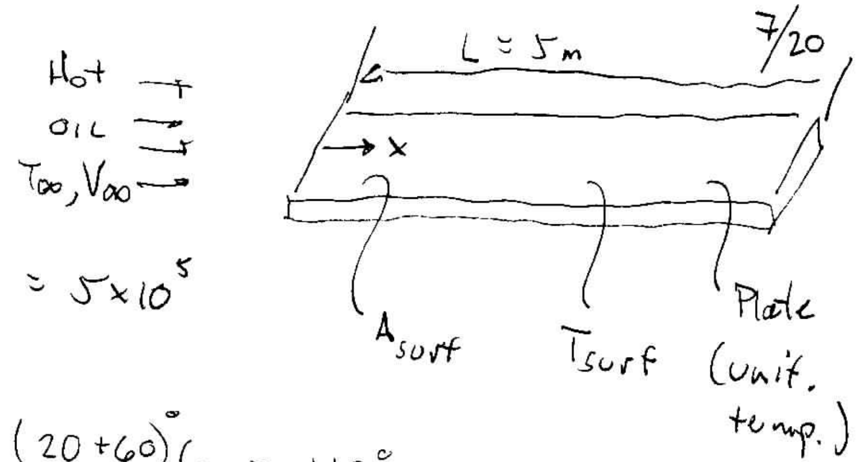
7/20

Ex 1 $T_\infty = 60^\circ C$ $V_\infty = 2\ m/s$



Assume • S.S. • $Re_{crit} = 5\times10^5$

• Incomp.

Mat'l prop. $T_{film} = \frac{T_s + T_\infty}{2} = \frac{(20+60)^\circ C}{2} = 40^\circ C$

so from Tables... $\rho = 876\ \frac{kg}{m^3}$ $Pr = 2962$

$k = 0.1444\ W/m\cdot K$ $\nu = 2.485\times10^{-4}\ m^2/s$

Soln: Re # at end of plate is $Re(x=L) = \frac{V_\infty L}{\nu} = \ldots = 4.024\times10^4$

$< Re_{crit}$

so we have laminar flow over entire plate.

Thus the average friction coef. is

$$C_f = 1.33\ Re_L^{-1/2} = \ldots = 0.00663$$

(Note pressure drag on a flat plate = 0 so only have fric. drag.)

so $C_D = C_f$ and so the drag force per unit width is

$$\frac{F_D}{W} = C_f A \frac{\rho V_\infty^2}{2} = \ldots = \frac{58.1\ N}{W}$$

$(5\ m^2)$

(Mult. this by width W for total drag. It feels like holding a 6 kg mass from falling.)

on to the heat transfer part...

