RIS520 TECHNICAL SAFETY

SOLUTIONS TO SOME EXERCISES 2018

Note that no guarantees are given regarding the correctness of the solutions. They are only provided in order to guide the student in finding appropriate solution procedures.

Also note that many of the exercises can be solved (controlled) by using Gexcon's web calculators

https://www.gexcon.com/page/Tools/en

Answer: Here you have to first calculate the speed of sound in the leaking gas after it has expanded to atmospheric pressure. To be able to do this you have to calculate the temperature in the expanded gas. This would either be based on isothermal expansion, i.e. no change in temperature, or adiabatic expansion, meaning no energy gain or loss in the expansion process. In this case assume isothermal expansion. Then you have to calculate the equivalent radius.

$c=sqrt(\gamma RT/M)$ $\quad\quad$ $r_0=sqrt(q/\pi c\rho_0)$

c=429,4 m/s $\quad\quad$ *r0=0.04m*

f) Calculate X_{LFL} and X_{UFL}.

Answer: these are the distances from the leak to a concentration in the jet of LFL or UFL.

X_LFL= 6.45 m, X_UFL = 1.93 m

g) After how long has the leak rate dropped to 50% of the initial rate?

Answer: Use formula $m_g= m_{0g} exp(-m_{0g} /w*t)$ $\quad\quad$ *t=16 s*

Exercise 2

An offshore module is 40 m long, 20 m wide and 10 m high. Equipment, piping, structure, vessels etc. fills 10% of the available volume. A large amount of methane leaks out, sufficient to fill the module with a stoichiometric mixture of gas and air. The module is open at both ends, the (long) sides and decks are plated (closed). The density of methane is 0.67 kg/m^3.

a) How many kg of methane does the cloud contain?

Answer: calculate gas cloud volume, then methane volume, then mass
*Available volume V=40m*20m*10m*0.9=7200 m3*
*Methane volume Vmethane=7200 m3*0.095=684 m3*
*Methane mass: m=rho*Vmethane=0.67kg/m3*684m3=458 kg*

b) The gas-air cloud explodes with a maximum overpressure of 1.5 barg. Calculate the blast pressure against the neighbouring platform 80 m from the centre of the module by using the Multi-Energy Method.

Answer: first calculate $R\text{-}=R/(E/P_0)^{1/3}$ *Then identify curve on ME-graph which corresponds to explosion (source) overpressure of 1.5 barg. Identify calculated R- value on x-axis, draw a vertical line up to identified curve on graph, go left and read off overpressure at given distance on y-axis. Check your answer on GexCon's web calculator:*
http://www2.gexcon.com/calculators/new/MEMethod.php

c) What is the duration of the shock wave as it hits the neighbouring platform?

Answer: use formula $D_{eq} = 2(v_l/\pi v_f)^{1/2}$ *Vl and vf are calculated earlier in the exercise. Use appropriate formulae for teq.*

D_eq=9,78 m *t_eq=22,3 s*

d) Assume that the fire is not affected by the presence of the tank. What is the flame height under quiescent conditions (no wind)?

Answer: use formulas $m_f = \rho v_f$ *and* $L = 42D\left[\frac{m''_f}{\rho_0\sqrt{gD}}\right]^{0.61}$

L = 21.4 m

Exercise 4.

A pipeline with inner diameter 80 cm transports natural gas which consists of 85% methane, 10 % ethane and 5 % propane. At a specific location the overpressure inside the pipe is 40 bar, the temperature 20 degrees C and the pressure gradient dp/dx is 40 N/m^3. Assume that the pipeline is severed at the defined location (guillotine break).

a) Calculate initial leak rate from the high pressure side of the breach. Explain why it is appropriate to use the chosen formula.

Answer: use formula for sonic leak of gas. This is appropriate initially, before the effect of friction becomes important and slows down the flow inside the pipe, towards the hole.

b) What is the leak rate after 1 minute, and how much gas has escaped?

