RIS520 TECHNICAL SAFETY

EXERCISES 2018

This document can NOT be used at the exam!

Exercise 1.

A 1 m^3 vessel is filled with methane gas at 0 ^oC. The pressure in the vessel is 45 bar. The universal gas constant R equals 8314 J/(kmolK). The molecular weight M of methane is 16 kg/kmol. The fraction between specific heat capacities, γ, is 1.3.

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

b) Write up the version of the equation of state that fits best for the conditions defined above. Provide a reason for your choice.

c) Find the density ρ of the gas. Calculate the mass m of gas in the vessel.

d) A pipe connection to the vessel is broken and an approximately circular, sharp-edged hole of 2 cm diameter is generated. Which formula should be used to calculate the initial leak rate from the hole – and why? Calculate the initial leak rate (in kg/s) from the vessel.

e) Calculate the equivalent radius for the leak (jet). (Tricky: assume isothermal expansion)

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

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

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?

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.

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

d) How large (i.e. how many m^3) does the gas cloud have to be in order to reduce the overpressure at the neighbouring platform by a factor of 2?

e) Explain the difference between side-on and reflected overpressure. Which one of these is predicted by the Multi-Energy Method?

f) A building is hit head-on by a blast wave with side-on pressure 0.1 barg. Prove a simple estimate of the overpressure at 1) the front of the building, 2) at the side and 3) at the back.

Exercise 3.

A butane tank of 5 m^3 leaks from a circular hole with diameter 4 cm. The hole is at the bottom of the tank. The liquid head (væskehøyden) is 3 m at the start of the leak. The ambient temperature is 10 degrees C, i.e. the vapour pressure in the tank is 1,5 bar. It can be assumed to be constant. The liquid density is 589 kg/m^3. The molecular weight of butane is 58 kg/kmol. The gravitational constant is g=9.81 m/s^2.

a) How large is the regression rate in m/s for infinitely large pools when the heat of combustion is ΔH_c = 45.8 MJ/kg, and the heat of vapourization is ΔH_v = 0,37 MJ/kg? Assume for simplicity that the butane is at the boiling point.

b) How large is the initial leak rate?

c) The butane is ignited and burns as a pool which is fed from a continuous release. How large is the pool's equilibrium diameter, and at what time is the equilibrium diameter reached?

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

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.

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

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

Exercise 5.

A pipeline with inner diameter 25 cm transports natural gas consisting of 85% methane, 11% ethane og 4 % propane. Somewhere along the pipeline the pressure is 40 bar, the temperature 20 degrees C and the pressure gradient dp/dx 30 N/m^3. Assume that the pipe suffers a guillotine break at the given location.

a) What is the leak rate of the high pressure part of the pipeline after one minute?
   How much gas has been released?

b) What is the average molecular weight of the gas mixture?
   What is the stoichiometric concentration with air of this gas mixture?
   Calculate the lower and upper flammability limits of the mixture.

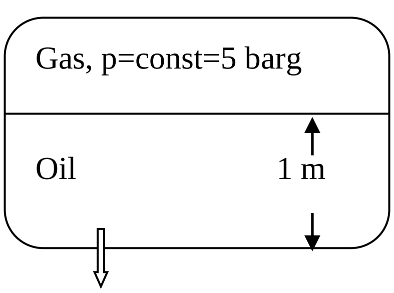
c) Assume that the amount of gas that has leaked out during the first minute has formed a stoichiometric gas-air mixture. What is the volume of this gas-air cloud?

d) The gas cloud is shaped like a hemisphere (halvkule). It is ignited in the centre.
   How large flame velocities are required in order to generate overpressures exceeding
   i) 0.3 barg and
   ii) 1 barg?

e) Assume that the maximum overpressure in the gas cloud is 1 barg.
   What is the distance from the cloud centre to the location where the overpressure has decayed to 0.02 barg? Provide a reason for your choice of calculation method.
   Give two examples of potential structural response (damage) from an overpressure of 0.02 barg.

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.

b) Calculate the regression rate for an ”infinite” pool in 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?

d) Can the regression rate calculated in 2b) be used for this pool? Provide an explanation of your answer..
What is the flame height??

e) Assume that the oil is collected in a quadratic dike with side length half of the equilibrium diameter and wall height sufficient to catch all the oil. What is the flame height in this situation?

f) Do you consider the use of this dike a good way of limiting the fire hazard? Give a brief explanation.

<u>Exercise 7</u>

a) Define a stoichiometric balance equation for butane in air.
Calculate the stoichiometric concentration for the gas-air mixture based on the stoichiometric equation.

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?

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?

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

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.

Exercise 8

A tank contains methane at a pressure of 120 bar (assumed constant) and a temperature of 20 degrees C. Gas leaks out of a hole with a diameter of 4 cm. Assume that the leaking methane gas expands adiabatically to atmospheric pressure. γ equals 1.3. The relationship between pressure and density in an adiabatic expansion is given by $p\rho^{-\gamma}$=constant. Assume that the leaking gas is shaped like a frustum (kuttet kjegle) with half top angle α=9.1 degrees (not radians!). Density of air is set to 1.2 kg/m^3. The universal gas constant R = 8314 J/(kmol*K).

a) Calculate the leak rate.

b) Calculate the density ρ and the temperature T of the gas after it has leaked out and expanded to atmospheric pressure.

c) Calculate the speed of sound in the expanded methane gas, and calculate the equivalent radius.

d) Calculate the distance from the leak location along the jet axis to where the gas concentration is 50% of the lower flammability limit for the methane-air mixture (use volume fraction in the calculation, not volume percent!)

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.

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.

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?

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..

d) The ability of a hot surface to ignite a gas-air mixture depends both on the temperature of the ignition source and its dimensions (size). Give two examples for a methane-air mixture..

Exercise 10.

a) A vessel of 10 m^3 is filled with methane gas at -10 grader C (below freezing). The pressure in the vessel is 200 bar. The universal gas constant R is 8314 J/(kmolK). The molecular weight M for methane is 16 kg/kmol. The specific heat capacity fraction, γ, is 1.3. Define the version of the equation of state most suitable for the gas in the vessel. Give a brief explanation.

b) Find the density ρ of the gas. Determine the mass m of methane gas in the vessel.

c) A pipe connection to the vessel is broken and a circular sharp-edged hole with diameter 1 cm is formed. Which formula would you use to calculate the initial leak rate from the hole? Explain.

