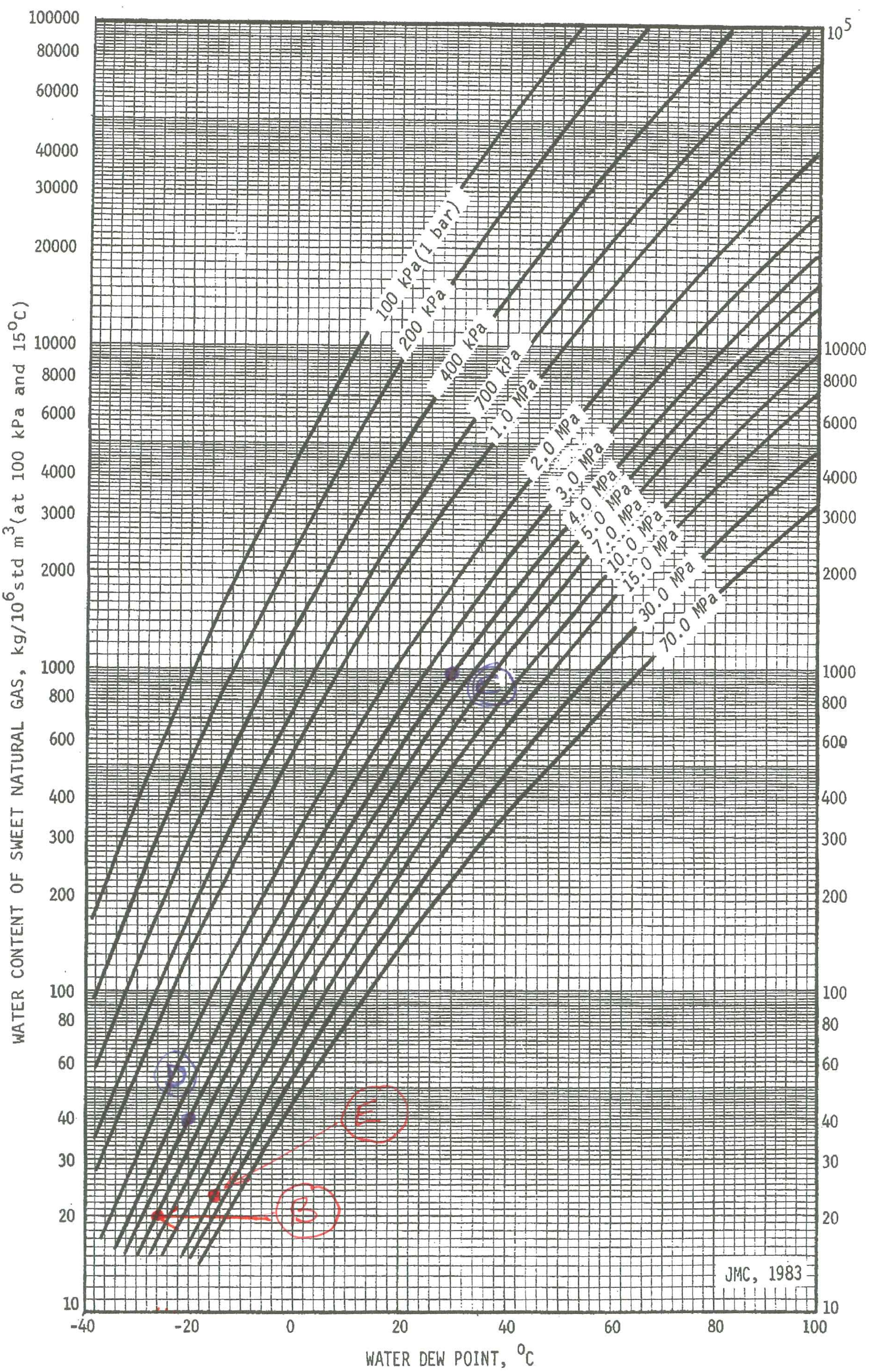
[3/8] **[1/8]** Comparing the dew point temperature with the dew point temperature of a gas with 20mg water/sm^3. Use water content chart - at contactor pressure (50 bara) the dew point temperature is -26°C (point B).$\checkmark_3$ Hence the contactor could not achieve the required pipeline specification of 20mg water/Sm^3 gas$\checkmark_1$. Alternatively we could compare what the dewpoint temperature of -8°C at 50 bara corresponds to 80 mg Sm^{-3}, which is again above the specification.