Answer: use formulas for q (leak rate) and Q (amount of escaped gas) in FCH

c) Calculate stoichiometric concentration as well as upper and lower flammability limit for the gas mixture.

Answer: use Le Chatelier to calculate L (LFL)

and then formulas

$L25 = 0.55 C_{st}$
$U25 = 4.8 C_{st}^{1/2}$

Give two examples of potential structural response (damage) from an overpressure of 0.02 barg.

Answer: Use the Multi-Energy Method, see GEH chapter 7.3 for reason.
Ř=10 from Fig. 7.6 in GEH

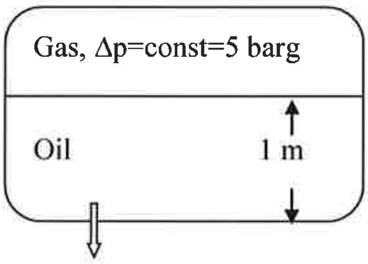
*(E/p0)**1/3 = 115.1*

*R= Ř*115.1=1151*

See Table 8.2 in GEH: Windows, doors and light partition walls might be damaged.

Exercise 6.

A tank leaks oil with density 800 kg/m^3 and temperature 20 degrees C. The air temperature is 10 degrees C. The enthalpies of combustion and evaporation for the oil are 42000 and 350 kJ/kg, respectively. The boiling point is 120 degrees C, the specific heat capacity is 1 kJ/kgK. The molecular weight is 100 kg/kmol. The hole at the bottom of the tank is round, sharp-edged and has a diameter of 4 cm. The height from the hole to the oil surface is 1 metre.



a) Calculate the leak rate.

Answer: $$m_l = c_D A \rho \sqrt{2\left[\left(\frac{p_1 - p_2}{\rho}\right) + \Delta Z \cdot g\right]} = 22.22 \text{ kg/s}$$

b) Calculate the regression rate for an "infinite" pool in m/s.

Answer: $$v_{f\infty} = 1.27 \cdot 10^{-6}\left[\frac{\Delta H_c}{\Delta H_v + c_p(T_b - T_0)}\right] = 1.185 \cdot 10^{-4} m/s$$

c) A burning pool is formed on the horizontal deck..
What is the equilibrium diameter of the pool and how long does it take to reach the equilibrium diameter?

Answer: $C_4H_{10} + 6.5(O_2+3.76N_2) = 4CO_2 + 5H_2O + 24.44N_2$

$$C_{st} = \frac{100\%}{1+6.5+24.44} = 3.12\%$$

b) What is the Minimum Ignition Energy (MIE) and Auto Ignition Temperature (AIT) for butane in air? How warm (at what temperature) must a metal wire of diameter 1 mm be to ignite the gas mixture? Explain briefly why this temperature deviates from the AIT?

Answer: See Tables 13 (MIE) and 15 (AIT) in Kuchta.

MIE=0.26 mJ; AIT = 370 degrees C

Table 16 indicates that a 1 mm Nichrome wire needs to reach a temperature of more than 1000 degrees C to be able to ignite stoichiometric butane-air. The gas will at lower temperatures be heated by the wire and due to expansion and buoyancy it will rise and flow away from the wire before it reaches AIT.

c) Find the flash point for liquid butane. What is the boiling point? Explain briefly how the gas concentration immediately above the liquid butane surface changes when the liquid temperature starts below the flash point and then increases past the flash point and up to the boiling point?

Answer: Flash and boiling points for butane are -74 and -0.5 degrees C, respectively, they can be found from Figure 13 and also App. A in Kuchta.

For a liquid temperature below the flash point the gas mixture immediately above the liquid surface is at a concentration below LFL. Increasing the temperature to and over the flash point means that the concentration will reach and pass LFL. When the temperature reaches boiling point, the gas concentration approaches 100% (pure gas).

d) Repeat 3c), but with propane instead of butane (you don't need to repeat the explanation at the end).