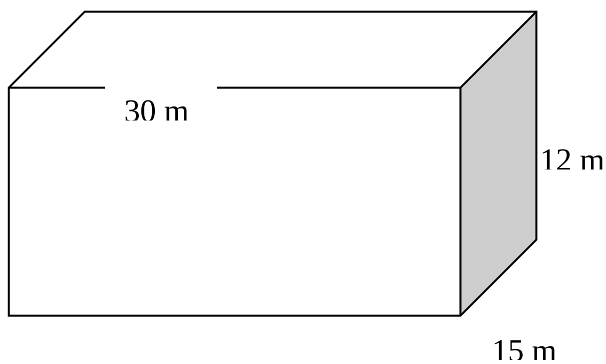
d) Calculate the initial leak rate (in kg/s) from the vessel.

e) Calculate the leak rate after 5 minutes..

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

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.

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.

c) Is it beneficial from the viewpoint of explosion safety to build long, narrow modules open at the ends (only)? Explain briefly.

Exercise 12.

A 2 m^3 vessel containing n-pentane (C_5H_{12}) leaks from a circular hole in the bottom of the tank . The hole diameter is 0,5 cm. The liquid head (height) is 1,2 m at the start of the leak. The ambient temperature (and initial liquid temperature) is 20 degrees C. The gas pressure (vapour pressure) in the tank is 0,57 barg. Assume that this pressure stays constant. The liquid density is 600 kg/m^3. The gravitational acceleration is g=9.81 m/s^2.

a) Calculate the initial leak rate.

b) The pentane is ignited and burns as a pool which is fed from a continuous release (assume constant leak rate). The regression rate is $1.3*10^{-4}$ m/s. Calculate the equilibrium diameter of the pool and the time to reach the equilibrium diameter.

c) Assume that the flames are not physically affected by the presence of the vessel. Calculate the flame height at quiescent (no wind) conditions.

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.

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

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!)

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.

b) Formulate a stoichiometric equation for ethylene in air. Calculate the stoichiometric concentration of the ethylene-air mixture by applying the stoichiometric equation..

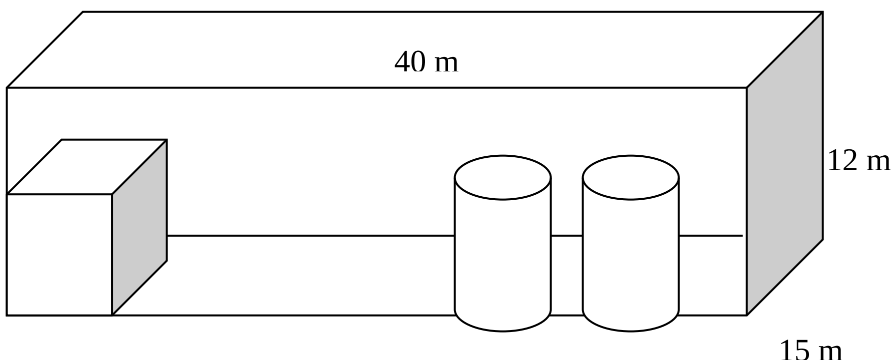
c) Find the minimum ignition energy (MIE) and ignition temperature (AIT) for ethylene. How do these parameters normally vary with increasing or decreasing molecular weight of the fuel? Is it likely that a spark from electrical equipment can ignite a stoichiometric ethylene-air mixture? Give a short explanation.

d) Find the maximum burning velocity for ethylene as well as methane in air. If you compare the burning velocity of ethylene with that of methane, which of the two gases do you think will give the highest overpressure in case of an explosion? Give a brief explanation.

e) Calculate upper and lower flammability limits (U_{25} and L_{25}) for ethylene in air. What are these limits at 100 degrees C?

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.



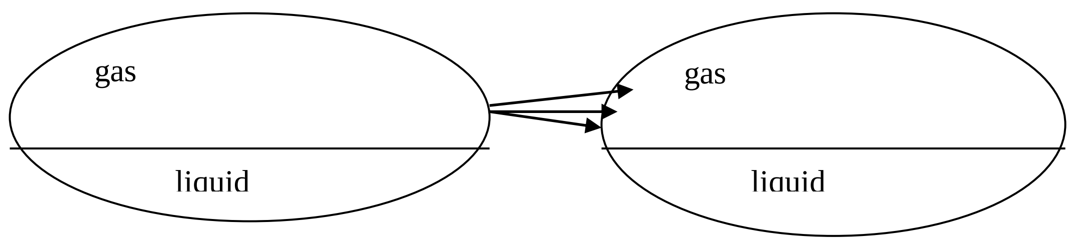
a) What is the volume of the gas cloud? Approximately how large a proportion of the cloud will contribute to overpressure generation in a possible explosion? Where would you locate the ignition point in order to generate as high an overpressure as possible? Give a brief explanation.
b) The gas cloud 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.
c) Perform the overpressure estimate from b) by using Harris & Wickens' modified TNT equivalence method.

d) Is there a difference between the results of b) and c)? If so, which result is most accurate? Give a short explanation.

e) Propose two specific measures which will reduce the overpressure in an explosion (at least one has to be related to layout). Explain briefly why the measures have the required effect.

Exercise 16

A trailer with two propane tanks is involved in a collision. A leak occurs in one of the tanks. The other tank capsizes such that the pressure relief valves no longer function. The ambient temperature is 20 degrees C, the overpressure in the tanks is 8.3 bar. At this state gaseous propane has a density of 18 kg/m^3 and liquid propane a density of 500 kg/m^3. It is assumed that the overpressure in the leaking tank is constant. $\gamma = 1.3$.



a) The propane leaks from a hole above the liquid surface, and the jet hits the other tank. The hole radius is 0.5 cm. What is the leak rate? Explain your choice of formula..

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 $\tan \alpha = 0.16$.