To achieve the required specification, a glycol purity of 99.7% is required.

(allow for inaccuracies with chart reading)



40
20
0
-20
-40
-60
-80
wt%
95.0
98.0
98.5
99.0
99.5
99.9
99.95
99.97
99.99
A
Equilibrium Dewpoint, °C
20
30
40
50
60
Contactor Temperature, °C


WATER CONTENT OF SWEET NATURAL GAS, kg/10^6 std m^3 (at 100 kPa and 15°C)
WATER DEW POINT, °C
100 kPa (1 bar)
200 kPa
400 kPa
700 kPa
1.0 MPa
2.0 MPa
3.0 MPa
4.0 MPa
5.0 MPa
7.0 MPa
10.0 MPa
15.0 MPa
30.0 MPa
70.0 MPa
JMC, 1983
C
D
E
B

b) Describe the key aspects of the molecular sieve process used for gas drying. **[6 marks]**

Solution:

Molecular sieves adsorb water molecules contained within the gas onto a solid surface. The process requires two (or more) vessels with one on-line removing water while the other is being regenerated. The process is normally on a time cycle - typically 4-24 hours. When the bed is taken off-line to be regenerated, the water is removed by heating the sieve to typically 230-320°C, depending on the desiccant used and the performance specification. The bed is heated using regeneration gas. The regeneration gas used to heat the bed is a slipstream of dry process gas or the feed gas. The regeneration gas is returned to the process after it has been cooled and the free water removed. Following the heating cycle the heater is switched off and the bed cooled.

Gas flow during adsorption is typically downflow. This allows higher gas velocities (thus smaller diameter towers) since bed fluidization is avoided. Regeneration gas flow is upflow during the heating cycle. In that way, any residual water left on the desiccant will be at the top of the bed and will not affect the effluent dewpoint when adsorption is resumed. In addition, upflow heating helps to strip any contaminants from the top of the bed extending desiccant life. Regeneration gas flow during the cooling cycle may be upflow if the gas is completely free of water. This saves two switching valves per tower which can reduce capital costs. If the cooling gas contains water, cooling flow should be downflow to avoid preloading of the desiccant at the bottom of the bed with water.

Finally, the note of the phenomena of breakthrough as well as the corresponding zones of saturation, mass transfer, and dry bed material are relevant points for discussion.

Key points for student to answer.(1 mark each, any 6 points are accepted)

(a) Adsorption of water onto a solid surface.
(b) Process involves one bed adsorbing whilst other regenerating.
(c) Process on a time cycle
(d) Regeneration requires heated slip stream of gas
(e) Bed requires to be cooled before being brought in-line
(f) Bed consists of a saturated/equilibrium zone, a mass transfer zone, and a depleted/fresh zone ready for transfer.
(g) Breakthrough of the water through the bed is designed to occur towards the end of design life (i.e. once the effectiveness of the adsorbent has degraded).

c) A molecular sieve dehydration unit is operating at 40 bara and 30°C. The unit is required to produce a product natural gas with a water dewpoint of minus 20°C. The gas entering the unit is water saturated and the flowrate is 2×10^6 sm^3/day. How much water is the unit required to remove? You will need the data in Fig. 3. **[3 marks]**

Solution:

Use the water saturation chart. Gas enters mol sieve at point C (960kg/10^6 sm^3) and leaves at point D (40kg/10^6 sm^3). Hence amount of water removed is, $960 -$

40 = 920 kg/10^6 sm^3. Thus amount of water removed = $2 \times 10^6 \times 920/10^6$ = 1840 kg day^{-1} = 76.7 kg hr^{-1}= 0.0213 kg s^{-1}.

