Loughborough University

22CGB001

Process Design and Safety

Semester 1 2022/23 | In-Person Exam paper

This examination is to take place in-person at a central University venue under exam conditions. The standard length of time for this paper is **2 hours**.

You will not be able to leave the exam hall for the first 30 or final 15 minutes of your exam. Your invigilator will collect your exam paper when you have finished.

Help during the exam

Invigilators are not able to answer queries about the content of your exam paper. Instead, please make a note of your query in your answer script to be considered during the marking process.

If you feel unwell, please raise your hand so that an invigilator can assist you.

You may use a calculator for this exam. It must comply with the University's Calculator Policy for In-Person exams, in particular that it must not be able to transmit or receive information (e.g. mobile devices and smart watches are **not** allowed).

Answer **TWO** questions – **ONE** question from Section A and **ONE** question from Section B.

Each question carries 25 marks.

Candidates should show full working for calculations and derivations.

SECTION A: Attempt ONE question

1. A leak of 0.1 kg hr^{-1} develops on a hydrogen sulphide line within a partially confined room (4 m x 4 m x 2 m), resulting in the formation of a toxic atmosphere.

   (a) Assuming a typical air change rate of 10 hr^{-1}, estimate the maximum accumulation (concentration) of H_2S in ppmv in the room. Clearly state any assumptions that you have made. [6 marks]

   (b) Predict the likelihood of death for a person who remains in the room for 1 hour. Compare your result to the expected graded response for hydrogen sulphide exposure. The probit table is provided in Table Q1 and the probit equation for hydrogen sulphide deaths is:

   $$Y = -31.42 + 3.008 \ln(C^{1.43} t)$$

   [4 marks]

   (c) After noticing the leak, an operator attempts to reroute the flow of hydrogen sulphide through a spare service line but is unaware that this line has already been connected to an 8 barg instrument air supply. This causes the back-flow of instrument air into the hydrogen sulphide storage tank, followed by ignition and explosion. At the time of the incident, the hydrogen sulphide tank contained 50 kg of H_2S at 5 barg and 10°C. The aim in this question is to calculate the maximum pressure which might be generated as a result of the explosion, if the explosion takes place at the earliest possible opportunity (with the minimum amount of air having entered the tank).

   (i) Given a lower and upper flammability limit of H_2S in air of 4.5 vol% and 45.5 vol%, respectively, determine the **minimum** amount of oxygen and nitrogen (in mols) that would have been present during the explosion. You may assume that air consists of 21 mol% oxygen and 79 mol% nitrogen. [4 marks]

   Hint: Consider at which flammability limit the amount of air in the system will be lower.

   (ii) Assuming that the reaction goes to completion (in terms of the limiting reactant), calculate the molar composition of the mixture before and after the explosion.

   [5 marks]

Continued/…

Q1 Continued/…

(iii) Calculate the heat released during the reaction, and resulting temperature increase of the reaction mixture. The heat of reaction for the complete combustion of hydrogen sulphide is 0.519 MJ mol^{-1}, and the average heat capacity of the product mixture is 33 J mol^{-1} K^{-1}. [4 marks]

(iv) Assuming ideal gas behaviour, determine the maximum pressure in the system during the explosion. [2 marks]

<u>Relevant equations:</u>

Concentration of gas in an enclosure

$$c = \frac{\dot{V}_G}{(\dot{V}_A + \dot{V}_G)}\left(1 - exp\left[-\frac{\dot{V}_G}{V}t\right]\right)$$

Where $\dot{V}_G$ and $\dot{V}_A$ are volumetric flow rate of gas and air into the enclosure, respectively, V is the enclosure volume and *t* is the duration of the leak

<u>Data</u>
Universal gas constant, R_u = 8.314 J mol^{-1} K^{-1}
Molecular weight of H_2S, M_{H2S} = 34.1 g mol^{-1}

Table Q1: Probit table

%	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	-	2.67	2.95	3.12	3.25	3.36	3.45	3.52	3.59	3.66
10	3.72	3.77	3.82	3.87	3.92	3.96	4.01	4.05	4.08	4.12
20	4.16	4.19	4.23	4.26	4.29	4.33	4.36	4.39	4.42	4.45
30	4.48	4.50	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.80	4.82	4.85	4.87	4.90	4.92	4.95	4.97
50	5.00	5.03	5.05	5.08	5.10	5.13	5.15	5.18	5.20	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.50
70	5.52	5.55	5.58	5.61	5.64	5.67	5.71	5.74	5.77	5.81
80	5.84	5.88	5.92	5.95	5.99	6.04	6.08	6.13	6.18	6.23
90	6.28	6.34	6.41	6.48	6.55	6.64	6.75	6.88	7.05	7.33

2. You have been asked to review the blowdown system for vessel V1 shown in Figure Q2. Methane gas enters through XV1 and is treated in the vessel before leaving through XV2. During an emergency, the vessel is automatically isolated by closing XV1 and XV2, and XV3 is opened to safely release the process inventory to the flare. The maximum operating pressure and temperature for the vessel are 60 barg and 25°C, respectively.

