Numerical Exercises in Hydrocarbon Production

being part of a course given at the Kazakh British University in 2014

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Introduction

I have spent a great deal of the first few months of 2014 developing from scratch a postgraduate course on hydrocarbon production technology which, when it was given at KBTU in April/May, involved me in forty-five contact hours. A course of this duration will involve a diversity of topics, taking in for example well completion and the carbon footprint of refining. Much of the effort expended was directed at developing numerical examples additional to suitable ones from my previous books including *Dictionary of Oil and Gas Production* and *Hydrocarbon Process Safety*. This was an intellectually rewarding endeavour results of which might be worth sharing. Thirty-five of the questions so developed have been prepared for publication as this short book. Repeat of material in the previous books has been totally avoided.

The result, inevitably, is a 'rag bag' since, as previously pointed out, the topics are so varied. This means that a mere thirty-five calculations will be impossible to consolidate into a text which is anything like seamless. I have mitigated this by providing introductions to most of the questions as well as comments on the solutions. The questions are in blue print, whilst solutions and notes are black. There are a few illustrations. The few questions towards the end on explosions are intended to add a dimension of process safety to a book otherwise focused on production. That any operation should not be treated in isolation from safety issues has of course been the philosophy of engineering accrediting bodies for a very long time.

I entertain a hope that this little book will be of use to students and teachers in the area. It was a splendid idea on the part of Dr. Keith Whittles that the book be made available electronically and free of charge and, as with all of my by now numerous Whittles titles, warm thanks are due to him and his staff.

Background to question 1

Darcy's Law applied to an oil or gas reservoir

Permeability (usual symbol k) is linked to Darcy's Law (1856) which is:

Pressure gradient treated as a single quantity

$$\downarrow$$

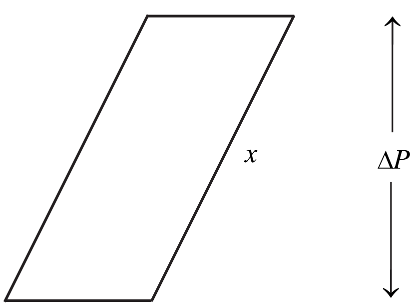
$$Q = -(\mathrm{k}A/\mu)(\Delta P/x)$$

where Q = volumetric rate of passage ($m^3\ s^{-1}$), k = permeability (m^2), A = cross sectional area (m^2), x = distance in the direction of flow (m), ΔP = pressure differential in the direction of flow ($N\ m^{-2}$) and μ = dynamic viscosity of the fluid ($kg\ m^{-1}s^{-1}$).

Permeabilities are most often expressed in units darcy, where:

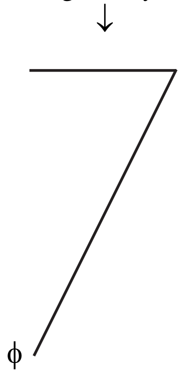
$$1 \text{ darcy} = 10^{-12}\ m^2$$

Geological formations containing oil and gas usually have permeabilities of much less than 1 darcy, and are therefore often quoted in millidarcy (md). 'Tight gas' might be in a formation of μd. Darcy's Law, first applied to groundwater, appears in the literature in various forms and most of them do not contain gravity explicitly. This point is examined below in a model in which we envisage the flow as a slanting cylinder with flat circular ends, as shown.



Further analysis follows.

For the circular ends the radius is given by $r = \sqrt{(A/\pi)}$.



Angle of direction of flow ϕ with the vertical = $\sin^{-1}\sqrt{(A/\pi x^2)}$.

Hence via this angle gravity makes an implicit appearance in the equation. Against this background a routine calculation using Darcy's Law for hydrocarbon flow will be attempted.

Question 1. Oil of dynamic viscosity 10^{-2} kg m^{-1}s^{-1} is present in a formation of permeability 1 millidarcy (md). The pumping provides for a pressure gradient of 1 bar per meter in the direction of flow. How many barrels per day would be yielded per square kilometre of area?

Solution:

Using Darcy's Law:

$$Q = -(kA/\mu)(\Delta P/x),\ k = 10^{-15}\ \text{m}^2,\ \mu = 10^{-2}\ \text{kg m}^{-1}\text{s}^{-1},$$
$$\Delta P/x = -1\ \text{bar m}^{-1} = -10^5\ (\text{N m}^{-2})\text{m}^{-1}$$

The negative sign precedes the pressure gradient because the pressure decreases in the direction of positive x.

$$A = 10^6\ \text{m}^2$$
$$Q = -(10^{-15}\ \text{m}^2 \times 10^6\ \text{m}^2/10^{-2}\ \text{kg m}^{-1}\text{s}^{-1}) \times -10^5\ (\text{N m}^{-2})\text{m}^{-1}$$
$$= 0.01\ \text{m}^3\ \text{s}^{-1}$$

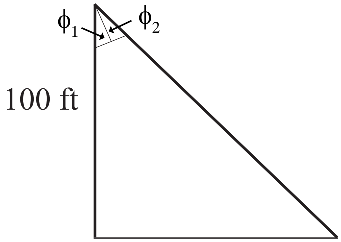
Converting to the required units:

$$(0.01\ \text{m}^3\ \text{s}^{-1}/0.159\ \text{m}^3\ \text{bbl}^{-1}) \times (24 \times 3600\ \text{s day}^{-1}) = \mathbf{5430\ bbl\ day^{-1}}$$

Background to question 2

In directional drilling the bit as it goes deeper into the formation will not retain the slope angle of the whipstock (ϕ_1) but will diverge. Referring to the sketch below and calling the angle created by a line to the bit when it is at a depth of a hundred feet below the apex of the whipstock ϕ_2 the dog leg severity is:

$(\phi_2 - \phi_1)$ degrees per hundred feet.



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Question 2. Refer to the figure above re directional drilling. If the whipstock slope angle is 3 degrees and the dog leg departure also 3 degrees what is the horizontal displacement per 100 feet of vertical distance drilled? If the dogleg severity is sustained what vertical depth will need to be reached for the displacement to be 200 feet?

