UNIVERSITY OF
KWAZULU-NATAL
INYUVESI
YAKWAZULU-NATALI

SCHOOL OF ENGINEERING

MAIN EXAMINATIONS: NOVEMBER 2019

COURSE AND CODE: CHEMICAL ENGINEERING FUNDAMENTALS ENCH2EF

DURATION: 3 HOURS

TOTAL MARKS: 100

INTERNAL EXAMINERS: PROF I GOVENDER
PROF R RAWATLAL

INTERNAL MODERATOR: MRS A SINGH

EXTERNAL MODERATOR: DR M CHETTY

INSTRUCTIONS:

1. **ALL** questions should be attempted.
2. **Two answer books are provided. Label them Book 1 and Book 2 respectively. Answer Section B in Book 1 and Section C in Book 2.**
3. Any programmable or non-programmable calculator may be used provided it has been cleared of any information that would subvert the purpose of the examination.
4. Calculations must be shown in sufficient detail to illustrate your understanding of the procedure.
5. This examination question paper, together with all associated diagrams **MUST BE HANDED IN TOGETHER WITH YOUR SCRIPT.**

SECTION A

QUESTION 1 (Multiple Choice)

- Choose that answer which in your opinion is the correct or best answer and mark (with a "X") the appropriate block on the answer sheet provided.
- If you are *sure* of your answer, mark also the block containing the question mark.
- Use only a PEN on your answer sheet.

1.1 Water flows smoothly through a 1-cm diameter pipe connected to ¼-cm diameter pipe. Compared to the speed of the water in the larger diameter pipe (V), the speed in the smaller diameter pipe is:

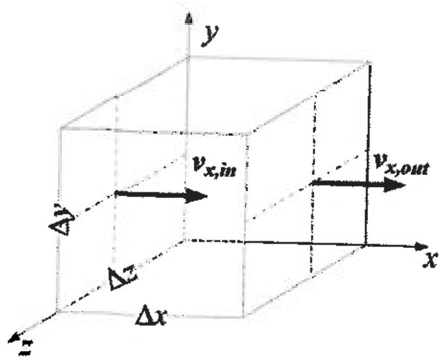
A. 4V

B. 16V

C. 2V

D. V

1.2. A horizontally flowing fluid enters the rectangular control volume through the face located at $x = 0$, and leaves through the face located at $x = \Delta x$ as shown in the figure. The x-momentum balance is written as follows:



$$\rho v_{x,\text{in}}^2 \Delta y \Delta z - \rho v_{x,\text{out}}^2 \Delta y \Delta z + L(\Delta x \Delta y \Delta z) = \left[\frac{d}{dt}(\rho v)\right](\Delta x \Delta y \Delta z).$$

What is the best description of the term L?

A. The momentum efflux

B. The resultant force

C. The rate of change of momentum density

D. The shear stress

1.3 Consider the steady-state heat transfer with no generation through the solid region of a hollow spherical shell with inner and outer radii of r_1 and r_2 respectively. The temperatures T_1 and T_2 at the inner and outer surfaces respectively are such that $T_1 > T_2$. Which of the following statements are true?

(i) Heat flux is inversely proportional to the square of the radius

(ii) Heat flux is directly proportional to the square of the radius

(iii) Temperature varies parabolically with radius

(iv) Temperature varies hyperbolically with radius

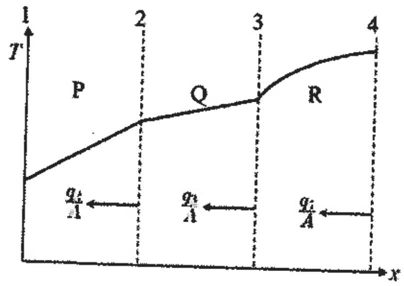
A. (i) and (iii) only

B. (ii) and (iii) only

C. (i) and (iv) only

D. (ii) and (iv) only

1.4 The steady-state temperature distribution in a composite plane of three different materials (P, Q, R), each of constant thermal conductivity (k_P, k_Q, k_R), is shown. Which of the following statements are TRUE for the heat efflux (q) and thermal conductivities (k)?