Answer: Flash and boiling points for propane are -104 and 42 degrees C, respectively

e) If you were to use a gas burner to boil water outdoors, at an ambient temperature of 3 degrees C below zero, would you then use a propane or a butane burner? Explain briefly.

Answer: Propane, because the butane would be at a temperature below boiling point and hence less gas would evaporate than for propane.

Answer:

$$x = \frac{r_0}{\tan\alpha}\left[\frac{1}{C}\sqrt{\left[C\cdot\rho_0 + (1-C)\rho_l\right]/\rho_0} - 1\right] = \frac{0.095}{0.16}\left[\frac{1}{0.025}\sqrt{\left[0.025\cdot 2.48 + (1-0.025)1.2\right]/2.48} - 1\right] = 16.15m$$

e) If you were to determine a safety zone around a potential leak source, which parameter would you base this zone on and which parameter value would you use to determine the zone? Give a brief explanation.

*Answer: Gas concentration. In the vicinity of a jet leak the appropriate concentration to use is ½*LEL, it has been observed that due to turbulence a jet can be ignited from a location at the jet edge where the measured, time-averaged concentration is as low as ½*LEL.*

Exercise 9

a) Generate a stoichiometric balance equation for methane (CH_4) in air. Calculate the stoichiometric concentration of methane in air based on the stoichiometric equation .

Answer: See in Kuchta

$CH4+2(O2+3.76N2) \rightarrow CO2+2H2O+7.52N2$

$1(1+2+7.52)=0.095$

b) Calculate upper and lower flammability limits (U_{25} and L_{25}) for methane in air. What are the flammability limits at a temperature of 200 degrees C?

Answer: Kuchta eq. 60 and 61:

$L25 = 0.55Cst = 5.2\%$
$U25 = 4.8Cst^{1/2} = 14.8\%$

Eq. 63 og 64:

$Lt/L25=1-0.000721(T-25)=0.873825 \rightarrow Lt = 4.5\%$
$Ut/U25=1+0.000721(T-25)=1.126175 \rightarrow Ut = 16.7\%$

c) Find the minimum ignition energy (MIE) and the auto ignition temperature (AIT) for methane in air. At which concentration (fraction of stoichiometric) is the minimum ignition energy the lowest? What is the MIE for methane-air at a gas concentration of 1.2 times the stoichiometric concentration? Explain briefly how you determine this.

Answer: Tables 13 and 15 in Kuchta give MIE=0.3mJ, AIT=630 degrees C.

Answer: $m_{0g}=1.8$ *kg/s*

e) Calculate the leak rate after 5 minutes.

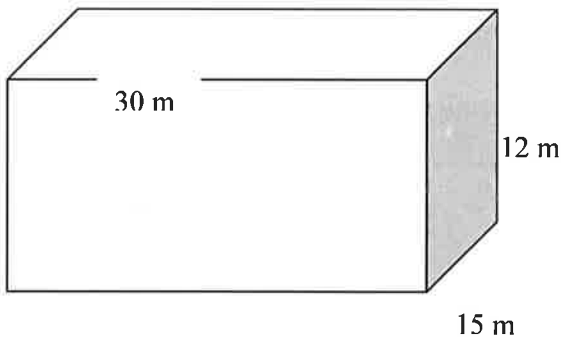
Answer : $m_g = m_{0g} \exp(-m_{0g}/w*t) = 1.4$ *kg/s*

g) Is it important to account for friction in the calculations above? Discuss briefly.

Answer: No, it may however be important in long pipes where friction is thought to be important.

Exercise 11

In a module which is 30 m long, 15 m wide and 12 m high, and where equipment, piping etc. fills 10% of the volume, enough methane leaks out to fill the module with a stoichiometric methanw-air mixture. The module is open at both ends, closed elsewhere. The density of methane is 0.67 kg/m^3.



a) How many kg of methane does the gas cloud contain? Where would you locate the ignition point to maximise the overpressure in an explosion? Explain.

