UNIVERSITY OF GHANA

BSC. MATERIALS SCIENCE AND ENGINEERING

SECOND SEMESTER EXAMINATIONS: 2015/2016

SCHOOL OF ENGINEERING SCIENCES

DEPARTMENT OF MATERIALS SCIENCE AND ENGINEEINRG

MTEN 308: HEAT AND MASS TRANSFER (3 CREDITS)

INSTRUCTIONS:
ANSWER ALL QUESTIONS IN BOTH SECTIONS A AND B. ANSWER BOTH SECTIONS IN THE BOOKLET PROVIDED. FOR SECTION A WRITE THE APPROPRIATE LETTER OF CHOICE IN THE ANSWER BOOKLET.

TIME ALLOWED: THREE (3) HOURS

SECTION A

ANSWER ALL QUESTIONS IN ANSWER BOOKLET. THIS SECTION CARRIES 60 MARKS.

1. Which of the following mold-molten metal interface contours diverges heat flow best?
   a. Plane mold surface
   b. Convex mold surface
   c. Concave mold surface
   d. Heat diffusivity

2. Which quantity is defined by $\rho k C_p$?
   a. Thermal diffusivity
   b. Heat conductivity
   c. Heat diffusivity
   d. Thermal emissivity

3. Which dimensionless quantity is defined by $\frac{hL}{k}$, k is the thermal conductivity of the solid?
   a. Fourier number
   b. Nusselt's number
   c. Biot number
   d. Prandtl number

4. What dimensionless quantity is described by $\frac{\alpha t}{L^2}$?
   a. Fourier number
   b. Nusselt's number
   c. Biot number
   d. Prandtl number

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5. The dimensionless number defined as $\frac{hL}{k}$, where k is the thermal conductivity of the fluid is called
   a. Fourier number
   b. Nusselt's number
   c. Biot number
   d. Prandtl number

6. The heat transfer mode in which the velocity and temperature distribution cannot be treated separately because the velocities are not know *priori* is known as
   a. Free convection.
   b. Forced convection.
   c. Convection .
   d. Neutral convection.

7. The thermal conductivity of air in a boundary layer at a temperature 325 K is 28.1×10^{-3} $Wm^{-1}K^{-1}$. If for a boundary layer that is 0.3 m long the Nusselt's number is 291. What is the heat transfer coefficient?
   a. 72.2 $Wm^{-2}K^{-1}$
   b. 27.2 $Wm^{-2}K^{-1}$
   c. 22.7 $Wm^{-2}K^{-1}$
   d. 32.7 $Wm^{-2}K^{-1}$

8. For the in question 7 above, if it is at a temperature 290 K and flows over a plate at 360 K, what is the rate of heat transfer from the plate? Take the area to be 0.03 m^2.
   a. 571 W
   b. 17.5 W
   c. 175 W
   d. 57.1 W

9. It is the ratio of momentum to thermal diffusivity, what is it?
   a. Fourier number
   b. Nusselt's number
   c. Biot number
   d. Prandtl number

10. In forced convection, when the Prandtl number is approximately equals 1
   a. $\delta_T \approx \delta$
   b. $\delta_T < \delta$
   c. $\delta_T >> \delta$
   d. $\delta_T << \delta$

11. For liquid metals in forced convection
   a. $\delta_T \approx \delta$
   b. $\delta_T < \delta$
   c. $\delta_T >> \delta$
   d. $\delta_T << \delta$

12. In forced convection,

a. The velocity profile is dependent on temperature profile.
b. The velocity profile is independent on temperature profile.
c. The velocity profile equals temperature profile.
d. The velocity profile changes significantly.

13. Which is the odd one?
   a. Stefan-Boltzmann law
   b. Newton's law of cooling
   c. Newton's law of viscosity
   d. Fourier law

14. Which of the following represents a steady-state one-dimensional heat diffusion equation?
   a. $\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$
   b. $\frac{\partial^2 T}{\partial x^2} = 0$
   c. $\frac{\partial T}{\partial t} = \nabla \cdot \alpha \nabla T$
   d. $\nabla^2 T = 0$

15. Which of the following represents the thermal resistance in an infinite slab of length L and area A?
   a. $\frac{1}{Ah}$
   b. $\frac{\ln(r_2/r_1)}{2\pi Lk}$
   c. $\frac{L}{Ak}$
   d. $\frac{k}{AL}$

16. Which of the following set of boundary conditions is valid for the development of a semi-infinite solution to the transient heat diffusion problem?
   a. $T(x,0) = T_i$; $T(0,t) = T_s$; $T(\infty,t) = T_i$
   b. $T(x,0) = T_s$; $T(0,t) = T_s$; $T(\infty,t) = T_i$
   c. $T(x,0) = T_i$; $T(0,t) = T_s$; $T(\infty,t) = T_s$
   d. $T(x,0) = T_i$; $T(0,t) = T$; $T(\infty,t) = T_i$