(i) $q_2 > q_3$

(ii) $k_P > k_Q$

(iii) $q_3 < q_4$

(iv) $k_Q < k_R$

A. All

B. None

C. (i), (ii) and (iv) only

D. (i), (ii) and (iii) only

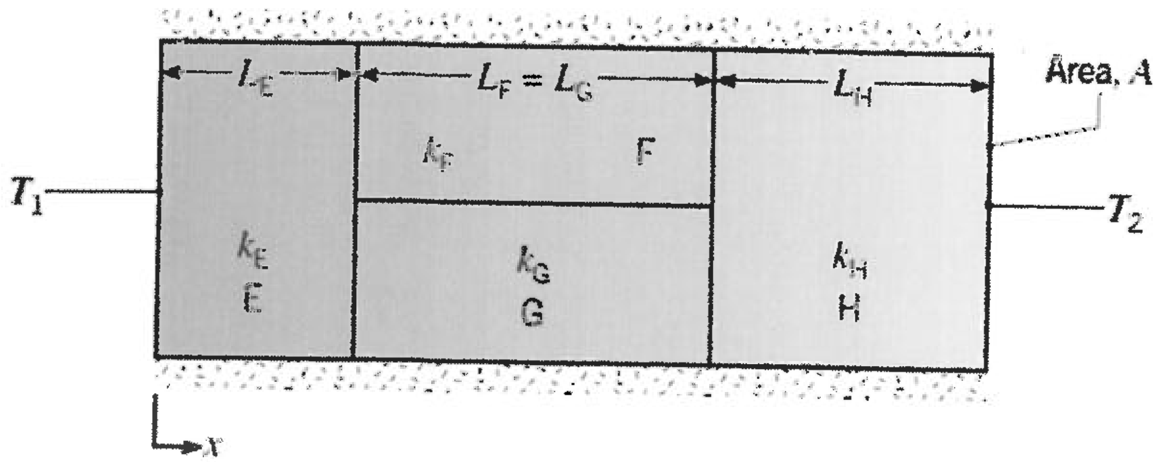
1.5 Consider the steady-state heat flow through the composite wall shown in the figure below. All thermal conductivities indicated in the diagram are constant. The total resistance for isothermal surfaces is equal to the total resistance for adiabatic surfaces when:

A. $k_F = k_G$

B. $k_E = k_H$

C. $k_F > k_G$

D. $k_E > k_H$



Section A continued on next page ...

The following description relates to **Questions 1.6 - 1.8**: Consider a solid particle of radius r_0 containing component-A at concentration $c_{A,p}$ suspended in a liquid solution B. Component-A dissolves into the solution in equimolar counter-diffusion to component B. The solution does not initially contain any of component-A. The particle size and particle concentration to A may be taken as approximately constant with time.
The equilibrium constant for component-A between the solid and the solution is K such that $c_{A,solution} = K.c_{A,solid}$. We wish to develop an efficient material balance with boundary conditions to solve for the concentration variation through the solution as time passes.

1.6 To develop an efficient balance, which choices are the most efficient:

A. The rate of accumulation in range $[r, r + \Delta r]$ is $\frac{d}{dt}[c_A\pi([r + \Delta r]^2 - r^2)]$ and the diffusion flux at r is $-D_{AB}\frac{\partial c_A}{\partial r}\Big|_r$

B. The rate of accumulation in range $[r, r + \Delta r]$ is $\frac{d}{dt}[c_A\pi([r + \Delta r]^2 - r^2)]$ and the diffusion rate at r is $-D_{AB}\frac{\partial c_A}{\partial r}\Big|_r$

C. The rate of accumulation in range $[r, r + \Delta r]$ is $\frac{d}{dt}[c_A\pi r^2\Delta r]$ and the diffusion flux at r is $-D_{AB}\frac{\partial c_A}{\partial r}\Big|_r$