*Answer: Volume of the mod: V=30*15*12 m3=5400 m3*
Available volume for gas (90%): 4860 m3
*How many m3 methane in a stoichiometric cloud?: Vmethane=Vavail*0.095=461.7 m3*
*Methane mass: Mmethane=Vmethane**ρ*=309 kg*

Ignition point in one end which gives the longest path for the flame will normally give the highest overpressure, at least when there is a lot of congestion in the module.

b) The gas cloud explodes with a maximum overpressure of 4 barg. Calculate the blast pressure at the neighbouring platform 150 m away by using the Multi-Energy-method. Calculate the duration of the blast pulse at the same location.

Density @ stoichiometric in atm page.

equivalent radius at page?

$r_0 = \sqrt{\frac{q}{\pi c \rho_0}}$

Exercise 13.

A vessel containing ethane has a pressure of 50 barg and a temperature of 10 degrees C. Assume that these parameters are constant. Gas leaks out at a rate of 0.3 kg/s. Assume that the leaking gas expands isothermally to atmospheric pressure. Assume that the leaking gas jet has the shape of a frustum cone (kjegle med avkuttet spiss) with half top angle α=9.1 degrees.

a) Find the density ρ of the gas after it has leaked out and expanded to atmospheric pressure.

Answer: $\rho=pM/RT=100000Pa*30kg/kmol/(8314\ J/kmol/K *283K)=1.28kg/m^3$

b) Find the speed of sound in the expanded ethane gas, then calculate the equivalent radius based on the initial leak rate.

Answer: $c=sqrt(\gamma RT/M)=319m/s$
$R0=sqrt(q/\pi c\rho 0)=sqrt(0.3/(3.14*319*1.28))=0.015m$

c) Calculate the distance from the leak location along the jet axis to the location where the gas-air concentration is at the lower flammability limit (use volume fraction not volume percent in the calculation!)

Answer: see eq. 5.2 in fire calc handbook. LFL for ethane can be found in app. A in Kuchta.

Air has a density of 1.205 kg/m3 at 20 degrees C. (tab 2 in Kuchta) Use the eq. of state to find density at 10 degrees C (assume that pressure is the same for 10 degrees ambient and 20 degrees ambient temp): $p=\rho RT/M \Rightarrow p=\rho_{10}R*283/30=1.205*R*293/30 \Rightarrow \rho_{10} = 1.205*293/283=1.25\ kg/m^3$

Distance

$$x=\frac{0.015}{0.16}\left[\frac{1}{0.03}\sqrt{[0.03*1.28+(1-0.03)*1.25]/1.28}-1\right]=2.95m$$

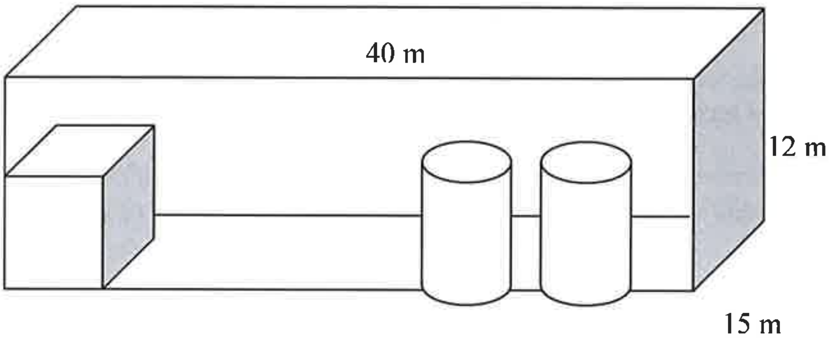
Exercise 14

a) Write the equation of state for ideal and real gases, respectively. Describe briefly which properties of a gas that will determine whether the real equation of state must be applied. State for ethylene (ethene; C_2H_4) a combination of temperature and pressure which will give a compressibility factor of approx. 0.6. Ethylene has a molecular weight of 28.

