B.M.S. COLLEGE OF ENGINEERING, BENGALURU 560019
(Autonomous Institution under VTU)

Department of Chemical Engineering

Accredited by NBA in Tier I of Washington Accord

Tutorial Book
For the course
Transport Phenomena
16CH6DCTRP
VI Semester

Name of the Student:

USN:

Faculty In-charge: Dr Sainath K

Prepared by: Dr Y K Suneetha and Dr Sainath K

January to May 2018

B.M.S. COLLEGE OF ENGINEERING, BENGALURU 560019
(Autonomous Institution under VTU)

DEPARTMENT OF CHEMICAL ENGINEERING

Tutorial Book

Unit No.	Date	Page No.
1.		
2.		
3.		
4.		
5.		

B.M.S. COLLEGE OF ENGINEERING, BENGALURU 560019
(Autonomous Institution under VTU)

Unit 1: Tutorial Problems

1. The lower plate is being pulled at a relative velocity of 0.4 m/s greater than top plate. The fluid is at 24°C and viscosity 0.4×10^{-2} Ns/m^2.

   (i) How far apart should the two plates be placed so that the shear stress, $\tau_{yx} = 0.3\,\text{N/m}^2$? and (ii) What is τ_{yx} and shear rate, if oil viscosity is 2×10^{-2} N s/m^2?

2. A material of area 3 m^2 and thickness, Y of 0.25 cm conducts heat at a rate of 6W. The temperature difference across is 40°C, estimate the thermal conductivity of the material.

3. The distance between two parallel plates is 9.14×10^{-3} m. The lower plate is being pulled at a relative velocity of 0.0366 m/s greater than the top plate. The fluid used in soya bean oil with viscosity 0.4×10^{-2} Pa s at 303 K.

   i. Calculate the shear stress and shear rate.
   ii.If glycerol at 293 K having a viscosity of 1.069 kg/m s is used instead of soya bean oil, what relative velocity is needed using the same distance between the places so that the same shear stress is obtained as (i) and what is the new shear rate?

4. A Newtonian fluid is contained in a space between two parallel plates 60 mm apart. The top plate is moving at a velocity of 25 cm/min and the bottom plate is moving at 80 cm/min in the opposite direction. The viscosity of the fluid is 1.5 Poise. Calculate the steady state velocity at 1 cm interval and plot the velocity profile.

5. Calculate the momentum flux for a system with lower plate moving with a velocity of 1 m/s. Distance between the plates is 1 mm and viscosity of one centipoise.

6. Compute the steady-state momentum flux in N/m^2 when the lower plate velocity is 0.3048 m/s in the positive x-direction, the plate separation is 0.3048×10^{-3} m and the fluid viscosity is 0.7 centipoise.

7. Estimate the viscosity of nitrogen at 50°C and 854 atm, given M = 28, p_c = 33.5 atm, T_C = 126.2 K and μ/μ_C = 2.39.

8. A plastic panel of area 1 ft^2 and thickness 0.252 inch was found to conduct heat at a rate of 3 W at steady-state with temperature of T_O = 24°C and T_1 = 26°C on the two main surfaces, What is the thermal conductivity of the plastic in W/m K at 25°C.

Unit 2: Tutorial Problems

1. A heavy oil is passed through a pipe of 5.08×10^{-2} m diameter. The pressure drop over a pipe is 68958 N/m^2. The viscosity of oil is 200 cP and density 800 kg/m^3. The length of pipe is 3.048 m. (i) Calculate the volumetric flow rate of oil (ii) Calculate and plot momentum flux profile.

2. Water enters a boiler at 18.33°C and 137.9 kPa through a pipe at an average velocity of 1.52 m/s exit stream at a height of 15.2 m above the liquid inlet leaves at 137.5 kPa, 148.9°C and 9.14 m/s in the outlet line. At steady state, how much heat must be added per kg mass of steam? The flow in two pipe is turbulent.

3. Determine the viscosity of glycerin in centi-Poise for the following data. Glycerin at 300 K is flowing through a horizontal pipe of 0.3048 m long and with 0.254 cm inside diameter. A pressure drop of 40 psi, the volume flow rate is 1.87×10^{-6} m^3/s. The density of the glycerin at 300 K is 1261 kg/m^3.