D. The rate of accumulation in range $[r, r + \Delta r]$ is $\frac{d}{dt}[c_A\pi r^2\Delta r]$ and the diffusion flux at r is $-D_{AB}\frac{\partial c_A}{\partial r}\Big|_r \pi r^2$

1.7 Which boundary conditions are relevant?

$1: c_A(t = 0, r) = 0$
$2: c_A(t = 0, r) = c_{A,p}$
$3: c_A(t = 0, r) = K.c_{A,p}$
$4: c_A(t = 0, r) = c_{A,p}$
$5: \frac{\partial c_A}{\partial r}\Big|_{r=0} = 0$
$6: c_A(t, r = r_0) = K.c_{A,p}$, $7: c_A(t, r \to \infty) = 0$

A. 3, 6, 7

B. 1, 6, 7

C. 1, 5, 7

D. 2, 4, 7

1.8 We wish to approximate the solution using the Film Theory. To do so, which of the following statements are true:

A. The film width will increase over time and its boundary will be where the concentration is 1% of $K.c_{A,p}$

B. The film width will remain the same over time and will be where the concentration is 0 (i.e. 99% of the bulk value = 0)

C. The film width will decrease over time and will be where the concentration is 1% of $K.c_{A,p}$

D. The film width will decrease over time and will be where the concentration is 0 (i.e. 99% of the bulk value = 0)

The following description applies to **Questions 1.9 and 1.10.**

Consider fluid of density 1200 $\frac{kg}{m^3}$, viscosity $9 \times 10^{-4} Pa.s$ flowing at 2 m/s in a 3 cm pipeline where the Chiltern-Colburn analogy applies:

$$J_D = \frac{k_c}{u_\infty} Sc^{\frac{2}{3}}, \quad J_H = \frac{h}{c_P \rho u_\infty} Pr^{\frac{2}{3}}, \quad J_D = J_H, \quad Sc = \frac{\mu}{\rho D_{AB}}, \quad Pr = \frac{c_P \mu}{k}, \quad Sh = \frac{k_c.d}{D_{AB}}$$

The Schmidt number is known to be 20. The Dittus-Boetler relationship holds in the pipeline:

$$Nu = 0.023\, Re^{0.8}.Pr^{1/3}$$

1.9 When combining the Chilton-Colburn analogy with the Dittus-Boetler correlation, we can show that

A. $Nu = 0.023\, Re^{0.8}.Sc^{1/3}$

B. $Nu = 0.023\, Pr^{0.8}.Sc^{1/3}$

C. $Sh = 0.023\, Re^{0.8}.Sc^{1/3}$

D. $Sh = 0.023\, Re^{0.8}.Pr^{1/3}$

1.10 The values of diffusivity $[m^2/s]$ and mass transfer coefficient $[m/s]$ are

A. $D_{AB} = 2 \times 10^{-4}, k_c = 4.2 \times 10^{-8}$

B. $D_{AB} = 2 \times 10^{-8}, k_c = 6.53 \times 10^{-8}$

C. $D_{AB} = 3.75 \times 10^{-8}, k_c = 4.2 \times 10^{-4}$

D. $D_{AB} = 3.75 \times 10^{-8}, k_c = 6.53 \times 10^{-4}$

TOTAL /50/

SECTION B

QUESTION 2

For the closed tank in the figure, all fluids are at 20°C, and the airspace is pressurized. It is found that the net outward hydrostatic force on the 30-by 40-cm panel at the bottom of the water layer is 8450 N. Estimate:

2.1) The pressure in the airspace.