Solution:

First part: Displacement = 100 ft × tan $(\phi_1 + \phi_2)$ = 10.5 feet

Second part: Vertical depth = 200 ft/tan 6° = 1900 ft (580 m)

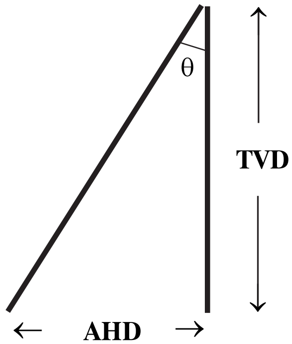
The next question relates to a drill bit.

Question 3. Measurement while drilling (MWD) enables drill rotary speed to be followed and correlated with WOB and ROP. The speed will vary with the degree of resistance to drilling by the formation. Imagine a fixed (non-roller) drill-bit of 8½ inch diameter at a rotation speed of 30 radians per second. What will be (a) the rate of rotation in r.p.m. and (b) the linear speed of the outer surface of the bit in contact with the formation?

Solution:

$$30 \text{ radians per second} = (30/2\pi) \text{ revolutions per second}$$
$$= 4.8 \text{ revolutions per second} = \omega$$
$$(= 285 \text{ r.p.m. which is fairly typical})$$
$$\text{Linear speed} = 2\pi r\omega \text{ where } r = \text{radius of the bit}$$
$$= (8.5 \times 0.5 \times 0.0254) \text{ m} = 0.108 \text{ m}$$
$$\text{Linear speed} = 2\pi \times 0.108 \text{ m} \times 4.8 \text{ s}^{-1} = 3.3 \text{ m s}^{-1} (= 7 \text{ m.p.h.})$$

A record in extended reach drilling is claimed for a well offshore California which has a true vertical depth (TVD) of 289 m and an along hole departure (AHD) of 1489 m. What is the angle θ according to the figure below?



Solution:

Referring to the figure $\theta = \tan^{-1}(AHD/TVD) = 79$ degrees.
This theme is continued into the next question with the added dimension of tortuosity.

<u>Question 4</u>. A well has a TVD of 5079 m and a measured depth of 5236 m. If the tortuosity is one degree angle per 10 m drilled what is the drilling difficulty index (DDI)?

Solution:

Angle θ (see previous diagram) = $\cos^{-1}(TVD/MD) = 14$ degrees.
where MD (measured depth) is the hypotenuse of the triangle above.

$$\text{AHD} = \text{TVD} \times \tan\theta = 1266\ \text{m}$$
$$\tau\ = \text{MD}/10\ \text{degrees}\ = 524\ \text{degrees}$$
$$\text{DDI} = \ \log[(\text{MD} \times \text{AHD}/\text{TVD})\tau]\ = 5.8$$

Background to question 5

The Genesis platform (below) in the GoM is a spar platform, relying on a cylindrical hull for support.

<u>Question 5</u>. The Genesis platform has a hull 122ft (37 m) in diameter and 705ft (215 m) in height. The topside, supported by the hull, weighs 9000 tonne. In the oversimplified limit where the hull was constructed as a thin-walled empty cylinder what weight of magnetite (density 5100 kg m^{-3}) would be needed as ballast to stabilise the structure if the draught – length of the cylinder above water – was to be negligible in comparison with the hull height? If the bulk density of the magnetite was two thirds of the particle density, what proportion of the internal volume of the hull would this occupy?

Solution:

Weight of water displaced by the cylinder

$$= (\pi \times 18.5^2 \times 215)\ \text{m}^3 \times 1000\ \text{kg m}^{-3} \times 10^{-3}\ \text{tonne kg}^{-1}\ =\ 231\ 200\ \text{tonne}$$

Magnetite to provide 222 200 tonne occupying:

$$222\ 200 \times 10^3\ \text{kg}/3397\ \text{kg m}^{-3} =\ 65\ 410\ \text{m}^3$$

$$\text{Fraction occupied} = 65410 \div (\pi \times 18.5^2 \times 215) = 0.28$$

The above should be seen as an illustration of how the ballast works and of how amounts needed are calculated rather than as a detailed analysis of Genesis. Sometimes the ballast is not within the hull but in containers mounted on it.

Question 6. A jack-up rig similar to that shown below* (prior to jacking) is in shallow water. Its weight of 15 000 tonnes is distributed evenly between the three legs. The seafloor can take without penetration a stress of 1 N mm^{-2}. What would be the minimum thickness of the three circular spud cans each of 8 m diameter needed to support the rig?

Solution:

Because the water depth is shallow and in any case the legs, being latticed, are not solid metal, Archimedean effects can be neglected.

Each spud can has to bear 5000 tonnes or:

$$(5\,000\,000 \text{ kg} \times 9.81 \text{ m s}^{-2}) \text{ N} = 5 \times 10^7 \text{ N}$$

$$(5 \times 10^7/A) = 1 \text{ N mm}^{-2} \text{ (1 MPa)}$$

where A is the area of one of the spud cans in mm^2

$$A = 5 \times 10^7 \text{ mm}^2 = 50 \text{ m}^2$$
$$\text{Minimum diameter} = 8 \text{ m}$$

The weight stress on the spud cans is orders of magnitude below the yield stress of the spud cans for thicknesses of plate available. The role of the spud cans is

* *"Constellation 1" by Remi Jouan - Own work. Licensed under Creative Commons Attribution-Share Alike 3.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Constellation_1.JPG#mediaviewer/File:Constellation_1.JPG*

in distributing the weight stress in going from a stronger to a weaker material. We are NOT being asked in this question to calculate the minimum diameter of spud can which can withstand the weight. The legs will sink slightly over time, because the stress assigned to the seafloor will vary with time depending on how consolidated the structure is. Sinking by a few metres is common.