(allow for inaccuracies with chart reading)

d) The export gas from the above molecular sieve later enters a cold plant operating at 150 bara and minus 15°C. Comment on the suitability of the molecular sieve treated gas for the cold plant operation. **[3 marks]**

Solution:

The conditions of the cold plant are indicated by point E (23 mg Sm^{-3}). The operating conditions of the cold plant are below the dew point temperature of the gas leaving the mol sieve. Hence water will condense within the cold plant. This would be unacceptable as the plant would be at risk from ice and hydrate formation.

(allow for inaccuracies with chart reading)

[Question total: 20 marks]

Q.5 **Question 5**
Energy efficiency

a) An anti-surge control system is to be designed for a centrifugal compressor. Three options are under consideration:

- suction throttling at constant speed.
- discharge gas recycling at constant speed.
- speed control.

In all cases the compressor discharge pressure is fixed. With respect to energy requirements discuss the merits or otherwise of the three options. **[6 marks]**

Solution:

Surge occurs at low volume throughputs.

Suction throttling increases the suction gas volume and reduces suction pressure. For a fixed discharge pressure the compression ratio will increase thus the energy required
[2/6] by the compressor will also increase.$\checkmark_2$

Gas recycling adds a portion of the discharge gas into the compressor suction. The
[2/6] mass of gas through the compressor will increase hence increasing compressor power.$\checkmark_2$

At low gas volumes speed control allows the compressor to be operated at lower volumes without surging. Speed control would use less energy than the other two
[2/6] options as neither suction volume or mass is increased.$\checkmark_2$

b) A refrigeration plant is to be designed using propane as the refrigerant. It is proposed to use a variable speed drive for the propane compressor to save energy during winter and summer operations. The mass of process gas is fixed and has to be cooled to -35°C at all times. The refrigeration system is a single stage design and refrigerant condensation is via an air cooler. Summer temperatures are 35°C and winter temperatures are 10°C.
Use the attached propane pressure-enthalpy chart in Fig. 4 to determine the percentage energy saving from winter to summer operations that speed control provides.
Assume the refrigeration cycle is isentropic and the temperature approach in the air cooler and evaporator is 5°C.
Include your marked up pressure-enthalpy chart with your exam paper. Put your student number on the chart. **[10 marks]**

Solution:

Assuming a 5°C temp approach the propane will require to be compressed to a temperature of:
Summer 35+5 = 40°C
Winter 10+5 = 15°C
[2/10] With the evaporator in both cases needing to reach -40°C.$\checkmark_2$