4. A 20 kg, 25 mm diameter, 30 cm tall cylindrical tank slides down a ramp with a constant speed of 3 cm/s. The uniform thickness oil layer on the ramp has a viscosity of 1 Pa s. Determine the angle of inclination of the ramp.

5. A test on water in a capillary viscometer gave the following data: flow rate = 880 mm^3/s, tube length = 1 m, tube diameter = 0.5 mm, and pressure drop = 10 MPa. Determine the viscosity of water and test the flow whether in laminar region.

6. Pure water at 25°C is flowing down through a vertical wetted column at 0.124 m^3/s, with a density of 1000 kg/m^3 and viscosity of 1×10^{-3} Pa s. Calculate the film thickness and average velocity.

7. Oil is flowing in a laminar region in a 1.27×10^{-2} m diameter tube at the rate of 22.72 l/min. The oil viscosity is 250×10^{-3} N s/m^2 and its density is 958 kg/m^3. Calculate (a) The pressure drop per meter of the pipe length and (b) Wall stress in N/m^2 (c) The velocity at the center of the tube and (d) Radial position at which the velocity is equal to the average velocity

8. A horizontal annulus is 30.48 cm long. The outer radius of the inner cylinder is

1.257 cm, the inside radius of outer cylinder is 2.794 cm. 80% aqueous solution of sucrose is to be pumped through the annulus at 20°C. At this temperature the fluid density is 1287 kg/m^3 and viscosity is 0.0565 kg/ms. Calculate the volumetric flow rate when the pressure drop is 0.38 bar.

9. An aqueous homogenous solution of two polymers is pumped through an annulus at 293 K. The horizontal annulus is 8.23 m long, the outside radius of the inner cylinder is 1.25 cm, the inside radius of the outer cylinder is 2.794 cm. The density is 1287 kg/m^3 and viscosity is 566×10^{-4} Pa s at 293 K. Calculate the volumetric flow rate when the impressed pressure drop is 37.16 kN/m^2.

10. A laminar flow is taking place in a pipe of diameter of 200 mm. The maximum velocity is 1.5 m/s. Find the mean velocity and the radius at which this velocity occur.

11. Determine the radius of capillary tube by measuring the rate of flow of a Newtonian liquid through the tube, for following data.

    Length of capillary tube = 50.02 cm, Kinematic viscosity of liquid = 4.03×10^{-5} m^2/s, Density of liquid = 0.9552×10^3 kg/m^3, Pressure drop in the horizontal tube = 4.829×10^5 Pa and Mass flow rate of flow = 2.997×10^{-3} kg/s

12. Ethyl alcohol is kept between the two parallel plates. The lower plate is suddenly set in motion with velocity 10 cm/s. The distance between the plates is 0.5 cm and ethyl alcohol has a viscosity of 1.77 cP. Calculate the shear stress and the shear rate for this system.

13. A Newtonian fluid is flowing through a pipe of diameter of 9 cm with a volumetric flow rate of 0.5×10^{-4} m^3/s. Pressure drop is 1.5×10^{-4} atm is existing at the two ends of pipe. Determine the viscosity of the fluid.

14. Two stainless steel tanks are connected at the bottom by a pipe of 10 cm diameter and 150 m length. The tanks contain an oil density of 900 kg/m^3 and viscosity of 0.12 Pa s. Determine the maximum difference in the elevation in the oil surfaces in the tanks for laminar flow in the pipe.

15. A Newtonian fluid is flowing through a pipe of diameter of 9 cm with a volumetric flow rate of 0.5×10–2 m3/s. A pressure drop of 1.5×10–4 atm is existing at the two ends of the pipe. Determine the viscosity of the fluid.

