Thermodynamics 1

Lecture 7:
Heat transfer
Open systems

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Energy Technology

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Summary lecture 6

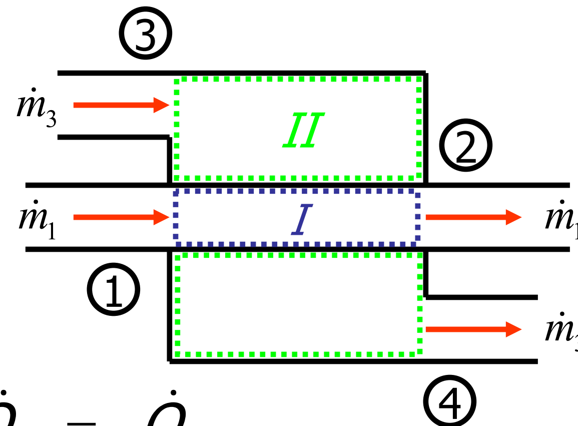
- Poisson relation
- efficiency of a two-stroke IC engine (Otto cycle)
- gas turbine with a heat exchanger
- open systems
- mass and energy balance
- 1st law of thermodynamics
- stationary open systems
- turbine, throttle, heat exchanger

Heat exchanger

1st law for stationary open system:

$$\dot{Q} = \dot{W}_{cv} + \dot{m}\left[\left(h_2 - h_1\right) + \tfrac{1}{2}\left(V_2^2 - V_1^2\right) + g\left(z_2 - z_1\right)\right]$$

with: $\dot{W}_{cv} = 0$, $\tfrac{1}{2}\left(V_2^2 - V_1^2\right) << \left|h_2 - h_1\right|$ and $g\left|z_2 - z_1\right| << \left|h_2 - h_1\right|$



system *I* $\quad \dot{Q}_I = \dot{m}_1\left(h_2 - h_1\right)$

system *II* $\quad \dot{Q}_{II} = \dot{m}_3\left(h_4 - h_3\right)$

heat transfer only through wall *I* / *II* $\quad \dot{Q}_{II} = -\dot{Q}_I$

$$\dot{m}_1\left(h_2 - h_1\right) + \dot{m}_3\left(h_4 - h_3\right) = 0$$

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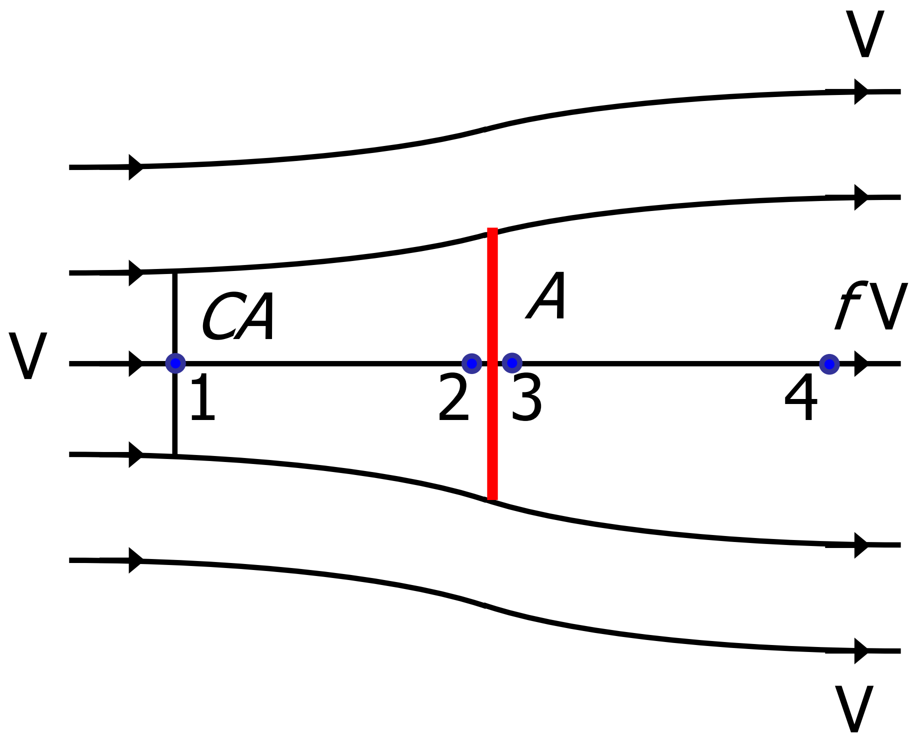
Wind turbine



