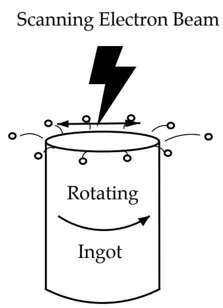
1. Electron beam centrifugal atomization of metal

   There are several methods for producing a spray from a liquid whose resulting size distribution is quite broad, that is, there is a wide range of spray droplet sizes that result from that process, and when they solidify, the resulting powder is a mixture of spheres of various sizes. For some materials applications, it's much better to have a powder with a narrow distribution, that is, with most of the droplets having the same size. One way to achieve this is by centrifugal atomization, in which we rotate a solid cylinder and melt it at a controlled rate so droplets break off at a size determined by the balance between centrifugal and surface tension forces:

$$R \sim \sqrt{\frac{\gamma}{\rho\omega^2 r}}$$

   where R is the droplet size, γ is the surface tension, ρ the liquid density, ω the rotation rate and r the distance from the rotation axis where the liquid droplet breaks free. An arrangement which produces this result is pictured below. The cylinder, called the ingot, is held vertically and rotated quickly while melting slowly from the top such that a thin film of liquid is accelerated out to the edges, where the liquid breaks into droplets.



   For this vertical atomization arrangement, we would like to calculate two things:

   - The amount of heat needed to melt and atomize at a certain rate.
   - The temperature distribution in the rotating ingot at steady-state.

   We will use titanium as the atomized material here, which has the following properties:

   - Melting point: 1667°C = 1940 K
   - Radiative emissivity: 0.55
   - Thermal conductivity: $20\frac{\mathrm{W}}{\mathrm{m\cdot K}}$
   - Density: $4700\frac{\mathrm{kg}}{\mathrm{m}^3}$
   - Molar mass: $0.0479\frac{\mathrm{kg}}{\mathrm{mol}}$
   - Heat capacity: $700\frac{\mathrm{J}}{\mathrm{kg\cdot K}}$
   - Heat of fusion: $300\frac{\mathrm{kJ}}{\mathrm{kg}}$
   - Vapor pressure constants: $A = 23200\mathrm{K}$, $B = 11.74$, $C = -0.66$, $D = 0$

$$\log_{10} p_v(\mathrm{torr}) = -\frac{A}{T} + B + C\log_{10} T + DT$$

   - Heat of vaporization: $\Delta H_e = 9.2\frac{\mathrm{MJ}}{\mathrm{kg}}$

   Source: E. Brandes, ed., *Smithells Metals Handbook* (6th edition), Boston: Butterworth & Co., 1983.

(a) Assuming the chamber is cold and black, and that the liquid film is all at the melting point, estimate the radiative heat loss from the top surface of the ingot.

(b) Assuming ideal Langmuir evaporation into a vacuum, calculate the evaporation rate and heat loss due to evaporation.

(c) If we would like to melt and atomize at a rate of 1 cm of ingot per minute, what is the required power density of the heat source? You may neglect losses from the sides of the ingot, but include energy required to heat the titanium from 300 K to its melting point, and to melt it, and the losses in parts 1a and 1b.

(d) Is the process more energy-efficient if it goes faster or slower?

(e) The ingot bottom temperature and initial temperature are both 300 K. If the ingot is 1 m long, can it be considered semi-infinite? When the process reaches steady-state, what is the relationship between temperature and distance from the top of the ingot?

(f) Use your answer from part 1e to calculate the heat flux into the top of the solid ingot. Which of the energy components from part 1c does this relate to? (Radiative/evaporative losses, heat of fusion, heat of raising the titanium to its melting point)

(g) Suppose the ingot were turned on its side, and hit on the top by a fixed (not scanning) electron beam while spun like a rolling pin. Give at least one advantage or disadvantage this different form of the process would have vs. that pictured above.