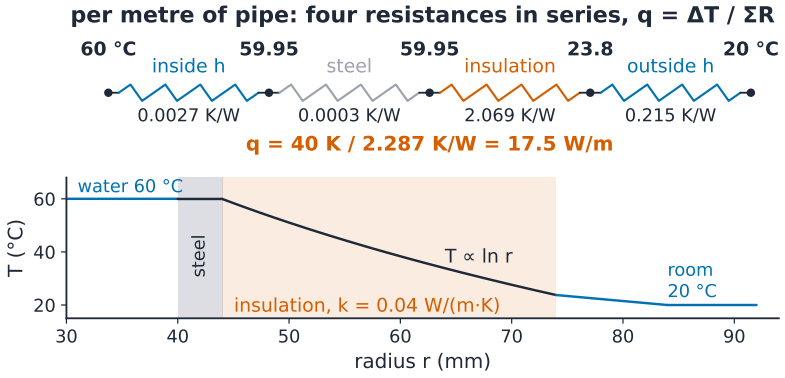
Heat Transfer

Curated undergraduate study track (not accredited, no external exam). Original explanations and practice only, following the reviewed course handout.

How fast heat moves

- The tenth course: Course 5 counted the energy; this one finds the rate.
- The loop again - warm pipes, quenched parts, the exchanger and the drive electronics.
- Draw the resistance network first: $q = \Delta T / \sum R$, and the largest R controls the answer.

The pipe as a resistance network



Per metre: $\sum R = 2.287$ K/W, $q = 40/2.287 = \mathbf{17.5}$ W/m; the bare pipe loses **110** W/m by convection.

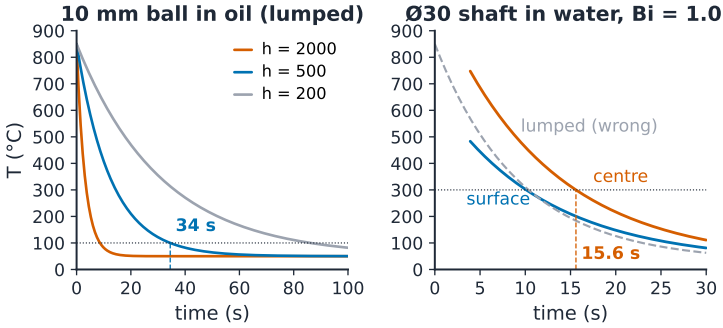
A composite wall

1. **Layers** Brick 200 mm, wool 50 mm, plaster 12 mm on 12 m^2; $h_i = 8$, $h_o = 25$.
2. **Sum** $0.0104 + 0.0238 + \mathbf{0.1042} + 0.0020 + 0.0033 = \mathbf{0.1437}$ K/W.
3. **Rate** $q = 27/0.1437 = \mathbf{188}$ W; the wool takes 73% of the drop.
4. **Critical radius** $r_c = k/h = 4$ mm $\ll 44$ mm, so pipe insulation can only help.

Decision

Put the insulation where the resistance network says it counts.

Quenching curves



Ball: $Bi = 0.019$, $\tau = \mathbf{12.4}$ s, 850 → 100 °C in $\mathbf{34}$ s. Shaft: $Bi = 1.05$, centre to 300 °C in $\mathbf{15.6}$ s.

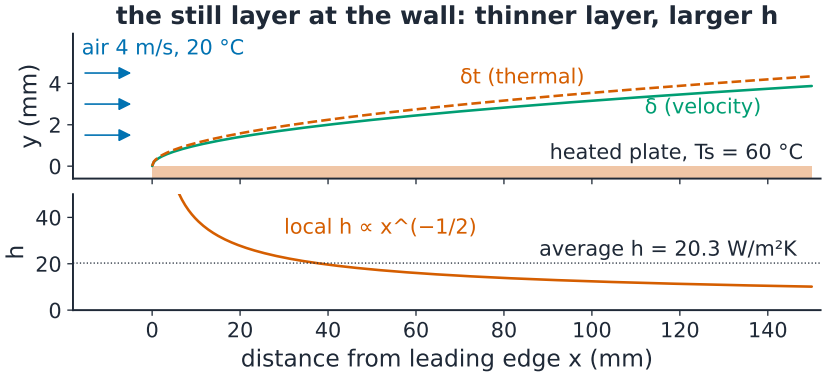
When lumped is wrong

1. **Biot** $Bi = 3000 \times 0.015/43 = \mathbf{1.05}$ - not lumped.
2. **One term** $\zeta_1 = 1.278$, $C_1 = 1.215$; $\theta_0 = 270/820 = 0.329$.
3. **Time** $Fo = \ln(C_1/\theta_0)/\zeta_1^2 = \mathbf{0.80}$, $t = \mathbf{15.6}$ s; surface about 200 °C.
4. **Lumped** Would say 10.4 s - 33% short, and blind to the 100 K gradient.

Decision

Above $Bi = 0.1$ the inside matters; the lumped answer is too optimistic.

The thermal boundary layer



Air 4 m/s on 150 mm: $Re = 37\,500$, $Nu = \mathbf{114.7}$, $h = \mathbf{20.3}$ W/m^{2}K.