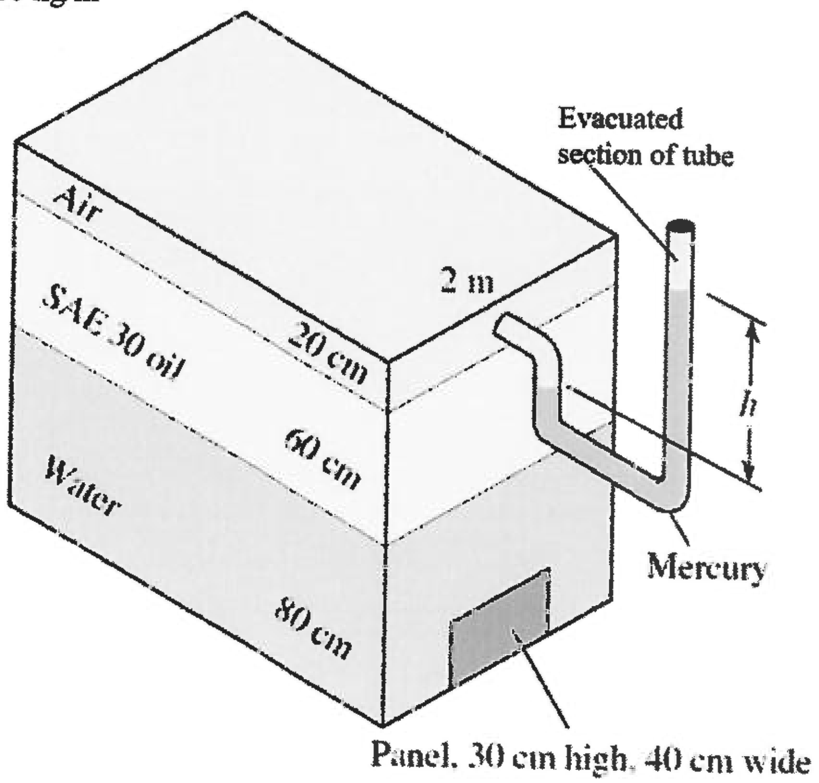
(6)

2.2) The reading h on the mercury manometer.

(4)

Use the following values for the densities:

SAE Oil: 891 kg/m^3
Water: 1000 kg/m^3
Air: 1.2 kg/m^3
Mercury: 13600 kg/m^3



TOTAL /10/

QUESTION 3

Consider the steady-state heat flow (without generation) through a hollow cylindrical shell of length L with inner and outer radii of r_1 and r_2 respectively. The solid region has a constant thermal conductivity k and obeys Fourier's law of heat conduction. The temperatures T_1 and T_2 at the inner and outer surfaces are such that $T_1 > T_2$.

3.1) Derive an expression for the heat efflux in the solid region in terms of r_1, r_2, k, L, T_1 and T_2.

(5)

3.2) The hollow cylindrical shell described in (3.1) is a cooling coil of 1.0 ft of 304 stainless steel tubing with an inside diameter of 0.25 in. and outside diameter of 0.40 in. The coil is being used to remove heat from a bath. The temperature at the inside surface of the tube is 40°F and 80°F on the outside. The thermal conductivity of 304 stainless steel is a function of temperature:

$$k = 7.75 + 7.78 \times 10^{-3} T$$

where k is in Btu/(h·ft·°F).

3.2.1) Show that the heat efflux in the solid region of the cylindrical shell is given by

$$q = \frac{T_1 - T_2}{R}$$

where $R = \frac{r_2 - r_1}{kA_{lm}}$ is the resistance to heat flow and A_{lm} is log mean area of the inside surface area $A(r_1)$ and outside surface area $A(r_2)$ of the tube.

(5)

3.2.2) Calculate the heat removal rate in Btu/s.

(5)

TOTAL /15/

SECTION C

QUESTION 4

Consider a fluid flowing in a cylindrical pipeline. The walls of the tube contain component-A at a concentration of c_{Aw}. Component A dissolves into the fluid. The equilibrium constant between the fluid and the wall is $K = c_F/c_W$, the diffusivity of A against the other species in the fluid is D_{Ae}, and flux from other components result in equimolar counter diffusion of A. Note that even though component-A is dissolving into the fluid, other inerts in the wall prevent it from collapsing or even changing in size.

4.1) Develop an efficient form of the unsteady state material balance that reveals the concentration of A in the fluid.