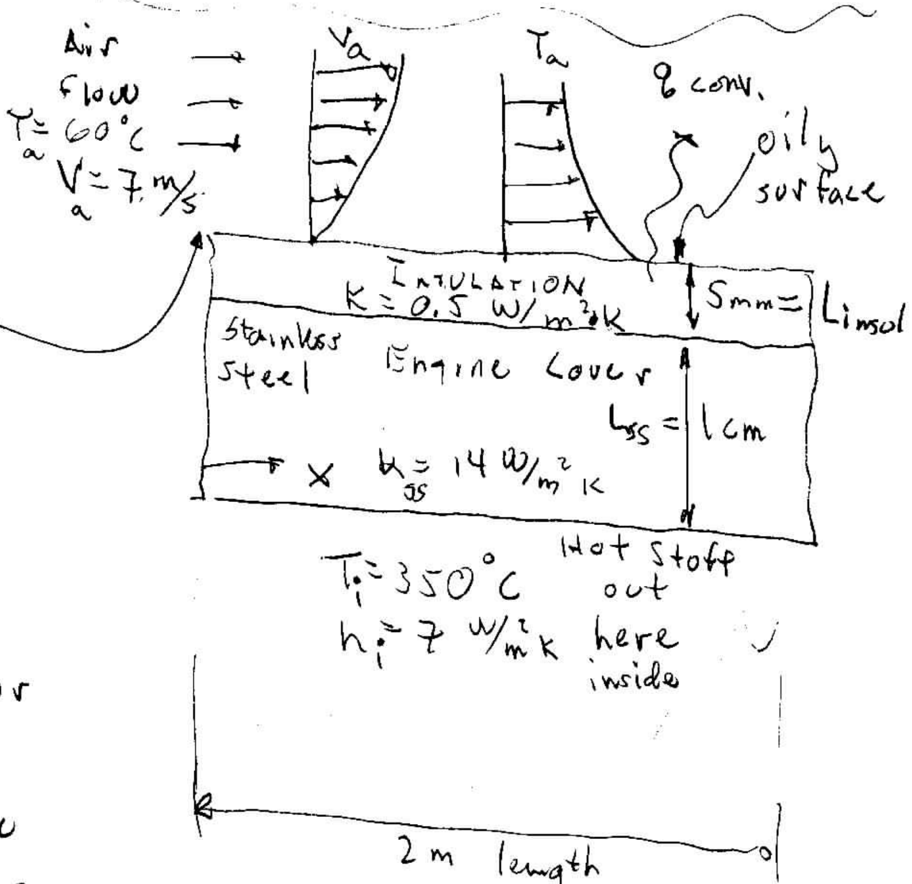
For laminar flow over a flat plate $\quad Nu_L = \frac{hL}{k} = 0.664\ Re_L^{1/2}\ Pr^{1/3}$

$$= \ldots = 1913$$

Also $\quad h = \frac{k}{L} Nu = \ldots = 55.25 \ \frac{W}{m^2 K}$

finally $\quad \dot{q} = hA_s \underbrace{(T_\infty - T_s)}_{\text{always } T_{high} - T_{low}} = \ldots = 11{,}050\,W$ (per unit width)

Ex/ You don't want oil on top of insulation to burn so keep this temp. < 180°C



Evaluate prop. of air at 120°C

Problem, current blower V is not sufficient for the job.

What happens if you increase V_{air} by 10%. Will this keep top of insulation < 180°C ?

Assume
- ¢ mtl. prop.
- 1-D q flow
- Uniform surf. Temp.
- Negl. contact resistance
- Rad. is negl.
- P_{atm} = 1 atm
- $Re_{crit} = 5 \times 10^5$

Soln: Prop are all from tables @ $T_{air} = T_{film} = 120°C$

$k_{air} = 0{,}03235 \ \frac{W}{m \cdot k}$ $\nu = 2{,}522 \times 10^{-5} \ m^2/s$

$P_r = 0{,}7073$

Increasing V_{air} by 10% so V_{air} is now $7{,}7 \ m/s = T_{air}$

plate length is $L = 2m$

so $Re_L = \frac{V_{air} L}{\nu_{air}} = 610{,}626 > 5 \times 10^5$

so we have combined Lam. and Turb. flow

Hence $Nu = \frac{hL}{k} = \left[0{,}037 \, Re_L^{0{,}8} - 871\right] Pr^{1/3}$

$= \cdots = 625.77$

hence the conv heat trans coef on surface

$h_{\substack{air \\ outside}} = N \frac{k}{L} = \cdots = 10.122 \ \frac{W}{m^2 k}$

Recall

$R_{conv, inside} = \frac{1}{h_i A}$ hot inside gas conv.

$R_{s.s.} = \frac{L_{ss}}{k_{ss} A}$ cond. through s.s.

$R_{ins} = \frac{L_{ins}}{k_{ins} A}$ cond. Through insul.

