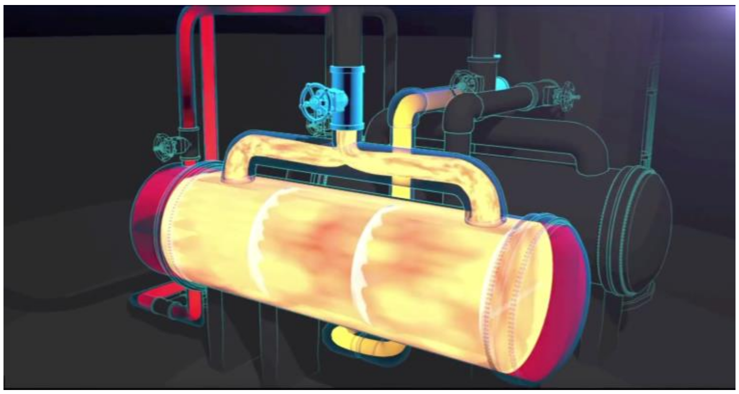
Heat and Mass Transfer

[i]**Safety Module 1:** Williams Owens Olefin Plant Explosion, Geismer, LA, June 13, 2013

Problem Statement: The Williams Owens Plant in Geismar, LA produces ethylene and propylene. A shell and tube reboiler on a fractionator column heats shell side propane and propylene using tube side hot water. Workers understood that oily tar tended to build up on the inside of the reboiler tubes, requiring periodic shut down for cleaning. The plant manager observed a significant decrease in hot water flow rate over the past day and attributed it to tar build up on the inside of the tube walls. Workers decided to switch to the stand-by exchanger, which had not been in use for 16 months. Unknown to workers, this stand-by heat exchanger was detached from its pressure relief valve and contained liquid propane. When hot water was introduced into this heat exchanger, it violently ruptured and exploded within three minutes. The incident killed two workers and injured 167.



Watch the Video: (*https://www.youtube.com/watch?v=Z1KaykPaF8M*)

Incident Report Available At: (*https://www.csb.gov/file.aspx?DocumentId=6004*)
(Pages 5, 9, 11-15, 56)

(a) It is important that chemical engineers understand what the accident was, why it happened and how it could have been prevented in order ensure similar accidents may be prevented. Applying a safety algorithm to the accident will help achieve this goal. In order to become familiar with a strategy for accident awareness and prevention, view the Chemical Safety Board video on the Williams Owens Olefin plant explosion and fill out the following algorithm. See definitions on the last page. If necessary, view the incident report.

Safety Algorithm

Activity: ____

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Hazard: ____

____

Incident: ____

Initiating Event: ____

Preventative Actions and Safeguards: ______________________________

____

Contingency Plan/ Mitigating Actions: ______________________________

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Lessons Learned: ______________________________

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Additional Information:

Inner and outer radius of heat exchanges tubes, r_i and r_o, can be taken as 0.4 inch and 0.5 inch, respectively. Conductivity of Carbon Steel, k_s and paraffin wax, k_{tar} are 54 $W/m \cdot K$ and 0.25 $W/m \cdot K$ respectively. Convective heat transfer coefficient for water, h_w, and propane, h_p, are and respectively. Assume convective heat transfer coefficient for water, h_w and for propane, h_p are 800 $W/m^2 \cdot K$ and 500 $W/m^2 \cdot K$ respectively.