Question 7. The Maari GBS platform can withstand a wind speed up to 100 m.p.h. (in the 'extreme hurricane' range) without toppling. Imagine wind at that speed and at 280 K moving in a direction orthogonal to gravity and encountering a vertical flat structure on the GBS. What force will be experienced by the vertical structure per unit area?

$$100 \text{ m.p.h.} = 44 \text{ m s}^{-1} = c$$

Ideal gas law with usual symbols:

$$PV = \text{n}\text{R}T$$

$$\text{n}/V = P/\text{R}T = [10^5 \text{N m}^{-2}/(8.314 \text{ J K}^{-1}\text{mol}^{-1} \times 280 \text{ K})] \text{ mol m}^{-3}$$
$$= 43 \text{ mol m}^{-3} = (43 \text{ mol m}^{-3} \times \underset{\substack{\uparrow \\ \text{molar mass of air}}}{0.0288 \text{ kg mol}^{-1}}) \text{ kg m}^{-3} = 1.24 \text{ kg m}^{-3}$$

Mass impingement rate per unit area of the flat structure

$$= 1.24 \text{ kg m}^{-3} \times 1 \text{ m}^2 \times 44 \text{ m s}^{-1} = 55 \text{ kg s}^{-1} = m$$

No movement of the structure means no thermodynamic work on it. At such speeds conversion of kinetic energy to thermal negligible.

Unit area of the structure receiving mechanical energy at a rate $\frac{1}{2}mc^2$

$$= 0.5 \times 55 \text{ kg s}^{-1} \times 44^2 \text{ m}^2 \text{ s}^{-2} = 53 \text{ kW} = 40 \text{ h.p.}$$

This is a half to a third the output from the engine of a typical saloon car and it is being applied constantly on unit area of the structure! If the support of the part of the GBS under consideration cannot withstand it there will be failure. Calculations of this sort have to be applied to different parts of an offshore structure.

<u>Question 8</u>. For offshore production at the Gulf Coast there are the following categories of hurricane on the 'Saffir/Simpson Scale':

Category 1: 74–95 mph winds

Category 2: 96–110 mph winds

Category 3: 111–130 mph winds

Category 4: 131–155 mph winds

Category 5: winds greater than 155 mph

To what horse power range when encountering a vertical surface does the range of speeds covered by the Scale conform?

Solution:

$$74 \text{ m.p.h} = 33 \text{ m s}^{-1}$$

$$\text{Rate of mass flow} = 40 \text{ kg s}^{-1}$$

$$\text{Rate of transfer of energy} = 0.5 \times 40 \text{ kg s}^{-1} \times 33^2 \text{ m}^2 \text{ s}^{-2}$$

$$= 22 \text{ kW} = 30\text{h.p.}$$

$$155 \text{ m.p.h.} = 69 \text{ m s}^{-1}$$

$$\text{Rate of mass flow} = 86 \text{ kg s}^{-1}$$

$$\text{Rate of transfer of energy} = 0.5 \times 86 \text{ kg s}^{-1} \times 69^2 \text{ m}^2 \text{ s}^{-2}$$

$$= 203 \text{ kW} = 270 \text{ h.p.}$$

So the range is 30 to 270 h.p.

Note on such calculations: justification of using atmospheric pressure (1 bar) under the conditions applying.

Even for Saffir/Simpson category 4 winds pressures at the centre are expected to be in the range 0.92 to 0.94 bar, higher still for the lower three categories. Large numerical errors are not expected from using 1 bar in a calculation. If more precision is required a better value for the pressure can be obtained from the wind-pressure relationship of the categories.

Question 9. In the Ursa field in the GoM there is a tension leg platform (TLP) of the following specifications:

Topside weight 12500 tonnes.

Four columns 85ft in diameter and 177 ft in height, total weight 26800 tonnes.

Pontoon height = 29 feet = depth of the column immersed

16 hollow tendons, four per corner, of diameter 32 inches and a wall thickness of 1.5inches. Tendon length 3800ft.

Calculate the weight of water displaced by the columns and hence the upthrust. Go on to calculate the load on the tendons.

Solution:
Weight of water displaced =

Number of columns
$\downarrow$

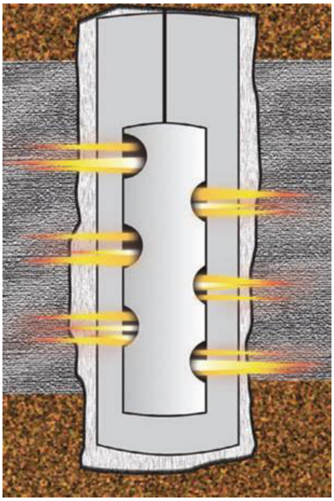
$$(4 \times \pi \times 42.5^2 \times 29)\ \text{ft}^3 \times 0.028\ \text{m}^3\ \text{ft}^{-3} \times 1000\ \text{kg m}^{-3} \times 10^{-3}\ \text{tonne kg}^{-1}$$
$$= 18\,433\ \text{tonnes}$$

The upthrust therefore exceeds the topside weight by 6000 tonnes and this has to be countered by the tendons.

Note: the bending stress of the tendons has to be considered against this load.

Background to question 10

In well completion, perforation is by detonation of charges in a perforating gun, as shown in the diagram. Pressures of over 100 MPa are created and the effect of these is passed along to the geological formation by a perforation fluid.



Action of a perforating gun.

An important quantity in well completion effectiveness is NPPR: Normalised Perforation to Permeability Ratio. This is influenced by the perforating fluid which affects the balance of forces during the 'shots'.

Question 10. In well completion the NPPR is of more interest than the perforation expressed in units of permeability. The NPPR is defined as:

$$\mathbf{k_{perf} / \sqrt{½(k^2_{perf} + k^2_{form})}}$$

where k is in mD for perforation and formation respectively. On this basis calculate k_{perf} for an initial formation permeability of 100 mD and a NPPR value of 1.4.

Solution:

Substituting gives: k_{perf} = 2000 mD or 2 D.

Note: It is not unknown for a formation to have this value. The effect of the perforating gun has been to convert a totally impermeable metal surface to a medium analogous to a high-permeability geological structure.