$f < 1 \quad V_4 = fV$

Area at 4: $CA\,/\,f$

Thrust ($F = \Delta p \cdot A$):

$(p_2 - p_3)A = \frac{1}{2}\rho V^2 A(1 - f^2)$

Momentum change

($F = \dot{m}\Delta V$): $\rho V^2 CA(1 - f)$

Balance of forces:

$C = \frac{1}{2}(1 + f)$

Power: $\dot{W} = \Delta\dot{E} = \frac{1}{4}\rho V^3 A(1+f)(1-f^2) \Rightarrow \boxed{\dot{W}_{max} = \frac{8\rho A V^3}{27}} \quad f = 1/3$

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$$E = f(\rho, R, t) \Rightarrow E = c \cdot \frac{\rho R^5}{t^2} \quad (c = 1.033)$$

$$\frac{kg \cdot m^2}{s^2} = \left(kg/m^3\right)^{\alpha} \cdot (m)^{\beta} \cdot (s)^{\gamma} \quad \Rightarrow \quad \alpha = 1 \quad \beta = 5 \quad \gamma = -2$$

t = 0.03 s, R = 130 m

$\Rightarrow E \sim 50 \times 10^{12}$ J (50 TJ)

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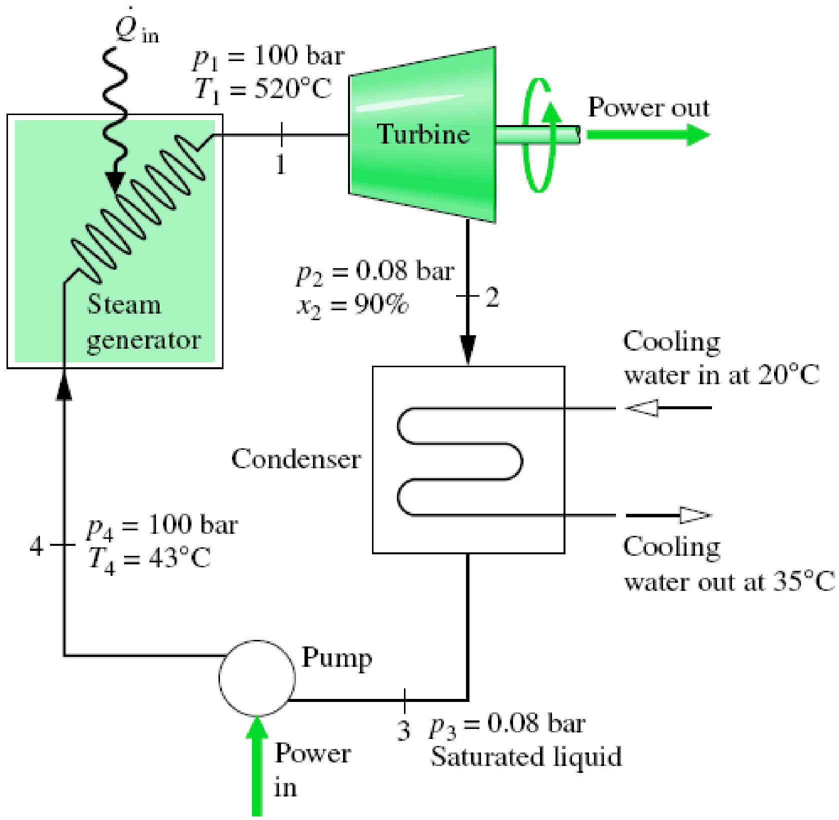
Problem 4.59

Figure P4.44 shows a simple vapor power plant operating at steady state with water circulating through the components. Relevant data at key locations are given on the figure. The mass flow rate of the water is 130 kg/s. Kinetic and potential energy effects are negligible.

