Review Problems:

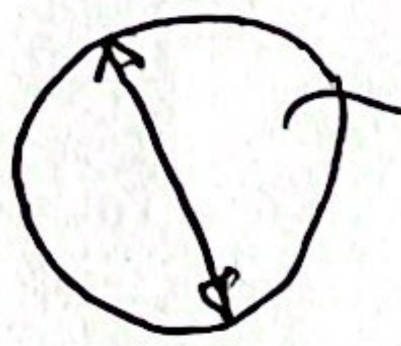
1- Steel balls 10 mm in diameter are annealed by heating to 1150 K and then slowly cooling to 450 K in an air environment for which T∞ = 325 K and h = 20 W/m².K. Assuming the properties of the steel to be k = 40 W/m.K, ρ = 7800 kg/m³, and c= 600 J/kg.K, estimate the time required for the cooling process.

$D = 0.01\,m$

Air

$T_\infty = 325K$

$h = 25\ W/m^2K$



steel

$T_i = 1150K$ $\quad T = 450K$

$k = 40\ W/mK$

$\rho = 7800\ kg/m^3$

$c = 600\ J/kg.K$

$$Bi = \frac{hL_c}{k} = \frac{h(r_o/3)}{k} = \frac{25 \times (0.005/3)}{40} = 0.001 < 0.1 \quad \text{LHC is valid}$$

$$\frac{\theta}{\theta_i} = \frac{T - T_\infty}{T_i - T_\infty} = \exp(-Bi\,Fo) \quad \text{eq 5-13}$$

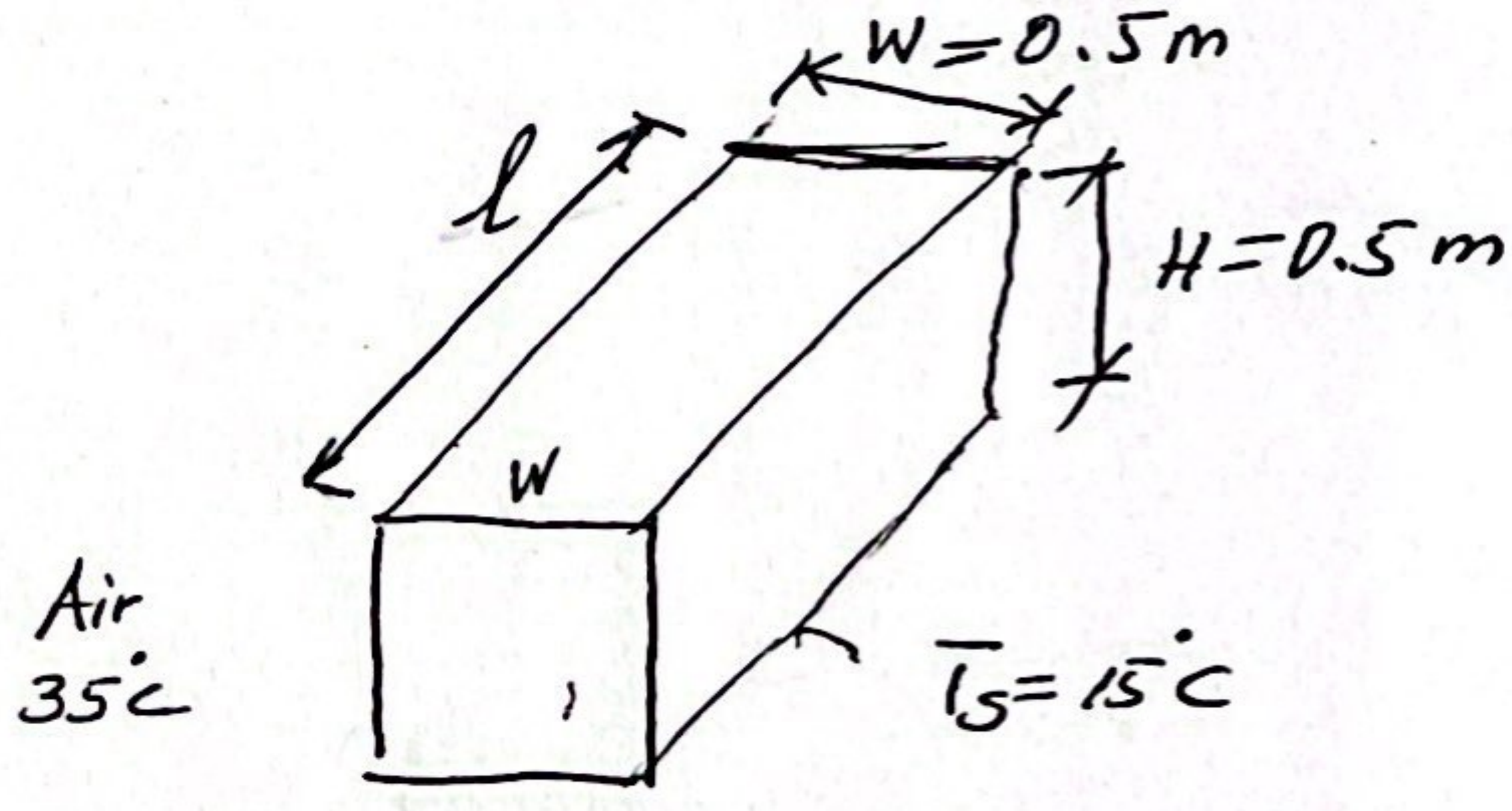
$$\frac{T - T_\infty}{T_i - T_\infty} = \exp\left(-\frac{hA_s t}{\rho V c}\right) \quad \text{eq 5.6}$$

