# National Exams December 2009

## 98-Met-A2, Metallurgical Rate Phenomena

**3 hours duration**

## NOTES:

1. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer paper, a clear statement of any assumptions made.
2. This is an OPEN BOOK EXAM.
   Any non-communicating calculator is permitted.
3. FIVE (5) questions constitute a complete exam paper.
4. Each question is of equal value.

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## 98-Met-A2 Metallurgical Rate Phenomena

**Answer question number one, plus any four others. Open Book**

1. General knowledge questions to be answered by all candidates. Answer true, false, or ambiguous, and briefly explain your reasoning.

   a. The exact form of Ficks 1st Law of diffusion for one dimensional mass flow of solute A, in the x direction, can be written as $\dot{N}_Z'' = UC_A - D_{A/B}\frac{\partial C_A}{\partial x}$ where the first term on the right takes into account convection of mass?

   b. This law can be applied to inter-diffusion of solutes in solids, such as the inter-diffusion of carbon and silicon in steel.

   c. If one considers the inter-diffusion of mercury vapor with argon, then the two would have the same values of their inter-diffusion coefficients? i.e. $D_{Hg/A} = D_{A/Hg}$?

   d. Write down Fourrier's First and Second Laws of Heat conduction, defining your terms. The first law relates to steady state flow of heat through a material, the second to transient conduction of heat, in the absence of any convection?

   e. The viscosity of gases increases with pressure and decreases with increasing temperature?

   f. The thermal conductivity of a metal drops significantly on transforming from the solid to liquid state, owing to the enhanced resistance to the flow of electrons?

   g. The solubility of oxygen in solid steel is zero. For that reason, liquid steel containing any oxygen must be "killed" with aluminum additions to the molten steel, in order to "getter" the oxygen, and transform the oxygen atoms into alumina inclusions within the molten steel by a process of heterogeneous nucleation, growth, and agglomeration.

   h. A well mixed reactor is more efficient than a plug flow reactor because the latter does not have any turbulence to improve mixing between the reactants?

   i. The Froude number represents the ratio of inertial to gravitational forces, while the Reynolds number represents the ratio of viscous to inertial forces?

   j. The Biot and Nusselt numbers can be represented by hL/k, where h = interfacial heat transfer coefficient, L is a characteristic length, and k relates to the thermal conductivity of the liquid/gas phase?

   k. Radiation can be transmitted or absorbed in gases, but cannot be reflected, unlike solids and liquids?

**2 Foaming in Basic Oxygen Furnaces**

Assuming we have a 1 metre deep bath of liquid slag overlaying a 1 metre deep bath of carbon saturated liquid iron in a top blown oxgen steelmaking (BOF = Basic Oxygen Furnace) vessel which is 4 metres high internally, from bottom bricks to the mouth of the vessel. We know that the oxygen jet will react with dissolved carbon in the iron to form CO gas, and that this gas must then escape through the upper layer of liquid slag. If this gas passes through the slag layer in the form of;

a) small spherical bubbles, whose rise velocity through the slag is 4 cm/s, then a foaming slag will be generated that is liable to "slop" over the top of the BOF. Estimate the maximum height the foaming slag might reach in the cylindrical reactor.

b) large, spherical cap type bubbles, with rise velocities of 1.3 m/s. Again, estimate the foam height in the cylindrical BOF

You may use the relationship determined by Lin and Guthrie, correlating the voidage in a foaming slag with the nominal gas velocity of gas evolved (Gas Flowrate / Cross sectional area of cylindrical vessel), according to which;

voidage ε, is defined as the [volume of gas/ total volume of (slag + gas)], is related to bubble slip velocities and nominal gas velocities, according to;

$$\varepsilon = \frac{\Delta h}{h + \Delta h} = \frac{U_{gas}}{U_{gas} + (U_{bubble})}$$

Data. Nominal velocity of gas through the vessel = 2.89 metres/sec

**3 Melting Time for an aluminium addition to a steel bath**

Explain briefly how alloy additions, whose melting points are below the melting point temperature of liquid steel, behave thermally, when added to steel.