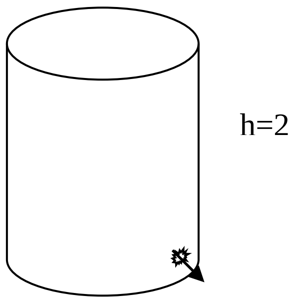
c) The gas ignites. What would the visible flame length and the maximum jet diameter have been if the jet had not hit the other tank?

d) The flame impacts on the other tank above the liquid level. The tank temperature increases. At for instance 80 degrees C the gas overpressure in the tank is 37.5 bar. What could happen with the steel wall of the tank as the temperature continues to increase, and what could the consequences be?

e) Would it have been better if the jet flame impacted on the other tank below the liquid level? Explain. What type of measures would you recommend to control the situation?

Exercise 17.

A butane tank of 2 m^3 leaks from a hole with diameter 1 cm. The hole is situated in the lower part of the tank, see figure below. The liquid height is 1,9 m at the start of the leak. The ambient temperature is 10 degrees C, the gas pressure in the tank is 1,5 bar and constant. The liquid density is 589 kg/m^3. The molecular weight of butane is 58 kg/kmol. The gravitational acceleration is g=9.81 m/s^2.



a) What is the regression rate in m/s for infinitely large pools when the heat of combustion ΔH_c = 45.8 MJ/kg, and the heat of vapourization ΔH_v = 0,37 MJ/kg? Assume for simplicity that the butane is at the boiling point.

b) How large is the initial leak rate?

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?

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

Exercise 18.

a) A cylindrical, vertical container of 1000 m3 contains stoichiometric propane-air mixture at atmospheric pressure. The gas is ignited in the cloud centre. What is the explosion overpressure when you assume that the container is infinitely strong?

If this gas-air cloud is ignited and burns in free space, what will be the volume of the burnt cloud?

b) How high flame velocities and what overpressure development do you expect when the burning cloud is neither confined nor congested? Discuss briefly.

c) Assume that the cylindrical gas-air cloud is confined by two horizontal decks, the distance between the decks being 10 m. How far from the cloud centre does the flame reach? If the maximum flame velocity is 100 m/s, what will the resulting explosion overpressure be? How do you determine this?

d) Can you provide two simple principles for equipment location in a module, such that the overpressure from an explosion is minimised? Give a brief explanation.

Exercise 19.

200 kg methane leaks into a module and forms a stoichiometric, uniform gas-air mixture which fills the entire module. The module is 60 m long, 15 m wide and 10 m high. It is fully open at one end (smallest wall). Equipment, piping etc. occupies 15% of the module volume. The density of methane can be set to 0.67 kg/m3.

a) What is the volume of the gas-air cloud? What is the percentage filling of the entire module?

b) Which combination of gas cloud location and ignition location results in the highest explosion overpressure? Explain why.

c) The gas explodes with an overpressure of 4 barg. Estimate the blast overpressure 80 m away from the cloud centre, by applying Harris and Wickens' modified TNT-method.

d) Calculate the overpressure for the case in c) by the Multi-Energy (ME)-method. Which method do you consider to be best of the TNT and the ME-methods, and why?

Exercise 20.

A 30 m^3 container is filled with a gas mixture consisting of 50% methane, 35% ethane and 15% propane (volume percent). The temperature inside the vessel is 20 degrees C. The pressure in the vessel is 10 bar. The universal gas constant R is 8314 J/(kmol*K). The specific heat capacity ratio, γ, is 1.3.

a) Provide lower and upper flammability limits as well as the stoichiometric gas concentration for each component in the mixture.

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

c) Calculate the average molecular weight M of the gas mixture. Calculate the density ρ and the mass m of gas in the container..

d) A leak occurs, from a circular hole with radius 0.5 cm. Calculate the initial leak rate (in kg/s) from the vessel. Provide a reason for the choice of formula.

e) The leak forms a jet like a frustum cone (avkuttet kjegle) with half top angle α of 9.1 degrees (not radians!). Calculate the equivalent radius r0 and the distance from the leak location to the lower flammability limit for the jet (the "length" of the jet). Assume that the gas expands isothermally to atmospheric pressure.

Exercise 21.

A tank containing 100m3 gasoline starts to leak. The leak rate is constant and equal to 3 kg/s till the tank is empty. The tank is placed on flat ground without any physical barriers. The molecular weight of the gasoline is 100 kg/kmole. The density is 870 kg/m^3. The heat of combustion is 43700 kJ/kg. The regression rate of an ”infinitely” large pool is $0.8*10^{-4}$ m/s. The density of gasoline vapour at the boiling point is 3.49 kg/m^3.

a) The pool is ignited immediately. Calculate the equilibrium diameter D_{eq} of the pool as well as the time t_{eq} to reach the equilibrium diameter.

b) How much gasoline burns in kg/s when the equilibrium diameter is reached?

c) Assume quiescent conditions (no wind) and calculate the flame height L at equilibrium pool diameter.

d) Predict the height over the pool at which smoke production starts.

e) How long does the leak last? Can you make any assessment of the duration of the fire?

Exercise 22.

A 5 m3 tank is filled with methane gas at 20 °C, which is also the ambient temperature. The pressure in the tank is 160 barg (overpressure). The universal gas constant R is 8314 J/(kmol*K). The molecular weight M of methane is 16 kg/kmol. The specific heat ratio, γ, is 1.3. Ambient pressure is 1 bar. The density of air can be taken to be 1.2 kg/m3.

a) Find the density ρ of the gas. Determine the mass of gas (m) in the tank. Which version of the equation of state do you use, and why?

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

c) Calculate the lower and upper flammability limits of methane in air.

d) A pipe connection to the vessel is broken and an approximately circular, sharp-edged hole of 3 cm diameter is generated. Which formula should be used to calculate the initial leak rate from the hole – and why? Calculate the initial leak rate (in kg/s) from the vessel.

e) What is the leak rate after 10 seconds?

f) Assume that the leaking gas expands isothermally (i.e. at constant temperature) to atmospheric pressure. Calculate the density of the expanded methane. Is the methane lighter or heavier than air?

g) Calculate the speed of sound in the expanded methane gas. Explain the term "equivalent radius", and calculate it based on the initial leak rate.

h) The leaking gas is shaped like a horizontal jet (a frustum - kuttet kjegle) with half top angle α=9.1 degrees (not radians!). How far is it from the hole to the location at the jet axis where the gas-air concentration has dropped to stoichiometric?