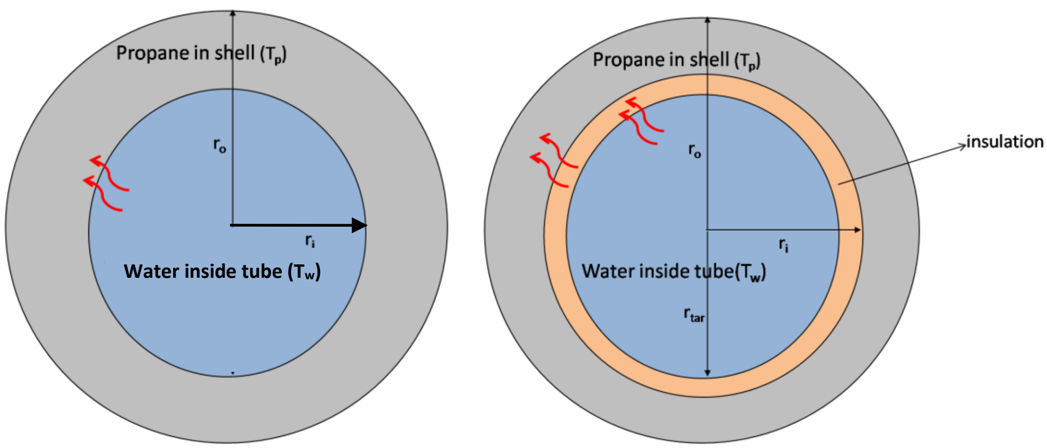


Figure 1.1 Schematic of fluid flow around the tubes of the shell before (left) and after fouling (right).

(b) Using a shell balance approach, prove that rq(r) = constant. (r is distance from center)

(c) r_{tar} is found to be approximately $\sqrt{0.2r_i}$, where r_i is the inner radius of the tube before fouling. Using this estimate for the incident, derive expressions for the following when there is no fouling:

1. The temperature difference T_w - T_p where, T_w is the temperature of water flowing inside the tubes , and T_p is the temperature of propylene flowing in the shell
2. The overall heat transfer coefficient, U at r = r_i
3. The energy flux, q_1 at r = r_i

r_i	0.4 inch (0.01016 m)
r_o	0.5 inch (0.0127m)
k_s	54 $W/m \cdot K$

k_{tar}	$0.25\, W/m \cdot K$
h_w	$800\ W/m^2 \cdot K$
h_p	$500\ W/m^2 \cdot K$

(d) Find an expression for the energy flux q_2 at $r = r_{tar}$ when fouling occurs. What is the percent reduction in heat flux when fouling occurs? [% reduction = $(q_2 - q_1)/q_2$]

(e) Fouling can occur because of the continuous buildup of oily tar on the inside of reboiler tubes. Consider a cylindrical tube with a radius R, shown in the figure below.

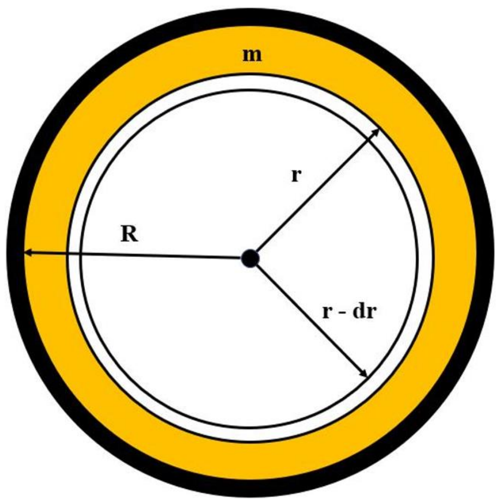


Figure 1.2: Schematic of tube with mass buildup

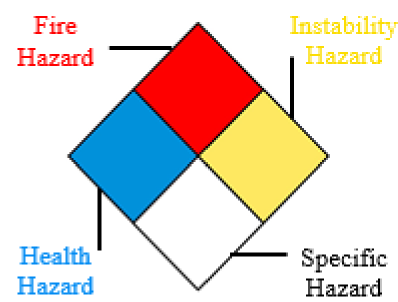
As tar uniformly builds up around the inside the tube, the radius available for flow, r, decreases with time. The amount of material deposited at any time from the start of operation can be given by

$$m(t) = m^*(1 - e^{-\lambda t})$$

Where m^* is the maximum mass loading on the surface (kg/m^2), λ is the normalized deposition rate constant (year^{-1}), and $m(t)$ is the total mass deposited per unit area (kg/m^2).

Derive a differential equation that describes how the radius of the tube changes with time by analyzing a thin cylindrical shell of thickness dr.

(f) Review the information in the NFPA Diamond tutorial. After reviewing the information, visit the CAMEO Chemicals website and fill out the blank NFPA Diamond to the right for propane.