A 3mm diameter sphere of cold aluminum is added to a bath of molten steel at 1600°C. Assuming it remains submerged during the time it takes for it to melt into the bath of steel, **derive an expression** that relates melting time to the thermal properties of the addition, and to the convective heat input into the addition from the steel bath. **State your assumptions.** You may use the following data:

Specific heat of solid aluminum = 0.9 kJ/kg K

Specific heat of molten aluminum = 1.09 kJ/kg K

Melting point of aluminum = 660°C

Melting point of (low Carbon ) steel = 1500°C

Latent heat of fusion of aluminum = 387kJ/kg

Density of solid aluminum = 2700 kg/m$^3$

Density of liquid aluminum = 2400 kg/m$^3$

Density of liquid steel = 7000 kg/m$^3$

Convective Heat Transfer Coefficient from steel bath to aluminum sphere = 5 kW m$^{-2}$K$^{-1}$

**4 Limestone powder additions to a steel bath.**

Sumitomo sometimes practices the addition of fine powdered limestone, $CaCO_3$ , to remove inclusions in a fourth stage refining step. Calculate the maximum size of $CO_2$ bubble that you would expect to form, following its injection into the steel bath and subsequent decrepitation into a particle of CaO and $CO_2$ gas, given the following data.

Size of limestone particle = 1 micron

Density of limestone = 2710 kg m$^{-3}$

Steel Bath Temperature = 1600°C

Depth of particle injection = 1.3 m

Density liquid steel = 7000kg m$^{-3}$

Surface tension of steel = 1.8 N m$^{-1}$

1 mole of gas at 0°C and 1 atmosphere occupies 22.4 litres

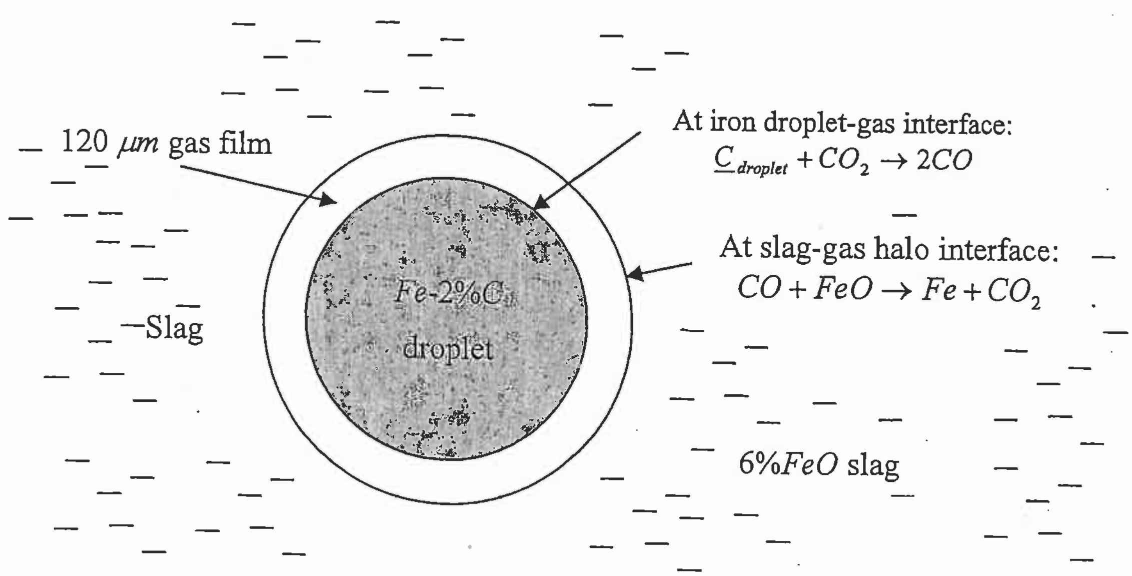
Molecular Wt Ca = 40, C = 12, O = 16 gm/gm mole

**5 Direct Steelmaking in slag foaming vessels**

In the direct steelmaking reactor based on the reduction of an oxidizing foaming slag by char (carbon) particles and droplets of iron containing 2% carbon, it is postulated that the rate controlling step governing the reduction of *FeO* within the slag is the transfer of *CO* and $CO_2$ across gas halos surrounding the iron droplets and char particles. In *AISI* plant trials, the smelting rate of iron was observed to be 4 *tonnes/hr* of *Fe,* for a slag *FeO* content of 6 *wt%*, and a slag weight of 40 *tonnes.* Estimate the total surface area of char and iron droplets needed to achieve the smelting rates observed. Assuming the average char and droplet diameters to be 1 *cm,* estimate the volumetric loading (i.e. volume percentage) of droplets and char corresponding to these smelting conditions. State any assumptions you see fit.