Exercise 23.

4000 kg of natural gas leaks out into a module on an offshore platform. The gas forms a stoichiometric, uniform mixture with air. The module is 40 m long, 20 m wide and 8 m high. It is open on one long side, otherwise closed, and gas-air mixture which flows out of the open module side remains as a homogeneous gas-air cloud outside the module, where there is no confinement or congestion. Equipment, pipework, cable trays, local rooms etc fill up 12% of available space inside the module. The density of natural gas at ambient temperature is 0.8 kg/m^3.

a) The natural gas consists of 80% methane, 12% ethane and 8% propane. What is the stoichiometric concentration in air of the gas mixture?

b) What is the total volume of the gas cloud, and how large (in %) is the fraction of the cloud inside the module?

c) The gas cloud explodes with a maximum overpressure of 4 barg. How large is the part of the gas cloud (in m3) which contributes to overpressure generation? Explain briefly.

d) Calculate the blast overpressure at the Living Quarter on the neighbouring platform (90 m away) by using the Multi-Energy method.

e) Calculate the duration of the pressure pulse, for the same explosion as above, for the same location.

Exercise 24.

A pipeline with inner diameter 30 cm transports methane. At a given location along the pipeline the overpressure is 70 barg, the temperature 20 degrees C and the pressure gradient dp/dx is 50 N/m3. Assume that the pipeline is cut off (guillotine break) at the given location, and that on the low pressure side of the break the pipeline is closed immediately.

a) Calculate the initial leak rate – and provide a reason why the chosen formula can be used (disregard the effect of the initial flow rate through the pipe).

b) What is the leak rate after 2 minutes, and how much gas has leaked out?

c) Assume that there is a weak wind in the direction of the leak. The gas is ignited some distance downwind from the leak. Describe qualitatively what type of fire situation(s) that will result.

d) Find minimum ignition energy (MIE) and auto ignition temperature (AIT) for methane in air. Is it likely that a spark from electrical equipment can ignite a stoichiometric methane-air mixture? Which parameter (AIT or MIE) is most relevant when you make this assessment – and why?

e) The leak is ignited. Calculate lift-off s and distance L from the leak to the visible flame tip immediately after the start of the leak.

Exercise 25.

Natural gas leaks from a hole in a pipe with a leak rate of 6 kg/s into a module on an offshore platform. The module is 30 m long, 12 m wide and 6 m high. It is open on both ends, otherwise closed. Equipment, structure, pipework, cable trays, local rooms etc fill up 8% of available space inside the module. The gas mixes with air and forms a stoichiometric, uniform gas-air cloud, which grows with time. The density of natural gas at normal temperature and pressure (20 degrees C and 1 atm) can be taken to be 0.9 kg/m^3.

a) The natural gas consists of 80% methane, 12% ethane and 8% propane. What is the stoichiometric concentration in air of the gas mixture?

b) Calculate the lower and upper flammability limits of the gas-air mixture.

c) How many seconds will it take for the stoichiometric gas-air cloud to fill the entire module?

d) When the gas cloud has filled the module, it explodes with a maximum overpressure of 5 barg. Calculate the blast overpressure at the Living Quarter on the neighbouring platform (100 m away) by using the Multi-Energy method.

Exercise 26.

A 1 m^3 vessel is filled with ethane gas at 20 ^oC. The pressure in the vessel is 50 bar. The universal gas constant R equals 8314 J/(kmol*K). The molecular weight M of ethane is 30 kg/kmol. The specific heat ratio, γ, is 1.3.

a) Generate a stoichiometric balance equation for ethane (C_2H_6) in air. Calculate the stoichiometric concentration of ethane in air based on the stoichiometric equation.

b) Find the density ρ of the gas. Calculate the mass m of gas in the vessel.

c) A pipe connection to the vessel is broken and an approximately circular, sharp-edged hole of 1 cm diameter is generated. Calculate the initial leak rate (in kg/s) from the vessel.

d) What is the density of the expanded jet when you assume that the leaking gas expands isothermally as its pressure drops to ambient?

e) Also calculate the density of the expanded gas based on the alternative assumption: that the gas expands adiabatically (which means that $p\rho^{-\gamma}$ = constant, i.e. it is the same inside as well as outside the vessel).

f) Calculate the equivalent radius for the leak (jet) based on the initial leak rate (assume isothermal expansion)

<u>Exercise 27.</u>

A pipeline with inner diameter 90 cm transports methane. At a given location the pressure inside the pipe is 100 bar, the temperature 10 degrees C and the pressure gradient dp/dx is 100 N/m3. Assume that the pipeline is cut (sheared) at the given location, and that the low-pressure part of the pipe is sealed off immediately.

a) Calculate the initial leak rate from the pipe.

b) What is the leak rate after 2 minutes, and how much gas has leaked out?

c) The leak is ignited. Calculate lift-off s and distance L from the leak to the visible flame tip immediately after the start of the leak (assume that the leak is oriented vertically).

<u>Exercise 28.</u>

An n-butane tank of 2 m^3 leaks from a circular hole with diameter 1 cm. The hole is at the bottom of the tank. The liquid head (væskehøyden) is 1 m at the start of the leak. The ambient temperature (and the liquid temperature) is -0.5 degrees C, i.e. the vapour pressure in the tank is 1 bar. It can be assumed to be constant. The liquid density is 589 kg/m3. The molecular weight of butane is 58 kg/kmol. The gravitational constant is g=9.81 m/s2. The heat of combustion of butane is ΔH_c = 45.8 MJ/kg, the heat of vapourization is ΔH_v = 0,37 MJ/kg and the boiling point is -0.5 degrees C.

a) How large is the initial leak rate?

b) How large is the regression rate in m/s for infinitely large pools?

c) The butane is ignited and burns as a pool which is fed from a continuous release. How large is the pool's equilibrium diameter, and at what time is the equilibrium diameter reached?

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

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

Exercise 1.

A 1 m^3 vessel is filled with methane gas at 0 ^oC. The pressure in the vessel is 45 bar. The universal gas constant R equals 8314 J/(kmolK). The molecular weight M of methane is 16 kg/kmol. The fraction between specific heat capacities, γ, is 1.3.