$R_{conv, air} = \frac{1}{h_a A}$ conv. To flowing air

10/20

So overall,

$$A R_{TOT} = A\left[R_{conv,inside} + R_{S.S.} + R_{ins} + R_{conv,out} \right]$$

$$= \frac{1}{h_i} + \frac{L_{SS}}{k_{SS}} + \frac{L_{ins}}{k_{ins}} + \frac{1}{h_o}$$

$$= 0.25237 \ m^2 K/W$$

$$= A R_{conv,out} = \frac{1}{10.222 \ W/m^2K}$$

solve for me

and then $$q'' = \frac{q}{A} = \frac{T_{\infty,i} - T_{\infty,o}}{A R_{TOT}} \quad \text{also} = \frac{T_{s,o} - T_{\infty,o}}{A R_{conv,o}}$$

(q'' is same through all the layers!)

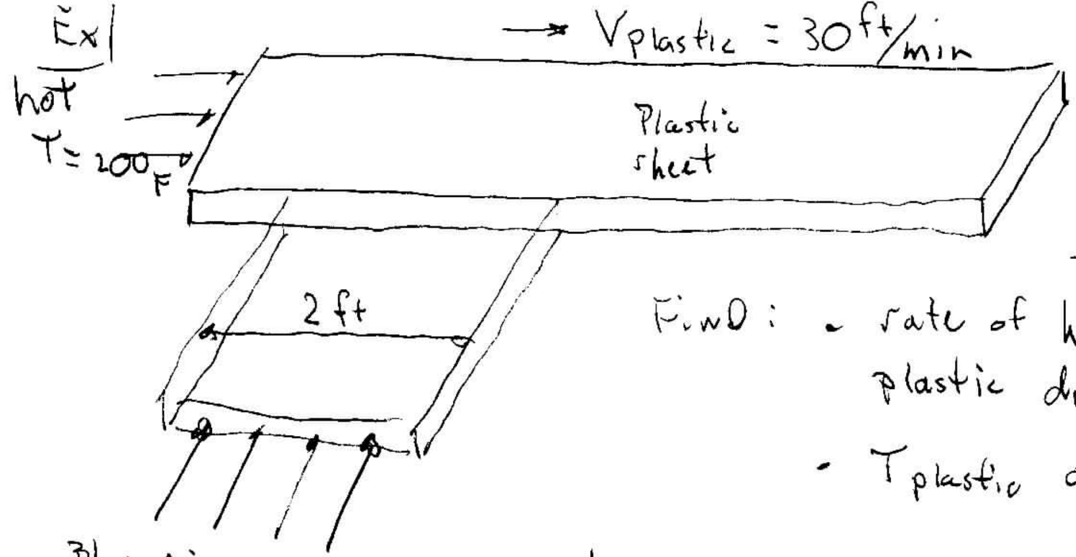
$$T_{s,o} = \frac{(A R_{conv,o})}{(A R_{TOT})} (T_{\infty,i} - T_{\infty,o}) + T_{\infty,o}$$

$$= \dots = 173.5\ ^\circ C < 180\ ^\circ C$$

So viable solution, buy better blower → lower legal costs.

11/20

Ex|



$T_a = T_\infty = 80°F$

$V_a = 10\ f/s$

Find: • rate of heat transfer from plastic due to conv. and rad.

• $T_{plastic}$ at end of cooling section

Assume: $\rho_{plastic} = 75\ \frac{lbm}{ft^3}$ $\quad \varepsilon_p = 0.9$

$c_{p,plas} = 0.4\ BTU/lb_m °F$

• Steady state

$Re_{crit} \approx 5 \times 10^5$

Air is IG

$P_{atm} = 1\ atm$

$T_{surround} = T_{air} = 80°F$

Prop: air @ $T_{film} = \frac{T_s + T_\infty}{2} = \frac{(200+80)F}{2} = 140°F$

$P_{atm} = 1\ atm$

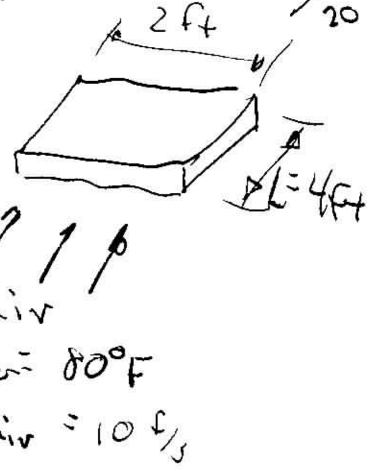
so $k_{air} = 0.01623\ BTU/hr \cdot ft \cdot F$ $\quad Pr_{air} = 0.7202$

$\nu_{air} = 0.204 \times 10^{-3}\ ft^2/s$

To get started assume entire sheet of plastic is @ $T_p = 200°F$

Do it again if we are really way off.