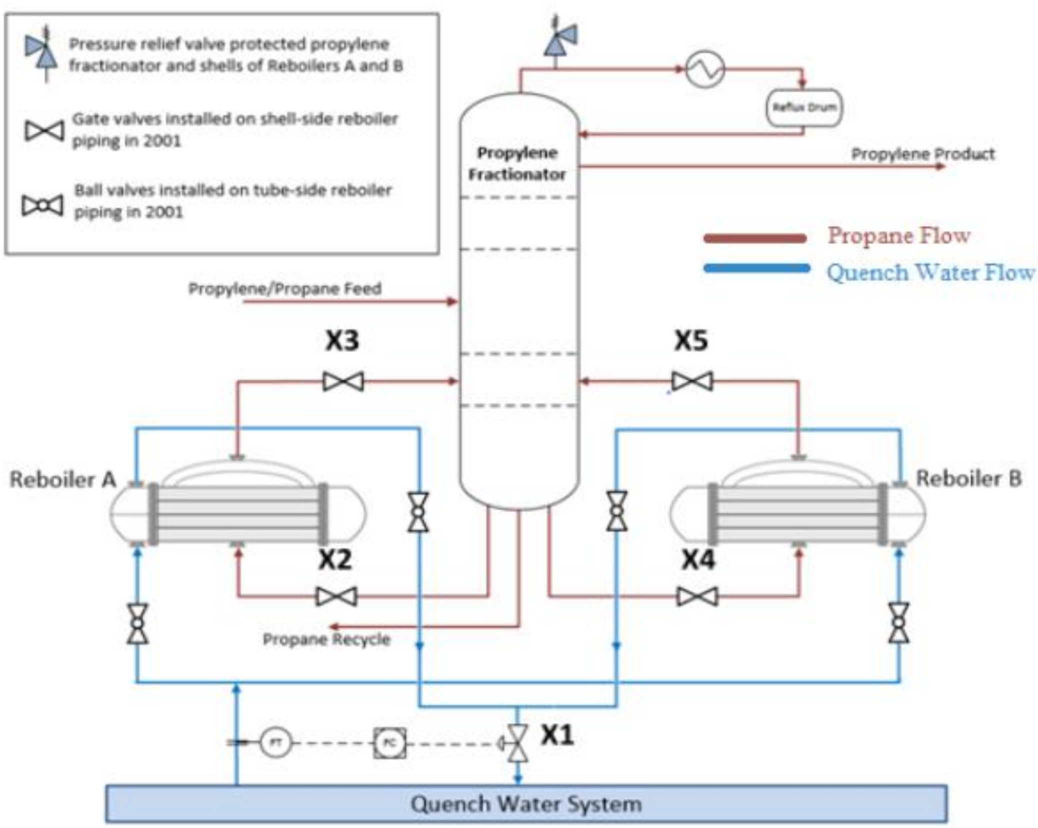


Parts **(g)-(i)** are based on industry practices used to assess process safety. For more information on process safety and its importance in chemical engineering, please visit the University of Michigan SafeChE website here. *It is recommended that professors only assign 1-2 of the following parts due to the similar nature of the questions.*

(g) Review the explanation of the components of a BowTie diagrams found here. After reviewing the information, create a BowTie diagram for Williams Owens Olefins Plant Explosion.

(h) A HAZOP study is structured analysis of process design to identify potential vulnerabilities in a facility. Review the background on how to conduct a HAZOP study here before completing one for the following system. It is important to note that not all guidewords and parameters will be relevant for different systems. Some information is given here for guidance:

System to consider: Bottom part of fractionator column that includes the active reboiler (A) and the stand-by reboiler (B). Hot quench water flows through the tube side of the reboiler while propane flows through the shell side of the reboiler. Car seals were used to lock open the outlet valve of the process fluid when the reboiler is in operation. It is also assumed that the standard operating procedure used while switching from the operating reboiler to the standby reboiler is first opening the quench water, and then opening the process fluid valve.



Process Parameters to Consider: Temperature, Pressure, Flow of process fluid, Flow of quench water, Start-up

(i) Fill out the HAZOP chart as shown in the tutorial. Some information has been filled out here for you.