17. Which of the following materials develops insignificant thermal gradient across it when two sides are exposed to different temperatures?
   a. MgO
   b. Al_2O_3

c. Sand
d. Aluminium

18. What is the heat flux across a plate of lead ($k = 35\ Wm^{-1}K^{-1}$) 1 cm thick that is subjected to 60 °C on one side and 10 °C on the colder side?
   a. 175 kW
   b. 157 kW
   c. 517 kW
   d. 715 kW

19. Which of the following materials has the best thermal insulation properties?
   a. Silver ($k = 427\ Wm^{-1}K^{-1}$)
   b. Mild steel ($k = 54\ Wm^{-1}K^{-1}$)
   c. Silica aerogel ($k = 0.024\ Wm^{-1}K^{-1}$)
   d. Ice ($k = 2.215\ Wm^{-1}K^{-1}$)

20. The concept of gray body approximates the absorptivity, α of a surface to be equal to its emissivity, ε. Under what conditions may this be valid?
   a. Varying emissivity over wide temperature range
   b. Constant emissivity over wide temperature range
   c. When the surface has a grayish appearance
   d. When the surface is a good reflector

21. The flux of thermal radiant energy incoming to a surface is the
   a. Total radiosity
   b. Emissive power
   c. Total irradiation
   d. Total absorptivity

22. The fraction of the radiation whih leaves surface i in all directions and is intercepted by surface j is known as?
   a. View factor
   b. Shape configuration
   c. Appearance factor
   d. Emissivity

23. Calculate the net heat flow by radiation to a furnace wall at 530 K from the furnace floor at 810 K. Both surfaces are black radiators. Take $F_{12} = 0.16$ area $A_1 = 6.66\ m^2$ and $\sigma = 5.699 \times 10^{-8}\ Wm^{-2}K^{-4}$.
   a. 24,240 W
   b. 21,240 W
   c. 22,420 W
   d. 12,420 W

24. The diffusion coefficient that depends on the mole ratios of the diffusing species and their intrinsic diffusivities is known as
   a. Self diffusion coefficient
   b. Intrinsic diffusion coefficient

c. Fick's diffusion coefficient
d. Inter-diffusion coefficient

25. Values of diffusion coefficient is dependent on temperature via the
    a. Stefan-Boltzmann equation
    b. Arrhenius equation
    c. Gibbs equation
    d. Mass transfer equation

26. For the Fick's second law, which solution will satisfy the following boundary conditions: $C(x,0) = C_1$, $C(\infty,t) = C_1$ and $C(0, t) = C_s$
    a. $\dfrac{C_s - C}{C - C_s} = erf\left(\dfrac{x}{2\sqrt{Dt}}\right)$
    b. $\dfrac{C - C_s}{C_1 - C_s} = erf\left(\dfrac{x}{2\sqrt{Dt}}\right)$
    c. $C(x,t) = \dfrac{\beta}{\sqrt{\pi Dt}}\exp\left(\dfrac{-x^2}{4Dt}\right)$
    d. $\dfrac{dC}{dt} = D\dfrac{d^2C}{dx^2}$

A piece of AISI 1020 steel is heated to 1255 K and subjected to carburizing atmosphere such that the reaction

$$2CO = CO_2 + \underline{C}$$

is in equilibrium with 1.0 %C in solution at the surface. If the initial C concentration is 0.2 %C and the D_c is 2.0×10^{-11} m^2/s. Use this information to answer questions 27 – 28.

27. Calculate the carbon content at a distance $x = 5.0 \times 10^{-4}$ m after 1 hour.
    a. C = 0.53 %
    b. C = 0.48 %
    c. C = 0.35 %
    d. C = 0.70 %

28. What will be the carbon at $x = 5.0 \times 10^{-4}$ m after 3 hour.
    a. 0.56 %C
    b. 0.65 %C
    c. 0.80 %C
    d. 0.45 %C

29. Compute the diffusion coefficient for magnesium in aluminum at 550 °C if $D_o = 1.2 \times 10^{-4}$ m^2/s and Q = 131 kJ/mol.
    a. $D = 8.5 \times 10^{-13}$ m^2/s
    b. $D = 6.8 \times 10^{-13}$ m^2/s
    c. $D = 8.5 \times 10^{-13}$ m^2/s

d. $D = 5.8 \times 10^{-13}$ m²/s

30. Which of the following defines Sievert's law

a. $j_x = K\sqrt{p}$

b. $S = K\sqrt{p}$

c. $j = -D\dfrac{dC}{dt}$

d. $P = PK$

SECTION B

ANSWER ALL QUESTIONS IN THIS SECTION. YOU MAY USE APPROPRIATE INFORMATION FROM THE DATA AND EQUATIONS PRESENTED ON PAGES 8 AND 9 TO ANSWER THE QUESTIONS IN THIS SECTION.