(10)

4.2) Propose suitable boundary conditions

(5)

4.3) If the Reynolds number equals 5000 and the system is at steady state, how may the balance be simplified? From a sample port at $z = 1\ m$, the concentration of A is measured to be $2.8 \times 10^{-3} mol.m^{-3}$. However, no other sampling ports are available. What will be the concentration of A 5 m down the tube?

(5)

We note that for

$$\frac{\partial^2 x}{\partial z^2} - \alpha\frac{\partial x}{\partial z} = 0$$

$$x(z = 0) = \beta_0, \frac{\partial x}{\partial z}(z = 0) = \beta_1$$

We have the solution

$$x(z) = \beta_0 + \frac{\beta_1}{\alpha}[\exp(\alpha z) - 1]$$

TOTAL /20/

QUESTION 5

Estimate the diffusivity of nitrous oxide in air at 310 K and 0.9 atm total pressure.

Note that

$$\frac{p.D_{AB}}{(p_{cA}p_{cB})^{1/3}(T_{cA}T_{cB})^{5/12}\left(\frac{1}{M_A}+\frac{1}{M_B}\right)^{\frac{1}{2}}} = a\left(\frac{T}{\sqrt{T_{cA}T_{cB}}}\right)^{b}$$

where for non-polar gas pairs excluding hydrogen and helium, $a = 2.745 \times 10^{-4}$ and $b = 1.823$, and $a = 3.640 \times 10^{-4}$ and $b = 2.334$ for pairs consisting of H_2O and a nonpolar gas.

Table E.1 Lennard-Jones (6–12) Potential Parameters and Critical Properties

Substance	Molecular Weight M	Lennard-Jones parameters: σ (Å)	ε/κ (K)	Ref.	Critical properties[a,b]: T_c (K)	p_c (atm)	$\tilde{V}_c$ (cm³/g-mole)	μ_c (g/cm·s × 10^6)	k_c (cal/cm·s·K × 10^6)
Light elements:									
H_2	2.016	2.915	38.0	a	33.3	12.80	65.0	34.7	—
He	4.003	2.576	10.2	a	5.26	2.26	57.8	25.4	—
Noble gases:									
Ne	20.180	2.789	35.7	a	44.5	26.9	41.7	156.	79.2
Ar	39.948	3.432	122.4	b	150.7	48.0	75.2	264.	71.0
Kr	83.80	3.675	170.0	b	209.4	54.3	92.2	396.	49.4
Xe	131.29	4.009	234.7	b	289.8	58.0	118.8	490.	40.2
Simple polyatomic gases:									
Air	28.964	3.617	97.0	a	132.4	37.0	86.7	193.	90.8
N_2	28.013	3.667	99.8	b	126.2	33.5	90.1	180.	86.8
O_2	31.999	3.433	113.	a	154.4	49.7	74.4	250.	105.3
CO	28.010	3.590	110.	a	132.9	34.5	93.1	190.	86.5
CO_2	44.010	3.996	190.	a	304.2	72.8	94.1	343.	122.
NO	30.006	3.470	119.	a	180.	64.	57.	258.	118.2
N_2O	44.012	3.879	220.	a	309.7	71.7	96.3	332.	131.
SO_2	64.065	4.026	363.	c	430.7	77.8	122.	411.	98.6
F_2	37.997	3.653	112.	a	—	—	—	—	—
Cl_2	70.905	4.115	357.	a	417.	76.1	124.	420.	97.0
Br_2	159.808	4.268	520.	a	584.	102.	144.	—	—
I_2	253.808	4.982	550.	a	800.	—	—	—	—
Hydrocarbons:									
CH_4	16.04	3.780	154.	b	191.1	45.8	98.7	159.	158.
$CH{\equiv}CH$	26.04	4.114	212.	d	308.7	61.6	112.9	237.	—
$CH_2{=}CH_2$	28.05	4.228	216.	b	282.4	50.0	124.	215.	—
C_2H_6	30.07	4.388	232.	b	305.4	48.2	148.	210.	203.
$CH_3C{\equiv}CH$	40.06	4.742	261.	d	394.8	—	—	—	—
$CH_3CH{=}CH_2$	42.08	4.766	275.	b	365.0	45.5	181.	233.	—
C_3H_8	44.10	4.934	273.	b	369.8	41.9	200.	228.	—
$n{-}C_4H_{10}$	58.12	5.604	304.	b	425.2	37.5	255.	239.	—