(a) Explain how blowdown of the vessel can be used to prevent further escalation of the incident. [4 marks]

(b) The maximum blowdown rate from the vessel to the flare system is restricted by a sharp edge orifice (C_d = 0.61) with an internal diameter of 5 mm. Methane has a heat capacity ratio, γ, of 1.32, internal heat of combustion, ΔH_C, of 55 MJ kg^{-1} and molecular weight of 0.016 kg mol^{-1}. You may assume that the back-pressure from the flare system is negligible (operates at atmospheric pressure).

(i) Determine whether this flow will be critical. [2 marks]

(ii) Calculate the maximum mass release rate and the associated heat flow rate when the gas is being flared. [6 marks]

(c) Next, you need to calculate the maximum capacity of the existing flare system. The flare stack is 30 m high and situated in an exclusion zone with a diameter of 60 m. It is assumed that the maximum angle of tilt of the flame in any direction will not exceed 45° from the vertical. The maximum incident thermal radiation, I, close to ground outside the exclusion zone must not exceed 1.5 kW m^2. The atmospheric transmissivity, τ, can be assumed to be 1.0, and the fraction of heat radiated, F_r, is 0.3.

(i) With the help of a clearly labelled diagram, show that the incident irradiation at the edge of the exclusion zone can be calculated from the following equation:

$$I = 75\frac{Q_c}{\pi}(1800 + 4.5(\sin 45)^2 Q_C^{0.8})^{-1}$$

Where Q_C is the heat release rate by combustion in MW.

Hint: sin(45°) = cos(45°) [10 marks]

(ii) Using trial and error, calculate the maximum permissible heat release rate. Comment on the adequacy of the current blowdown system design. [3 marks]

Continued/…

Q2 Continued/…

Relevant equations:

Critical pressure ratio:

$$\frac{P_c}{P_1} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}}$$

Where P_1 and P_c are the absolute pressure upstream of the orifice and critical pressure in N m^{-2}, respectively.

Jet fire length, L_F, in m: $L_F = 3Q_C^{0.4}$,

where Q_C is the heat release rate by combustion in MW.

Incident thermal radiation, I, in kW m^{-2}: $I = 1000\frac{\tau F_r Q_c}{4\pi S^2}$

Where S is the distance between the centre of the flame and the location of interest

Subcritical gas release: $\dot{m} = C_d A\rho\sqrt{2\left(\frac{P_1-P_2}{\rho}\right)}$

Supercritical gas release: $\dot{m} = C_d A P_1\sqrt{\frac{\gamma M}{R_u T_1 z}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$

Where all symbols have the usual meanings

Relevant data:

Universal gas constant, R_u = 8.314 J mol^{-1} K^{-1}

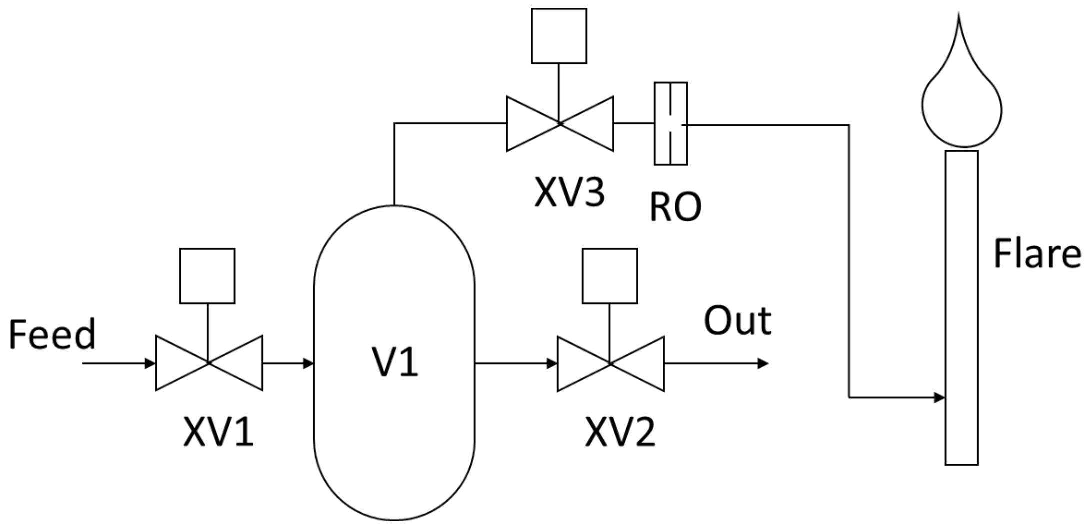


Figure Q2

SECTION B: Attempt ONE question

3. Figure Q3.1 shows a protective system that prevents liquid from entering the suction inlet of a compressor. The feed mixture is first passed through a separator to remove liquid from the gas. The gas stream then passes through a suction Knock Out drum (KO drum) to further remove any entrained liquid before entering the compressor. Level control systems are used to maintain safe liquid levels in the separator and KO drum. The system is protected by an interlock system to shut off the feed flow in case of high liquid level in the separator or KO drum.