Determine:

a. The thermal efficiency
b. The mass flow rate of the cooling water passing through the condenser, in kg/s



▲ Figure P4.59

$\eta = 0.332$; $\Phi_m = 4485$ kg/s

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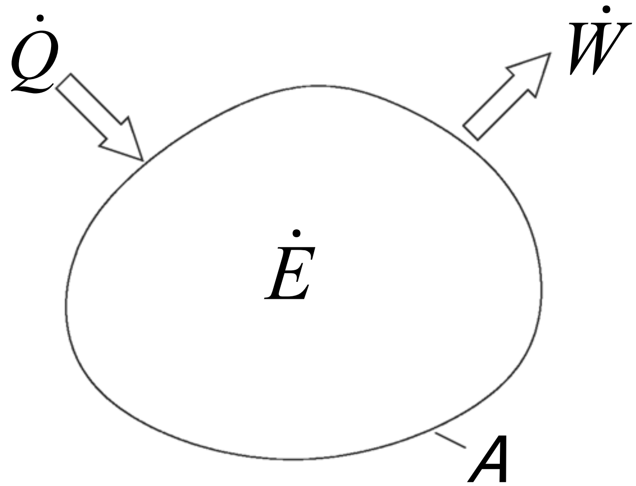
Energy transfer by heat



Energy equation closed system:

$$\dot{E} = \dot{Q} - \dot{W}$$

Heat flux $\dot{Q}$ through area A:

$$\int_A \dot{q} dA$$

where $\dot{q}$ is the specific heat flux

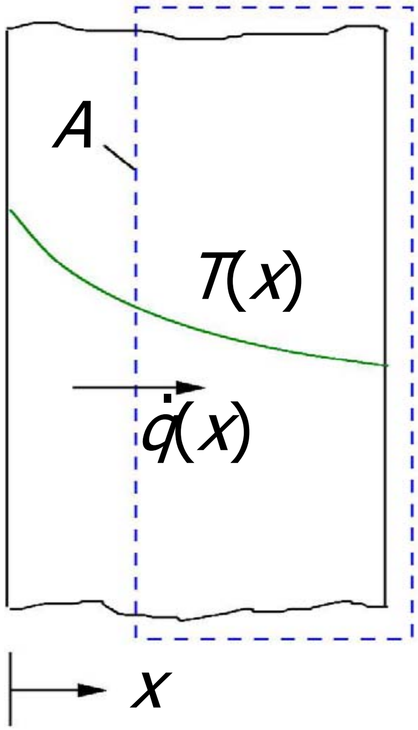
Two principal ways of heat transfer: ***conduction*** and ***radiation*** occur due to temperature differences: in general ***no*** *equilibrium*
(Thermodynamic) equilibrium only for ideal case of quasistatic processes:
– time does not play a role
– infinitesimal temperature differences

Heat transfer by conduction

Fourier's Law:

$$\dot{q}_x = -\kappa \frac{dT}{dx}$$

where κ is the *heat conduction coefficient*



Total heat flux:

$$\dot{Q}_x = -\kappa A \frac{dT}{dx}$$

where A is the surface area

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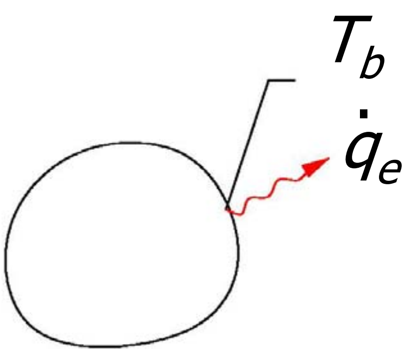
Heat transfer by radiation

Stefan-Boltzmann Law:

$$\dot{q}_e = \sigma T_b^4 \qquad \text{'black body'}$$

$$\dot{q}_e = \varepsilon \sigma T_b^4 \qquad \text{'gray body'}$$



with: $\sigma = 5.67\times10^{-8}$ W m^{-2} K^{-4}

$0 \leq \varepsilon \leq 1$

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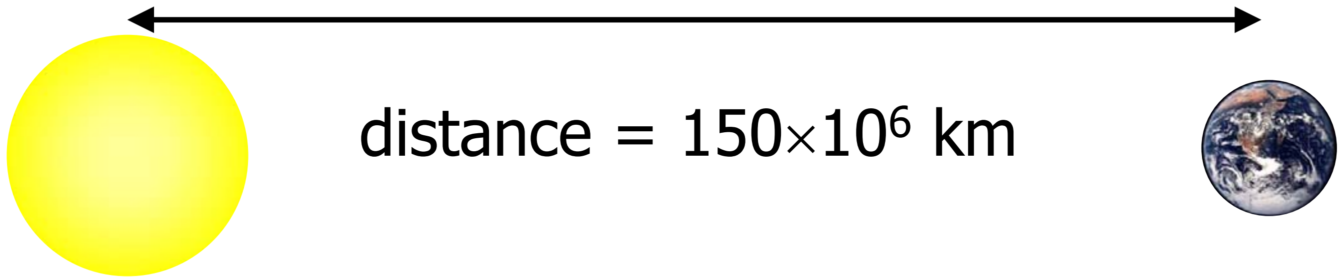

Sun

$T_s = 5.8\times10^3$ K

$R = 0.7\times10^6$ km

$$\dot{q}_1 = \sigma T^4 = 5.67\times10^{-8}\cdot\left(5.8\times10^3\right)^4 = 64\times10^6 \text{ W/m}^2$$

$$\dot{q}_1 4\pi R_1^2 = \dot{q}_2 4\pi R_2^2 \Rightarrow \dot{q}_2 = \dot{q}_1\left(R_1/R_2\right)^2$$

$$\dot{q}_2 = 64\times10^6\left(0.7/150\right)^2 = 1.4\times10^3 \text{ W/m}^2$$

$$T = \left(0.25\,\dot{q}_2/\sigma\right)^{1/4} = 280\text{ K} \ \ (+7^\circ\text{ C})$$

$$\frac{\text{projected surface}}{\text{total surface}} = \frac{\pi R_2^2}{4\pi R_2^2} = \frac{1}{4}$$

http://www.junkscience.com/GMT/

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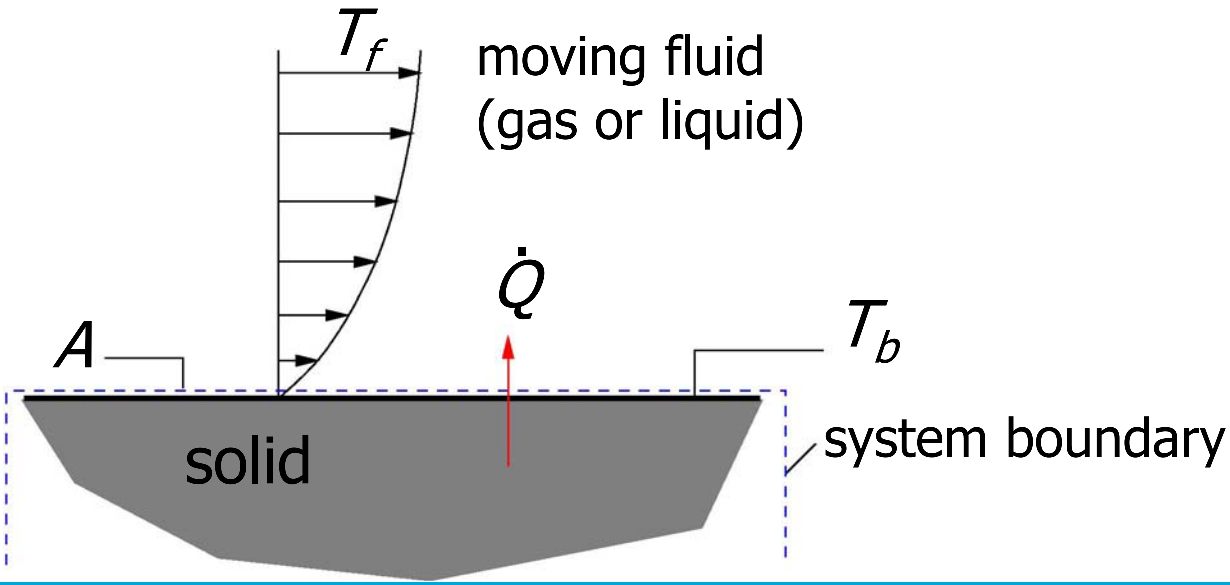
Heat transfer by convection