$$t = \frac{\rho V c}{hA_s} \ln\left(\frac{T_i - T_\infty}{T - T_\infty}\right) = \frac{\rho(\cancel{\pi} D^{\cancel{3}}/6)c}{h\cancel{\pi}\cancel{D^2}} \ln\left(\frac{T_i - T_\infty}{T - T_\infty}\right)$$

$$= \frac{7800 \times (0.01/6) \times 600}{25} \times \ln\frac{(1150 - 325)}{(450 - 325)}$$

$$= 589\,s = 0.164\,h$$

2- Airflow through a long, 0.5-m-square air conditioning duct maintains the outer duct surface temperature at 15°C. If the horizontal duct is uninsulated and exposed to air at 35°C in the crawlspace beneath a home, what is the heat gain per unit length of the duct from top and bottom side? Evaluate the properties of air at T_f=300 K.



$$T_f = \frac{T_s + T_\infty}{2} = \frac{15+35}{2} = 25°C \ (298K)$$

at 300K from table A.4 for air

$$\nu = 15.71 \times 10^{-6} \ m^2/s, \quad K = 0.0261 \ W/m.K$$

$$\alpha = 22.2 \times 10^{-6} \ m^2/s, \quad P_r = 0.708$$

$$\beta = \frac{1}{T_f} = 0.0033557 \ K^{-1}$$

$$L_c = \frac{A_s}{P} = \frac{l \times W}{2(l+W)} = \frac{W}{2} = \frac{0.5}{2} = 0.25 m \qquad l \gg W$$

$$Ra_L = \frac{g\beta(T_\infty - T_s) L_c^3}{\nu \times \alpha} = \frac{9.81 \times 0.0033557 (35-15)(0.25)^3}{15.71 \times 10^{-6} \times 22.2 \times 10^{-6}}$$

$$= 29.5 \times 10^6$$

For the bottom surface, hot surface facing upward:

(eq 9.31) $\overline{Nu}_L = 0.15 \, Ra_L^{1/3} = 46.32$

$$\bar{h}_b = \frac{K}{L_c} \times \overline{Nu}_L = \frac{0.0261}{0.25} \times 46.32 = 4.836 \ W/m^2.K$$

Fo the top surface, hot surface facing downward

(eq 9.32) $\overline{Nu}_L = 0.52 \, Ra_L^{1/5} = 16.21 \Rightarrow \bar{h}_t = \frac{K}{L_c} \times \overline{Nu}_L = 1.693 \ W/m^2.K$

$$q' = \frac{q}{l} = \bar{h}_b W (T_\infty - T_s) + \bar{h}_t W (T_\infty - T_s)$$

$$= W(T_\infty - T_s)(\bar{h}_b + \bar{h}_t)$$

$$= 0.5(35-15)(4.836 + 1.693) = 65.29 \ W$$

3- Water flows at 7.55 kg/s through a 12 cm diameter, 110 m long plastic drainage pipe. The water temperature at the pipe inlet is 25 ˚C, and the ground in which the pipe is buried maintains the temperature of the inside pipe surface at 15 ˚C.