16. Calculate the pressure drop for a flow of fluid in a horizontal smooth circular pipe of an inside diameter of 30 mm and at volumetric flow rate of 1.4 l/s at 20°C. Data: density = 0.935 kg/m^3 and friction factor = 0.0063

Unit 3: Tutorial Problems

1. The inside temperature of a furnace wall of 200 mm thick is 1350°C. The mean thermal conductivity of the wall material is 1.35 W/mK. The heat transfer coefficient of the outside surface is $h = 7.85 + 0.08\ \Delta T$, where ΔT is the temperature difference between outside wall surface and surroundings. Determine the rate of heat transfer per unit area if the surrounding temperature is 40°C.

2. Oil which is used as lubricant for a pair of cylindrical surfaces has density of 1.22 g/cc, viscosity of 92.3 cP and thermal conductivity of 0.0055 cal/cm°C. Outer cylinder is rotating at 7908 rpm. Radius of rotating cylinder is 5.06 cm and the clearance between which lubricant is filled in is 0.027 cm. calculate

   i. Temperature at a distance 0.019 cm when rotating surface is at 70°C and surrounding atmosphere is at 30°C.

   ii. Maximum temperature in the oil if surfaces are at thermal equilibrium at 70°C.

3. A copper wire has a diameter of 3 mm and a length of 5 m. For what voltage drop would the temperature at the wire axis be 10°C, if the surface temperature of the wire is 20°C? Data: Lorenz number of copper = $k/(k_e T_0) = 2.23\times10^{-8}$ volt^2/K^2.

4. Two slabs each of 120 mm thickness have thermal conductivities of 14.5 and 210 W/mK respectively. These are placed in contact but due to roughness only 50% of the area is in contact and the gap in the remaining area is 0.025 mm thick and is filled with air. If the temperature of the face of hot surface is 220°C and the outside surface of the other slab is at 30°C, determine the rate of heat flow through composite system, the contact resistance and temperature drop in contact. Assume that the conductivity of air as 0.032 W/mK.

5. A furnace wall consists of 3 layers (i) A layer of heat resistant or refractory brick, (ii) a layer of insulating brick, and (iii) a steel plate of 0.635×10^{-2} m thick, for protection. Calculate the thickness of each layer of brick to give minimum total

wall thickness if the heat loss through the wall is to be 15.77 kW/m^2, assuming that the layers are in excellent thermal contact. The following information is available.

Material	Maximum allowable temperature (K)	Thermal conductivity (W/m^{2}K)	
		At 311 K	At 1366 K
Refractory brick	1700	10.22	20.44
Insulating brick	1366	5.11	10.22
Steel	-	148.20	-

6. Heat is generated within a sphere at a rate of 20×10^5 kW/m^3. The diameter of the sphere is 0.163 m. The surface temperature of sphere is 100°C. The thermal conductivity of the metal of the sphere is 1400 W/m°C. Calculate the temperature at the center of the sphere and at radius of 0.04 m.

7. A copper wire has a radius of 2 mm and a length of 5 m. For what voltage drop would the temperature rise at the wire axis is 10°C, if the surface temperature of the wire is 20°C?

8. An electric current of 2000 Amps is passed through a copper wire of radius of 1.26 mm and length of 91 cm. The wire has resistance of 0.126 Ohms. The outer surface temperature is held at 422.1 K. The average thermal conductivity is 22.5 W/mK. Calculate the centerline temperature.

9. A furnace wall is exposed to hot flue gases at 1100 K. The wall consists of 0.12 m of fire brick and 0.25 of common brick. Heat transfer coefficient on the hot side is 3000 W/m^{2}K and 22 W/m^{2}K on the outside. Ambient air is at 300 K. Calculate the heat transfer rate per m^2 of wall and temperature at the interface of the two bricks. The thermal conductivity of the both the bricks is 0.138 W/mK.

10. A current of 300 Amps is passed through a stainless steel wire of 2.5 mm in diameter. The resistivity of the wire is 10 mill Ohm-m and length of wire is 1.5 m. If the outer surface temperature of wire is at 200°C, calculate the center

temperature of wire. The thermal conductivity of the wire is 40 W/m°C.

The heat source is $Se = \frac{i}{A^2} R_e$, where R_e is resistivity of wire.