Background to question 11

In simple mineral acid workover:

$$2H^+ + CO_3^{2-} \rightarrow H_2O + CO_2$$

and the products easily escape.

Whilst simple mineral acids applied to sandstone will as noted remove contaminants, the sandstone formation itself can be attacked by hydrofluoric acid HF. The process is:

$$SiO_2 + 6HF \rightarrow \underset{\substack{\uparrow \\ \text{fluosilicic acid}}}{H_2SiF_6} + 2H_2O$$

This acid forms salts with sodium and potassium ions present, partially depositing on the rock during removal. This is a disadvantage with HF as a workover medium. HF also attacks clay.

Question 11. A common form of the workover fluid is 3%HF + 12% HCl by weight, balance water. How much sand would 1 US ton of this remove? Atomic weights: H = 1, O = 16, Si 28, F 19.
1 US ton = 0.907 tonne.

Solution:

$$\text{Weight of the agent available} = 907 \text{ kg containing:}$$
$$907 \text{ kg} \times 0.03/0.020 \text{ kg mol}^{-1} \text{ mol of HF}$$
$$= 1360 \text{ mol equivalent to } (1/6) \times 1360 \text{ mol } SiO_2 = 227 \text{ mol or:}$$
$$227 \times 0.06 \text{ kg} = \mathbf{13.5\ kg}$$

Note: This represents not bulky amounts reacted but creation of pores in sandstone *in situ*.

Background to question 12

It relates to a beam pump a.k.a. a pump jack or a 'nodding donkey', illustration below*. These have become an icon of the onshore oil industry.

[Question 12](). The average production of an oil well across the industry is 3000 barrels per day. What power of pump, in 24-hour operation, would be required to raise that amount up a well 250 m deep? Use a value of 900 kg m^{-3} for the density of the crude oil.

Solution:

$$\text{Power} =$$

$$900 \text{ kg m}^{-3} \times (3000 \times 0.159) \text{ m}^3 \times 9.81 \text{ m s}^{-2} \times 250\text{m}/(24 \times 3600)] \text{ s}$$
$$= 12 \text{ kW (16 h.p.)}$$

Note: The above is the rate of mechanical work, not the required rate of electricity supply.

* *"Pump Jack" by Sanjay Acharya - Own work. Licensed under Creative Commons Attribution-Share Alike 3.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Pump_Jack.jpg#mediaviewer/File:Pump_Jack.jpg*

Background to question 13

The Productivity index (PI) at a well has units barrels per day per p.s.i. (or equivalent). No distinction is made between on- and offshore fields in the application of the definition of PI. For gas production cubic metres replaces barrels in the definition. There are serious difficulties in interpreting different PI values across a range of wells. One is that circumstances can be adjusted to raise it; choking is such a means of adjustment. Moreover, the features of the completion have an effect.

Question 13. At the Karazhanbas oilfield in Kazakhstan, a particular well over the period 2001 to 2004 the PI displayed a maximum in early 2002 of approximately 40 m^3 of oil MPa^{-1} day^{-1}. Convert this to value in barrels per p.s.i. per day.

Solution:

$$1 \text{ MPa} = 150 \text{ p.s.i. approx.}$$

$$40 \text{ m}^3 \text{ per MPa per day} = (40/150) \text{ m}^3 \text{ per p.s.i. per day}$$

$$= 0.27 \text{ m}^3 \text{ per p.s.i. per day}$$

$$= (0.27/0.159) \text{ bbl per p.s.i. per day}$$

$$= 1.7 \text{ bbl per p.s.i. per day.}$$

Background to question 14

The reference work *Fundamentals of Reservoir Engineering* (edited by L.P. Dake ISBN: 978-0-444-41667-4) gives the following expression for the PI at an oil well:

$$\text{PI} = q/(P_e - P_{wf})$$

where q = steady production rate; P_e = reservoir pressure; P_{wf} = 'bottom hole pressure' sometimes referred to as the 'flowing pressure', and the 'pressure' in a PI calculation should be understood as this pressure difference. It is due to the drill mud.

Question 14. If a well flows at a 1000 bbl per day with a flowing pressure of 1500 psi and at an average reservoir pressure of 2000 psi, what is the productivity index?

Solution:

$$PI = 1000 /(2000 - 1500) = 2 \text{ bbl day}^{-1} \text{ psi}^{-1}$$

Background to question 15

Densities of drill fluids are expressed in pounds per gallon.

Question 15. The hydrostatic pressure of a drill fluid is given by:

$$P = \rho \times TVD \times 0.052$$

where ρ is the drilling fluid density in pounds per gallon, the TVD [previously encountered in question 3] is in feet and 0.052 is a unit conversion factor chosen such that *P* results in units p.s.i. What would be the pressure due to the drill fluid at a depth of 2000 feet? Use a value of 9 p.p.g. for the density.

Solution:

At a TVD of 2000 feet this would create a pressure of:

$$9 \times 2000 \times 0.052 \text{ p.s.i.} = 940 \text{ p.s.i. (63 bar)}$$

Background to question 16

This is a return to the theme of pump jacks and data are for an actual oil field.

Question 16. Consider a pump jack with bore diameter of 1 inch and a stroke length of 36 inches operating at 10 strokes per minute. How many barrels of oil per day will this lift?

How many such pumps would be needed to produce 12 million barrels per year? At what power would each such pump need to work? These data relate to the Lost Hills oil field in California.

Solution:

Using a value of 36 inches for the stroke and a bore diameter of 1 inch, the swept volume is:

$$\pi \times 0.5^2 \times 36 = 28 \text{ cubic inches or } 0.46 \text{ litres, } 0.0029 \text{ barrels}$$

If the pump jack operates at 10 strokes per minute the oil yield is 0.029 barrels per minute or 42 barrels per day.

The Lost Hills oil field produced in 2006 approximately 12 million barrels or:

$(12 \times 10^6/365)$ barrels per day = 33 000 barrels per day
requiring 33 000/42 pump jacks = 785 pump jacks,
broadly consistent with the figure of 'several hundred' given for Lost Hills on web sources.