Re# at end of cross flow of width $L = 4ft$ 12/20



$$Re_L = \frac{V_{air} L}{\nu_{air}} = 1.961 \times 10^5 < Re_{crit} = 5 \times 10^5$$

so we have laminar flow.

thus

$$Nu = \frac{h_{air} L}{K_{air}} = 0.664\ Re_{L}^{1/2}\ Pr_{air}^{1/3}$$

$$= 263.6$$

But then

$$h_{air} = \frac{Nu\ K_{air}}{L} = 1.07\ BTU/hr\text{-}ft^2\cdot°F$$

also $A_{s\,total} = (2ft)(4ft)(2\text{ sides}) = 16\ ft^2$

or

$$q_{conv} = hA_s\,(T_s - T_{\infty}) = 2054\ BTU/hr$$

don't forget

$$q_{rad.} = \varepsilon \sigma A_s (\underbrace{T_s^4}_{660\,R} - \underbrace{T_{\infty}^4}_{540\,R})$$

σ: $0.1714 \times 10^{-8}\ BTU/hr\ ft^2\ R^4$

$$= 2585\ BTU/hr$$

so

$$q_{Total} = q_{conv.} + q_{rad} = 4639\ BTU/hr$$

Now for the mass flow rate of the plastic passing blower section

$$\dot{m}_{plast.} = \rho\, A_{cross}\, V_{plast.} = \ldots = 0.5\ lbm/s$$

ρ: $75\ lbm/ft^3$

Energy balance on plastic section exposed to blower

$$\dot{q} = \dot{m}\, c_{p,p} (T_2 - T_1) \Rightarrow T_2 = T_1 + \frac{\dot{q}}{\dot{m}\, c_p}$$

known ~2054 $\frac{BTU}{hr}$ 'cause heat loss from plastic

solve for this exit temp

$T = 200\,°F$

or

$T_2 = 193.6\,°F$

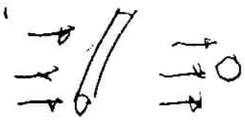
(not a huge change)