Answer:
$p=\rho RT/M$ *og* $p=Z\rho RT/M$
High pressures and low temperatures will make Z deviate from 1
*T=282.8 degrees C and p=0.75*50.7 bar=38 bar will result in Z ~0.6 (of course there are many other possible combinations, this is just one example)*

Exercise 15

3000 kg of methane leaks out into a module. The gas forms a stoichiometric, uniform gas mixture with air. The module is 40 m long, 15 m wide and 12 m high. It is open on one long side, otherwise closed, and gas which flows out of the opening is transported away from the platform by the wind. Equipment, piping, local rooms etc. fill 20% of the volume in the module. The density of methane can be set to 0.67 kg/m^3. The module looks like the module below, with the open side to the front, showing an equipment room and two tanks.



a) What is the volume of the gas cloud? Approximately how large a proportion of the cloud will contribute to overpressure generation in a possible explosion? Where would you locate the ignition point in order to generate as high an overpressure as possible? Give a brief explanation.

Answer: $V = m / C_{st}\rho = 3000kg/(0.095*0.67kg/m^3) = 47133m^3$

Gas cloud

The part of the cloud inside the module will contribute to overpressure generation. Available module volume is

$V_{modul} = 0.8*40*12*15m^3 = 5760m^3$ *i.e.. 5760/47133 = approx 12% of the cloud contributes.*

The ignition point should be located low in one of the corners probably behind the room. That will give the most blockage and the longest flame path i.e. the highest overpressure.

b) The gas cloud explodes with a maximum overpressure of 8 barg. Calculate the blast overpressure against the Living Quarter on the neighbouring platform 100 m away by using the Multi-Energy method. Calculate the duration of the overpressure pulse at the same location.

Answer: 5760 m3 gas, 8 barg which means explosion strength 9-10.

$(E/p_0)^{1/3} = (3.5MJ/m^3 \bullet 5760m^3 / 1 \bullet 10^5 N/m^2)^{1/3} = 58.6$

$\overline{R} = 100\,m/58.6 = 1.7 \Rightarrow p_{100m} = 0.15 barg$

$C_0 = 340\ m/s \wedge \overline{t_+} \approx 0.35 \Rightarrow t_+ = \overline{t_+}(E/p_0)^{1/3} = 0.06s$

b) What would the distance have been to the lower flammability limit for the gas jet if it did not hit the other tank? Use $\tan\alpha = 0.16$

Answer: use eq. 5.1 and 5.2 in FCH.

$$r_0 = \sqrt{q/\pi \cdot c \cdot \rho_0}\ \_and\_\ x = \frac{r_0}{\tan\alpha}\left[\frac{1}{C}\sqrt{[C\cdot\rho_0 + (1-C)\rho_l]/\rho_0} - 1\right]$$

Need ρ_0 which is gas density after expansion to atmospheric pressure, as well as c (speed of sound in the gas after expansion). Assume isothermal expansion due to low leak rate, which means that p_0/ρ_0 (outside)= $p_1/(Z^*\rho_1)$ (inside). $p/p_{cr}\sim0.2$ and $T/T_{cr}\sim0.74$ which gives $Z\sim0.8$.

This results in $\rho_0 = 1/9.3*0.8*18 kg/m^3 = 1{,}55\ kg/m^3$.

$$c = \sqrt{\frac{\gamma RT}{M}} = \sqrt{\frac{1.3\cdot 8314\cdot 293}{44}} = 268 m/s$$

This gives: $r_0 = \sqrt{0.13/(\pi\cdot 268\cdot 1.55)} = 1cm$

$$x = \frac{0.01}{0.16}\left[\frac{1}{0.021}\sqrt{[0.021\cdot 1.55 + (1-0.021)\cdot 1.205]/1.55} - 1\right] = 2.55m$$

c) The gas ignites. What would the visible flame length and the maximum jet diameter have been if the jet had not hit the other tank?