Guideword + Parameter = Deviation	**Causes**	**Consequences**	**Safeguards**	**Recommendations**
More Flow of Quench Water into Reboiler A				
No/Less Flow of Process Fluid into Reboiler A	Closure of valve X2 due to human error			
More (High) Temperature of the process fluid in the shell side of Reboiler A	Closure of the outlet valve X3 isolating the reboiler from the only pressure safety valve			
More (High) Pressure in Reboiler A				
Other (Start-Up) of Reboiler B	Fouling in the operating reboiler			

(ii) When conducting a HAZOP, you will often find combinations of guidewords and parameters that describe a possible situation for the system that is not hazardous. For the given process parameters, give an example, explain why the situation is not hazardous, and describe another consequence that could occur. *HINT: Consider process efficiency*

(iii) Write a short conclusion on some takeaways from completing a HAZOP for this system and recommendations you would make.

(i) A Layers of Protection Analysis (LOPA) is a semi-quantitative study to identify available safeguards and determine if the safeguards sufficiently protect against a given risk. Review the background on how to conduct a LOPA study here before filling the table out for the system described in this module. Some information is given for guidance:

- Assume that the plant can only accept a moderate risk
- Assume that the reboilers undergo maintenance once per year
- The explosion caused 2 fatalities and injured many more

LOPA Study for William Owens Explosion		
Initiating Event	Cause:	Operator Error (Followed incorrect procedure while switching reboilers)
	Consequence:	Increase in Pressure inside the reboiler leading to an explosion
	FOIE:	
IPL(s)	Description of IPL_1, IPL_2, ...	
	$PFD = PFD_1 \times PFD_2 \times ...$	
MCF	MCF = FOIE x PFD	
	Category of MCF:	
Severity	Impact:	Multiple fatalities
	Category:	
Risk	Type of risk:	
	Acceptable / Unacceptable?	
If risk evaluated above is unacceptable, please continue below:		
Proposed IPL(s) (P-IPL(s))	Description of P-IPL_1, P-IPL_2, ...	
	P-PFD = P-PFD_1 x P-PFD_2 x ...	
MCF	MCF = FOIE x PFD x P-PFD	
	Category of MCF:	
Risk	Type of risk:	
	Acceptable / Unacceptable?	

(j) Describe what was the most unsettling to you about the incident.

Wolfram
Click here to download Wolfram CDF Player for free.

Click here to view CDF installation tutorial.

Click here to download Wolfram code for this module.

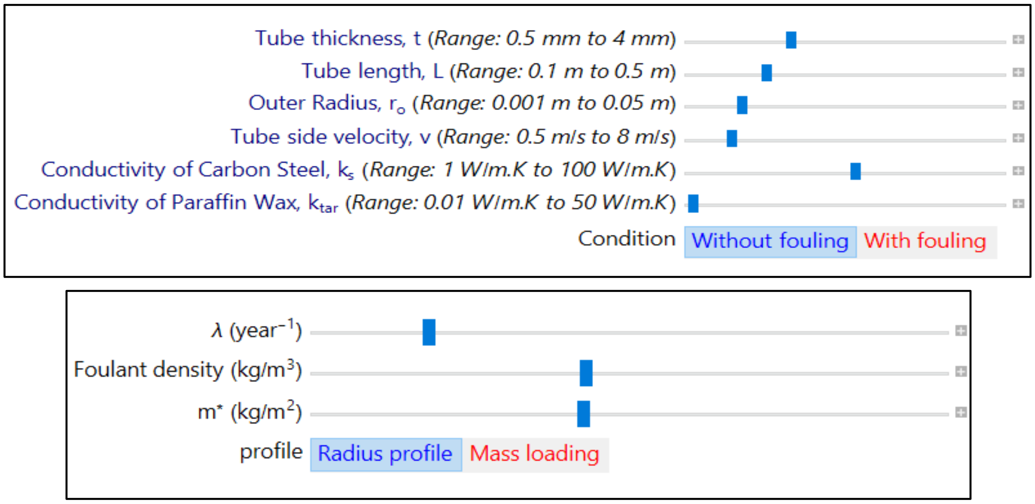


Fig 1.3 Wolfram sliders

Wolfram graphs:

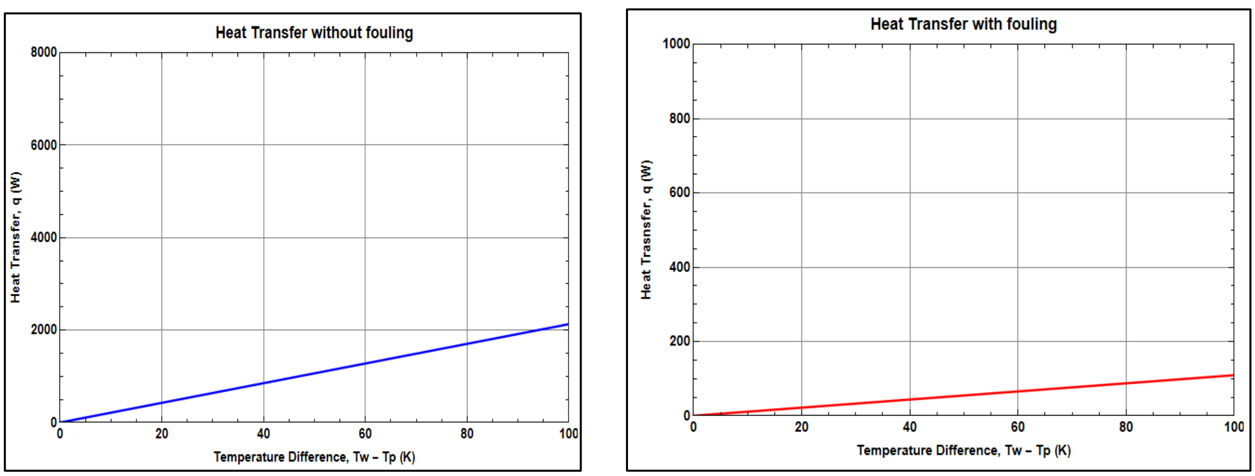


Fig 1.4 Heat transfer vs. Temperature difference, with and without fouling

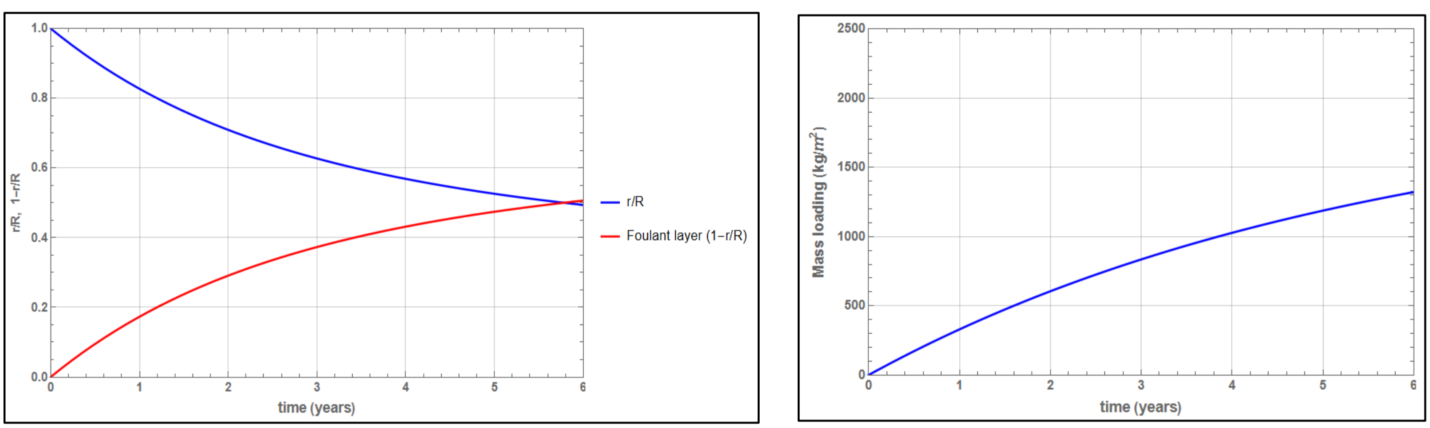


Fig 1.5 Tar buildup in heat exchanger tubes

Questions:

(i) How is the profile of heat transfer rate with fouling different from that without fouling? Vary the slider for conductivity of paraffin wax (k_{tar}) and carbon steel (k_s) and observe how the profile of heat transfer rate changes.