TOTAL /5/

ENCH2EF: Formula Sheet

Reynolds Number: $R_e = \frac{Dv\rho}{\mu}$

Newton's Law of Viscosity: $\tau_{rx} = -\mu \frac{dv_x(r)}{dr}$

Mass balance: $\int_{cs} \rho\vec{v}\cdot\overrightarrow{dA} + \frac{\partial}{\partial t}\int_{cv} \rho dV =$ Rate of mass generation

Momentum balance: $\int_{cs} \vec{v}\rho\vec{v}\cdot\overrightarrow{dA} + \frac{\partial}{\partial t}\int_{cv} \rho\vec{v} dV = \sum$ Forces

Energy balance: $\int_{cs} \overline{E'}\rho\vec{v}\cdot\overrightarrow{dA} + \frac{\partial}{\partial t}\int_{cv} \overline{E}\rho dV = q - \dot{W}$

Bernoulli's Equation: $P + \frac{1}{2}\rho v^2 + \rho g h =$ constant

Continuity Equation: $\rho A v =$ constant

Enthalpy balance: $\overline{H}_1 + \frac{v_{1,\mathrm{av}}^2}{2\alpha} + g y_1 \pm \overline{W}_s = \overline{H}_2 + \frac{v_{2,\mathrm{av}}^2}{2\alpha} + g y_2 + \overline{Q}$

Mechanical energy balance: $\frac{v_{1,\mathrm{av}}^2}{2\alpha} + g y_1 + \frac{P_1}{\rho} \pm \overline{W}_s = \frac{v_{2,\mathrm{av}}^2}{2\alpha} + g y_2 + \frac{P_2}{\rho} + \sum \overline{F}$

Head loss balance: $\frac{v_{1,\mathrm{av}}^2}{2\alpha g} + y_1 + \frac{P_1}{\rho g} \pm H_E = \frac{v_{2,\mathrm{av}}^2}{2\alpha g} + y_2 + \frac{P_2}{\rho g} + H_f$

Power: $\rho g F H_E$, where F is the volumetric flowrate

Hagen-Poiseuille Equation: $\Delta P_f = \frac{32\mu(\Delta\ell)v_{av}}{D^2}$

Frictional pressure drop (any R_e): $\Delta P_f = 2\rho f \frac{\Delta\ell}{D} v_{\mathrm{av}}^2$, where f is the Fanning friction factor

Laminar pipe flow: $v_x(r) = \frac{|\Delta P| R^2}{4\mu L}\left[1 - \left(\frac{r}{R}\right)^2\right]$

Fourier's Law: $\frac{q_x}{A} = -k\frac{dT}{dx}$ In the x-direction

Newton's Law of Colling: $q = hA(T_s - T_e)$ $T_s > T_e$

Molar flux of component-A: $N_A = -cD_{AB}\partial x_A/\partial z + x_A \sum_i N_i$

STUDENT NUMBER:

UNIVERSITY OF KWAZULU NATAL
CHEMICAL ENGINEERING
ENCH2EF

MULTIPLE CHOICE ANSWER SHEET

Use only a PEN on this answer sheet.

If you are *sure* of your answer, mark also the block containing the question mark.

1	A	B	C	D	?
2	A	B	C	D	?
3	A	B	C	D	?
4	A	B	C	D	?
5	A	B	C	D	?
6	A	B	C	D	?
7	A	B	C	D	?
8	A	B	C	D	?
9	A	B	C	D	?
10	A	B	C	D	?

Mark scheme:	
Correct, sure	5
Correct, unsure	4
Incorrect, unsure	1
Incorrect, sure	0
More than one option chosen	0
Blank	0