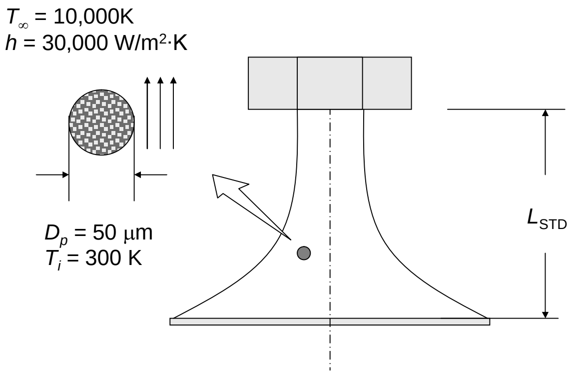
PROBLEM 5.26

KNOWN: Diameter and initial temperature of nanostructured ceramic particle. Plasma temperature and convection heat transfer coefficient. Properties and velocity of particles.

FIND: (a) Time-in-flight corresponding to 30% of the particle mass being melted. (b) Time-in-flight corresponding to the particle being 70% melted. (c) Standoff distances between the nozzle and the substrate associated with parts (a) and (b).

SCHEMATIC:



ASSUMPTIONS: (1) Constant properties. (2) Negligible radiation.

PROPERTIES: Given; k = 5 W/m·K, ρ = 3800 kg/m^3, c_p = 1560 J/kg·K, h_{sf} = 3577 kJ/kg, T_{mp} = 2318 K.

ANALYSIS: (a) To determine whether the lumped capacitance assumption is appropriate, the Biot number is calculated as

$$Bi = \frac{h(r_o/3)}{k} = \frac{hD}{6k} = \frac{30{,}000\ \text{W/m}^2\cdot\text{K}\times 50\times10^{-6}\ \text{m}}{6\times 5\ \text{W/m}\cdot\text{K}} = 0.05$$

Since Bi < 0.1, the lumped capacitance approximation is valid. The particle heating process can be divided into two stages.

<u>Stage 1: Heating to the melting temperature</u>. The time-of-flight for the first stage is found from Equation 5.5.

$$t_1 = \frac{\rho Vc}{hA_s}\ln\frac{\theta_i}{\theta} = \frac{\rho Dc}{6h}\ln\frac{T_i - T_\infty}{T_{\text{mp}} - T_\infty}$$

$$= \frac{3800\ \text{kg/m}^3\times 50\times10^{-6}\ \text{m}\times 1560\ \text{J/kg}\cdot\text{K}}{6\times 30{,}000\ \text{W/m}^2\cdot\text{K}}\ln\frac{300\ \text{K} - 10{,}000\ \text{K}}{2318\ \text{K} - 10{,}000\ \text{K}}$$

= 0.00038 s

<u>Stage 2: Melting to 30% liquid</u>. The second stage involves heat transfer to the particle which is isothermal at its melting point temperature. Hence

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PROBLEM 5.26 (Cont.)

$$t_{2,0.3} = \frac{\Delta E}{q} = \frac{0.3\rho V h_{sf}}{hA_s(T_\infty - T_{\text{mp}})} = \frac{0.05\rho D h_{sf}}{h(T_\infty - T_{\text{mp}})}$$

$$= \frac{0.05 \times 3800\text{kg/m}^3 \times 50 \times 10^{-6}\ \text{m} \times 3577 \times 10^3\ \text{J/kg}}{30{,}000\text{W/m}^2 \cdot \text{K} \times \left(10{,}000 - 2318\right)\text{K}} = 0.00015\ \text{s}$$

Therefore the required time-of-flight is $t_{\text{tot},0.3} = t_1 + t_{2,\,0.3}$ = 0.00038 s + 0.00015 s = 0.00053 s <

(b) The calculation for the second stage may be repeated for 70% liquid, yielding $t_{2,\,0.7}$ = 0.00034 s. Therefore the required time-of-flight is $t_{\text{tot},\,0.7} = t_1 + t_{2,\,0.7}$ = 0.00038 s + 0.000341 s = 0.00072 s <

(c) The required standoff distances are

$$L_{\text{STD},0.3} = Vt_{\text{tot},0.3} = 35\ \text{m/s} \times 0.00053\ \text{s} = 0.019\ \text{m} = 19\ \text{mm}$$ <

$$L_{\text{STD},0.7} = Vt_{\text{tot},0.7} = 35\ \text{m/s} \times 0.00072\ \text{s} = 0.025\ \text{m} = 25\ \text{mm}$$

COMMENTS: (1) Assuming the particles to have an emissivity of ε_{p} = 0.4 and radiation is exchanged with surroundings at an assumed temperature of T_{sur} = 300 K, the radiation heat transfer coefficient may be found from Equation 1.9 as

$$h_r = \varepsilon_p \sigma (T_{\text{mp}} + T_{\text{sur}})(T_{\text{mp}}^2 + T_{\text{sur}}^2) = 0.4 \times 5.67 \times 10^{-8}\ \frac{\text{W}}{\text{m}^2 \cdot \text{K}^4}\left(2318 + 300\right)\text{K} \times \left(2318\text{K}^2 + 300\text{K}^2\right) = 320$$ W/m^2·K.

Hence $h_r << h_{\text{conv}}$ and radiation heat transfer is negligible. (2) To deliver a partially-molten droplet to the substrate, standoff distances on the order of 20 mm need to be maintained. This is a reasonable requirement. (3) See I. Ahmed and T.L. Bergman, "Simulation of Thermal Plasma Spraying of Partially Molten Ceramics: Effect of Carrier Gas on Particle Deposition and Phase Change Phenomena," *ASME Journal of Heat Transfer*, vol. 123, pp. 188-196, 2001, for more information.