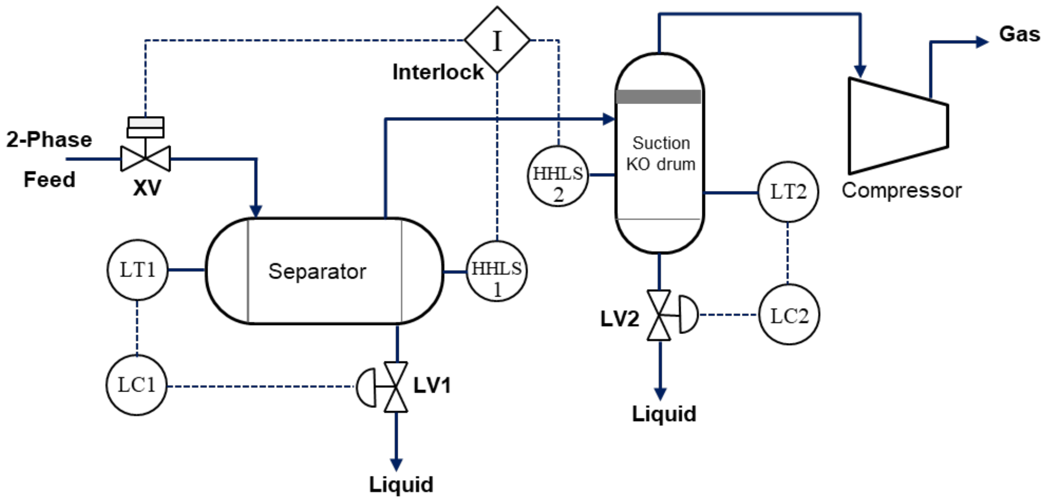


Figure Q3.1

(a) Draw the fault tree of the event "Liquid enters compressor". [9 marks]

(b) Determine the probability of the event "Liquid enters compressor".

The following data are available:

Separator Level control system failure rate (overall: LT1, LC1, LV1): 0.5 occ/yr

KO drum Level control system failure rate (overall: LT2, LC2, LV2): 0.4 occ/yr

High liquid level interlock system 1 failure rate (overall: HHLS1, XV1): 0.3 occ/yr

High liquid level interlock system 2 failure rate (overall: HHLS2, XV2): 0.2 occ/yr

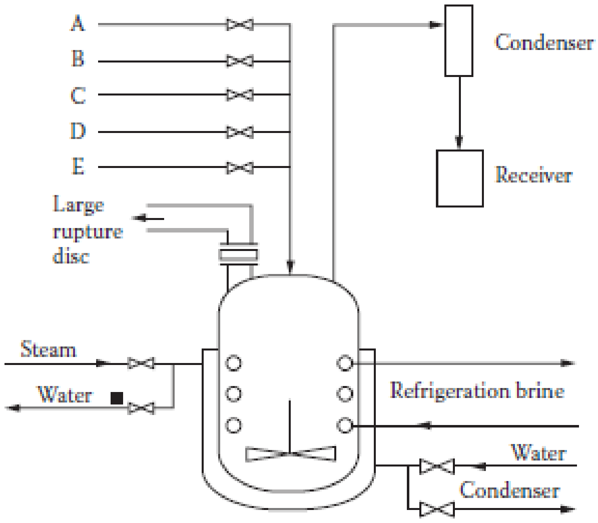
Proof test interval for the interlock systems: 6 months

[9 marks]