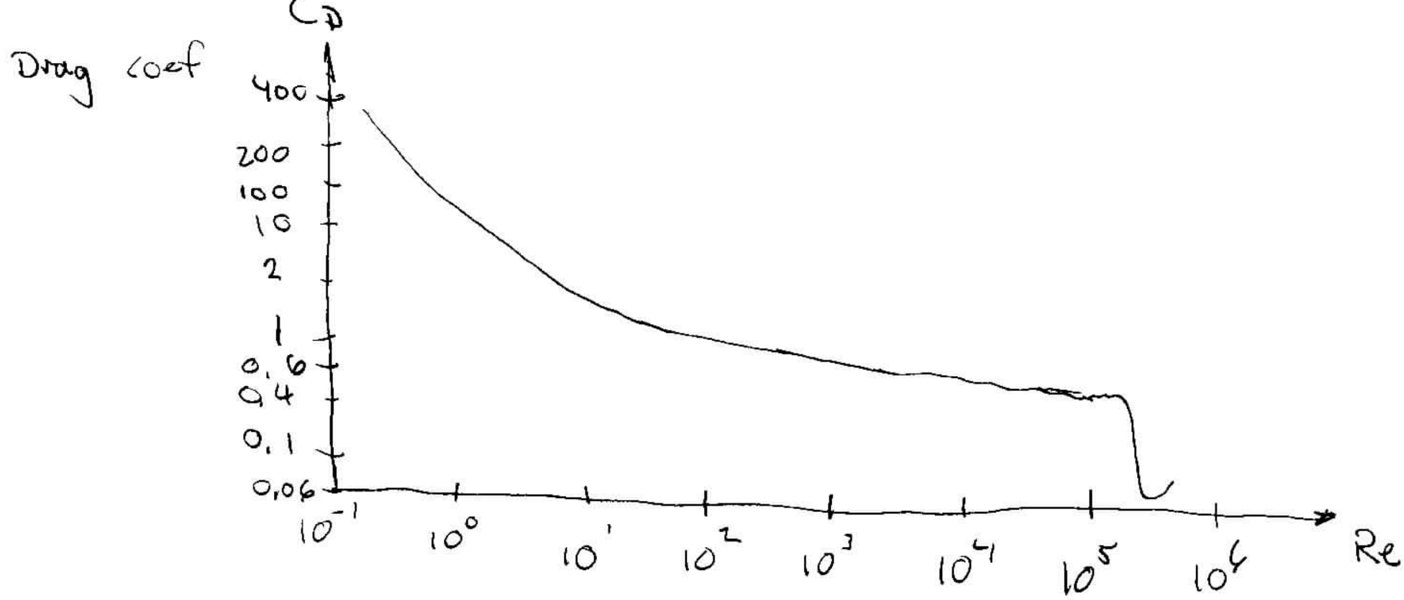
But you could rework prob at $T_{plast_{avg}} = 196.8\,°F$

but will not see much of a change though.

//

Flow across cylinders and spheres.





$Re < 10^0$ Stokes flow (creeping flow)

$Re \sim 10^1$ Separation starts at rear of body

$Re \sim 10^3$ Drag is about 95% pressure drag

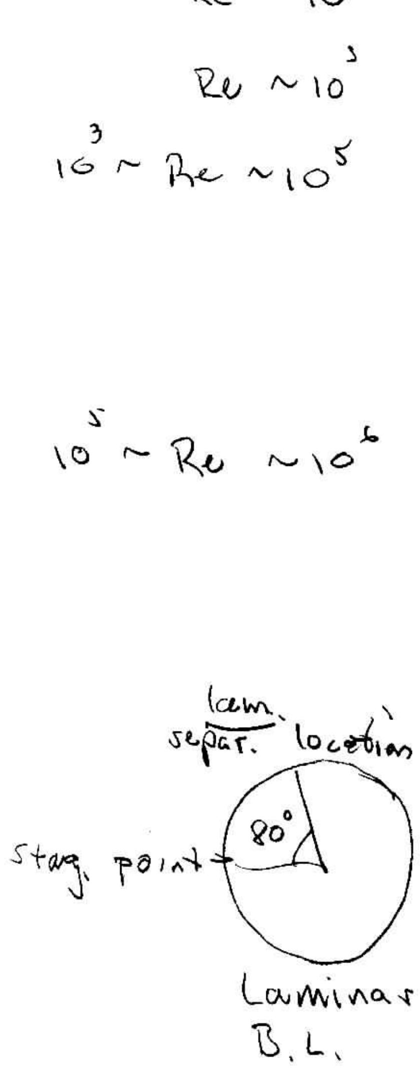
$10^3 \sim Re \sim 10^5$ C_D is ~ constant