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

Answer: See Kuchta

CH4+2(O2+3.76N2) → CO2+2H2O+7.52N2

1/(1+2+7.52)=0.095

b) Write up the version of the equation of state that fits best for the conditions defined above. Provide a reason for your choice.

Answer: See Kuchta, calculate compressibility factor Z (~0.8 - 0.9) – which means you have to use the compressible version

c) Find the density ρ of the gas. Calculate the mass m of gas in the vessel.

Hint: Use eq. of state to calculate density: ρ=PM/(ZRT). M=ρV
Using Z=0.9 gives density = 35.2 kg/m3 and m = 35.2 kg.

d) A pipe connection to the vessel is broken and an approximately circular, sharp-edged hole of 2 cm diameter is generated. Which formula should be used to calculate the initial leak rate from the hole – and why? Calculate the initial leak rate (in kg/s) from the vessel.

Answer: pressure is very high (more than 2 bar), so leak is sonic. Use formula 4.2 in fire calculation handbook

$$m_{0g} = A \bullet C_D \sqrt{\gamma \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}} \bullet \frac{p_2}{\sqrt{\frac{TR}{M}}}$$

A = 0.000314 m2
Square root containing gamma is 0.67
P2 = 45*10E5 Pascal (4 500 000 Pa) (absolute pressure)
Sqrt(TR/M)=377
M0g=1.55 kg/s

e) Calculate the equivalent radius for the leak (jet).

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

$c=429{,}4$ m/s $r0=0.04$m

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 $m_g= m_{0g} \exp(-m_{0g} /w*t)$ $t=16$ s

<u>Exercise 2</u>

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 graph for duration given in Multi-energy method. Check answer on web calculator.

d) How large (i.e. how many m^3) does the gas cloud have to be in order to reduce the overpressure at the neighbouring platform by a factor of 2?

Answer: Read off R- for reduced pressure (use same curve). Calculate new E that corresponds to this R-. Use E=3.5V (MJ) to calculate new V.

e) Explain the difference between side-on and reflected overpressure. Which one of these is predicted by the Multi-Energy Method?

Answer: see chapter 2.18 in GEH. ME method predicts side-on pressure.

f) A building is hit head-on by a blast wave with side-on pressure 0.1 barg. Prove a simple estimate of the overpressure at 1) the front of the building, 2) at the side and 3) at the back.

Answer: see fig. 7.13 in GEH.

<u>Exercise 3.</u>

A butane tank of 5 m^3 leaks from a circular hole with diameter 4 cm. The hole is at the bottom of the tank. The liquid head (væskehøyden) is 3 m at the start of the leak. The ambient temperature is 10 degrees C, i.e. the vapour pressure in the tank is 1,5 bar. It can be assumed to be constant. The liquid density is 589 kg/m^3. The molecular weight of butane is 58 kg/kmol. The gravitational constant is g=9.81 m/s^2.

a) How large is the regression rate in m/s for infinitely large pools when the heat of combustion is ΔH_c = 45.8 MJ/kg, and the heat of vapourization is ΔH_v = 0,37 MJ/kg? Assume for simplicity that the butane is at the boiling point.

Answer: use formula in FCH. Note that cp is not needed!
V_f = 0.000157 m/s

b) How large is the initial leak rate?

Answer: use formula $m_l = C_D A \rho \sqrt{2\left(\frac{p_1 - p_2}{\rho}\right) + 2\Delta Z g}$

M_i=6,94 kg/s

c) The butane is ignited and burns as a pool which is fed from a continuous release. How large is the pool's equilibrium diameter, and at what time is the equilibrium diameter reached?

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

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

Exercise 5.

A pipeline with inner diameter 25 cm transports natural gas consisting of 85% methane, 11% ethane og 4 % propane. Somewhere along the pipeline the pressure is 40 bar, the temperature 20 degrees C and the pressure gradient dp/dx 30 N/m^3. Assume that the pipe suffers a guillotine break at the given location.

a) What is the leak rate of the high pressure part of the pipeline after one minute?
How much gas has been released?

Answer: Use HFC eq. 4.4: q=26.07 kg/s and Q = 2802.25 kg

b) What is the average molecular weight of the gas mixture?
What is the stoichiometric concentration with air of this gas mixture?
Calculate the lower and upper flammability limits of the mixture.

Answer: M = 18.66 kg/kmol
*Cst=8.4 %; LFL = 0.55 Cst = 4.62%; UFL = 4.8 Cst**0.5= 13.91%*

c) Assume that the amount of gas that has leaked out during the first minute has formed a stoichiometric gas-air mixture. What is the volume of this gas-air cloud?

Answer: Find first rho = pM/RT=0.766 kg/m3
Vgas = m/rho= 2802.25 kg/0.766 kg/m3 = 3658 m3
Vcloud = Vgas/Cst= 3658 m3/0.084 = 43551 m3

d) The gas cloud is shaped like a hemisphere (halvkule). It is ignited in the centre.
How large flame velocities are required in order to generate overpressures exceeding
i) 0.3 barg and
ii) 1 barg?

Answer: From Fig. 5.5 in Gas Explosion Handbook:
i) 150 m/s
ii) 300 m/s

e) Assume that the maximum overpressure in the gas cloud is 1 barg.
What is the distance from the cloud centre to the location where the overpressure has decayed to 0.02 barg? Provide a reason for your choice of calculation method.

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

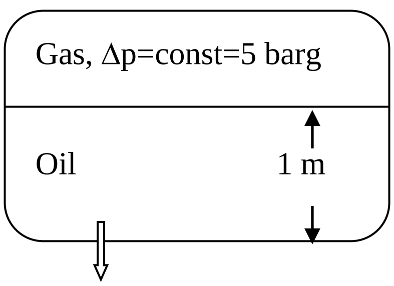
*(E/p0)**1/3 = 115.1*

*R= Ř*115.1=1151*

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

<u>Exercise 6.</u>

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

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: $D_{eq} = 2\left[\frac{v_L}{\pi v_f}\right]^{\frac{1}{2}} = 2\left[\frac{22.22/800}{\pi \cdot 1.185 \cdot 10^{-4} m/s}\right]^{\frac{1}{2}} = 17.28m$

$$t_{eq} = \frac{0.564 D_{eq}}{\left[g v_f D_{eq}\right]^{\frac{1}{3}}} = 36.1s$$

d) Can the regression rate calculated in 2b) be used for this pool? Provide an explanation of your answer..
What is the flame height??