11. A standard steel pipe of inside diameter 5.2 cm and wall thickness 0.31 cm is carrying steam and is insulated with 5 cm layer of 85% magnesia covered with 10 cm layer of cork material. Estimate heat loss per hour per meter of pipe if the inside surface of pipe is maintained at 140°C and outer surface of cork is 30°C. Given k_{steel} = 42.2 W/mK, $k_{\text{85\% magnesia}}$ = 0.09 W/mK and k_{cork} = 0.03 W/mK. Calculate the interface temperature.

12. A brick wall of area 8 m^2 and thickness 30 cm has surface temperatures of 350°C and 80°C under steady state heat loss by conduction. The outside temperature of 80°C is found to be high. It is desired to bring it down to 25°C or less. Keeping the dimensions, heat loss same and inner temperature same, determine the thermal conductivity of new material to replace brick. Thermal conductivity of brick wall is 63 W/mK.

13. The heat flux q is 6000 W/m^2 at the surface of an electric heater. The heater temperature is 120°C when it is cooled by air at 70°C. What is the average convective heat transfer coefficient $\bar{h}$? What will the heater temperature be if the power is reduced so that q is 2000 W/m^2?

14. A long cylindrical annulus of 50 mm ID and 100 mm OD is having thermal conductivity of 14.5 W/m°C. The inner surface is maintained at 100°C and outer surface at 30°C. Make a plot of temperature profile in the annulus. What are the temperature gradients at the inner and outer boundaries?

15. One end of a heavy long aluminum rod of 4 mm diameter is connected to a wall at 467 K, while the other end protrudes into a space whose temperature is 300 K. Determine the total heat dissipated by the rod. Data: thermal conductivity of aluminum is 150 W/mK and film coefficient 310 W/m^{2}K.

16. A standard schedule 40, 2 inch. steel pipe of internal diameter of 52.5 mm and wall thickness of 4 mm is carrying super-heated steam is lagged with 51 mm of

85% magnesia and covered with 51 mm of cork. Estimate the heat loss per meter of length of the pipe. The inner surface of the steel pipe is at 121°C and the outer surface of the cork at 32°C. The thermal conductivity of the steel is 45.15 W/mK, 85% magnesia is 0.0692 W/mK. Also estimate the temperature at the contact point between the materials.

17. Determine the Brinkman number for a viscous fluid of viscosity 5 cP and velocity of 0.1 m/s flowing through a cavity of metal with thermal conductivity of 0.055 cal/cm °C cm. The temperature difference between the metal wall is 10°C.
18. Oil is acting as a lubricant for a pair of cylindrical surfaces. The angular velocity of outer cylinder is 7900 rpm. Outer cylinder has a radius of 6 cm and the clearance between the cylinders is 0.02 cm. What is the maximum temperature in the oil if both wall temperatures are known to be 160°C?

Unit 4: Tutorial Problems

1. Oxygen (X) is diffusing through carbon monoxide (Y) under steady state conditions with carbon monoxide non-diffusing. The total pressure is 1×10^{7} Pa, and the temperature 10°C. The partial pressure of oxygen at two planes 2 mm apart is 13,000 and 6500 Pa respectively. The diffusivity of the mixture is 1.87×10^{-6} m^2/s.

   (i) Calculate the rate of diffusion of oxygen in kmol/s through each square meter of two phases. and (ii) Calculate the rate of diffusion of oxygen in kmol/s through each square meter of two phases, where non-diffusing carbon monoxide is replaced by methane (Y) and hydrogen (H).

   Data: $D_{O2\text{-}H2} = 6.99\times10^{-5}$ m^2/s and $D_{O2\text{-}CH4} = 1.86\times10^{-5}$ m^2/s

2. Chloropicric (CCl_3NO_2) is kept in a Arnold cell and the liquid is evaporating in the stagnant air at 25°C. Determine the rate of evaporation from the following data.