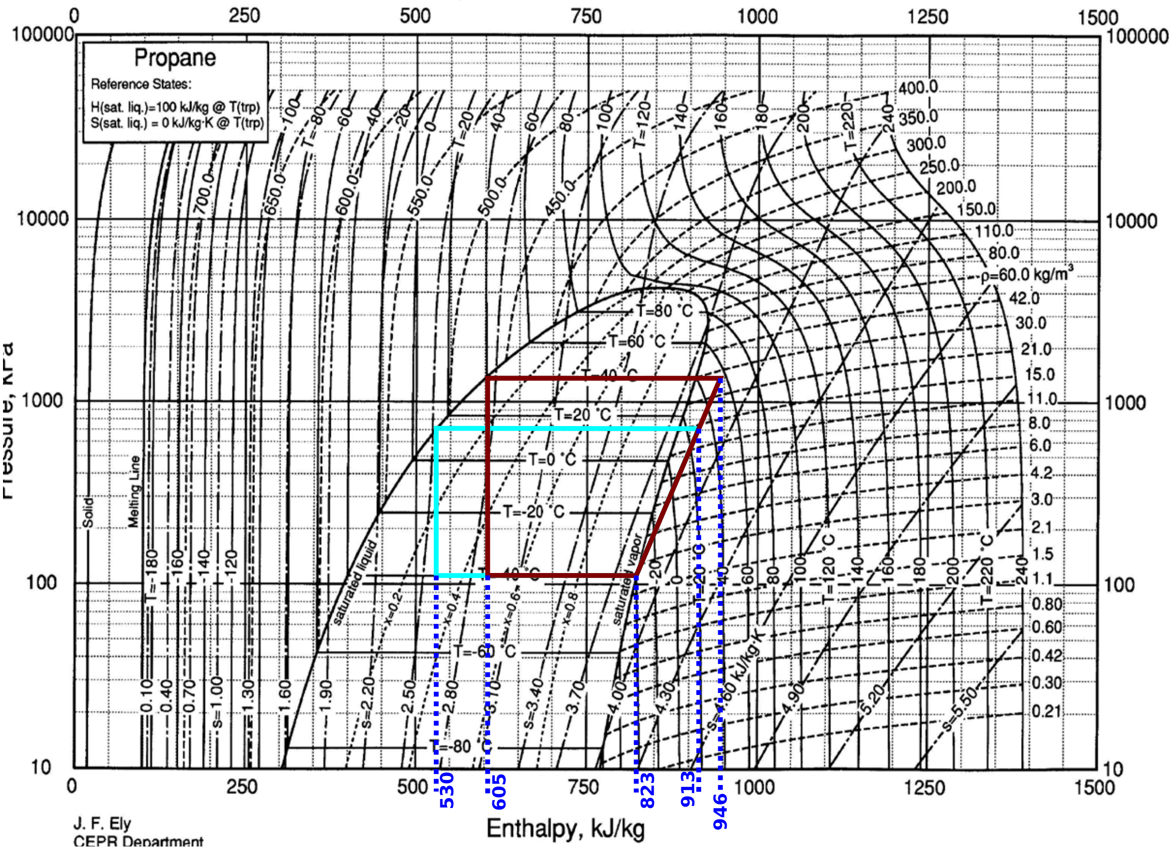
[5/10] The student should sketch both winter and summer cycles onto P-H chart$\checkmark_5$

	Winter	Summer	Units
Compression	913 – 823 = 90	946 – 823 = 123	kJ/kg
Evaporation	823 – 530 = 293	823 – 605 = 218	kJ/kg

Thus in summer the unit has a refrigeration efficiency of 218/123 = 1.77 (it removes
[1/10] 1.77 Joules per Joule of compression energy) and in winter its 293/90 = 3.26✓$_1$.

Without speed control, the summer cycle must be used all year round, but with speed
[1/10] control only 1.77/3.26 = 54% of the energy is required in winter, so a saving of 46%✓$_1$.

No marks to be deducted for slightly different numbers extracted from PH chart.



c) Estimate the percentage speed reduction of the refrigeration compressor from summer to winter. **[4 marks]**

Solution:

From p-H chart summer compression pressure = 1400 kPa

[1/4] From p-H chart winter compression pressure = 700 kPa✓$_1$

Precision is challenging with the log scale, so wide allowance for pressure estimates is given.

Pressure is proportional to impeller tip speed V^2; hence, summer to winter speed
[2/4] change = $(700/1400)^{1/2} = 0.707$✓$_2$

[1/4] So % change in speed summer to winter, $\approx$ 30% reduction$\checkmark_1$

[Question total: 20 marks]

