CHARLES DARWIN UNIVERSITY

Family Name	
Given Names	
Student Number	
Teaching Period	Semester 2, 2016

FINAL EXAMINATION	DURATION
ENG248 – Unit Operations	Reading Time: **10** minutes Writing Time: **180** minutes

INSTRUCTIONS TO CANDIDATES

EXAM CONDITIONS

You may begin writing from the commencement of the examination session. The reading time indicated above is provided as a guide only.

This is a RESTRICTED OPEN BOOK examination

Any non-programmable calculator is permitted

One A4 sheet of handwritten double-sided notes permitted

No dictionaries are permitted

ADDITIONAL AUTHORISED MATERIALS	EXAMINATION MATERIALS TO BE SUPPLIED
No additional printed material is permitted	1 x 16 Page Book 2 x Scrap Paper

THIS EXAMINATION IS PRINTED

DOUBLE-SIDED.

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Problem #1 (34%)

A shell-and-tube heat exchanger consists of 135 thin walled tubes (d = 12.5mm) in a 2-pass arrangement. The total surface area of the heat exchanger is 47.5m^2. 6.5 kg/s of water (the tube-side fluid) enters the heat exchanger at 15°C and is heated by an exhaust gas stream entering at 200°C and 5 kg/s. The gas may be assumed to have the properties of atmospheric air. The overall heat transfer coefficient is approximately 200 W/(m^2.K).

a) What are the gas and water outlet temperatures?

b) Assuming fully developed flow, what is the tube-side convection coefficient?

Problem #2 (33%)

Waste cooking oil can be converted to Biodiesel by several methods. One of them is the gas-phase pyrolysis, which basically involves the following first-order irreversible reactions:

$$\mathbf{(RC(O)OCH_2)_3 \rightarrow (RCH_2)_3 + 3\,CO_2 \qquad (A \rightarrow B + 3C)}$$

The rate constant k has the value of 5x10^{-3} min^{-1} at 150^{o}C, and the activation energy is E_a=85 kJ/mol. Waste cooking oil is injected into a hot reactor at a rate of 2.5moles/min. The temperature of the reactor is T=227^{o}C. The steady-state pressure in the reactor is P = 10 atm. All the species are in the vapour phase at this condition.

a) What is the required CSTR volume to achieve 90% conversion?

b) If the reactor is a PFR and the pressure drop is negligible, what is the required volume to achieve 90% conversion?

c) A CSTR with half of the volume calculated in part (a) is put in front of a PFR with half of the volume calculated in part (b) to make a reactor combination in series. Calculate the conversion in this reactor combination.

This integral formula may be helpful:

$$\int_{x_1}^{x_2} \frac{(1+mx)}{(1-x)}dx = (1+m)\ln\left[\frac{1-x_1}{1-x_2}\right] + m(x_1 - x_2)$$

Problem #3 (33%)

Suppose the reaction in Problem#2 is carried out in a batch reactor. Initially, the reactor is charged with only waste cooking oil. The reactor's temperature is 227^{o}C and the initial pressure in the reactor is 2.7 atm. All the species are in the vapour phase at this condition.

a) What is the pressure in an isothermal batch reactor if the conversion is 90%?

b) Calculate the batch reactor volume to process 3,600 moles of waste cooking oil per day (= 2.5 moles/minute). Assume that the batch reactor can be emptied and refilled very rapidly, and that it is not necessary to clean the reactor between batches.

c) Which reactor (CSTR, PFR, batch reactor) would you recommend to be used for this process? Explain briefly. (Refer to the results obtained in Problem #2).