   Total pressure = 770 mmHg, Diffusivity = 8.8 $\times10^{-6}$ m^2/s, Vapor pressure = 23.8 mmHg, Distance of liquid level to the top of the tube = 11.14 cm, Molecular weight = 164.35, Density of CCl_3NO_2 = 1650 g/cc and Surface area of the liquid exposed for evaporating = 2.29 cm^2

3. Aniline is absorbed from air-aniline mixture using oil in a wetted wall tower experiment. Wash oil flows at a velocity of 12 cm/s. What is the rate of absorption in kmol/s if diffusion co-efficient is 32×10^{-5} m^2/s. Air contains 3% aniline at 1 atm pressure and 24°C. Wash oil is 2 m thickness flows over a tube of length 15 cm and radius 2 cm.

4. A mixture of benzene and toluene is distilled in a mass transfer laboratory unit at one plane in a vertical tube. The vapor contains 85.3 mol% benzene, and at the adjacent liquid film contains 70 mol% benzene at the temperature of 87°C. The gas layer between is assumed to be stagnant and 0.254 cm thick. The molar latent heats of vaporization of benzene and toluene are same implying

equimolar counter diffusion. The vapor pressure of toluene at 87°C is given as 368 mmHg. Calculate the rate of interchange of benzene and toluene between the vapor and liquid by diffusion coefficient of benzene-toluene vapor is 5.06×10^{-6} m^2/s.

5. The diffusivity of methanol in air is determined by observing the steady state evaporation of CH_3OH into a tube containing air. The distance between the methanol liquid level and the top of the tube is 16 cm. The pressure and temperature are 1 atm and 298 K. The vapor pressure of methanol at 298 K is 17 kPa and its specific gravity is 0.7914. The cross-sectional area of the tube is 0.8 cm^2. It is found that 0.0887 cc of methanol evaporates in a 10 hour period after steady state has been attained. Estimate the diffusivity of methanol-air.

6. A gas mixture at a total pressure of 2.5×10^5 Pa and 315 K contains 15% H_2, 25% O_2 and 60% H_2O vapor by weight. The absolute velocities of each species are 15 m/s, - 12 m/s and 10 m/s respectively. Determine the molar and mass average velocities.

7. The diffusivity of the gas pair oxygen-carbon tetrachloride is determined by observing the steady state evaporation of CCl_4 into a tube containing O_2. The distance between the CCl_4 liquid level and top of the tube is 17.1 cm. The total pressure on the system is 755 mmHg and the temperature is 0°C. The vapor pressure of CCl_4 at that temperature is 33 mmHg. The cross sectional area of the diffusion tube is 0.82 cm^2. It is found that 0.0208 cm^3 of CCl_4 evaporate in a 10 hour period after steady state has been attained. What is the diffusivity of the gas pair CCl_4–O_2? Data: density of CCl_4 = 1.59 g/cc and molecular weight of CCl_4 = 154 g/mol.

8. A mixture of He and N_2 gas contained in a pipe is at 298 K and 1 atm total pressure, which is constant. At one point of the pipe, the partial pressure of He is p_{A1} = 0.6 atm and at the other end 0.2 m away p_{A2} = 0.2 atm. Calculate the flux of He at steady state if the diffusivity is 0.687×10^{-4} m^2/s.

9. Air at 273 K flows over a steam lined naphthalene body. Naphthalene sublimes into air and its vapor pressure is 20 mmHg. The heat transfer coefficient for the

same shape and air velocity was previously found to be 22 W/m^2°C. The concentration of naphthalene in the bulk of air steam is negligibly small. The mean diffusivity of naphthalene in air is 0.02873 m^2/h. Calculate the mass transfer coefficient and the mass flux for the system.

Properties of air at 273 K

Kinematic viscosity = 23.13×10^{-6} m^2/s

Thermal conductivity = 3.21×10^{-2} W/m°C

Specific heat (C_P) = 1.009 kJ/kg°C

Density = 0.946 kg/m^3

10. If an O_2-N_2 gas mixture at 1 atm and 25°C, the concentration of O_2 at two planes 2 mm apart are 10 and 20% (v/v) respectively. Calculate the flux of diffusion of O_2 for the cases where