END OF PAPER

Total Paper Marks:100

If you use this graph, you must attach it to your exam booklet using the provided tag.
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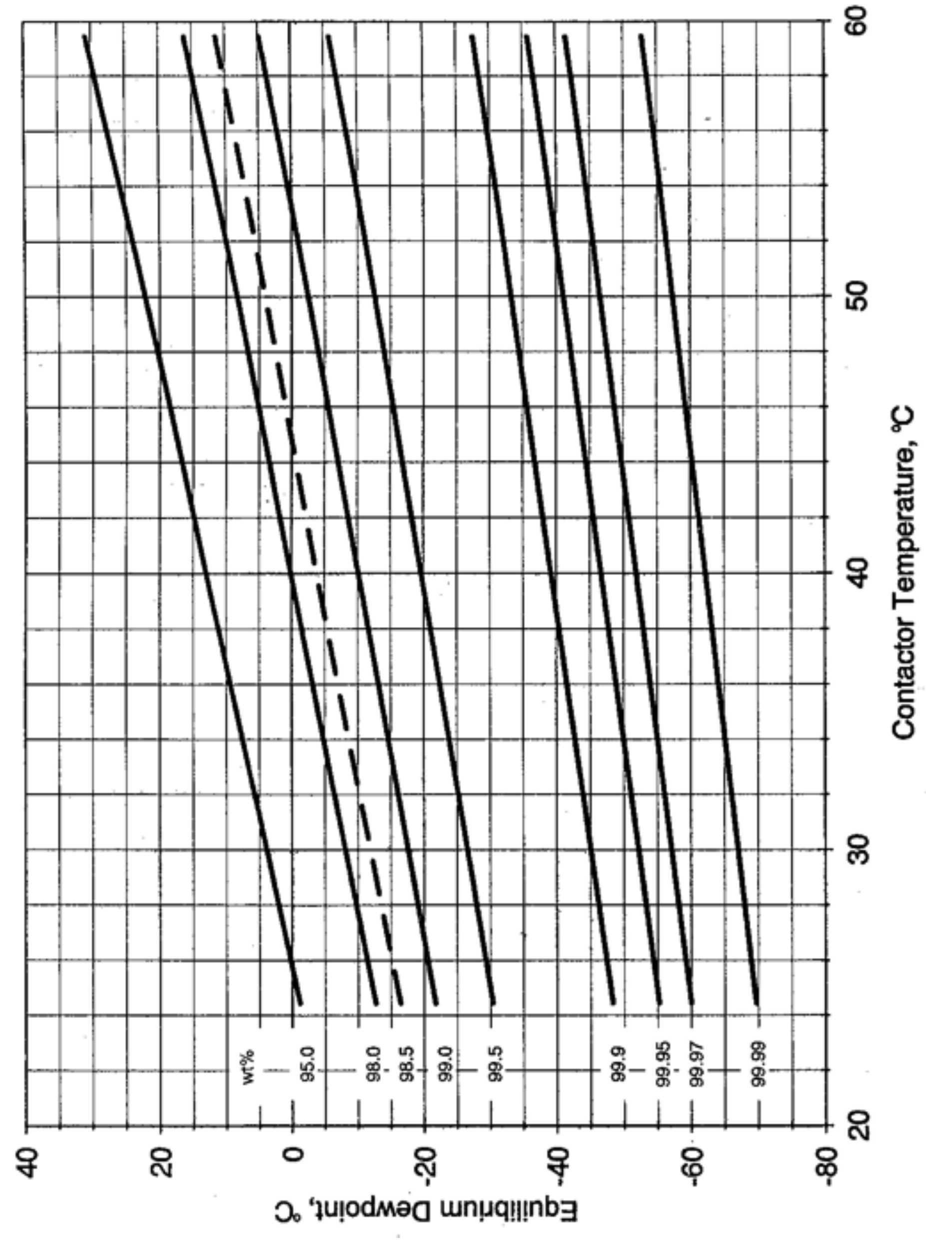