Answer: Yes, because it is more than approx. 1-3 m in diameter(see eq.(7.19) and footnote below

Note that $m_f'' = \rho v_f$

$$L = 42D\left[\frac{m_f''}{\left(\rho_0\sqrt{gD}\right)}\right]^{0.61} = 42 \cdot 17.28\left[\frac{0.095}{\left(1.2\sqrt{9.81 \cdot 17.28}\right)}\right]^{0.61} = 32.3m$$

e) Assume that the oil is collected in a quadratic dike with side length half of the equilibrium diameter and wall height sufficient to catch all the oil. What is the flame height in this situation?

Answer: B=0.5D=8.64m

$$L = 42D\left[\frac{m_f''}{\left(\rho_0\sqrt{gD}\right)}\right]^{0.61} = 42 \cdot 8.64\left[\frac{0.095}{\left(1.2\sqrt{9.81 \cdot 8.64}\right)}\right]^{0.61} = 19.9m$$

f) Do you consider the use of this dike a good way of limiting the fire hazard? Give a brief explanation.

Answer: When this dike is used the flame is smaller but the fire lasts longer. This would normally be a good measure, but it depends on whether the original flame size would be a problem or not.

Exercise 7

a) Define a stoichiometric balance equation for butane in air.
Calculate the stoichiometric concentration for the gas-air mixture based on the stoichiometric equation.

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.

Exercise 8

A tank contains methane at a pressure of 120 bar (assumed constant) and a temperature of 20 degrees C. Gas leaks out of a hole with a diameter of 4 cm. Assume that the leaking methane gas expands adiabatically to atmospheric pressure. γ equals 1.3. The relationship between pressure and density in an adiabatic expansion is given by $p\rho^{-\gamma}$=constant. Assume that the leaking gas is shaped like a frustum (kuttet kjegle) with half top angle α=9.1 degrees (not radians!). Density of air is set to 1.2 kg/m^3. The universal gas constant R = 8314 J/(kmol*K).

a) Calculate the leak rate.

Answer: $m_{0g} = AC_D\sqrt{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}\frac{p_2}{\sqrt{\frac{TR}{M}}} = 16kg/s$

b) Calculate the density ρ and the temperature T of the gas after it has leaked out and expanded to atmospheric pressure.

Answer: Adiabatic expansion means that $\left(p\rho^{-\gamma}\right)_{before\,expansion} = \left(p\rho^{-\gamma}\right)_{after\,expansion}$
Before expansion = i(nner), After expansion = o(uter)

Check if real or ideal eq. of state applies.
p/pc=120/45.8=2.62 and T/Tc=293/191.1=1.53 which gives Z=0.8, i.e. use real eq. of state.

$$p_i = Z\frac{\rho_i RT_i}{M} \Rightarrow \rho_i = \frac{p_i M}{ZRT_i} = 98.5kg/m^3$$

$$\left(p\rho^{-\gamma}\right)_i = \left(p\rho^{-\gamma}\right)_o \Rightarrow \rho_o^{-\gamma} = \rho_i^{-\gamma}\cdot\frac{p_i}{p_o} = 120\rho_i^{-\gamma} \Rightarrow \rho_o = \left(120\rho_i^{-\gamma}\right)^{-\frac{1}{\gamma}} = \left(120*98.5^{-1.3}\right)^{-\frac{1}{1.3}} = 2.48kg/m^3$$

$$T_o = \frac{p_0 M}{R\rho_o} = 77.6K$$

c) Calculate the speed of sound in the expanded methane gas, and calculate the equivalent radius.

Answer: $c = \sqrt{\frac{\gamma RT}{M}} = \sqrt{\frac{1.3\cdot 8314\cdot 77.6}{16}} = 229m/s$

$$r_0 = \sqrt{q/\pi\cdot c\cdot\rho_0} = \sqrt{16/\pi\cdot 229\cdot 248} = 0.095m$$

d) Calculate the distance from the leak location along the jet axis to where the gas concentration is 50% of the lower flammability limit for the methane-air mixture (use volume fraction in the calculation, not volume percent!)

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.

Fig 45 shows that the MIE is lowest at approx 0.9 times stoichiometric concentration. The same figure shows that at 1.2 times stoich the MIE is just above 1 mJ.

d) The ability of a hot surface to ignite a gas-air mixture depends both on the temperature of the ignition source and its dimensions (size). Give two examples for a methane-air mixture..

Answer: Tab. 16 in Kuchta shows that in a heated glass vessel of 4-5 cm diameter the ignition temperature is 630 degrees C, and if the ignition source is a Ni-chrome wire the source temperature at ignition is 1220 degrees C.

Exercise 10.

a) A vessel of 10 m^3 is filled with methane gas at -10 grader C (below freezing). The pressure in the vessel is 200 bar. The universal gas constant R is 8314 J/(kmolK). The molecular weight M for methane is 16 kg/kmol. The specific heat capacity fraction, γ, is 1.3. Define the version of the equation of state most suitable for the gas in the vessel. Give a brief explanation.

Answer: Reduced pressure: P/Pc=200/45.8=4.4
Red temp: T/Tc=263/191=1.38
Fig 1 in Kuchta gives a compressibility factor of approx. 0.7, which means that one should use the real gas law:

$P=Z\rho RT/M$

b) Find the density ρ of the gas. Determine the mass m of methane gas in the vessel.

Answer: $\rho=PM/(ZRT)=200*10^5 Pa*16 kg/kmol/(0.7*8314 J/kmolK*263K)=209 kg/m3$
$M=\rho V=209*10 kg=2090$ *kg*

c) A pipe connection to the vessel is broken and a circular sharp-edged hole with diameter 1 cm is formed. Which formula would you use to calculate the initial leak rate from the hole? Explain.

Answer : pressure over 2 bar means sonic leak, i.e. (eq 4.2 Fire Calc Handbook)

$$m_{0g} = A \bullet C_D \sqrt{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \bullet \frac{p_2}{\sqrt{\frac{TR}{M}}}$$

d) Calculate the initial leak rate (in kg/s) from the vessel.