Data:

| | | |
|---|---|---|
| Atomic weight of *Fe* | : | 56 g/mol |
| Gas constant, *R* | : | 8.314 *J/mol·K* |
| Temperature of Foaming Slag | : | 1600 °*C* |
| Volume %$CO_2$ in gas phase halos at slag interfaces | : | 6 % |
| Gas pressure within halos | : | 1.2 *atm* |
| Gaseous Diffusion Coefficients ($D_{CO} = D_{CO_2}$) | : | $1.0\times10^{-3}$ $m^2/s$ |
| Density of molten slag | : | 3300 $kg/m^3$ |




**6 A dimensional analysis problem**

You are asked to design a process to create foamed sheets of aluminum. The concept is to gasify the liquid metal with tiny bubbles so as to create a foamed bed, and to then freeze it. Assuming that the thickness of the foamed sheet, *t,* depends on the viscosity of the liquid metal, $\mu$, its surface tension, $\sigma$, gas flowrate, $Q_g$, metal flowrate, $Q_m$, belt speed, $U_B$, and specific weight, $\rho g$, use dimensional analysis to show how the thickness should be related to the independent variables tested.

$$t = f\left(\mu, \sigma, Q_m, Q_g, U_B, \rho g\right).$$

In one experiment the viscosity of aluminum was 1.4 *mPa·s* and the surface tension of aluminum was 0.9 *N/m*, the thickness was measured to be 10 *mm* at a belt speed of 0.2 *m/s*. Estimate a corresponding belt speed and thickness of foamed steel plate, if equivalent experiments were to be conducted with liquid steel.

Data: Viscosity of liquid steel : 7 *mPa·s*
Surface tension of steel : 1.8 *N/m*

**7 A heat transfer correlation for liquid metals passing along a flat plate**

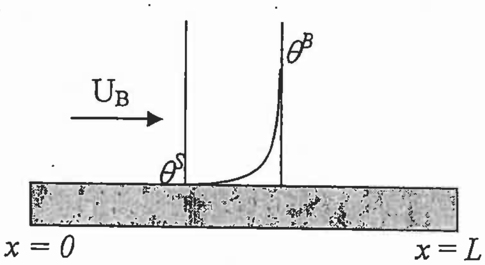
Liquid Metal flows at a velocity $U$ and temperature $\theta^B$ over a flat plate of length $L$, held at temperature $\theta^S$, in plug flow. Solve for the developing temperature profile within the liquid metal (assume semi-infinite approximation with a fixed value at the interface), as it flows across the surface and thereby show that the interfacial heat flux;

$$\dot{q}'' = -\frac{k\left(\theta^B - \theta^s\right)}{\sqrt{\pi \alpha t}}$$

Show that this can be expressed in the form

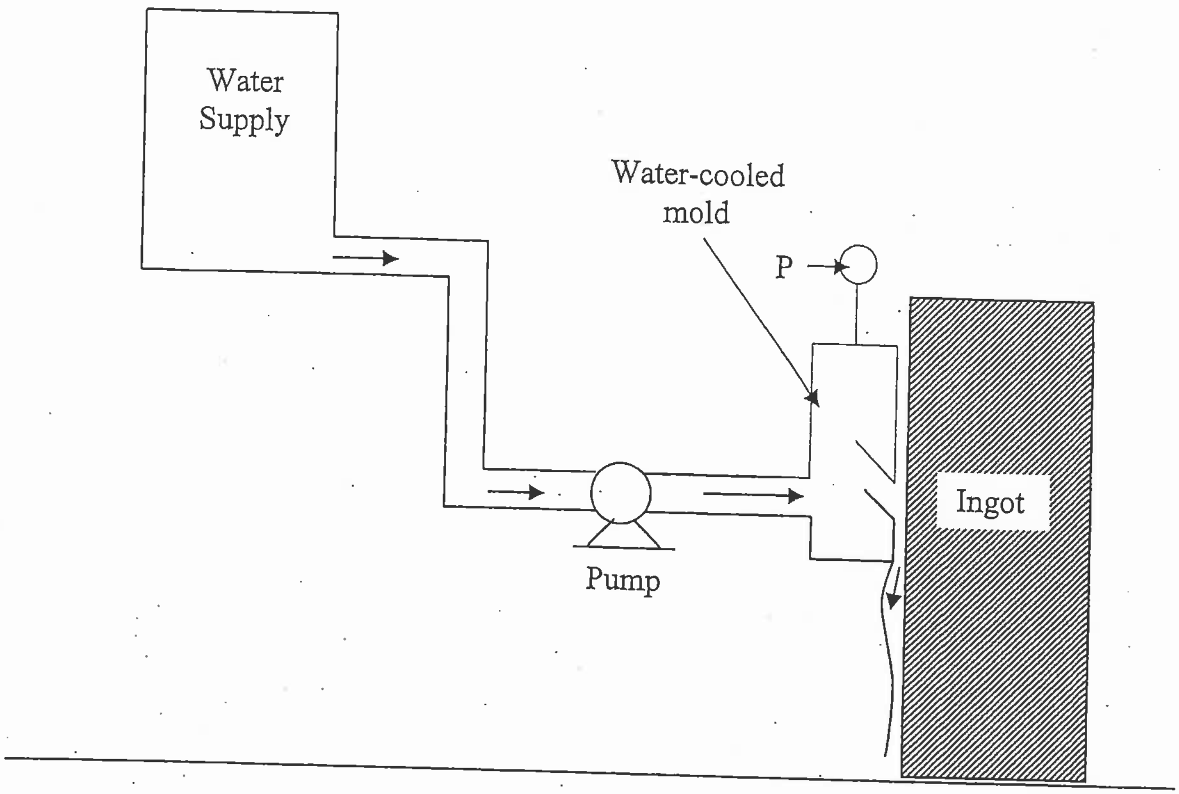
$$Nu_x = \sqrt{\frac{\mathrm{Re}_x \cdot \mathrm{Pr}}{\pi}}$$