Work done in raising 33 000 barrels of oil through a distance of 36 inches =

$$\underbrace{785}_{\textit{number of pumps}} \times 33000\,\text{bbl} \times 0.159\,\text{m}^3\text{bbl}^{-1} \times \underbrace{950\,\text{kg m}^{-3}}_{\textit{density of the crude oil}} \times \underbrace{(36 \times 0.0254)}_{\textit{inches to metres}}\text{m} \times 9.81\,\text{m s}^{-2} = 35\,\text{GJ}$$

Rate of work = 35×10^9 J/(24×3600) s = 406 kW or 544 h.p.
Note: Each of the 785 pumps operates at slightly under one h.p.

Question 17. In a salt cavern gas storage cavern in Marysville Michigan about 341 million cubic feet of gas are stored at a pressure of 1100 psia. As at any such facility, about 25% of the gas has to be retained in the cavern as 'cushion gas' to ensure sufficient pressure for gas removal. On that basis what is the weight of the accessible gas at the cavern? Use a value for the temperature of 273K and express your answer in tonnes.

Solution:

Ideal gas equation using the conventional symbols:

$$PV = \mathrm{n}RT$$

$$\mathrm{n} = [(1100/14.7) \times 10^5\ \text{N m}^{-2} \times 341 \times 10^6 \times 0.028\ \text{m}^3]$$
$$/(8.314\ \text{J K}^{-1}\ \text{mol}^{-1} \times 273\text{K})\ \text{mol}$$

Question 19= 3.1×10^{10} mol or 0.5 million tonnes of which:
0.375 million tonnes is accessible.

Note: Use of the ideal gas equation at such a high pressure is correct at such temperatures.

Background to question 18

Natural gas is a common choice of fuel at refineries. Sometimes it occurs as relatively small amounts of associated gas having little if any potential for economic distribution and therefore obtainable at low cost at a refinery. The next question is concerned with the carbon footprint of refining.

<u>Question 18</u>. The carbon footprint of refining of a barrel of oil is 50 kg of CO_2. A tree absorbs a tonne of carbon dioxide in 40 years. How many trees would on this basis offset a refinery producing 0.1 million barrels of oil per day?

Solution:

1 tonne in 40 years is 25 kg in one year, equivalent to the carbon footprint of half a barrel of oil.

$$0.2 \times 365 \text{ million trees would therefore be needed} = 73 \text{ million.}$$

<u>Question 19</u>. The world produces 80 million barrels per day of oil, 40% of it from OPEC countries. How much carbon dioxide per day does refining of the OPEC oil add to the atmosphere. If the mass of the atmosphere is 5.1×10^{18} kg, what is the annual rise in p.p.m. weight basis due to the refining of OPEC oil?

Solution:

The carbon footprint of refining of a barrel of oil is 50 kg of CO_2.

$$\text{Daily amount} = 0.4 \times 80 \times 10^6 \times 50 \text{ kg} = 1.6 \times 10^9 \text{ kg}$$
$$\text{Annual rise} = [(1.6 \times 10^9 \times 365)/(5.1 \times 10^{18})] \times 10^6 \text{ p.p.m.}$$
$$= 0.11 \text{ p.p.m. weight basis.}$$

<u>Question 20</u>. The practice of compressing vapour in equilibrium with crude oil to ignite it as a means of enhanced oil recovery is prevalent. Imagine that is a stoichiometric amount of air such a vapour at 300°C reservoir temperature requires raising to 450° C for ignition. By what factor will it have to be compressed?

Use the expression (usual symbols)

$$PV^m = \text{ a constant}$$

where m is the polytropic index for the compression and a value of 1.5 for m.

Solution:

$$P_1V_1^m = P_2V_2^m$$

where 1 and 2 denote before and after compression. The ideal gas equation applies to both states so:

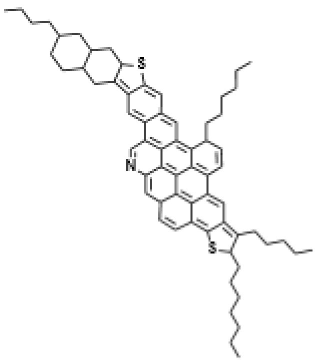
$$P_1V_1 = P_2V_2$$

Dividing one equation by the other:

$$V_2/V_1 = (T_1/T_2)^{1/(m-1)} = (573/723)^2 = 0.63 = \text{compression ratio.}$$

Background to question 21

Asphaltenes occur in the heaviest parts of the crude oil. They cause blockages in pipelines so their control is relevant to 'flow assurance'. Below is a chemical structure typical of an asphaltene*.



A quick count gives an estimate ≈12 six-membered rings and ≈20 carbons in non-cyclic structures for the above. (A reader might care to attempt a more accurate count, but the author has eschewed this on the grounds that the above is only generic.)

Question 21. Although the approximate empirical formula CH_2 applies to residual fuel oil it does not apply to asphaltenes and $CH_{1.2}$ is sometimes suggested for these. On this basis what will be the molar mass of the asphaltene structure above? Include the heteroatoms.

Solution:

The formula would be $C_{92}H_{110}$ which would have a molar mass of 1214g. Adding 2 S (= 64g) + N (= 14g) gives 1292g ≈1300g, a typical value.

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* *"Possible asphaltene molecule" by Paginazero - "Bitumi e derivati" - corso di tecnologia chimica. Licensed under Public domain via Wikimedia Commons - http://commons.wikimedia.org/ wiki/ File:Possible_asphaltene_molecule.svg#mediaviewer/File:Possible_asphaltene_molecule.svg*

Background to question 22

Greater depths of oil in a geological formation tend to lead to lighter oil This is because within a formation greater depth means higher temperature with a more advanced breakdown of the original material over 'geological time'. The range of depths in a field reflects undulations in the formation. One has to remember that the API gravity index is so formulated that the lower the density the higher the API index.