Thermophysical Properties

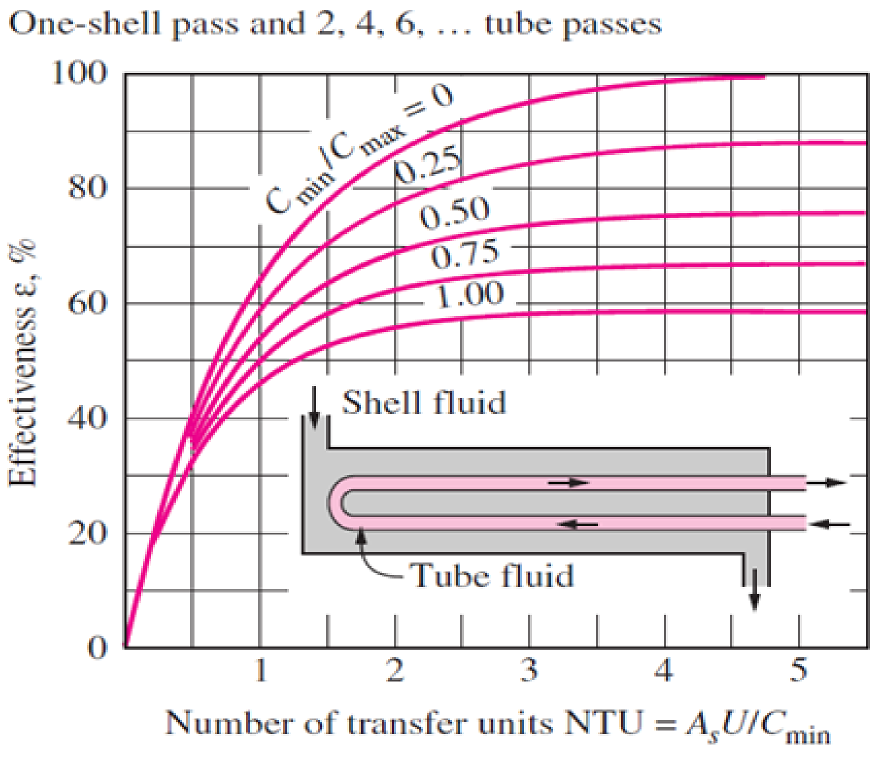
Air

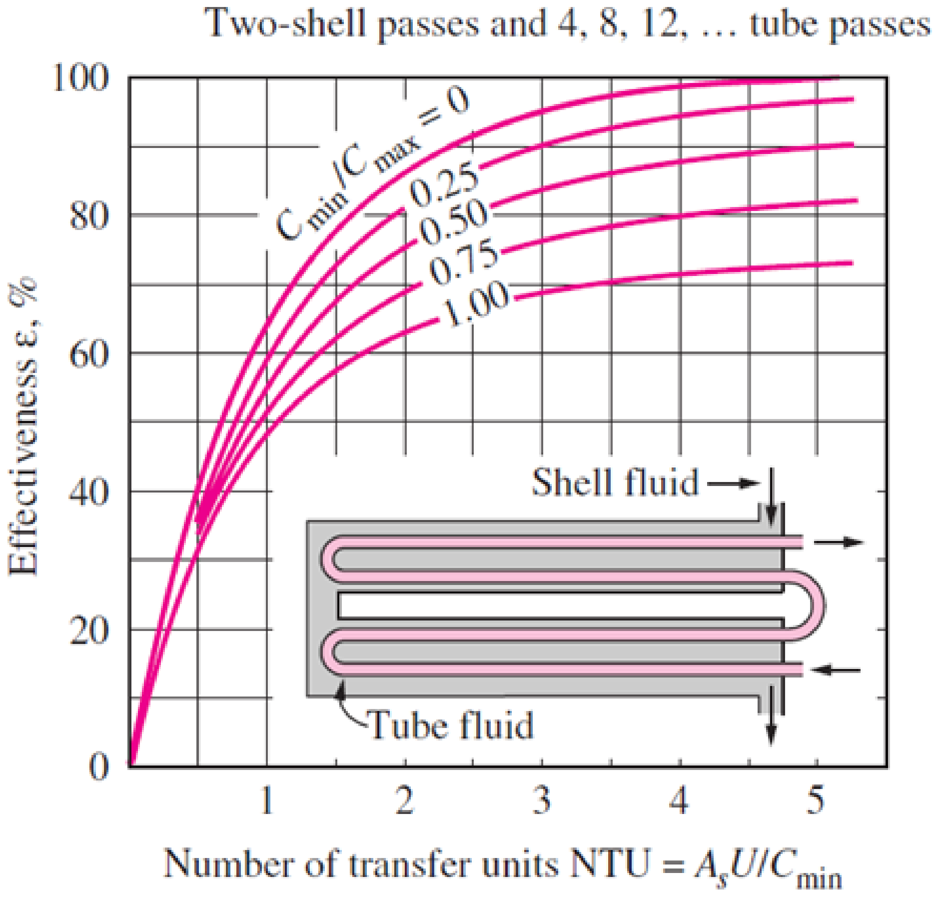
T (K)	ρ ($\mathrm{kg/m^3}$)	c_p ($\mathrm{kJ/kg\cdot K}$)	$\mu \cdot 10^7$ ($\mathrm{N\cdot s/m^2}$)	$\nu \cdot 10^6$ ($\mathrm{m^2/s}$)	$k \cdot 10^3$ ($\mathrm{W/m\cdot K}$)	$\alpha \cdot 10^6$ ($\mathrm{m^2/s}$)	Pr
100	3.5562	1.032	71.1	2.00	9.34	2.54	0.786
150	2.3364	1.012	103.4	4.426	13.8	5.84	0.758
200	1.7458	1.007	132.5	7.590	18.1	10.3	0.737
250	1.3947	1.006	159.6	11.44	22.3	15.9	0.720
300	1.1614	1.007	184.6	15.89	26.3	22.5	0.707
350	0.9950	1.009	208.2	20.92	30.0	29.9	0.700
400	0.8711	1.014	230.1	26.41	33.8	38.3	0.690
450	0.7740	1.021	250.7	32.39	37.3	47.2	0.686
500	0.6964	1.030	270.1	38.79	40.7	56.7	0.684
550	0.6329	1.040	288.4	45.57	43.9	66.7	0.683