In many practical situations we also have to deal with *heat transfer by convection.*
For this case we have *Newton's cooling law* (emperical):

$$\dot{Q} = hA\left(T_b - T_f\right)$$

where *h* is the heat transfer *heat transfer coefficient*



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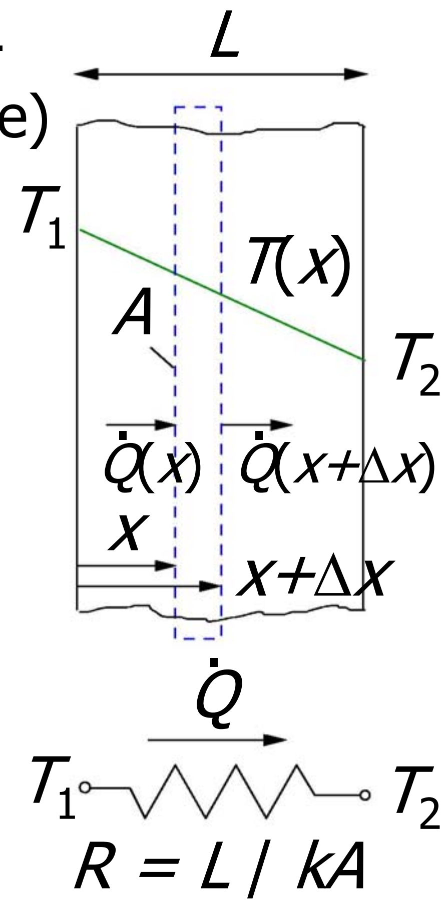
Stationary 1-D heat conduction

Stationary: temperature T does not change as a function of time; **1-dimensional**: only one independent coordinate $T(x)$ (plane wall), $T(r)$ (sphere)



Plane wall:

stationary energy equation ($\dot{E} = 0$, $\dot{W} = 0$):

$$\dot{Q}(x) = \dot{Q}(x+\Delta x) \quad \text{or} \quad \dot{Q}(x) = \text{constant}$$

with Fourier's law $\left(\dot{q}_x = -k\, dT/dx\right)$:

$$\dot{Q} = \int_0^L dx = -A\int_{T_1}^{T_2} k\, dT$$

neglecting the temperature dependence of k:

$$\dot{Q} = -\frac{kA}{L}\left(T_2 - T_1\right) = \frac{T_1 - T_2}{L/kA} = \frac{T_1 - T_2}{R}$$

with 'thermal resistance' $R = L / kA$.

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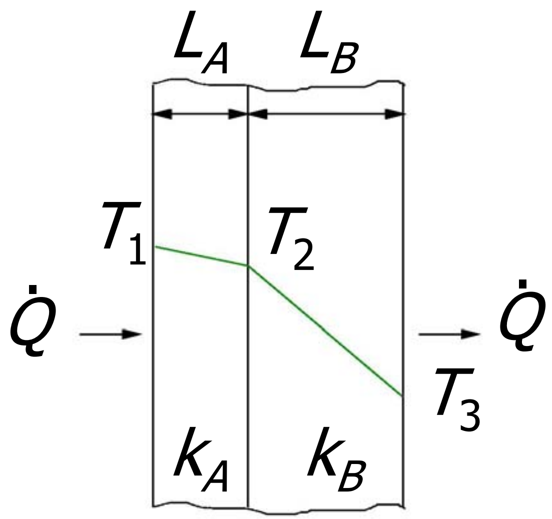
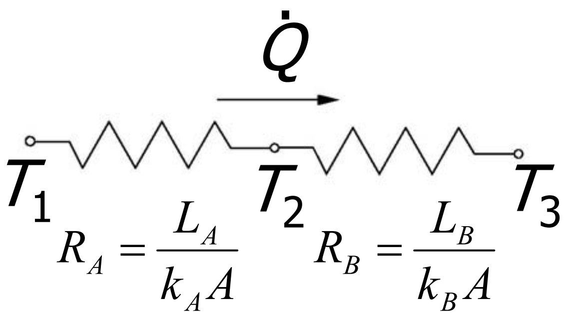
Multiple layers





$$\dot{Q} = \frac{T_1 - T_2}{L_A / k_A A} = \frac{T_2 - T_3}{L_B / k_B A}$$

eliminate T_2:

$$\dot{Q} = \frac{T_1 - T_3}{L_A / k_A A + L_B / k_B A} = \frac{T_1 - T_3}{R_A + R_B}$$