Question 22. From published data for API index versus well depth for two N. American fields, the author has obtained the following approximate correlation:

40^{o} rise in API index per 10 000 feet depth increment

At a field crude from a well of depth 5000 feet has a density of 950 kg m^{-3}. At what depth would a well at the same formation (if such a depth were attainable: see comment following the solution) produce oil of density 900 kg m^{-3}?

Solution.

$$\text{degrees API} = (141.5/\text{density, water} = 1) - 131.5$$
$$950 \text{ kg m}^{-3} \equiv 17 \text{ degrees API}$$
$$900 \text{ kg m}^{-3} \equiv 26 \text{ degrees API}$$

Depth increment required = [(26 – 17)/40] × 10 000 feet = 2250 feet (685 m) Undulation can be sufficient for well depths within a formation to differ by this much (or more). The depth is the TVD.

Question 23. At the Lenina coal mine in Karaganda region of Kazakhstan there is *in situ* use of CBM for part of the coal mine's own energy requirements. The generator at Lenina (below) produces 1.4 MW of

electricity at 35% efficiency. What will be the required daily rate of supply of gas? To how many barrels of heavy fuel oil is this thermally equivalent?

Solution.

$$\text{rate of generation of heat} = 1.4/0.35 \ \text{MW} = 4 \ \text{MW}$$

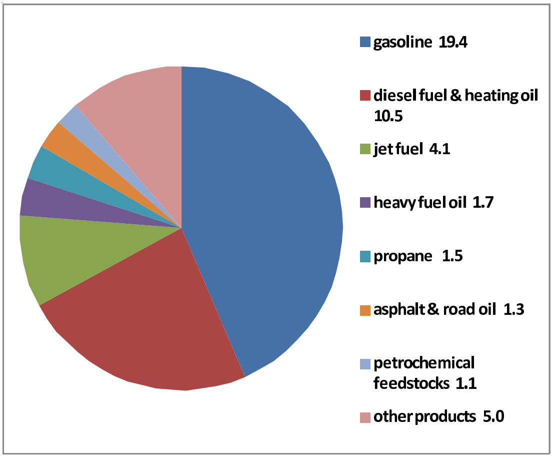
The rate of consumption of fuel is therefore:

$$4 \times 10^6 \ \text{J s}^{-1}/(37 \times 10^6) \ \text{J m}^{-3}$$
$$\downarrow$$
$$\approx 10000 \ \text{m}^3 \ \text{per day}$$

Taking the calorific value of the heavy fuel oil to be 43 MJ kg^{-1} and the density 975 kg m^{-3}:

$$\text{Barrels required}$$
$$= [(4 \times 10^6 \ \text{J s}^{-1})/(43 \times 10^6 \ \text{J kg}^{-1} \times 975 \ \text{kg m}^{-3} \times 0.159 \ \text{m}^3 \ \text{bbl}^{-1})]$$
$$\times (24 \times 3600) \ \text{s day}^{-1} \approx 50 \ \text{bbl per day.}$$

<u>Question 24</u>. The figure below is for the breakdown into distillates and residue of one barrel of a particular crude oil. Sum the components and comment on your answer. Figures are in US gallons.



Solution:

Summed total = 44.6 gallons. 1 barrel is 42 US gallons. Therefore there has been expansion, commonly called refinery gain. Mass is conserved, but there is no law of physics requiring volume to be conserved. Refinery gain is typically 7% (6% in this example) and has to be factored into refinery design.

Question 25. Enhanced oil recovery takes place with supercritical carbon dioxide at 100 bar and temperature 200°C. From the below ascertain the temperature of the supercritical fluid.
http://www.peacesoftware.de/einigewerte/co2_e.html

Solution:

From the calculator the density is 122 kg m^{-3}.
Note: a crude oil having a density of 950 kg m^{-3} would have a density of about 855 kg m^{-3} at 200°C according to:
http://www.jiskoot.com/samplertool/densitycalc.php?callback=yes&API=

The carbon dioxide density in this example is therefore about 15% of the oil density. A related example follows.

Question 26. In the previous question carbon dioxide at 100 bar and temperature 200°C was considered as a fluid for EOR and it was shown that under these conditions carbon dioxide is supercritical. Determine the proportions of xenon (molar weight 131g) and argon (molar weight 40 g) in a mixture having the same molar mass as carbon dioxide (44 g) and note that such a mixture would not be supercritical at 100 bar and temperature 200°C . Determine the density of this mixture and compare it with that of supercritical carbon dioxide under the same conditions.

Solution:

Letting x be the molar proportion of argon:

$$40x + 131(1-x) = 44 \rightarrow x = 0.96$$

So the composition is 96% argon 4% xenon.

$$PV = \mathrm{n}\mathrm{R}T \text{ (usual symbols)}$$
$$\mathrm{n}/V = P/\mathrm{R}T$$
$$= 10^7 \text{ N m}^{-2}/(8.314 \text{ J K}^{-1} \text{ mol}^{-1} \times 473 \text{ K})$$
$$= 2542 \text{ mol m}^{-3}$$
$$\text{density } \rho = 112 \text{ kg m}^{-3}$$

Density of the supercritical CO_2 = 122 kg m^{-3} ≈ 10% higher.
Note: Sometimes the difference is more marked than this. Even so the important factor in EOR is miscibility rather than whether the fluid is in gaseous or supercritical state.

Safety aspects: TNT equivalents

Imagine that at an accident at a hydrocarbon production plant be x barrels of hydrocarbon of calorific value 44 MJ kg^{-1} and density 850 kg m^{-3} explode.

Heat released in the event of total burning =

$$x \text{ bbl} \times \underset{\substack{\uparrow \\ \textit{conversion factor}}}{0.159 \text{ m}^3 \text{ bbl}^{-1}} \times 850 \text{ kg m}^{-3} \times 44 \text{ MJ kg}^{-1} = 6000\,x \text{ MJ}$$

Now when a hydrocarbon burns explosively the blast, which represents heat converted to mechanical work, is usually about 5% of the total heat released. In the above case therefore the blast energy is:

$$6000\,x \times 0.05 \text{ MJ} = 300\,x \text{ MJ}$$

Now 1 kg of TNT creates 4.2 MJ of blast energy on explosion.