Figure 2: *A TEG equilibrium chart.*

If you use this graph, you must attach it to your exam booklet using the provided tag.
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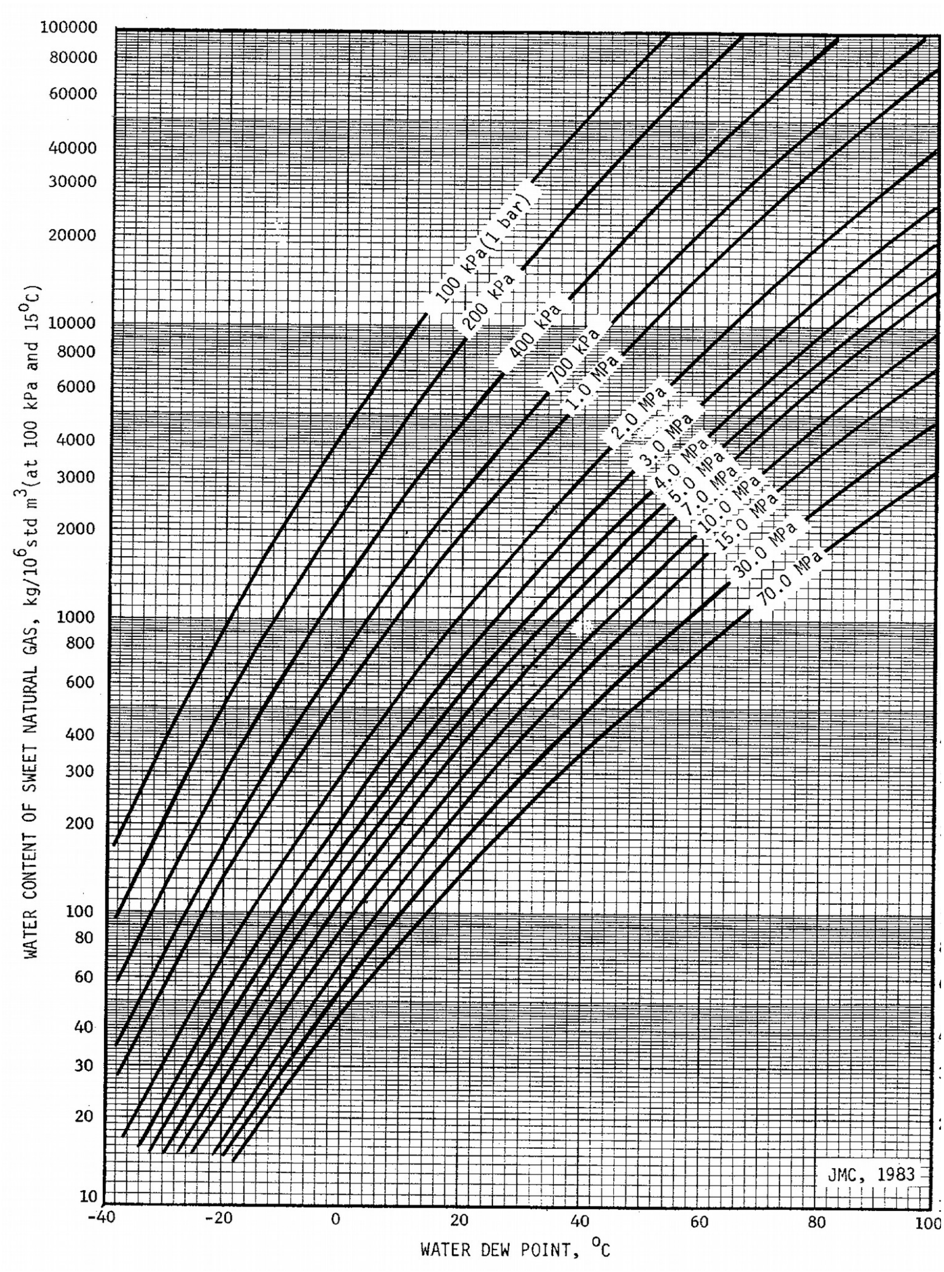