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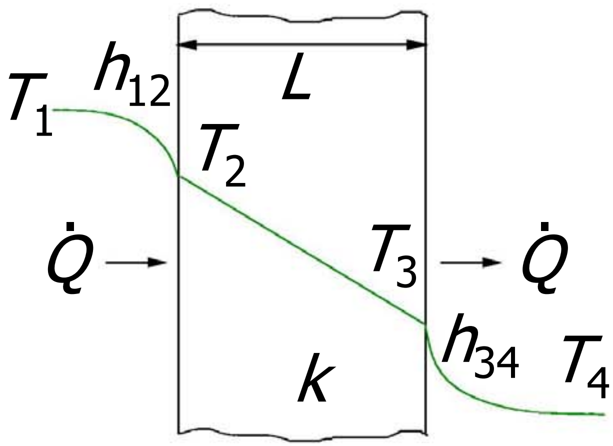

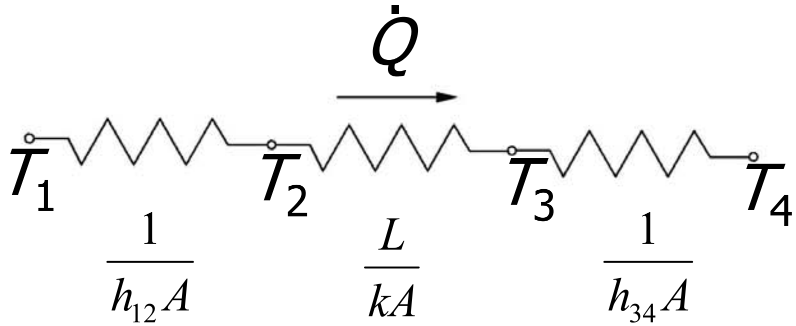

Constant heat flux (with Newton's cooling law, Fourier's law):

$$\dot{Q} = h_{12}A\left(T_1 - T_2\right) = \frac{T_2 - T_3}{L/kA} = h_{34}A\left(T_3 - T_4\right)$$

Eliminate T_2 and T_3:

$$\dot{Q} = \frac{T_1 - T_4}{1/h_{12}A + L/kA + 1/h_{34}A} = UA\left(T_1 - T_4\right)$$

where U is the heat transfer coefficient: $\frac{1}{U} = \frac{1}{h_{12}} + \frac{L}{k} + \frac{1}{h_{34}}$

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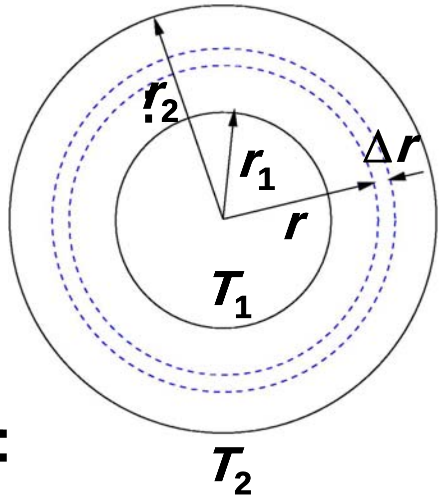
Cylindrical walls

Stationary energy equation ($\dot{E} = 0$, $\dot{W} = 0$):

$$\dot{Q}(r) = \dot{Q}(r + \Delta r) \quad \Rightarrow \quad \dot{Q} = \text{constant}$$

with Fourier's law $\left(\dot{Q} = -kA\frac{dT}{dx} = -k2\pi rL\frac{dT}{dr}\right)$

$$\dot{Q}\int_{r_1}^{r_2}\frac{1}{r}dr = -2\pi L\int_{T_1}^{T_2}k\,dT$$



neglecting the temperature dependence of k:

$$\dot{Q} = -2\pi kL\frac{T_2 - T_1}{\ln\left(r_2/r_1\right)} = \frac{T_2 - T_1}{R}$$