The amount of TNT equivalent to x barrels of hydrocarbon is therefore:

$$300\,x \text{ MJ}/4.2 \text{ MJ kg}^{-1} = 0.071x \text{ tonne} = \text{'TNT equivalence'}$$

Question 27. There are crude oil storage tanks in Saudi Arabia which can hold up to 1.5 million barrels of oil. What would be the TNT equivalence if one of these were to explode?

Solution:

From the equation, TNT equivalence were one of these to 'go up'
= 107 kilotonne.

For comparison, the TNT equivalent at the atomic bomb in Hiroshima in 1945 = 15 kilotonnes.

TNT equivalent at the hydrogen bomb test at Bikini Atoll in 1954
= 15 megatonnes.

In general nuclear fission reactions can be equalled in TNT equivalence by explosion of large amounts of hydrocarbons, but not nuclear fusion reactions.

Question 28. The previous question is for a static application, a tank of fluid undergoing no directional movement and no processing. This is often not so: for example at the Geismar LA olefins plant in 2013 there was an explosion which involved one death and 77 (precise figures for this vary between coverages) non-fatal injuries. The explosion began through leakage of butadiene from a heat exchanger and estimates of the amount so released are many and cover a wide range. One such

estimate is that a single quantity of 13 800 pounds was released and exploded. The most likely event is that it all evaporated before exploding, but in this treatment we use units of barrels of liquid in the calculation. Explosion energies are so much larger than heats of vaporisation that nothing at all is achieved by attempting to incorporate the latter. Using a value of 615 kg m^{-3} for the liquid density of butadiene, determine the TNT equivalence.

Solution:

$$13\,800 \text{ pound}/(2.205 \text{ pound kg}^{-1} \times 0.615 \text{ kg m}^{-3} \times 0.159 \text{ m}^3 \text{ bbl}^{-1}) = 64\,000 \text{ bbl}$$

$$\downarrow$$

TNT equivalence 4.5 kilotonne.

Comment:

Although lower than those discussed so far in this volume this is a high TNT equivalence. It can be compared with that at West Texas in 2013 which involved ammonium nitrate fertiliser and, according to several web sources, had a TNT equivalence of up to 5 tonnes, a thousandth of that at Geismar. Note that one could not apply the equation for TNT equivalence developed earlier in this section for an ammonium nitrate explosion: the equation is for hydrocarbons burning in air only.

Question 29. A 'Winchester bottle' for laboratory use holds 2.5 litres. What would be the TNT equivalence if the 'Winchester' filled with cyclohexane exploded?

Solution:

$$2.5 \text{ litres} \equiv 0.016 \text{ bbl}$$

TNT equivalence = 0.0011 tonne (1 kg or 1 millitonne).

A TNT equivalence of the order of kg does not signify negligible effects. It actually means production of 4.2 MJ of mechanical energy. A Nissan Micra needs about 40 kW to sustain cruising speed, so 4.2 MJ from its power unit would suffice for about 100 s. Who could doubt then that this quantity of energy not so profitably directed could cause damage, injury or death?

Question 30. An autoclave contains quantity of 5 tonnes of water at 3 bar pressure. If it breaks open and a non-chemical explosion results what will be the TNT equivalence?

Solution:

The pressure energy is:

$$(3 \times 10^5 \text{N m}^{-2}/1000 \text{ kg m}^{-3}) = 300 \text{ m}^2\text{s}^{-2} \text{ J kg}^{-1}$$

$$\text{Total pressure energy } 5 \times 10^3 \text{ kg} \times 300 \text{ J kg}^{-1} = 1.5 \text{ MJ}$$

$$\text{TNT equivalence} = (1.5/4.2) \text{ kg} \approx 0.35 \text{ kg or } 0.35 \text{ millitonnes.}$$

Background to gravity settlement of oil from produced water

The simplest and most obvious means of 'treating' produced water is gravity settlement, and it might be used alone or it might be the first step in a 'polishing' process. Crude oils are slightly less dense than water so once the produced water is in a settled state only time is needed for separation. That the water is *settled* is important: if it is not, centrifugal action is needed. The behaviour often observed in gravity settlement is that small droplets of oil coalesce to form larger ones which migrate to the water surface where they form a film. Once the settlement device has done its job the water layer is analysed, as if there is to be no further treatment the oil remaining in that will be discharged.

Imagine a gravity settlement tank through which produced water is passed at a rate Q m^3 s^{-1}. If the settlement area is A m^2 the velocity will be v_o:

$$v_o = Q/A \text{ m s}^{-1}$$

If the velocity as calculated above exceeds the settling velocity (usual symbol v_d) there will not be total removal.
The settling velocity is given by Stokes' Law :

$$v_d = \text{g}\Delta\rho d^2/18\mu$$

where g = acceleration due to gravity, $\Delta\rho$ = difference in density between oil and water, d = oil droplet diameter and μ = dynamic viscosity of the water.

$$\text{For } v_o > v_d \text{ percentage settlement} = (v_d/v_o) \times 100$$

Question 31. Oil of API gravity 35 and median droplet size 150 microns is suspended in produced water. What would be the settlement velocity? Use a value of 1000 kg m^{-3} for the density of water and a value of 0.001 kg m^{-1}s^{-1} for the dynamic viscosity. If in this application the throughput of produced water is 0.5 m^3 s^{-1} what is the minimum settlement area for a total effect?

Solution:

$$35 \text{ degrees API} = 850 \text{ kg m}^{-3}$$

Substituting into Stokes' equation, noting that all quantities have to be in SI:

$v_d = 0.002$ m s^{-1} (2 mm s^{-1}) to one place of decimals.

If the throughput rate of produced water is 0.5 m^3 s^{-1} the minimum settlement area for a total effect can be calculated.