Figure 3: *Sweet-gas/water dew point graph.*

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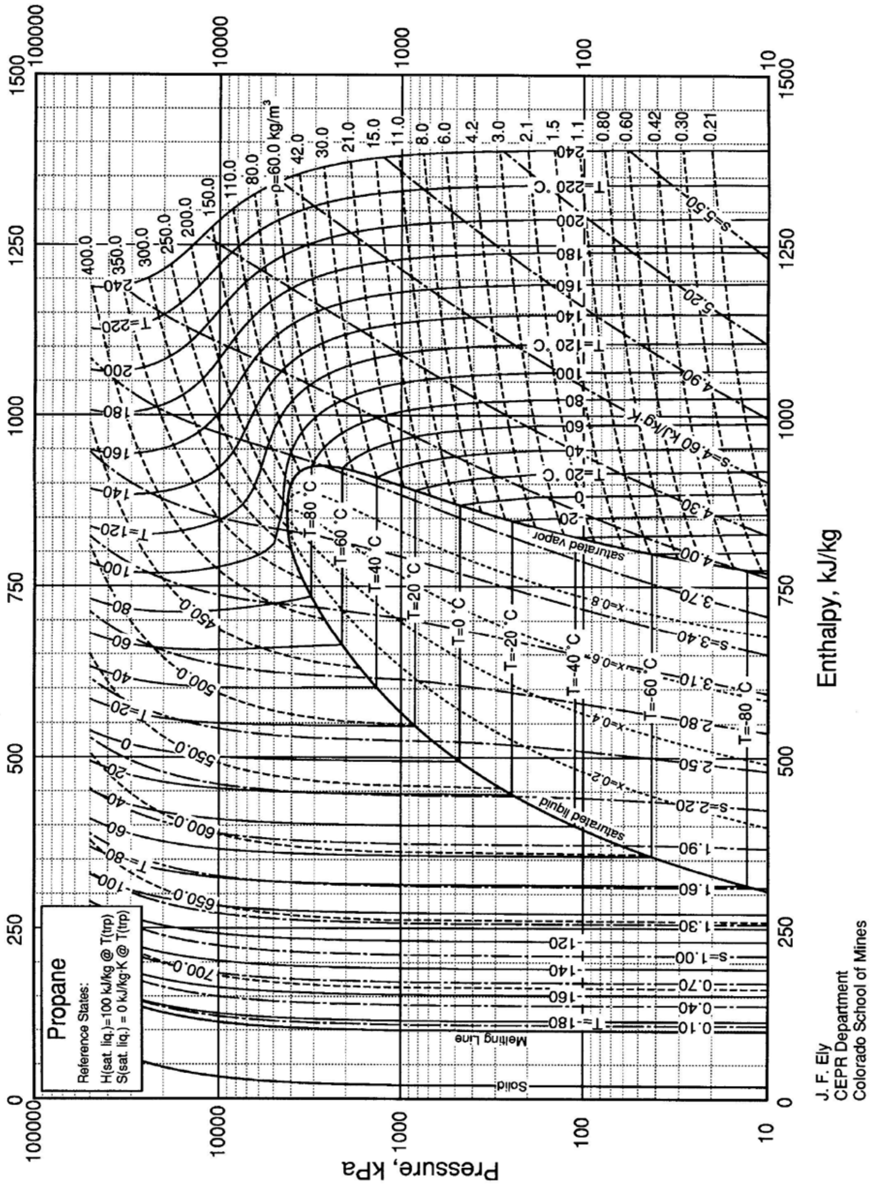

Figure 4: *A Mollier chart for propane.*

Unit conversions

1 US barrel = 42 US gallons = 0.159 m^3

1 ft = 12 in = 0.3048 m

1 lb = 0.453592 kg

$°F = (°C \times 9/5) + 32$

$°C = (°F - 32)\,5/9$

Physical constants/properties

Air molecular weight = 29 g mol^{-1}

Darcy's equation

$$\Delta p = \frac{\rho\, f\, L\, v^2}{2\, D}$$

Blasius correlation (turbulent flow)

$$f = 0.316\,\mathrm{Re}^{-0.25}$$

Pipe fitting	Equiv. length (L/D)
90° standard elbow	30
45° standard elbow	16
90° long elbow	20
90° street elbow	50
45° street elbow	26
Square corner elbow	57
Standard tee (flow through run)	20
Standard tee (flow through branch)	60
Close pattern return bend	50

Table 1: *A list of equivalent lengths for single phase fluid flow calculations.*