Water inside the pipe

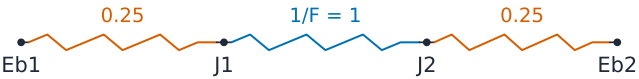
1. **Flow** 16.8 L/s in 80 mm at 40 °C: $V = 3.34$ m/s, $Re = \mathbf{4.06 \times 10^5}$.
2. **Range** Dittus-Boelter needs $Re > 10^4$, $0.6 < Pr < 160$ - here $Pr = 4.32$.
3. **Nu** $Nu = 0.023 Re^{0.8} Pr^{0.4} = \mathbf{1268}$, $h \approx \mathbf{10\,000}$ W/m^{2}K.

Decision

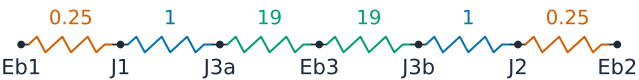
This is why the inside film resistance was negligible in the pipe network.

Radiation as a network

surface resistances (1−ε)/ε and space resistances 1/F (per m²)



ΣR = 1.5: q = σ(600⁴ − 300⁴)/1.5 = 4593 W/m²



shield ε = 0.05 adds 39: q = 170 W/m², 3.7% of before

600 K / 300 K plates, $\varepsilon = 0.8$: $\mathbf{4593}$ W/m^2; a shield with $\varepsilon = 0.05$ cuts it to $\mathbf{170}$ W/m^2.

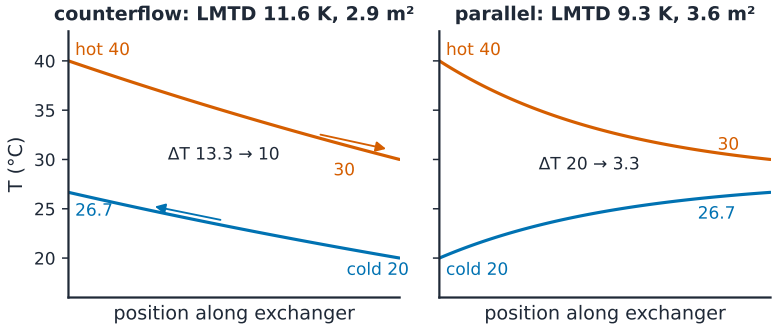
The bare pipe, honestly

1. **h_r** $h_r = \varepsilon\sigma(T_s^2 + T_{sur}^2)(T_s + T_{sur}) = \mathbf{5.58}$ W/m^{2}K at 59.5 °C.
2. **Bare** $q = \mathbf{170}$ W/m - convection 109, radiation $\mathbf{61}$.
3. **Insulated** Surface 22.7 °C, $q = \mathbf{18.0}$ W/m.

Decision

Ignoring radiation hid a third of the loss; the true saving is 89%, not 84%.

Counterflow beats parallel flow



83.6 kW, loop 40 $\rightarrow$ 30 °C, plant 20 $\rightarrow$ 26.7 °C: **counterflow** $\Delta T_{lm} = \mathbf{11.6}$ K, $A = \mathbf{2.89}$ m^2; parallel 3.59 m^2.

Rating with fouling

1. **Clean** 3.0 m^2, $NTU = 0.897$, $\varepsilon = \mathbf{0.511}$, $Q = \mathbf{85.5}$ kW - meets 83.6.
2. **Fouled** $R_f = 0.0002 \rightarrow U = 1667$, $\varepsilon = 0.398$, $Q = \mathbf{66.6}$ kW - short.
3. **Resize** Fouled U needs $\mathbf{4.33}$ m^2; more plates also cut velocity, pressure drop and h.

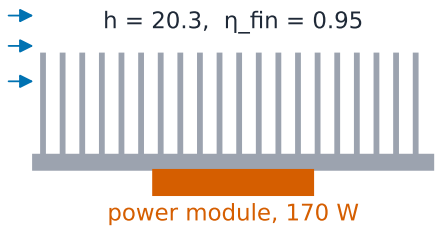
Decision

Buy the area that still works after a year of scale.

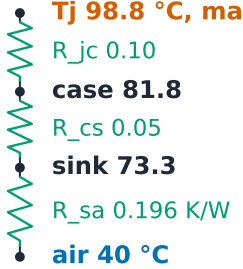
Cooling the drive electronics

20 fins, 40 × 2 mm, 150 mm long

air 4 m/s, 40 °C



junction to air: limit 125 °C



Allowed $R_{sa} \leq \mathbf{0.35}$ K/W; 20 **fins** give $\eta_f = 0.95$, $R_{sa} = \mathbf{0.196}$ K/W, $T_j = \mathbf{98.8}$ °C.

exercises.lol exercises.com.cn

Margins and assumptions

1. **Options** 30 **fins** $\rightarrow$ 88.6 °C; 60 mm fins $\rightarrow$ 89.8 °C.
2. **Sensitivity** h is $\pm 25\%$ uncertain; at $h = 15$, $T_j = 110$ °C, still below 125.
3. **Conservative** Radiation from the sink (about 10%) ignored.
4. **Not covered** Fan failure - needs a thermal trip.

Decision

A thermal design is a number, a margin and the assumption that could break it.

Check yourself

- The wall and the pipe? (0.1437 K/W, 188 W; 17.5 W/m insulated, 170 W/m bare with radiation.)
- The ball and the shaft? (Bi 0.019, 34 s; Bi 1.05, 15.6 s, lumped 10.4 s.)
- The two h values? (Air plate 20.3; loop water about 10 000 W/m^2K.)
- The shield, the exchanger, the sink? (170 W/m^2; 2.89 m^2, 4.33 m^2 fouled; 0.196 K/W, 98.8 °C.)