(a) find heat transfer coefficient

(b) water temperature at the pipe outlet

(c) total convective heat transfer

at $T_{m,i} = 25^\circ C$ ⇒ From A.6

$$\left\{ \begin{aligned} \rho &= 997\ kg/m^3 \\ C_p &= 4183\ J/kg.K \\ \mu &= 890.5 \times 10^{-6}\ Pa.s \\ \nu &= 89.32 \times 10^{-8}\ m^2/s \\ K &= 0.6071\ W/m.K \\ P_r &= 6.14 \end{aligned} \right.$$

$\dot{m} = \rho A V$ $\qquad A_c = \pi D^2/4$

$$V = \frac{\dot{m}}{\rho A} = \frac{4\dot{m}}{\rho \frac{\pi D^2}{4}} = 0.669\ m/s$$

$$Re_D = \frac{\rho V D}{\mu} = \frac{997 \times 0.669 \times 0.12}{890.5 \times 10^{-6}}$$

$$= 8.99 \times 10^4 \Rightarrow \text{turbulent flow}$$

$$\overline{Nu}_D = 0.023\, Re_D^{4/5}\, P_r^{n}$$ $n = 0.4$ heating, $n = 0.3$ cooling

25% errors

8.62 $$\overline{Nu}_D = \frac{(f/8)(Re_D - 1000) P_r}{1 + 12.7(\sqrt{f/8})(P_r^{2/3} - 1)}$$ 10% errors

8.21 ⇒ $$f = (0.790 \ln Re_D - 1.64)^{-2}$$ $3000 \leq Re_D \leq 5 \times 10^6$

$$= 0.0184$$

From 8.62 ⇒ $\overline{Nu}_D = 514$

$$\bar{h} = \frac{K}{D} \overline{Nu}_D = \frac{0.6071}{0.12} \times 514 = 2600\ W/m^2K$$

eq 8.41b $\Rightarrow T_{m,o} = T_s - (T_s - T_{m,i}) \exp\left(-\frac{PL\bar{h}}{\dot{m} c_p}\right)$

$= 15.3^\circ C$

$q = \dot{m} c_p (T_{mo} - T_{m,i}) = -3.06 \times 10^5$ W

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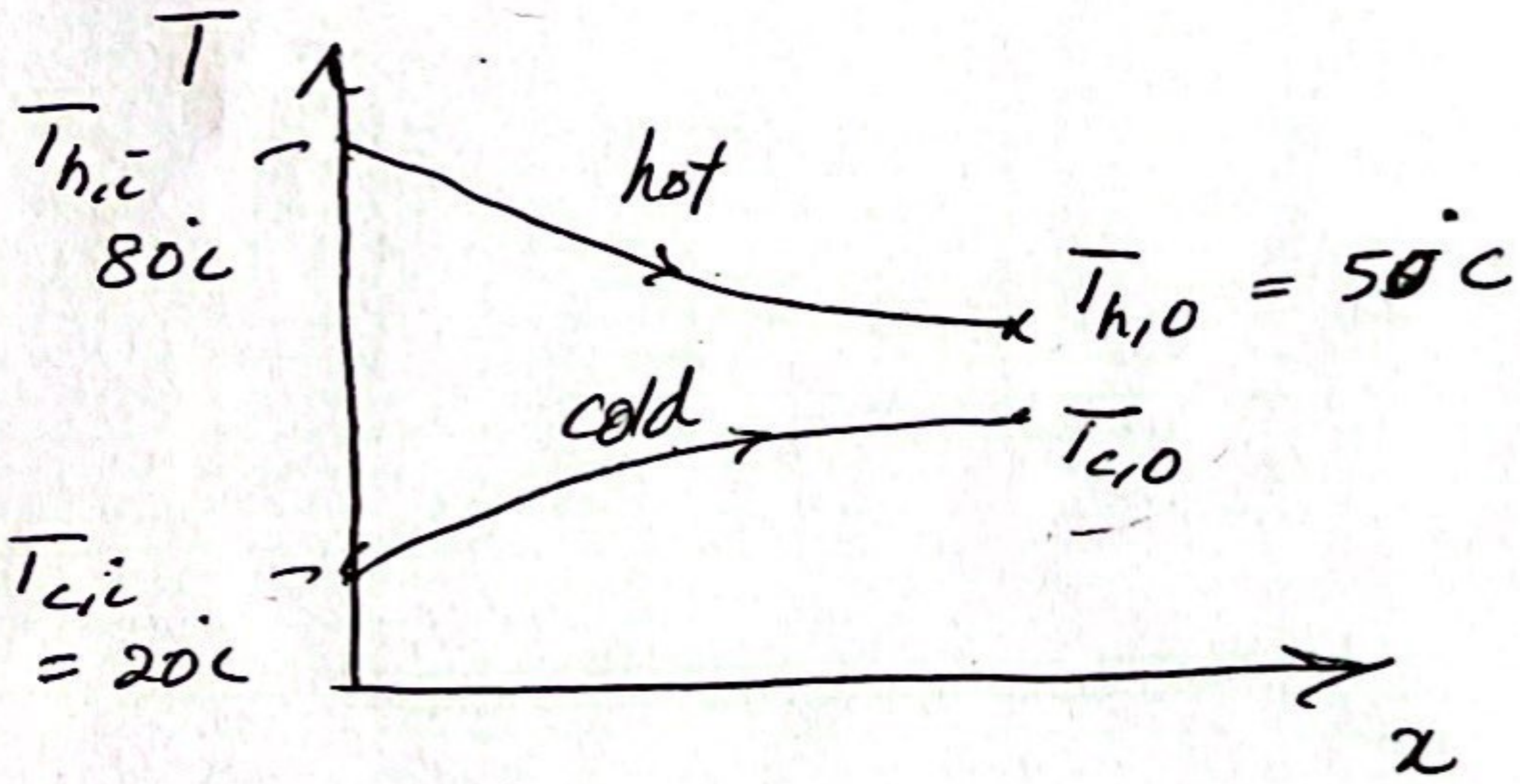
4- A process fluid having a specific heat of 3500 J/kg. K and flowing at 2 kg/s is to be cooled from 80 °C to 50 °C with chilled water, which is supplied at temperature of 20 °C and a flow rate of 3.0 kg/s. Assuming overall heat transfer coefficient of 2000 W/m². K, calculate the required area for the parallel flow heat exchanger. Take the specific heat of water at 300K.