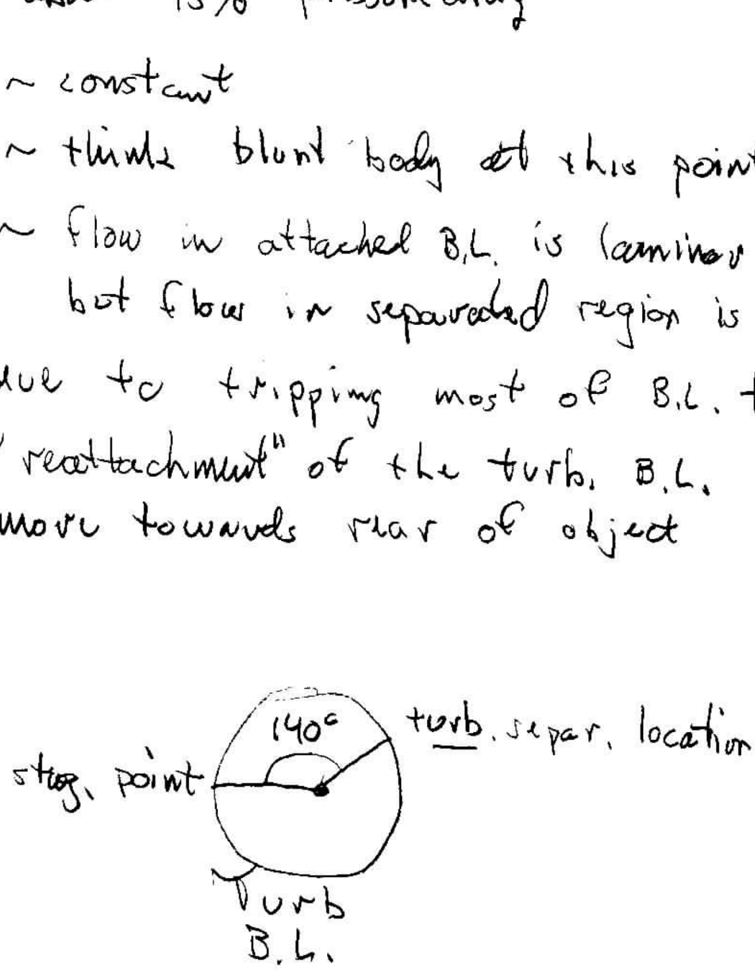
~ think blunt body at this point

~ flow in attached B.L. is laminar but flow in separated region is turb.

$10^5 \sim Re \sim 10^6$ $C_D \downarrow$ due to tripping most of B.L. to turb

"reattachment" of the turb. B.L. move towards rear of object

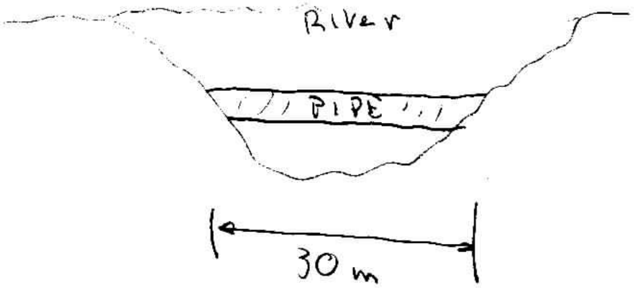




Don't forget surface roughness! ε/D stuff!

B.L. trips earlier than for smooth surface

Ex)



$D_{pipe} = 2.2$ cm O.D. pipe across river

$V_{river} \sim 4$ m/s

$T_{river} \sim 15°C$

Calc. force on pipe.

Assume
- Smooth outer pipe surface
- Steady state
- Flow is ⊥ to pipe
- River is laminar flow

Prop. @ $T = 15°C$ $\rho_{water} = 999.1$ kg/m³ $\mu = 1.138 \times 10^{-3}$ kg/m.s

Tables

$$Re_{D\,pipe} = \frac{V_r D_p}{\nu_r} = \ldots = 7.73 \times 10^4 < Re_{crit}$$

From C_D graph $C_D = 1.0$

Frontal area of pipe $= A_{blunt\,face} = L \cdot D$

so

$$F_D = C_D A_{face} \frac{\rho_r V_r^2}{2} = \ldots = 5275 \text{ N}$$

Think spring run off condition

Heat Transfer

1/6/20

So long analytical solutions, into the lab we go.

Buckingham Π theorem + dimensional analysis to the rescue.

$$\Pi_1 = f(\Pi_2, \Pi_3, \Pi_4, \ldots)$$

known dimensionless parameters but the function is unknown.