(i) the N_2 is non-diffusing

(ii) there is equimolar counter-diffusion of the gases

Data: $D_{O_2-N_2}$ at 0°C = 1.86×10^{-5} m^2/s

Unit 5: Tutorial Problems

1. Oil is manufactured by the vapor phase catalytic reaction. The reaction gas mixture leaving the catalytic reactor in the plant is condensed in a shell- and-tube heat exchanger. The condensation occurs on the shell side while the cooling water flows through the tubes. The tubes are 3 m long and 25 mm outside diameter, 14 BWG (Birmingham Wire Gauge). Water flows at a rate of 0.057 m^3/min per tube. Water enters at 32°C. The tube wall temperature may be assumed to be constant at 80°C. Calculate the heat transfer coefficient by the Reynolds analogy. Data: properties of water: density = 995 kg/m^3, viscosity = 7.65×10^{-4} kg/ms, thermal conductivity = 0.623 W/m°C, specific heat = 4.17 kJ/kg°C, Internal diameter of the tube (14 BWG) = 21.2 mm and the fanning friction factor can be calculated by the equation, $f = 0.0014 + 0.125(\mathrm{Re})^{-0.32}$.

2. Oil is manufactured by the vapor phase catalytic reaction. The reaction gas mixture leaving the catalytic reactor in the plant is condensed in a shell- and-tube heat exchanger. The condensation occurs on the shell side while the cooling water flows through the tubes. The tubes are 3 m long and 25 mm outside diameter, 14 BWG (Birmingham Wire Gauge). Water flows at a rate of 0.057 m^3/min per tube. Water enters at 32°C. The tube wall temperature may be assumed to be constant at 80°C. Calculate the heat transfer coefficient by the Prandtl analogy. Data: properties of water: density = 995 kg/m^3, viscosity = 7.65×10^{-4} kg/ms, thermal conductivity = 0.623 W/m°C, specific heat = 4.17 kJ/kg°C, the fanning friction factor can be calculated by the equation, $f = 0.0014 + 0.125(\mathrm{Re})^{-0.32}$.

3. Oil is manufactured by the vapor phase catalytic reaction. The reaction gas mixture leaving the catalytic reactor in the plant is condensed in a shell- and-tube heat exchanger. The condensation occurs on the shell side while the cooling water flows through the tubes. The tubes are 3 m long and 25 mm outside diameter, 14 BWG (Birmingham Wire Gauge). Water flows at a rate of 0.057 m^3/min per tube. Water enters at 32°C. The tube wall temperature may be assumed to be constant at 80°C. Calculate the heat transfer coefficient by the Chilton-Colburn analogy. Data: properties of water: density = 995 kg/m^3, viscosity = 7.65×10^{-4} kg/ms, thermal conductivity = 0.623 W/m°C, specific heat = 4.17 kJ/kg°C, the fanning

friction factor can be calculated by the equation, $f = 0.0014 + 0.125(\text{Re})^{-0.32}$.

4. Aniline is manufactured by the vapor phase catalytic reaction of nitrobenzene and hydrogen. The reaction gas mixture leaving the catalytic reactor in the plant is condensed in a shell- and-tube heat exchanger. The condensation occurs on the shell side while the cooling water flows through the tubes. The tubes are 3 m long and 25 mm outside diameter, 14 BWG (Birmingham Wire Gauge). Water flows at a rate of 0.057 m^3/min per tube. Water enters at 32°C. The tube wall temperature may be assumed to be constant at 80°C. Calculate the rise in temperature of water as it flows through the tube. The heat transfer coefficient may be estimated from the Dittus-Boelter equation. Compare the results from different analogies. Assume one tube. Internal diameter of the tube (14 BWG) = 21.2 mm

   Data: properties of water: density at 32°C = 995 kg/m^3, viscosity = 7.65×10^{-4} kg/ms, thermal conductivity = 0.623 W/m°C, specific heat = 4.17 kJ/kg°C, the fanning friction factor can be calculated by the equation, $f = 0.0014 + 0.125(\text{Re})^{-0.32}$.

References

1. **Question papers of previous years, Department of Chemical Engineering, BMSCE.**
2. **Edwin N. Lightfoot, Robert Byron Bird, and Warren E. Stewart, Transport Phenomena, 2nd edition, Wiley-India, 2006.**