where; $h \equiv \dfrac{\bar{\dot{q}}''}{\theta^B - \theta^S}$.




**8. Power / pumping requirements**

Water is pumped from a storage tank to a mold designed to produce nonferrous ingots by the "direct-chill" process. The water supply is at ambient pressure ($1.0133 \times 10^5$ $N/m^2$), and the water leaving the mold impinges upon the surface of the ingot, which is also at ambient pressure. A pressure gauge mounted in the manifold portion of the mold (pressure gauge P in the diagram) indicates an absolute pressure of $1.22 \times 10^5$ $N/m^2$, when the volume flow rate is $3.93 \times 10^{-3}$ $m^3/s$. The water level in the tank is 2-*m*, and the vertical length of the pipe is 4-*m*. Calculate the theoretical power of the pump needed to supply the required flow of water. Assume that the tank for the water supply has a very large diameter, and that the kinetic energy of the water within the manifold portion of the mold is negligible. Piping Information: total length of straight pipe, 9.14 *m*; diameter, 30.5 *mm*; $L_e/D = 25$ (elbows); $f = 0.004$; $e_{s.c} = 0.4$; $e_{s.e} = 0.8$.




**9. Continuous casting of steel billets.**

Steel is poured into a 140mm x 140mm square copper mould, 1.2m long, effective contact length with liquid steel, $L_e$ = 1.0m. The strand casting rate is 37mm/s. Develop an expression from first principles, stating your assumptions, to show that the thickness, x, of the steel shell formed at a contact time t = t, is given by the expression;

$$x = \sqrt{\frac{2k(T_{mp} - T_{surface})}{\rho LH}}\sqrt{t}$$

x = shell thickness at time t.
$T_{mp}$ is the freezing point of steel = 1492 °C
$T_{surface}$ is the (assumed constant) surface temperature of the forming shell= 1000°C
ρ is the density of liquid steel = 7100 kg/m$^3$
LH = latent heat of solidification = 260 kJ/kg
k = thermal conductivity of steel = 25 W/m °C
$t_e$ = contact time of steel shell with mould before exiting into the water spray cooling zones.

In order to cross check these calculations by doing a heat balance, it was decided that the increase in water temperature through the cooling passages should be monitored and the

net sensible heat given up by the forming strand as it exits the mould, be compared with the rise in the cooling water's enthalpy. Temperature rises were measured to be steady at 9°C, for a total water flowrate of 500 US gallons per minute (3.785 kg of water = 1 US gallon). Estimate the heat extracted (kJ/s) from the mould, based on this information, given $C_p$ the heat capacity for $H_2O$ = 4.18 kJ/kg K.
Compare this with the enthalpy (heat) lost from the steel strand between its entry and exit from the mould, by calculating;

**a)** The release of heat associated with a total loss in superheat from the liquid steel on entering the mould, prior to steel shell formation, given an entry superheat temperature from the tundish of 22 °C ,

**b)** The latent heat given up by frozen shell, of thickness $x_{Le}$ exiting mould (Le = 1 metre)

**c)** Loss in sensible heat within cooling steel shell as strand exits the mould

Explain your calculations, sketching temperature profiles at the entry, mid-depth, and exit planes of the mould. Compare the two estimates. You may ignore any electromagnetic heating effects as being negligible.

Data; $Cp_{liquid\ steel}$ = 0.7485 kJ/kg K, density = 7100 kg/m$^3$
$Cp_{solid\ steel}$ = 0.850 kJ/kg K, density 7800 kg/m$^3$