1.

a. A thermocouple with an emissivity of 0.7 measures the temperature of a gas flowing in a long duct whose internal wall surfaces are at 533 K. The temperature indicated by the thermocouple is 811 K, and the convective heat transfer coefficient between the gas and the surface of the thermocouple is 110 $Wm^{-2}K^{-1}$. Determine the true temperature of the gas. The Stefan-Boltzmann constant, $\sigma = 5.699 \times 10\text{-}8$ $Wm^{-2}K^{-4}$.

(10 marks).

b. Consider a very long cylindrical stainless steel bar, 127 mm in diameter, which is heated to 478 K uniformly across its diameter. The bar is then cooled in a blast of fan forced air at 300 K with h = 142 $Wm^{-2}K^{-1}$. The thermal properties of stainless steel are k = 16 $Wm^{-1}K^{-1}$ and $\alpha = 4.08 \times 10^{-6}$ m^2s^{-1}.

i. Find the time it takes to for the center to reach 310 K.

ii. When the center reaches 310 K, what is the surface temperature?

(10 marks).

c. Differentiate the concepts of forced and natural convections. Include in each case how the heat transfer coefficient may be determined.

(5 marks).

2. In the fabrication of solid-state microelectronic devices, semiconducting thin films can be made by impregnating either phosphorous or boron into a silicon wafer. This process is called doping. The doping of phosphorous atoms into crystalline silicon makes an n-type semiconductor, whereas the doping of boron atoms into crystalline silicon makes a p-type semiconductor. The formation of the semiconducting thin film is controlled by the molecular diffusion of the dopant atoms through crystalline-silicon matrix. Methods to deliver phosphorous atoms to the silicon wafer surface include chemical vapor deposition and ion implantation. In one typical process, phosphorous oxychloride, $POCl_3$, which has a normal boiling point

of 105.3 °C, is vaporized. The $POCl_3$ vapors are fed into a chemical vapor deposition (CVD) reactor at elevated temperature and reduced system pressure (e.g.,0.1atm), where $POCl_3$ decomposes on the silicon surface according to the reaction

$$Si_{(s)} + 2POCl_{3\,(g)} \rightarrow SiO_{2\,(g)} + 2Cl_2 + 2P_{(s)}$$

A SiO_2 coating rich in molecular phosphorous (P) is formed over the crystalline-silicon surface. The molecular phosphorous then diffuses through the crystalline silicon to form the Si–P thin film. So the coating is the source for mass transfer of phosphorous, and the silicon wafer is the sink for mass transfer of phosphorous.

As one can see in Figure 1 below , the process for making Si–P thin films can be quite complex with many species diffusing and reacting simultaneously. But consider a simplified case where the P-atom concentration is constant at the interface. As the diffusion coefficient of P atoms in crystalline silicon is very low, and only a thin film of Si–P is desired, phosphorous atoms do not penetrate very far into the silicon. Therefore, the phosphorous atoms cannot ''see'' through the entire thickness of the wafer, and the Si solid serves as a semi-infinite sink for the diffusion process. It is desirable to predict the properties of the Si–P thin film as a function of doping conditions. The concentration profile of the doped phosphorous atoms is particularly important for controlling the electrical conductivity of the semiconducting thin film.

Consider the phosphorous doping of crystalline silicon at 1100 °C, a temperature high enough to promote phosphorous diffusion. The surface concentration of phosphorous (C_s) in the silicon is 2.5×10^{20} atoms P/cm^3 solid Si, which is relatively dilute, as pure solid silicon is 5.0×10^{22} atoms S/cm^3 solid. Furthermore, the phosphorous-rich coating is considered as an infinite source relative to the amount of P atoms transferred, so that C_s is constant. Predict the depth of the Si–P thin film after 1 hour, if the target concentration is 1% of the surface value (2.5×10^{18} atoms P/cm^3 solid Si) and the equation for the concentration profile of P atoms after 1 h.

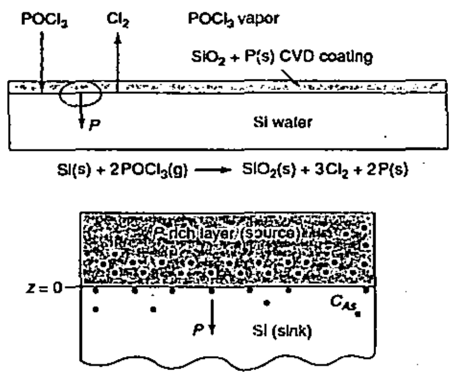

Figure 1

(15 marks).