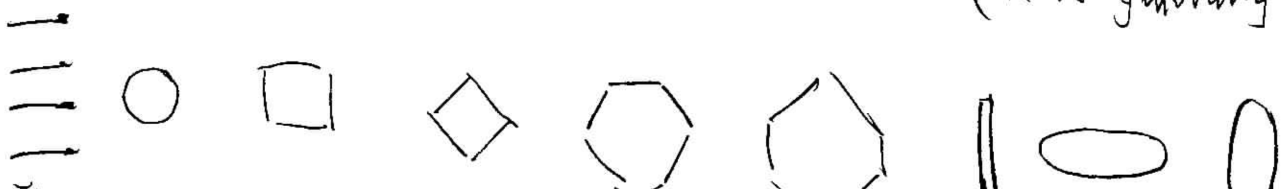
Everybody with a M.S. or Ph.D. did one in fluids or H.T.

Often for overall results the form

$$\overline{Nu}_{sph} = \frac{\bar{h}D}{k} = C\, Re^m\, Pr^n$$

Then for a specific geometry look up C, m, and n values.

(n is generally $\approx 1/3$)



Flow across the cylinders. (Single cylinders)

Given geometry
dimensions
Re

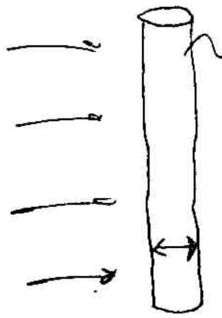
look up C, m (and sometimes n)

Ex1

Wind

$T_\infty = 10^\circ C$

$V = 8 \, m/s$



$T_s = 110^\circ C$

$D = 0.1 \, m$

• Calculate rate of heat loss per unit length.

Assume: • Steady state
• Negl. radiation effects
• Air is IG

Prop: get air prop. @ $T_{film} = \dfrac{T_s + T_\infty}{2} = 60^\circ C$

$P_{air} = 1 \, atm$

Look in tables $k_{air} = 0.02808 \, W/m \cdot k$ $\quad Pr_a = 0.7202$

$\nu_a = 1.896 \times 10^{-5} \, m^2/s$

Off we go $\quad Re = \dfrac{V_a D_{pipe}}{\nu_a} = \ldots = 4.219 \times 10^4$

Let's use $\quad Nu = \dfrac{h_a D_p}{k_a} = 0.3 + \dfrac{0.62 \, Re^{1/2} Pr^{1/3}}{\left[1 + \left(\dfrac{0.4}{Pr}\right)^{2/3}\right]^{1/4}} \left[1 + \left(\dfrac{Re}{282{,}000}\right)^{5/8}\right]^{4/5}$

$= \ldots = 124$

in which case $\quad h_a = Nu \dfrac{k_a}{D_p} = \ldots = 34.8 \, \dfrac{W}{m^2 \, K}$

Calc $A_{surf} = (\text{perim}) L = \pi D_p L_p = \ldots = 0.314 \, m^2$

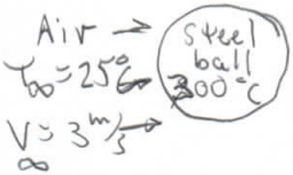
so

$q = h A_{surf} (T_s - T_\infty) = \ldots = 1093 \, W$ (per unit length of pipe)

//

oh, other relations are within $\approx$ 3 or 4%

Ex



Ball is initially @ uniform temp of 300°C.

Then blow air at 1 atm & 25°C over it @ 3 m/s.

Eventually $T_{surf} = 200°C$,

How long did it take?

Assume:
- Steady state
- Neg. rad.
- Air is IG
- Uniform outer surface temp T_s (spatial)
- $T_s(t)$ varies with time.

  ∴ $h(t)$ as well.

  Will try $\bar{T}_s = \frac{(300+200)°C}{2} = 250°C$

  as a constant over time.