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

e) Calculate the leak rate after 5 minutes.

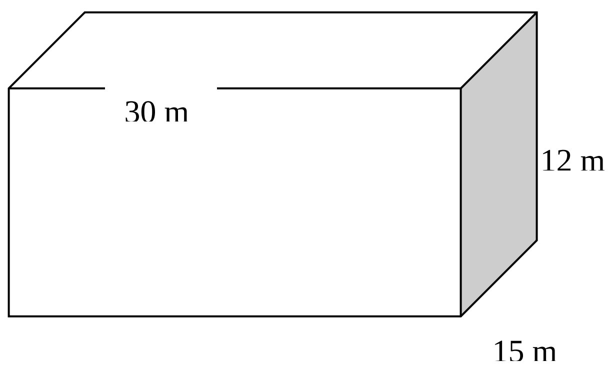
Answer : $m_g = m_{0g} \exp(-m_{0g}/w*t) = 1.4$ kg/s

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=Vmethaneρ=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.

*Answer: R- =R/(E/P0)$^{1/3}$ =150m/(3.5*4860MJ/101325Pa)$^{1/3}$ =150m/55m=2.7*
Read off from fig 7.6 (approx. explosion strength is 9) in GEH, gives a far field blast at 150 m of approx 0.1 barg.
*T+- in the same figure can be read off as approx. 0.4 for an explosion of strength 9 and R- of 2.7, this results in a positive phase duration of t+=0.4*55m/340m/s=0.065s*

c) Is it beneficial from the viewpoint of explosion safety to build long, narrow modules open at the ends (only)? Explain briefly.

Answer: No, since the flame path is potentially very long and the possibility for significant flame acceleration therefore exists

Exercise 12.

A 2 m^3 vessel containing n-pentane (C_5H_{12}) leaks from a circular hole in the bottom of the tank . The hole diameter is 0,5 cm. The liquid head (height) is 1,2 m at the start of the leak. The ambient temperature (and initial liquid temperature) is 20 degrees C. The gas pressure (vapour pressure) in the tank is 0,57 barg. Assume that this pressure stays constant. The liquid density is 600 kg/m^3. The gravitational acceleration is g=9.81 m/s^2.

a) Calculate the initial leak rate.

Answer: the Bernoulli equation gives

$$m_l = C_D A\rho\sqrt{2\left(\frac{p_1-p_2}{\rho}\right)+2\Delta Zg} = 0.62*600*1.96*10^{-5}\sqrt{2\left(\frac{1{,}57-1}{600}\right)*10^5+2*1.2*9.81} =$$

*0.107 kg/s=1.77*10^{-4} m^3/s*

b) The pentane is ignited and burns as a pool which is fed from a continuous release (assume constant leak rate). The regression rate is 1.3*10^{-4} m/s. Calculate the equilibrium diameter of the pool and the time to reach the equilibrium?

Answer: $D_{eq} = 2(v_l/\pi v_f)^{1/2}$ *= 1.32m,* t_{eq}*=6.25s*

c) Assume that the flames are not physically affected by the presence of the vessel. Calculate the flame height at quiescent (no wind) conditions.

Answer: $m_f=\rho v_f$*=600*1.3*10^{-4} kg/s/m^2=0.078 kg/s/m^2*

$$L = 42D\left[\frac{m''_f}{\rho_0\sqrt{gD}}\right]^{0.61} = 4.78m$$

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): $p=\rho RT/M \Rightarrow p=\rho_{10}R*283/30=1.205*R*293/30 \Rightarrow \rho_{10} = 1.205*293/283=1.25\ kg/m^3$

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

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)*

b) Formulate a stoichiometric equation for ethylene in air. Calculate the stoichiometric concentration of the ethylene-air mixture by applying the stoichiometric equation..

.

Answer: $C_2H_4 + 3(O_2+3.773N_2) = 2CO_2 + 2H_2O + 11.319N_2$

$$C_{st} = \frac{100\%}{1+3+11.319} = 6.5\%$$

I may have used a wrong number of molecules for N2, but the principle is the same

c) Find the minimum ignition energy (MIE) and ignition temperature (AIT) for ethylene. How do these parameters normally vary with increasing or decreasing molecular weight of the fuel? Is it likely that a spark from electrical equipment can ignite a stoichiometric ethylene-air mixture? Give a short explanation.

.

Answer: Tab. 7 and 8 in Kuchta: MIE=0.07 mJ and AIT = 490 deg C. MIE does not vary much, AIT decreases with increasing molecular weight.. Electrical sparks have normally significantly higher energy than MIE for hydrocarbons, so ignition is likely

d) Find the maximum burning velocity for ethylene as well as methane in air. If you compare the burning velocity of ethylene with that of methane, which of the two gases do you think will give the highest overpressure in case of an explosion? Give a brief explanation.

Answer: Ethylene: 74.5 cm/s and methane 45 cm/s (table 17 in Kuchta). Higher burning velocity indicates higher flame velocity i.e. higher overpressure

Note that in the first pages of Kuchta there is a list of illustrations – using this can save time when you look for a particular type of information

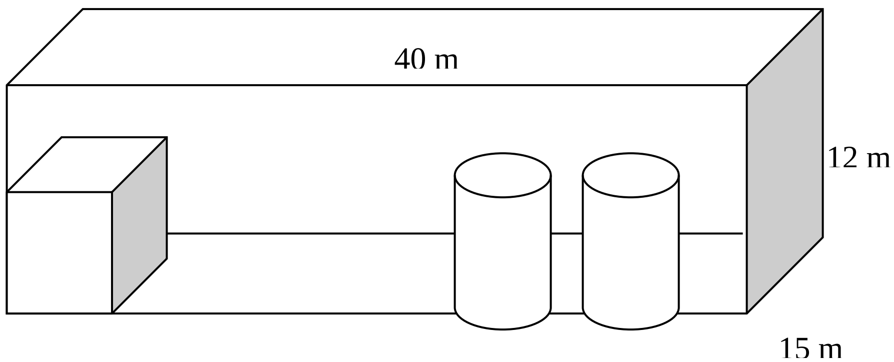
e) Calculate upper and lower flammability limits (U_{25} and L_{25}) for ethylene in air. What are these limits at 100 degrees C?

$$\text{Answer: } U_{25} = 4.8C_{st}^{1/2} = 12.3\%,\;\; L_{25} = 0.55C_{st} = 3.6\%$$

$$U_{100} = U_{25}(1+0.000721 * 75) = 12.9\% \;\; \text{and} \;\; L_{100} = L_{25}(1-0.000721 * 75) = 3.4\%$$

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

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.

$$(\mathrm{E}/\mathrm{p}_0)^{1/3} = (3.5\mathrm{MJ}/\mathrm{m}^3 \bullet 5760\mathrm{m}^3 / 1 \bullet 10^5\,\mathrm{N}/\mathrm{m}^2)^{1/3} = 58.6$$

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

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

c) Perform the overpressure estimate from b) by using Harris & Wickens' modified TNT equivalence method.