(ii) Vary the sliders for the dimensions of the pipe (length of tube, tube thickness, outer radius) and describe how the heat transfer profile changes for both cases of fouling and no fouling. Which dimension of the pipe would you suggest changing to decrease the effect of fouling?

(iii) The fractional layer thickness (1 - r/R) shows how tar has built up inside a tube with an initial radius of R. Vary the sliders for foulant density, maximum mass loading (m^*), and deposition rate (λ) and describe how the fractional layer thickness and variation of r/R change.

(iv) Consider the case where $m^* = 2000$ kg/m^2, $\lambda = 0.18$ year^{-1}, and the foulant density is 1150 kg/m^3. The reboiler will need to be placed under maintenance when the foulant layer thickness is 20% of R. Find the time when the reboiler will need to be placed under maintenance.

(v) Write a short set of conclusions based on your experiments in the previous parts.

Table of Nomenclature:

Symbol	Description	Unit
T_w	Temperature of water inside tube	K
T_p	Temperature of propane on shell side	K
k_s	Conductivity of carbon steel	W/m.K
k_{tar}	Conductivity of paraffin wax	W/m.K
r_i	Inner radius	m
r_o	Outer radius	m
r_{tar}	Effective inner radius with fouling	m
h_w	Heat transfer coefficient of water	W/m^2.K
h_p	Heat transfer coefficient of propane	W/m^2.K

Definitions

Activity: The process, situation, or activity for which risk to people, property or the environment is being evaluated.
Hazard: A chemical or physical characteristic that has the potential to cause damage to people, property, or the environment.
Incident: What happened? Description of the event or sum of the events along with the steps that lead to one or more undesirable consequences, such as harm to people, damage to property, harm to the environment, or asset/business losses.
Initiating Event: The event that triggers the incident, (e.g., failure of equipment, instrumentation, human actions, flammable release, etc.). Could also include precursor events, (e.g., no flow from pump, valve closed, inadvertent human action, ignition). The root cause of the sum events in causing the incident.
Preventative Actions and Safeguards: Steps that can be taken to prevent the initiating event from occurring and becoming an incident that causes damage to people, property, or the environment. Brainstorm all problems that could go wrong and then actions that could be taken to prevent them from occurring.
Contingency Plan/ Mitigating Actions: These actions occur after the initiating event. They are steps that reduce or mitigate the incident after the preventative action fails and the initiating event occurred.
Lessons Learned: What we have learned and can pass on to others that can prevent similar incidents from occurring
BowTie Diagram: A qualitative hazard analysis tool through which potential problems and consequences associated with a hazard are studied through a pictorial representation. Necessary preventive and mitigating barriers are determined to reduce the process safety risk.
Hazard and Operability Study (HAZOP): A qualitative hazard analysis tool that uses a set of guide words to determine whether deviations from design or operating intent can lead to undesirable consequences. The existing safeguards are evaluated and if required, actions are recommended to mitigate the consequences.
Layer of Protection Analysis (LOPA): A semi-quantitative study that determines initiating event frequency, consequence severity, and likelihood of failure of independent protection layers (IPLs) to calculate the risk of a scenario. If the existing risk is intolerable, then additional IPLs are suggested to bring down risk to an acceptable level.

Module Specific to Williams Owens Olefin Plant Explosion

Fouling: The accumulation of unwanted material on solid surfaces to the detriment of function
Boiling Liquid Expanding Vapor Explosion (BLEVE)[†]: A BLEVE occurs when a vessel containing a liquid at a temperature above its atmospheric boiling point ruptures. The subsequent BLEVE is an explosive vaporization of a large fraction of the vessel contents that can be followed by combustion or explosion of the vaporized cloud. BLEVE occurs when an external heat source heats the contents of the vessel thereby increasing the vapor pressure in the vessel and reducing its structural integrity.

[i]In collaboration with Kara Steshetz, University of Michigan, KS Reshma Indian Institute of Technology Bombay, and Professor Fei Wen, University of Michigan.

[†] From Crowl, D. A. and J.F. Louvar, *Chemical Process Safety with Applications,* Prentice Hall, Upper Saddle River, NJ.