Prop: $\mu_a\big|_{250°C} = 2.76 \times 10^{-5} \frac{kg}{m \cdot s}$

250°C avg surf temp (film)

Air @ freestream cond: $T_a = 25°C$ $\quad P_a = 1\,atm$

$k_a = 0.02551 \frac{W}{mK}$

$\mu_a = 1.849 \times 10^{-5} \frac{kg}{m \cdot s}$

$\nu_a = 1.562 \times 10^{-5}\, m^2/s$

$Pr = 0.7296$

Calculations: $Re = \frac{V_\infty D}{\nu_a} = \ldots = 4.802 \times 10^4$

$$\overline{Nu} = \frac{\bar{h}_a D}{k_a} = 2 + \left[0.4\, Re^{1/2} + 0.06\, Re^{2/3}\right] Pr^{0.4} \left(\frac{\mu_\infty}{\mu_s}\right)^{1/4}$$

$$= \ldots = 135$$

We now know $\bar{h}_a = \bar{Nu}\,\frac{k_a}{D} = \ldots = 13.8\ \frac{W}{m^2 \cdot K}$

Calc average rate of heat transfer using Newton's law of Cooling with average surface temperature (over time)

$$A_{surf} = \pi D^2 = 0.1963\ m^2$$

so

$$\dot{q}_{avg} = \bar{h}_a A_s (\bar{T}_{s\,avg} - T_\infty) = \ldots = 610\ W$$

Now calc total heat removed from ball as it cools from 300 °C to 200 °C

$$m_{ball} = \rho V = \tfrac{1}{6}\rho\pi D^3 = \ldots = 65.9\ kg$$

so

$$Q_{total} = m c_p (\underset{300^\circ C}{T_2} - \underset{200^\circ C}{T_1}) = \ldots = 3{,}163\ kJ$$

We assumed the entire ball was @ 200°C. Not really true.
($T_{inside} > T_{surf.}$)

Perhaps a good estimate might be

$$\Delta t \approx \frac{Q_{Total}}{\dot{q}_{avg}} = 5185\ s = 1\ h\ 26\ min$$

Better yet ... use transient solution for a sphere.

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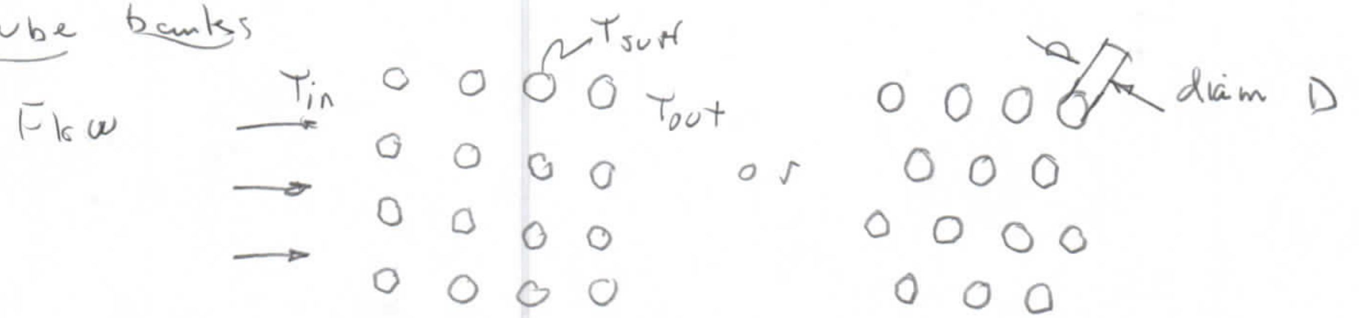
Tube banks



Need an orientation and some dimensions. (See §7.6 in text)

Need to get a handle on velocity (max.) over the bank.

Is always done in a lab, but the idea is the same

$$Nu_D = \frac{hD}{k} = C\, Re_D^m\, Pr^n \left(\frac{Pr}{Pr_s}\right)^{1/4}$$

All properties are evaluated for fluid @ $\bar{T} = \frac{T_i + T_o}{2}$

except Pr_s which is based on the tube surface temp T_s.

See text for an example.

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