IMPORTANT EQUATIONS

1. $Nu_L = 0.664\,\mathrm{Pr}^{0.343}\,\mathrm{Re}_L^{0.5}$;

2. $Nu_L = 0.664\sqrt[4]{\dfrac{Gr_L \cdot \mathrm{Pr}^2}{4(0.861+\mathrm{Pr})}}$;

3. $\beta = \dfrac{1}{T}\,(\textit{for ideal gas})$

4. $\dfrac{\delta}{x} = \dfrac{5.0}{\sqrt{V_\infty x/\upsilon}}$; $\dfrac{\delta_T}{x} = \dfrac{5.0}{\sqrt{V_\infty x/\upsilon}}$;

5. $\dfrac{\delta_T}{\delta} = 0.975\,\mathrm{Pr}^{-1/3}$;

6. $Gr_x = \dfrac{g\beta(T_o - T_\infty)x^3}{\upsilon^2}$

7. $C(x,t) = \dfrac{\beta}{\sqrt{\pi D^{\bullet} t}}\exp\left[\dfrac{x^2}{4D^{\bullet} t}\right]$;

$$\frac{C-C_s}{C_2-C_s} = erf\left(\frac{x}{\sqrt{Dt}}\right)$$

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IMPORTANT DATA

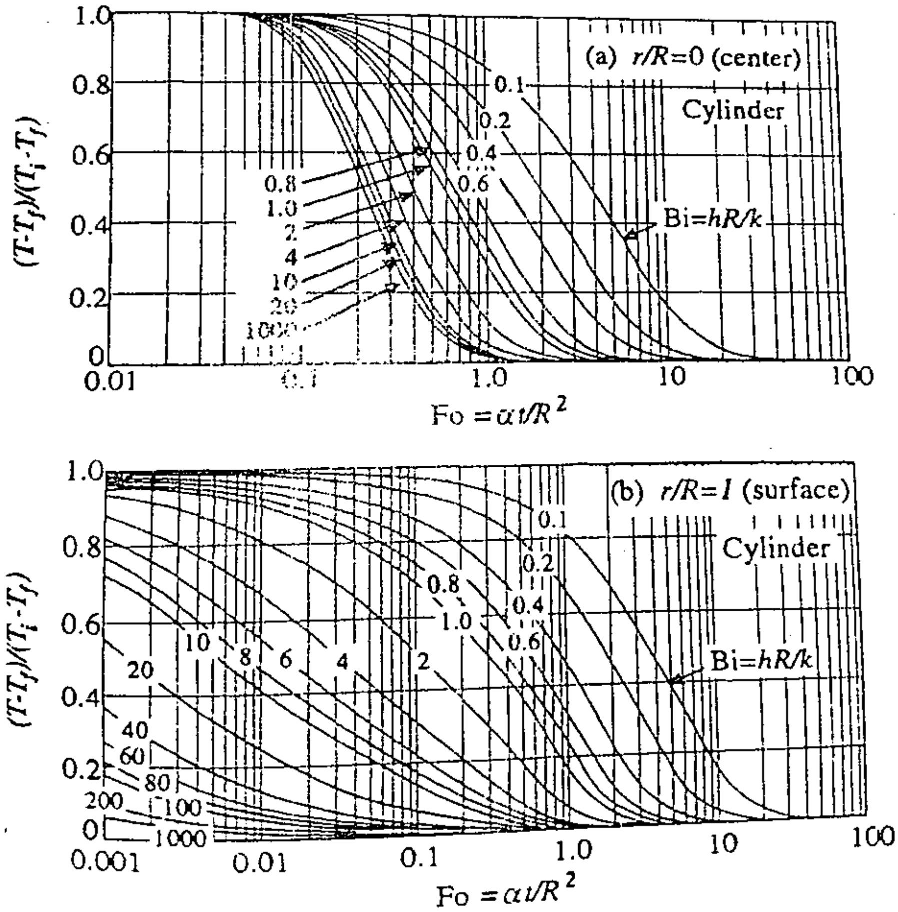

Figure 3 Temperature response of an infinite cylinder initially at a uniform temperature T_i, and the subjected to a convective environment at T_f.

Table of error function

N	erf N	N	erf N	N	erf N	N	erf N
0.00	0.00000	0.40	0.4284	0.80	0.7421	1.40	0.9523
0.05	0.05637	0.45	0.4755	0.85	0.7707	1.50	0.9661
0.10	0.1125	0.50	0.5205	0.90	0.7969	1.60	0.9763
0.15	0.1680	0.55	0.5633	0.95	0.8209	1.70	0.9838
0.20	0.2227	0.60	0.6039	1.00	0.8427	1.80	0.9891
0.25	0.2763	0.65	0.6420	1.10	0.8802	1.90	0.9928
0.30	0.3286	0.70	0.6778	1.20	0.9103	2.00	0.9953
0.35	0.3794	0.75	0.7112	1.30	0.9340		

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