Answer: $W_{TNT} = 0.16V = 922\ kg$
$R^* = R/W^{1/3} = 10.3$, *from fig. 7.4 i GEH:* $p_{side\text{-}on} = 0.15\ barg$

d) Is there a difference between the results of b) and c)? If so, which result is most accurate? Give a short explanation.

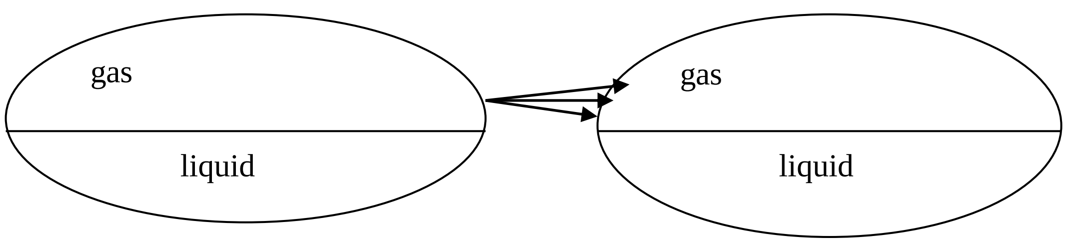
Answer: There was no difference in this case. Normally the ME-method is best, in particular for low overpressure explosions. For strong explosions the difference is less.

e) Propose two specific measures which will reduce the overpressure in an explosion (at least one has to be related to layout). Explain briefly why the measures have the required effect.

Answer: Move tanks and room into the module, this gives less blockage of the open wall. In addition open more walls and decks, this also provides better ventilation of gas and also better explosion venting.

Exercise 16

A trailer with two propane tanks is involved in a collision. A leak occurs in one of the tanks. The other tank capsizes such that the pressure relief valves no longer function. The ambient temperature is 20 degrees C, the overpressure in the tanks is 8.3 bar. At this state gaseous propane has a density of 18 kg/m^3 and liquid propane a density of 500 kg/m^3. It is assumed that the overpressure in the leaking tank is constant. $\gamma = 1.3$.



a) The propane leaks from a hole above the liquid surface, and the jet hits the other tank. The hole radius is 0.5 cm. What is the leak rate? Explain your choice of formula..

Answer: Overpressure over 2 bar means sonic leak, use eq. (4.2) in FCH. Remember use absolute, not overpressure.

$$m_{0g} = AC_D\sqrt{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}\frac{p_2}{\sqrt{\frac{TR}{M}}} = 7.85\cdot10^{-5}m^2\cdot0.62\sqrt{0.4452}\cdot\frac{9.3\cdot10^5\,Pa}{\sqrt{\frac{293K\cdot8314J/kgK}{44kg/kmol}}} = 0.13kg/s$$

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 α = 0.16

Answer: use eq. 5.1 and 5.2 in FCH.

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

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}~0.2 and T/T_{cr}~0.74 which gives Z~0.8.

*This results in ρ_0 = 1/9.3*0.8*18kg/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: $r_0 = \sqrt{0.13/(\pi\cdot 268\cdot 1.55)} = 1cm$

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

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:

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

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

$s = \frac{6.4\pi D_e u_e}{4u_a} = 4\pi D_e$ 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

d) The flame impacts on the other tank above the liquid level. The tank temperature increases. At for instance 80 degrees C the gas overpressure in the tank is 37.5 bar. What could happen with the steel wall of the tank as the temperature continues to increase, and what could the consequences be?

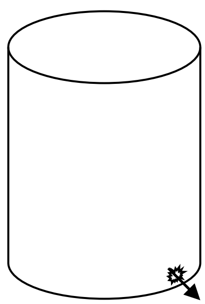
Answer: The pressure increases and the steel weakens. Therefore there possibility that the steel tank ruptures and results in a BLEVE is increasing..

e) Would it have been better if the jet flame impacted on the other tank below the liquid level? Explain. What type of measures would you recommend to control the situation?

Answer: Yes, because the liquid has higher heat capacity than the gas. Therefore the temperature will remain lower for a longer period. Cooling of tanks and flames by use of water is good.

Exercise 17.

A butane tank of 2 m^3 leaks from a hole with diameter 1 cm. The hole is situated in the lower part of the tank, see figure below. The liquid height is 1,9 m at the start of the leak. The ambient temperature is 10 degrees C, the gas pressure in the tank is 1,5 bar and constant. The liquid density is 589 kg/m^3. The molecular weight of butane is 58 kg/kmol. The gravitational acceleration is $g=9.81\ m/s^2$.



h=2

a) What is the regression rate in m/s for infinitely large pools when the heat of combustion ΔH_c = 45.8 MJ/kg, and the heat of vapourization ΔH_v = 0,37 MJ/kg? Assume for simplicity that the butane is at the boiling point.

Answer: Eq. 7.19 in FCH, T_b set equal to T_0.

$$v_{f\infty} = 1.27 \cdot 10^{-6}\left[\frac{\Delta H_c}{\Delta H_v + c_p\left(T_b - T_0\right)}\right] = 1.27 \cdot 10^{-6}\left[\frac{45.8 \cdot 10^6\ J/kg}{0.37 \cdot 10^6\ J/kg + 0}\right] = 1.57 \cdot 10^{-4}\ m/s$$

b) How large is the initial leak rate?

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

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

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

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

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.*

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

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

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

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