with 'thermal resistance' $R = \ln\left(r_2/r_1\right)/2\pi kL$

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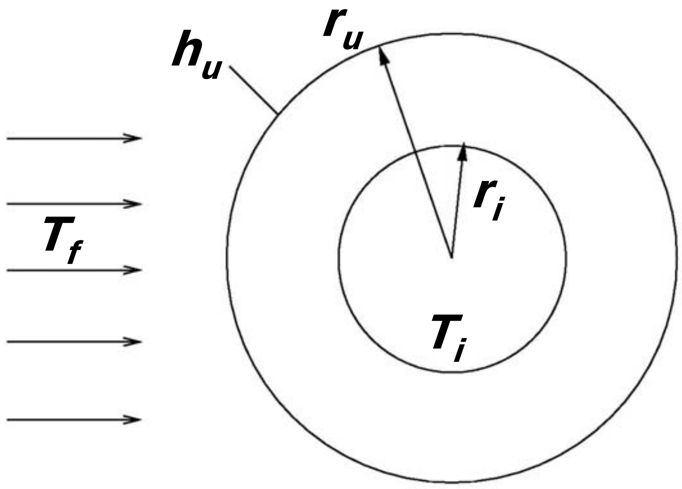
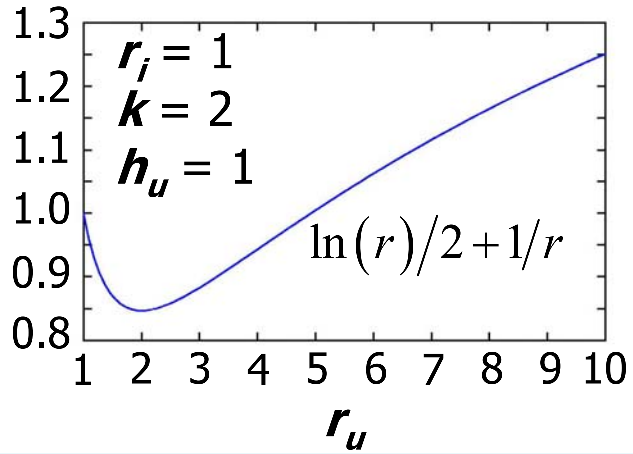
Critical isolation thickness

heat transfer rate: $\dot{Q} = \frac{T_i - T_f}{R}$



with: $$R = \frac{\ln(r_u/r_i)}{2\pi k L} + \frac{1}{h_u 2\pi r_u L}$$
$$= \frac{1}{2\pi L}\left(\frac{\ln(r_u/r_i)}{k} + \frac{1}{h_u r_u}\right)$$

minimum heat resistance
(dR / dr_u = 0): $r_u = r_{cr} = \frac{k}{h_u}$



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Exercise

A thick-walled pipe of stainless steel (k = 19 W/m·K) with a 2 cm inner diameter and a 4 cm outer diameter is covered by a 3 cm thick insulation layer (k = 0.2 W/m·K). The temperature is 600 ºC on the inside and 100 ºC on the outside.

Determine:
a) the heat transfer rate Q per unit pipe length in W/m;
b) the temperature at the pipe/insulation interface in ºC.

(Answers: a) 680 W/m, b) 596 ºC)

Exercise (homework)

Water at 50 ºC flows through a pipe with an inner diameter of 2.5 cm, with an inner heat transfer coefficient of
h_i = 3500 W/m²·K.
The pipe has a 0.8 mm thick wall and a heat conduction coefficient k of 16 W/m·K. The heat transfer to the surroundings (air at 20ºC) on the outside of the pipe is by free convection with a heat transfer coefficient of
h_u = 7.6 W/m2·K.

Determine:
a) the coefficient $U A$ per unit pipe length in W/m·K;
b) the total heat flux Q per unit pipe length in W/m.

(Answers: a) 0.633 W/m·K, b) 19 W/m)

Instructions for study

- Ch. 1- 4 of Moran & Shapiro have been discussed; also study now §2.4.2 (heat transfer).
- Study §§4.1-4.3, including all examples. Study examples in §4.4 on instationary systems. For the exams you need to be able to work with the stationary energy balance.
- Do exercises 4.20, 4.22 & 4.23. For 4.22, use mass and energy balances for multiple inlets and outlets
- We have discussed from Mills *Basic Heat & Mass Transfer* (2nd Ed.): §1.3.1, first part of §1.3.2 (radiation), Ch. 2 till §2.3.3. Heat transfer by radiation (i.e., $h_{c,o}$) will not be required for the exam
- Do the exercises on heat transfer (homework)