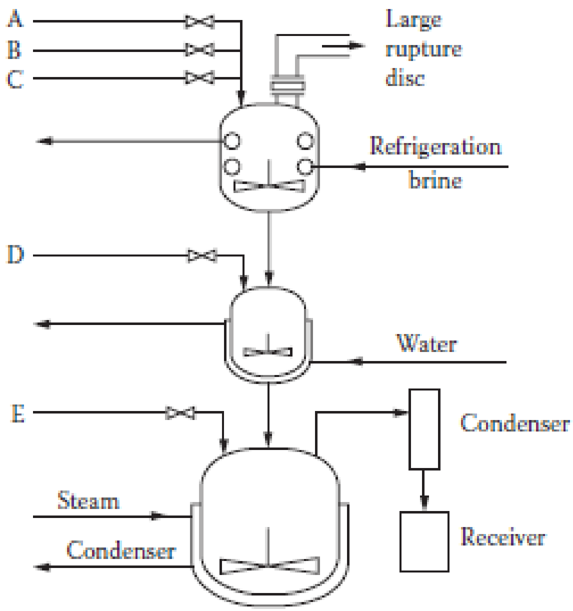
Continued/…

Q3 Continued/…

(c) Two processes shown in Figure Q3.2 were designed to synthesise the same product. All synthesis steps were designed to operate as fed-batch (semi-continuous) reactors. Discuss the two alternative designs from an inherent safety standpoint. [7 marks]



Design 1



Design 2

Figure Q3.2

4. Liquid petroleum gas, LPG, is supplied to an intermediate liquid storage vessel before being piped to a heating device. The flow rate of LPG to the intermediate storage vessel is always capable of being greater than the maximum flow rate to the heating device. Hence without any control and protective systems, the intermediate storage vessel could be overfilled and may rupture. To prevent this from happening, the level of LPG in the storage vessel is controlled using a level control system (Level Transmitter (LT), Level Controller (LC), and Control Valve (CV)). An independent high level alarm (HLA) is provided to warn the operator if the level continues to rise and reaches the high level limit. A separate trip system (High-High Level Switch (HHLS) and a Trip Valve (TV)) is also available to shut down the process if the level reaches the high high level limit (maximum safe operating level). In addition, the storage vessel is equipped with a relief valve connected to a wet flare header.

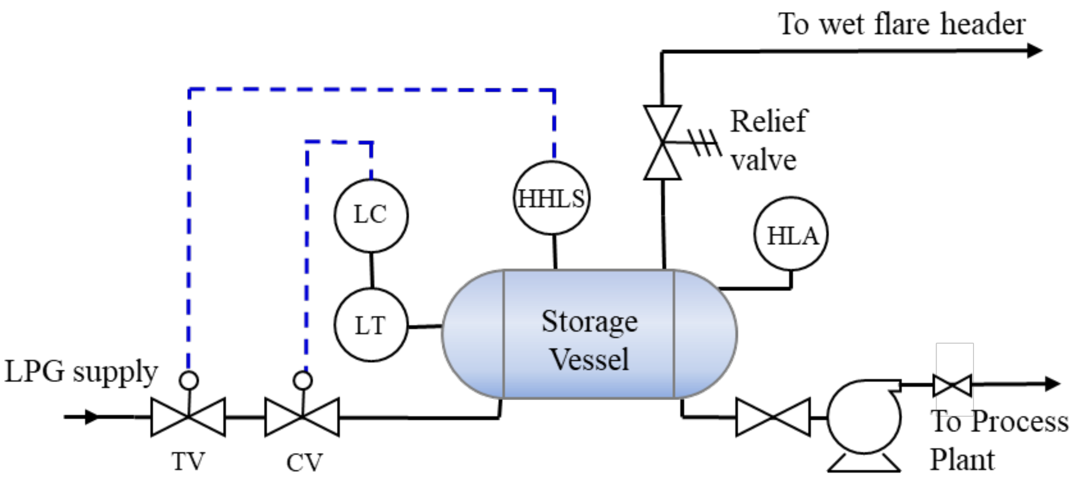


Figure Q4

The failure frequencies of the equipment and operator, expressed in occurrence per year (occ/yr), are as follows:

Level transmitter faults	0.25 occ/yr
Level controller faults	0.10 occ/yr
Control valve faults	0.20 occ/yr
Alarm system failure	0.30 occ/yr
High-high level switch faults	0.20 occ/yr
Trip valve faults	0.05 occ/yr
Relief valve faults	0.10 occ/yr
Operator failure	0.05 occ/yr

Continued/…

Q4 Continued/…

(a) Draw the fault tree for the event “storage vessel ruptures”. [10 marks]

(b) From the fault tree, determine the frequency of the top event.

For all protective systems, assume a six-month proof test interval, the system is disarmed for 1 hour during testing and the probability of being reinstalled in a non-working condition, P_{TE}, is 0.005. The total fractional dead time, *fdt*, is expressed by Equation Q4 A below:

$$fdt = \frac{\lambda T}{2} + \frac{Test\ time}{T} + P_{TE} \qquad \text{Equation Q4 A}$$

[8 marks]

(c) Determine the optimum proof test interval for the High Level Alarm (HLA), i.e. the proof test interval at which the fractional dead time is minimum. Determine the new frequency of the top event given that only the High Level Alarm will be proof tested at the optimal proof test period. Comment on your results. [7 marks]

END OF PAPER

B Benyahia, J Wagner