at 300K $\xrightarrow{A.6}$ $c_p = 4179 \ J/kg.K$

$$q_h = \dot{m}_h c_{p,h} (T_{h,i} - T_{h,o})$$

$$= 2 \times 3500 (80 - 50) = 210{,}000 \ W$$

$$q_c = \dot{m}_c c_{p,c} (T_{c,o} - T_{c,i}) \Rightarrow T_{c,o} = 20 + \frac{210{,}000}{3 \times 4179} = 36.75 °C$$

$$C_h = \dot{m}_h c_{p,h} = 2 \times 3500 = 7000 \Rightarrow C_h = C_{min}$$

$$C_c = \dot{m}_c c_{p,c} = 3 \times 4179 = 12{,}537 \Rightarrow C_c = C_{max}$$

$$C_r = \frac{C_{min}}{C_{max}} = \frac{7000}{12537} = 0.558$$

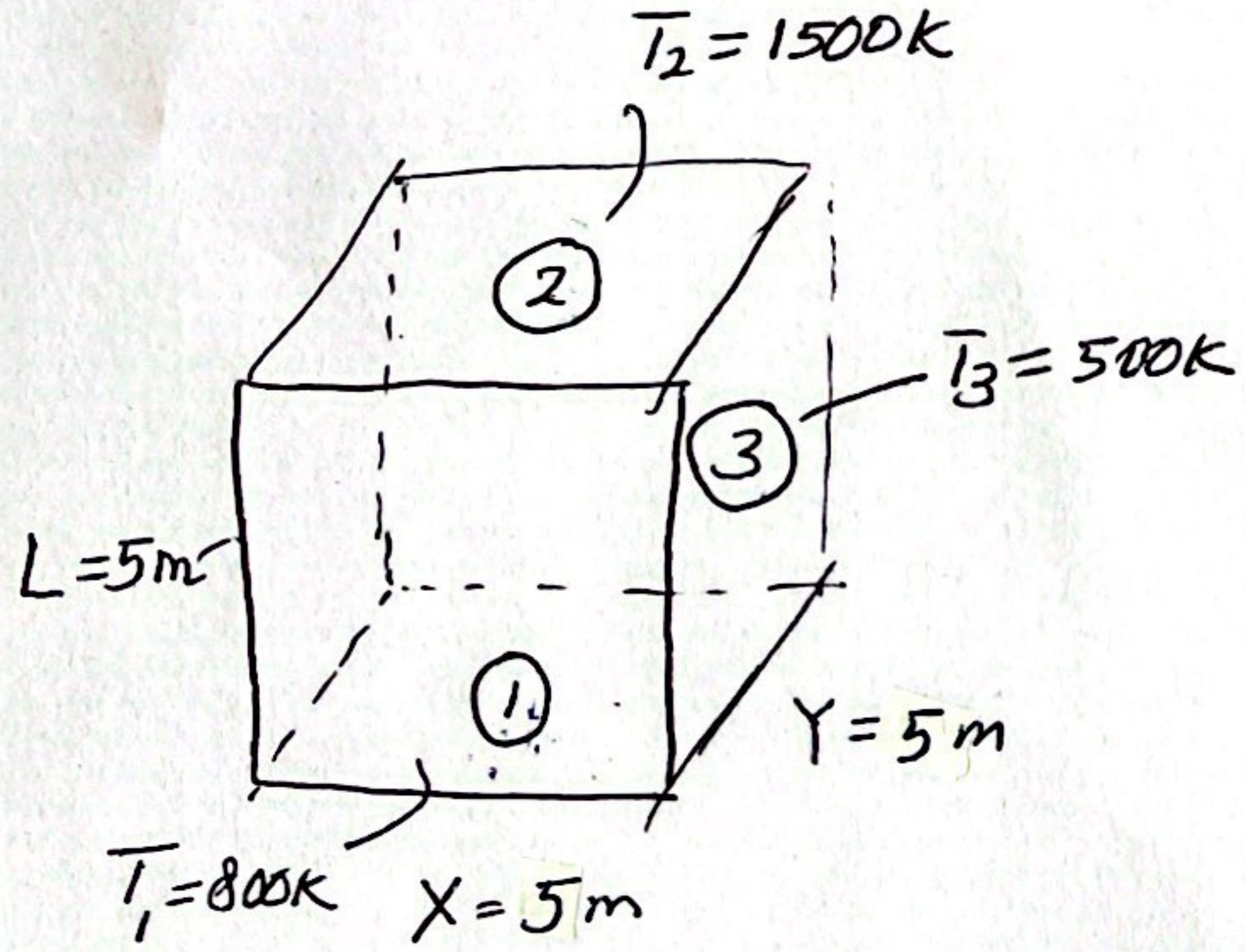
$$\varepsilon = \frac{q}{q_{max}} = \frac{q}{C_{min}(T_{h,i} - T_{c,i})} = \frac{210{,}000}{7000(80 - 20)} = 0.4615$$

