National Exams December 2018

-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 Casio or Sharp approved model calculator is permitted.
3. FIVE (5) questions constitute a complete exam paper.
4. Each question is of equal value.

Answer question number one, plus any four others.

1. General knowledge questions to be answered by all candidates. Answer true, false, or ambiguous, and briefly explain your reasoning.
   a. Ficks 1st Law of diffusion for one dimensional mass flow can be written $\dot{N}_Z'' = -D_{A/B}\dfrac{\partial C_A}{\partial x}$
   b. Ficks Law can take into account the convection of mass?
   c. Write down Newtons equation of viscosity. Can this equation be applied to liquid metals and alloys?
   d. The viscosity of a gas increases with pressure and with temperature?
   e. The thermal conductivity of a metal increases significantly on transforming from the solid to liquid state?
   f. If the contact angle, ϕ, of a liquid wetting the surface of a container is 180°, sketch the shape of a gas bubble entering such a liquid through a small orifice set in the bottom of such a container.
   g. The solubility of oxygen in iron is small, but still finite (e.g. in *ppm/litre*).
   h. The solubility limit of carbon in solid steel is approximately 2% by weight at the Fe-C eutectic temperature of 1140°C?
   i. A well mixed reactor is generally more efficient than a plug flow reactor for **first order** chemical reactions?
   j. The Froude number represents the ratio of inertial to gravitational forces, while the Reynolds number represents the ratio of inertial forces to viscous forces.
   k. Fouriers Second Law of heat conduction contains the thermal conductivity of a substance in the thermal diffusivity term?
   l. The difference between the Biot number and the Nusselt number relates to the thermal conductivity of the phases involved in the heat transfer process?
   m. Liquid metals have much thicker thermal boundary layers compared to all other liquids, on account of their much higher thermal conductivities?
   n. Radiation can be transmitted, reflected, but not absorbed?

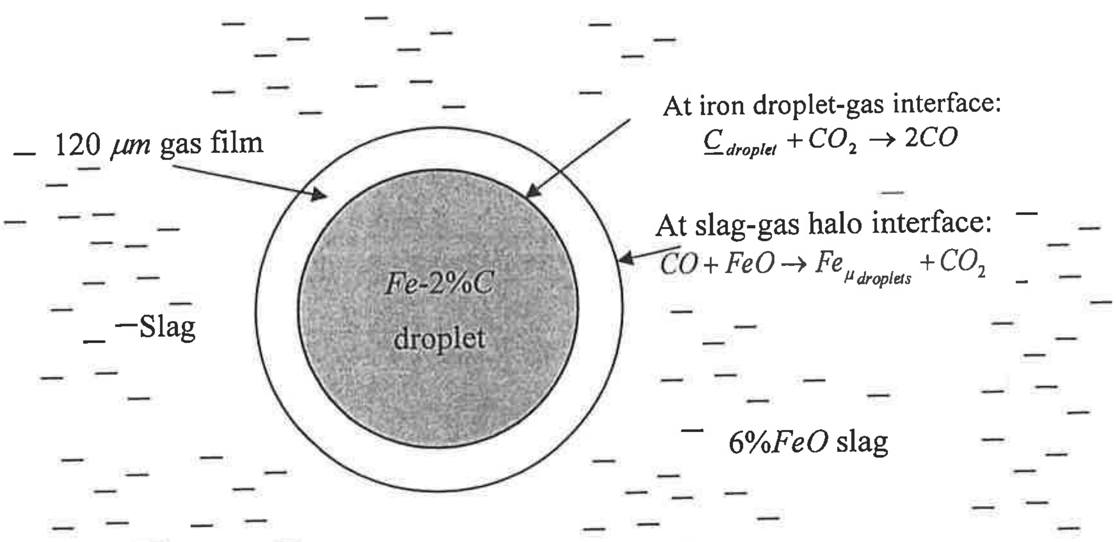
---

2. During continuous casting, a change in steel grades is to be made from a low carbon steel (700 *ppm C*), to an ultra-low carbon heat (40 *ppm C*). The new ladle containing the ultra-low carbon steel is fed into a 10 *tonne* tundish at a rate of 1 *tonne per minute*. Given that the tundish operates as a reactor that can be characterized as having a plug flow volume of 20%, and a well mixed volume of 80%, estimate the time required for the steel replacing the old heat (700 *ppm C*), to come within 10% of the final spec. (i.e to 44 *ppm C*).