The maximum speed for total settlement is $v_o = Q/A = 0.002$ m s^{-1}

$$\downarrow$$

$$A = 250 \text{ m}^2$$

Question 32. An onshore oil well in quite a 'watered out' condition produces 50 000 barrels per day of water. The settling velocity is 0.004 m s^{-1}. Working at or close to the settling velocity, what will be the necessary settlement area if the water from a day's operation of the well is to be processed in a single operating period of the gravity tank of six hours?

Solution:

Throughput needed = 50 000 barrels in six hours or:

$$50\,000 \times 0.159/(6 \times 3600) \text{ m}^3\text{s}^{-1}$$
$$= 0.37 \text{ m}^3\text{s}^{-1}$$

We set the actual velocity 10% below the settling velocity, that is, at 0.0036 m s^{-1}

$$Q/A = 0.036 \text{ m s}^{-1} = 0.37 \text{ m}^3\text{s}^{-1}/A \text{ m}^2$$

$$\downarrow$$

$$A = 10.3 \text{ m}^2$$

Background to question 33

When a gas pipeline is pigged condensate having collected on the inside surface of the pipe is removed so as to prevent ignition hazards and to promote flow assurance.

Question 33. The source
http://petrowiki.org/Pipeline_pigging#Slug_catchers
gives the following equation for pigging of a gas pipeline:
$Q_L = 5000 Q_g T/P$
Q_L = liquid low rate in front of the pig (barrels per day) Q_g = gas flow rate behind the pig (million cubic feet per day) T = temperature (°R) and P = line pressure (psia).

Gas at 100 bar absolute and 5°C propels a pig which removes condensate having deposited in the pipeline so that it will not become either a

difficulty in flow assurance or an ignition hazard. At what volumetric rate will gas need to flow for the condensate to move at a volumetric rate of 1 barrel per minute? If the pipe is 28 inches in diameter what will be the flow speed in m s^{-1} of the gas?

Solution:

$$Q_g = Q_L P/5000\,T$$
1 barrel per minute = 1440 barrels per day
5°C = 501°R
100 bar abs. = 1470 p.s.i.a
↓
Q_g = 0.85 million cubic feet per day = 0.024 million cubic metres per day

Flow speed = volumetric flow rate/cross-sectional area
Volumetric flow rate = $[0.024 \times 10^6\ m^3\ day^{-1}/(24 \times 3600)\ s\ day^{-1}]$
$= 0.28\ m^3\ s^{-1}$
Cross-sectional area = $\pi \times 7^2$ square inches = 154 square inches = 0.099 m^2
Flow speed = $(0.28/0.099)\ m\ s^{-1}$
$= 2.8\ m\ s^{-1}$ (6 m.p.h.)

<u>Question 34</u>. The refining capacity of Japan is about 4 million barrels per day. (The remainder is imported as refined product.) What will be the daily carbon footprint of the refining in Japan? By how much will it increase the CO_2 level of the atmosphere in a year? Express your answer in p.p.b. weight basis.

Solution:

The carbon footprint of refining of a barrel of oil is 50 kg of CO_2
Carbon footprint = $[4 \times 10^6\ bbl \times 50\ kg\ bbl^{-1}]$ kg
= 0.2 million tonnes
Increase in the CO_2 level of the atmosphere =
mass of the atmosphere
↓
$(0.2 \times 10^9\ kg/ 5.1 \times 10^{18}\ kg) \times 10^9$ p.p.b.
= 0.04 p.p.b.

Question 35. It was stated in the previous question that 50 kg of carbon dioxide are produced per barrel of oil refined. In a situation in which all of the heat for refining was supplied by natural gas determine the quantity in kg of carbon dioxide burnt per barrel refined. Compare the heat released from the burning of the gas with the heat released from burning a barrel of refined product which is 6 GJ. The molar heat of combustion of methane is 889 kJ.

Solution:

$$50 \text{ kg } CO_2 = (50/0.044) \text{ mol}$$

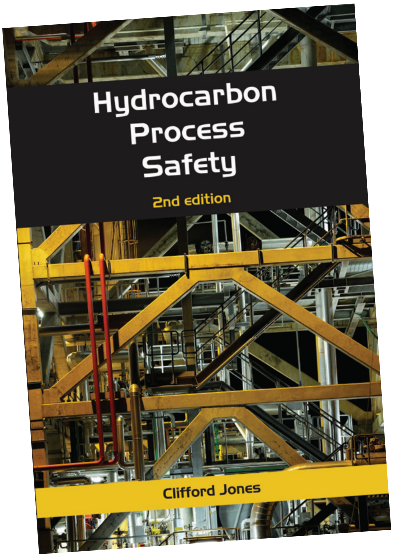
= 1136 mol having come from 1136 mol (18 kg) of methane capable of releasing:

1136 mol × 889 kJ mol^{-1} = 1 GJ or 1/6th the heat from the burning of the distillate.

Postscript

The advantage of an electronic book is that it can be added to progressively, avoiding the labour of a 'new edition' for a conventional book. As I continue my duties as a teacher of hydrocarbon production technology I can imagine that it might become possible to expand this book. I can do so most effectively if I have feedback from readers, and this is earnestly requested.

By the same author



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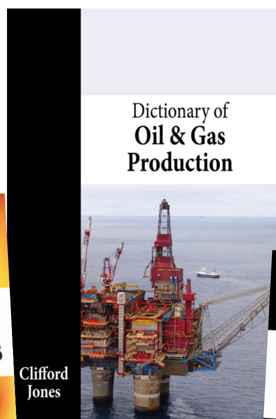

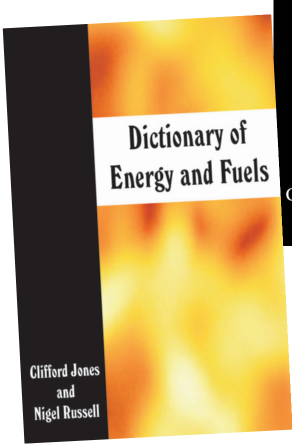

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