eq 11.28 b $\Rightarrow$ $NTU = -\dfrac{\ln[1 - \varepsilon(1 + C_r)]}{1 + C_r} = 0.8148$

$$NTU = \frac{UA}{C_{min}} \Rightarrow A = \frac{NTU \times C_{min}}{U} = \frac{0.8148 \times 7000}{2000} = 2.85 \ m^2$$

use Fig 11.10 $\Rightarrow$ $NTU = 0.8$ $\Rightarrow A = 2.8 \ m^2$

5- Consider a rectangular furnace with dimensions of 5m×5m×5m (X, Y, L) The surfaces are estimated as black bodies. Temperatures of base (1), top (2) and walls (3) are 800 K, 1500 K and 500 K, respectively. Determine: a) All view factors, b) Net thermal radiation heat transfer between base and walls, c) Net thermal radiation heat transfer between base and top.



$$q_{13} = A_1 F_{13} \sigma (T_1^4 - T_3^4)$$

from Fig 13.4 $\begin{cases} \frac{X}{L} = \frac{5}{5} = 1.0 \\ \frac{Y}{L} = \frac{5}{5} = 1.0 \end{cases}$

$$F_{12} = 0.2$$

Enclosure Law: $\cancel{F_{11}}^{0} + F_{12} + F_{13} = 1.0$

$$0.2 + F_{13} = 1.0 \Rightarrow F_{13} = 0.8$$

Therefore $q_{13} = (5\times5)\times 0.8 \times 5.67\times10^{-8} (800^4 - 500^4) = 393611\ W \simeq 394\ kW$

$$q_{12} = A_1 F_{12} \sigma (T_1^4 - T_2^4)$$

$$= (5\times5) \times 0.2 \times 5.67\times10^{-8} (800^4 - 1500^4)$$

$$= -1319097\ W = -131.9\ kW$$

The minus sign indicates That the net rate of radiation heat transfer would be from surface 2 to 1.

$\cancelto{0}{F_{11}}$ $\cancelto{0.2}{F_{12}}$ $\cancelto{0.8}{F_{13}}$

$\cancelto{0.2}{F_{21}}$ $\cancelto{0}{F_{22}}$ $\cancelto{0.8}{F_{23}}$

$\cancelto{0.2}{F_{31}}$ $\cancelto{0.2}{F_{32}}$ $\cancelto{0.6}{F_{33}}$

$$F_{13} A_1 = F_{31} A_3$$

$$F_{31} = F_{13} \times \frac{A_1}{A_3} = 0.8 \times \frac{25}{100} = 0.2$$