Water

T, °C	ρ, $\mathrm{kg/m^3}$	c_p, $\mathrm{J/kg\cdot K}$	μ, $\mathrm{kg/m\cdot s}$	k, $\mathrm{W/m\cdot K}$	Pr
5	999.9	4205	1.519×10^{-3}	0.571	11.2
10	999.7	4194	1.307×10^{-3}	0.580	9.45
15	999.1	4185	1.138×10^{-3}	0.589	8.09
20	998.0	4182	1.002×10^{-3}	0.598	7.01
25	997.0	4180	0.891×10^{-3}	0.607	6.14
30	996.0	4178	0.798×10^{-3}	0.615	5.42
35	994.0	4178	0.720×10^{-3}	0.623	4.83
40	992.1	4179	0.653×10^{-3}	0.631	4.32
45	990.1	4180	0.596×10^{-3}	0.637	3.91
50	988.1	4181	0.547×10^{-3}	0.644	3.55

Shell-Tube HX





Effectiveness relations for heat exchangers: $\mathrm{NTU} = UA_s/C_{\min}$ and $c = C_{\min}/C_{\max} = (\dot{m}C_p)_{\min}/(\dot{m}C_p)_{\max}$ (Kays and London, Ref. 5.)

Heat exchanger type	Effectiveness relation
1 *Double pipe:*	
Parallel-flow	$\varepsilon = \dfrac{1 - \exp[-\mathrm{NTU}(1 + c)]}{1 + c}$
Counter-flow	$\varepsilon = \dfrac{1 - \exp[-\mathrm{NTU}(1 - c)]}{1 - c\exp[-\mathrm{NTU}(1 - c)]}$
2 *Shell and tube:* One-shell pass 2, 4, . . . tube passes	$\varepsilon = 2\left\{1 + c + \sqrt{1 + c^2}\,\dfrac{1 + \exp[-\mathrm{NTU}\sqrt{1 + c^2}]}{1 - \exp[-\mathrm{NTU}\sqrt{1 + c^2}]}\right\}^{-1}$
3 *Cross-flow (single-pass)*	
Both fluids unmixed	$\varepsilon = 1 - \exp\left\{\dfrac{\mathrm{NTU}^{0.22}}{c}[\exp(-c\,\mathrm{NTU}^{0.78}) - 1]\right\}$
$C_{\max}$ mixed, $C_{\min}$ unmixed	$\varepsilon = \dfrac{1}{c}(1 - \exp\{1 - c[1 - \exp(-\mathrm{NTU})]\})$
$C_{\min}$ mixed, $C_{\max}$ unmixed	$\varepsilon = 1 - \exp\left\{-\dfrac{1}{c}[1 - \exp(-c\,\mathrm{NTU})]\right\}$
4 *All heat exchangers with $c = 0$*	$\varepsilon = 1 - \exp(-\mathrm{NTU})$

NTU relations for heat exchangers $\mathrm{NTU} = UA_s/C_{\min}$ and $c = C_{\min}/C_{\max} = (\dot{m}C_p)_{\min}/(\dot{m}C_p)_{\max}$ (Kays and London, Ref. 5.)

Heat exchanger type	NTU relation
1 *Double-pipe:* Parallel-flow	$\mathrm{NTU} = -\dfrac{\ln[1 - \varepsilon(1 + c)]}{1 + c}$
Counter-flow	$\mathrm{NTU} = \dfrac{1}{c - 1}\ln\left(\dfrac{\varepsilon - 1}{\varepsilon c - 1}\right)$
2 *Shell and tube:* One-shell pass 2, 4, . . . tube passes	$\mathrm{NTU} = -\dfrac{1}{\sqrt{1 + c^2}}\ln\left(\dfrac{2/\varepsilon - 1 - c - \sqrt{1 + c^2}}{2/\varepsilon - 1 - c + \sqrt{1 + c^2}}\right)$
3 *Cross-flow (single-pass)* $C_{\max}$ mixed, $C_{\min}$ unmixed	$\mathrm{NTU} = -\ln\left[1 + \dfrac{\ln(1 - \varepsilon c)}{c}\right]$
$C_{\min}$ mixed, $C_{\max}$ unmixed	$\mathrm{NTU} = -\dfrac{\ln[c\ln(1 - \varepsilon) + 1]}{c}$
4 *All heat exchangers with $c = 0$*	$\mathrm{NTU} = -\ln(1 - \varepsilon)$