3. 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, of thickness $120\mu m$, 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 ($D_{CO} = D_{CO_2}$)	:	1.0×10^{-3} m^2/s
Density of molten slag	:	3300 kg/m^3



4. **Scale-up of Regenerator Stoves**
A vertical cylindrical tank filled with hot metal spheres, is used to transfer heat to the incoming ambient (cold) air. Using the method of dimensional analysis (e.g. the π method), derive the form of expression relating $\Delta\theta_{g,t}$ (the total rise in temperature of the gas as it passes through the packed bed of spheres in the regenerator at time t), to the following independent variables.

$\Delta\theta_o$	Initial temperature difference between incoming ambient air, and the hot spheres, at time zero.
t	Time after ambient air has started to flow through regenerator.
C_g	Volume specific heat of gas (cal/°C.cm^3 or J/K.m^3)
C_s	Volume specific heat of metal spheres (cal/°C.cm^3 or J/K.m^3)
U_o	Velocity of the gas (m/s)
k	Thermal conductivity of the gas (cal. cm^{-1}°C^{-1} s^{-1} or J/m K) , etc.
μ_o	Viscosity of the gas phase (kg.m^{-1}t^{-1})
ρ	Density of gas (kg/m^3)
L	Characteristic linear dimension of the regenerator (e.g. Height)
d	Diameter of metal spheres

Do you think that these variables are sufficient to describe the system, particularly if the metal spheres are replaced with ceramic spheres? Also, comment on the possibility of building a geometrically similar regenerator of double the linear dimensions, to raise the temperature of twice the amount of gas flowing through the second regenerator (i.e. $U_2L_2^2 = 2U_1L_1^2$) by the same amount, $\Delta\theta$. Then calculate the relative times taken in the two regenerators for the same $\Delta\theta$ to be registered.

5. A hot rolling mill superintendent considered the possibility of increasing his mills tonnage capacity by increasing the lengths of the slabs charged to the reheat furnaces. These slabs are rolled down to 32-mm-thick, transfer bars, in the rougher stand. From there, they exit at 1590 *K*, and then pass along an entry (or holding) table into the finishing stands. Slab temperature rundown during this period is an important constraint on the finishing operation. Thus, in order to avoid overloading the electric motors running the finishing stands, the slab temperature must never drop below 1422 *K* before entering into the first rolling stand, F1. Assuming the critical conditions of a minimum lag of 5 *s* between each slab and a coiling speed of 20 *m/s* on 2.3 *mm* gauge material, calculate the maximum thickness of slab that could be handled by the operation, and the new theoretical annual mill capacity (i.e. in tonnes / annum on a 24 hour basis of operation with no shut-downs, producing 2.3 *mm* gauge material). For the purposes of this calculation, take into account radiation heat losses. Briefly justify why one can ignore temperature gradients across the slab, natural convection from the slab surfaces, conduction into rollers and, finally, back-radiation from the plant.

Data:

Density of steel slab (transfer bar)	:	7450 kg/m^3
Thickness of transfer bar	:	32 mm
Temperature of slab on exit from rougher	:	1590 K
Minimum temperature of slab entering finishing stands	:	1422 K
Slab thickness	:	0.61 m
Width of slab	:	1.21 m
Heat capacity of slab	:	0.45 $kJ/kg\cdot K$
Thickness of strip	:	2.3 mm
Coiling speed (speed of strip)	:	20 m/s
View factor of slab, $F_{slab/\infty}$	:	1
Emissivity of slab	:	0.8
Stefan-Boltzmann constant	:	5.67×10^{-8} $W/m^2\cdot K^4$

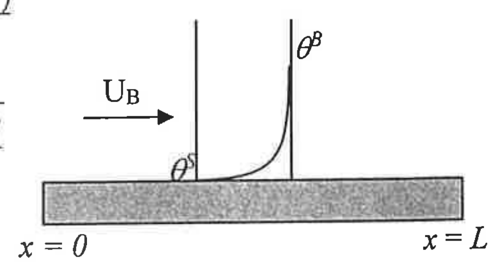
6. Liquid Metal Flows at a velocity U and temperature θ^B over a flat plate of length L, held at temperature θ^S, in plug flow. Solve for the developing temperature profile within the liquid metal (assume semi-infinite approximation with a fixed value at the interface), as it flows across the surface 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

