

## 3.185 Problem Set 6

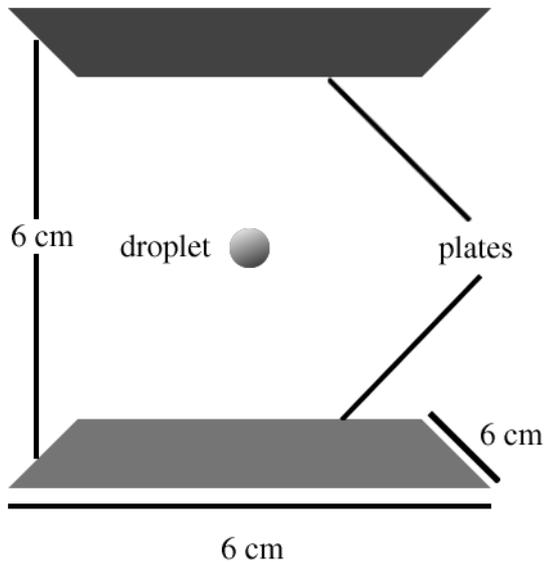
Radiation, Intro to Fluid Flow

Due Monday November 3, 2003

### 1. Heat transfer in electrostatic levitation (25)

Electrostatic levitation is used for property measurements in a pure liquid, with its containerless nature removing a major possible source of contamination.

Below is a picture of a simplified levitator, with a charged droplet of the test liquid suspended exactly centered between two square plates.



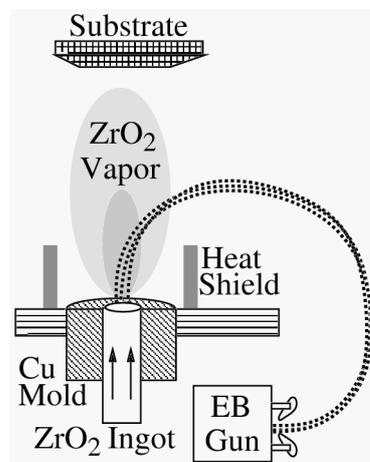
Data:

- Plates' emissivity: 0.8
  - Droplet emissivity: 0.5
  - Droplet diameter: 0.5 cm (sphere surface area is  $4\pi R^2 = \pi d^2$ )
- (a) Considering the droplet surface as  $S_1$ , and the upper and lower plate surfaces facing the droplet collectively as  $S_2$ , calculate the viewfactor from the droplet to the upper and lower plates  $F_{12}$ . (Hint: think of the plates as sides of a cube.) (4)
- (b) Calculate the viewfactor from the plates to the droplet. (5)
- (c) Using a graph in W<sup>3</sup>R, calculate the viewfactor  $F_{22}$  (which is equal to the viewfactor from one plate to the other), *not* including the influence of the droplet (*i.e.* as if it weren't there). (5)

- (d) If the droplet is at 800 K, and the plates at 1000 K, calculate the total power radiated in each direction (*i.e.*  $Q_{12}$  from droplet to plates,  $Q_{21}$  from plates to droplet). (6)
- (e) If its actual thermal conductivity as measured in the levitator (*e.g.* by a laser flash technique) is 20% higher than that predicted by the Wiedmann-Franz law for electronic heat conduction, what other heat conduction mechanism could be active (name one)? (5)

2. Radiation in Zirconia Physical Vapor Deposition (20)

**Background:** Ytria-stabilized zirconia is used as a thermal barrier coating for high-temperature turbine blades, such as those found in jet engines and gas turbine generators. The coating is applied to the turbine blades using electron beam physical vapor deposition. In this process, conducted in a vacuum chamber, an electron beam heats, melts, and evaporates zirconia from a cylindrical “ingot” 5 cm in diameter, which is surrounded by a water-cooled copper mold. (The electron beam is bent into the shape shown by a large magnet.) The zirconia vapors then travel to the substrate, where they condense to form a coating. The ingot is continuously fed upward to replace the material lost to evaporation, such that the top of the thin liquid zirconia pool (typically 2-5 mm deep) remains level with the top of the mold.



Unfortunately, engineers underestimated the amount of heat radiated from the liquid zirconia to the sides of the chamber, and some pieces of the chamber melted. The proposed solution involves inserting a cylindrical “collar” heat shield around the zirconia, with a 20 cm inner diameter and 10 cm height.

Data:

- Liquid zirconia emissivity: 0.3
- Radiation constant  $\sigma = 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \cdot \text{K}^4}$

- (a) Using the viewfactor graph in the text and viewfactor algebra, calculate the radiation viewfactor from the top surface disc of liquid zirconia to the inner surface of the proposed heat shield,  $F_{12}$ . (7)
- (b) The zirconia reaches a steady-state temperature of about 2100 K. Estimate the average radiative heat flux arriving at the inner surface of the heat shield, in watts per square meter, by dividing the total power arriving there  $Q_{12}$  by its surface area  $A_2$ . (6)
- (c) The heat shield also reflects a lot of heat back to itself. To start to estimate this reflective heat flux, calculate the viewfactor between the inner surface of the heat shield and itself,  $F_{22}$ . (7)

3. Shear stress and couette flow (15)

- (a) W<sup>3</sup>R problem 7.15. (7)

(b) W<sup>3</sup>R problem 7.16. (8)

4. Glass Viscosity (15)

- (a) Assume that the viscosity of a silicate glass follows an Arrhenius dependence on temperature. If this glass at 1700K has a viscosity of  $20 \text{ N} \cdot \text{s}/\text{m}^2$ , and at 1500K of  $100 \text{ N} \cdot \text{s}/\text{m}^2$ , then estimate its viscosity at 1450K. (10)
- (b) Why might it be unwise to extrapolate the viscosity of a glass downward as you just did in part 4a? (5)

5. Plate Glass Casting (25)

High-quality plate glass is cast with extremely flat surfaces by floating it on molten tin and letting it cool as the glass and tin flow down a gently inclined plane.

Data:

- Liquid glass entering the process:  $\rho = 3.2 \frac{\text{g}}{\text{cm}^3}$ ,  $\mu = 1.0 \frac{\text{N} \cdot \text{s}}{\text{m}^2}$ , layer thickness=1mm.
  - Liquid tin:  $\rho = 7.0 \frac{\text{g}}{\text{cm}^3}$ ,  $\mu = 3 \times 10^{-3} \frac{\text{N} \cdot \text{s}}{\text{m}^2}$ , layer thickness=1mm.
  - Inclined plane angle:  $2^\circ$ .
- (a) Write the general solution to the equation for momentum conservation down the inclined plane in the flow direction. (3)
- (b) What is the interface boundary condition at the glass-tin interface? (3)
- (c) Calculate the velocity distribution in both the glass and the tin. (10)
- (d) What are the maximum and average velocities in the glass and tin? (5)
- (e) Comment on the Reynolds numbers in the glass and tin. Do you think flow will remain laminar in both layers? (4)