Answer:

$$M_{ef} = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{p_v}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} = 2.12 \qquad \text{and} \qquad \frac{D_{ef}}{D_e} = \frac{1}{\sqrt{M_{ef}}}\left[\frac{2+(\gamma-1)M_{ef}^{\ 2}}{\gamma+1}\right]^{\frac{\gamma+1}{4(\gamma-1)}} = 1.41$$

which gives $L - s = \dfrac{15D_{ef}}{C_t}\left[\dfrac{M_0}{M_f}\right]^{\frac{1}{2}} = \dfrac{15\cdot 0.01m\cdot 1.41}{0.038}\left[\dfrac{29}{44}\right]^{\frac{1}{2}} = 4.52m$

$s = \dfrac{6.4\pi D_e u_e}{4u_a} = 4\pi D_e$ because $u_a = 0.4u_e$. Here one must use D_{ef} instead of D_e (sonic leak – high pressure), so $s = 4\pi D_{ef} = 4\pi\cdot 1.41\cdot 0.01m = 0.18m$

This results in $L = 4.7m$ and $D_{jmax} = 0.12L = 0.56m$

Answer: $m_l = c_D A \rho \sqrt{2\left[\left(\frac{p_1 - p_2}{\rho}\right) + \Delta Z \cdot g\right]} =$

$$0.62 \cdot \left(\pi \cdot 0.005^2\right) m^2 \cdot 589 kg/m^3 \sqrt{2\left[\left(\frac{1.5 \cdot 10^5 Pa - 1 \cdot 10^5 Pa}{589 kg/m^3}\right) + 1.9m \cdot 9.81 m/s^2\right]} =$$

$$0.029 kg/m \sqrt{2\left[84.89 m^2/s^2 + 18.64 m^2/s^2\right]} = 0.42 kg/s$$

$$v_L = m_l / \rho = \frac{0.42 kg/s}{589 kg/m^3} = 7 \cdot 10^{-4} m^3/s$$

c) The butane is ignited and burns as a pool which is fed by a continuous release. What is the equilibrium diameter and what is the time to reach equilibrium diameter?

Answer: $D_{eq} = 2\left[\frac{v_L}{\pi v_f}\right]^{\frac{1}{2}} = 2\left[\frac{7 \cdot 10^{-4} m^3/s}{\pi \cdot 1.57 \cdot 10^{-4} m/s}\right]^{\frac{1}{2}} = 2.38m$. *This indicates that the pool is large enough that we can use the formula for regression rate for "infinitely" large pools.*

$$t_{eq} = \frac{0.564 D_{eq}}{\left[g v_f D_{eq}\right]^{\frac{1}{3}}} = \frac{0.564 \cdot 2.38m}{\left[9.81 m/s^2 \cdot 1.57 \cdot 10^{-4} m/s \cdot 2.38m\right]^{\frac{1}{3}}} = \frac{1.34m}{0.154 m/s} = 8.69s$$

d) Assume that the flames are not affected by the presence of the tank. What is the flame height in calm weather?

Answer: $L = 42D\left[\frac{m''_f}{\left(\rho_0 \sqrt{gD}\right)}\right]^{0.61} = 42 \cdot 2.38\left[\frac{\rho v_f}{\left(\rho_0 \sqrt{gD}\right)}\right]^{0.61} =$

$$42 \cdot 2.38m\left[\frac{589 kg/m^3 \cdot 1.57 \cdot 10^{-4} m/s}{\left(1.2 kg/m^3 \sqrt{9.81 m/s^2 \cdot 2.38m}\right)}\right]^{0.61} = 99.96m\left[\frac{0.0925}{5.798}\right]^{0.61} = 8.0m$$