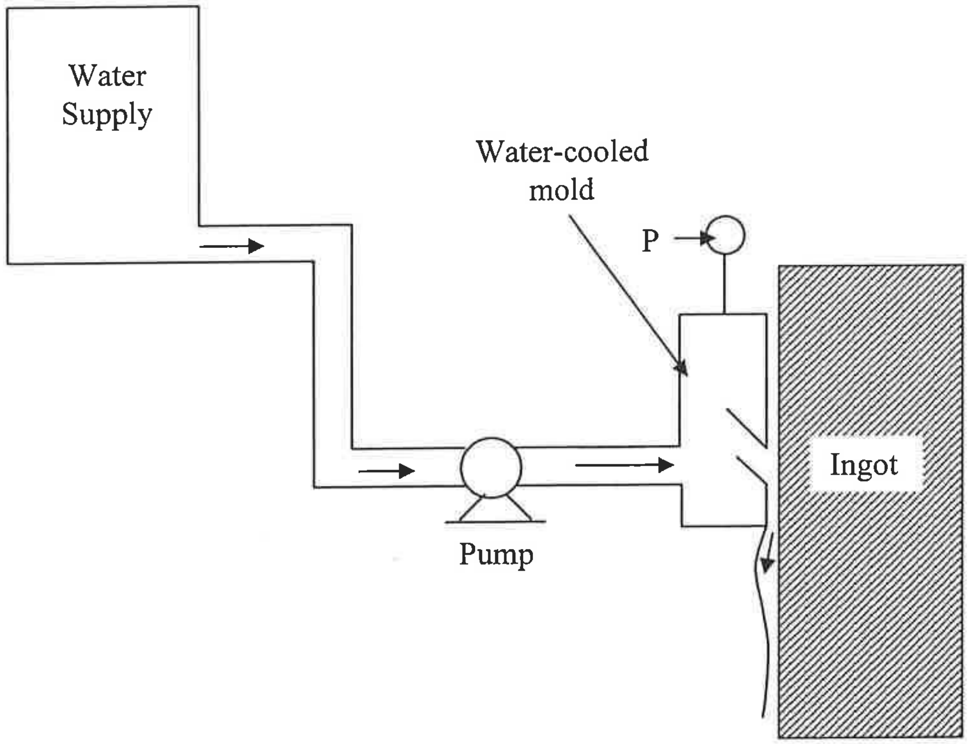
$$Nu_x = \sqrt{\frac{\mathrm{Re}_x \cdot \mathrm{Pr}}{\pi}}$$

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



7. Water is pumped from a storage tank to a mold designed to produce non-ferrous aluminum ingots by the Direct-Chill Casting Process. The water supply is at ambient pressure (1.0133×10^5 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 1.22×10^5 N/m^2, when the volume flow rate is 3.93×10^{-3} m^3/s. The water level in the tank is **3-*m***, and the vertical length of the pipe is **3-*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:

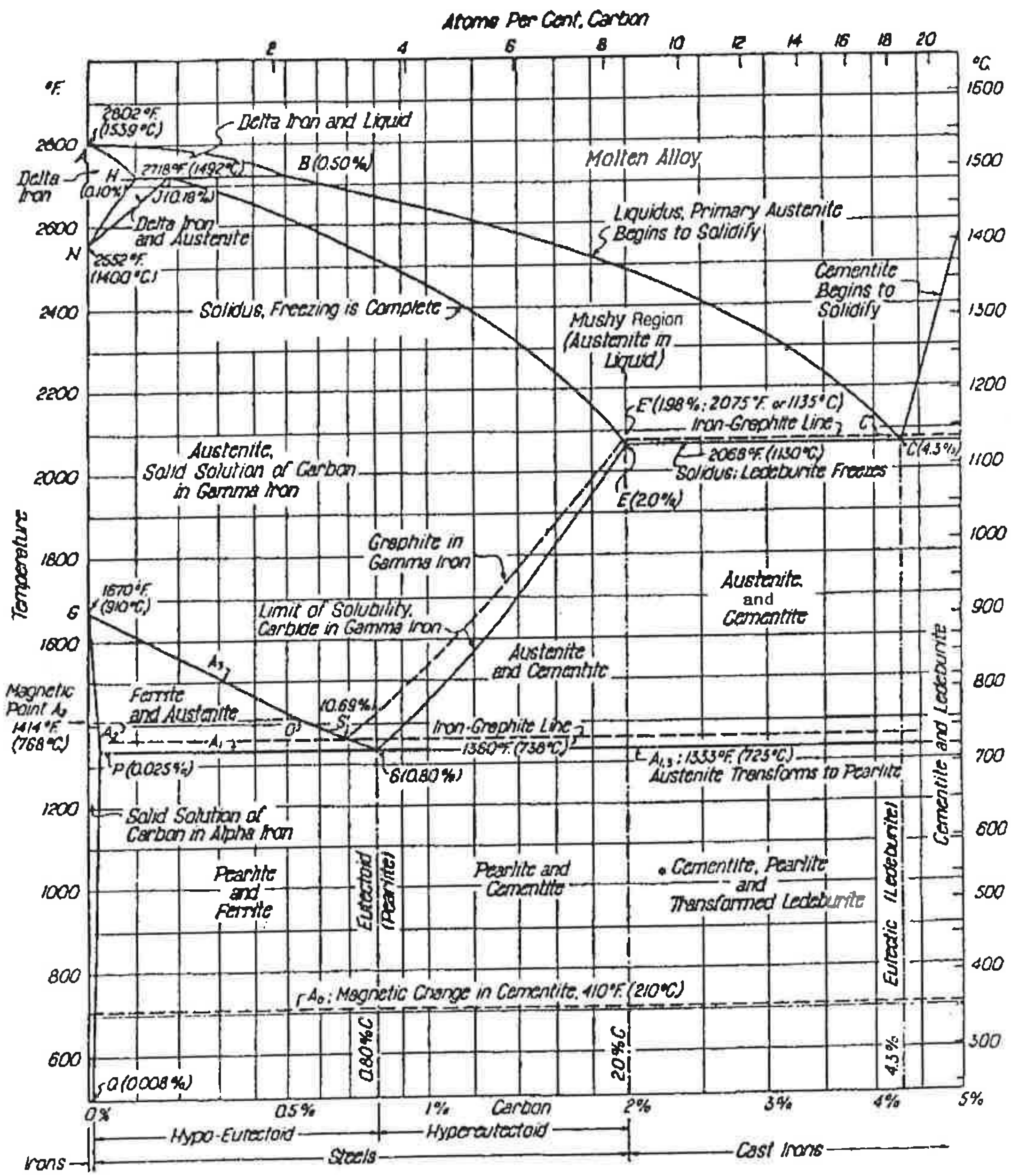
total length of straight piping, 9.14 m; diameter, 30.5 mm; $L_e/D = 25$ (elbows); $f = 0.004$; $e_{s.entry} = 0.4$; $e_{s.exit} = 0.8$. These e_s values refer to entry and exit flow head loss fractions.



8. Consider the casting forces generated on the upper and lower segments of a mold just filled with liquid metal, prior to any freezing. Explain why the natural hydrostatic forces exerted by the liquid metal on the interior surfaces of the mold tends to lift up the upper mold segment. Consider a hollow mold for producing a die-cast zinc metal sphere. It is filled with molten zinc alloy through a small cylindrical hole, length L, set in the top-half of the mold. Calculate the resultant vertical forces exerted by the metal on the top half, and on the bottom half, of the inside surface of the mold. Please express your result in terms of the total weight of metal. Given the result, do you think it would be appropriate to increase L as far as possible, so as to create better contact between the liquid metal and the inner surface of the mold during subsequent freezing?

   Hint; Take z=0, at the top of the mold, and z= +D, at the bottom of the mold, and then resolve the hydrostatic forces acting on the top and bottom halves of the mold, by integrating the hydrostatic pressure forces acting on the die walls between z = 0, and z=R for the top half, and then between z=R and z= D for the bottom half.

This iron-carbon diagram is always useful to have available.



Ferrite = solid solution of carbon in lower temperature, body centered cubic form of iron.
Austenite = solid solution of carbon in the high temperature, face centered cubic form of iron.
Ledeburite = eutectic mixture of carbide and austenite
Cementite = iron carbide, Fe_3C.

The iron–carbon phase diagram. *Ferrite* = solid solution of carbon in the lower-temperature, body-centred cubic form of iron. *Austenite* = solid solution of carbon in the high-temperature, face-centred cubic form of iron. *Ledeburite* = eutectic mixture of carbide and austenite. *Cementite* = iron carbide, Fe_3C. *Pearlite* = mixture of ferrite and iron carbide. *Delta iron* = solid solution of carbon in the very-high-temperature body-centred cubic form of iron.