Energy & Heat Transfer

Lecture 2

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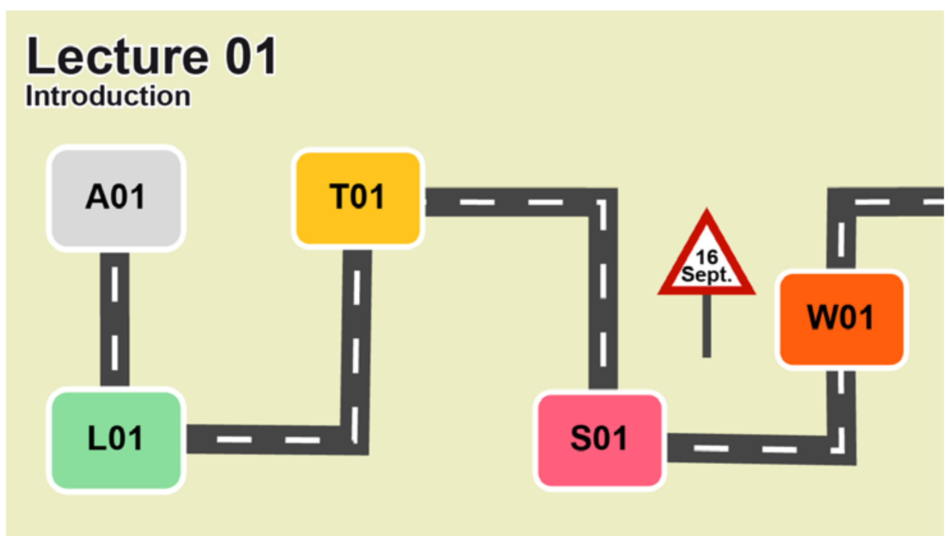
Lectorial

- Lectorial : Friday, 9th September,13:45 - 15:30

Energy & heat transfer:
Learning path

HEATQUIZ

Course Description | Course Manual | Tables with Properties | Practice Exam | User Key



Recap of lecture 1

- Work (W), energy (E), power (P)
- Work (*W*), Energy (*E*) in $\mathrm{J} = \mathrm{N} \cdot \mathrm{m} = \frac{\mathrm{kg} \cdot \mathrm{m}}{\mathrm{s}^2} \cdot \mathrm{m}$
- Power : $P = \frac{\Delta E}{\Delta t}$ in Watt (W) = J / s
- Units kWh, kcal, hp, ….

Recap of lecture 1

- Potential energy : $E = F \cdot h$

- Thermal energy : $Q = m \cdot c \cdot \Delta T$
  - c is specific heat capacity in J / (kg · K)

- Electrical power: $P = U \cdot I$
  - Electrical energy: $E = P \cdot t = U \cdot I \cdot t$
  - Ohm's law: $U = I \cdot R$

$$\left.\begin{array}{l} P = U \cdot I \\ E = P \cdot t = U \cdot I \cdot t \\ U = I \cdot R \end{array}\right\} \quad \begin{array}{l} P = I^2 \cdot R \\ E = I^2 \cdot R \cdot t \end{array}$$

Learning objectives lecture 2

- **Energy in general**
  - Using an energy balance
  - Determine efficiency
  - Calculate losses for electric resistors

- **Conductive heat transfer**
  - *Explaining* conduction principles
  - *Calculate* conductive heat transfer
  - Using *thermal resistances* and insulation values

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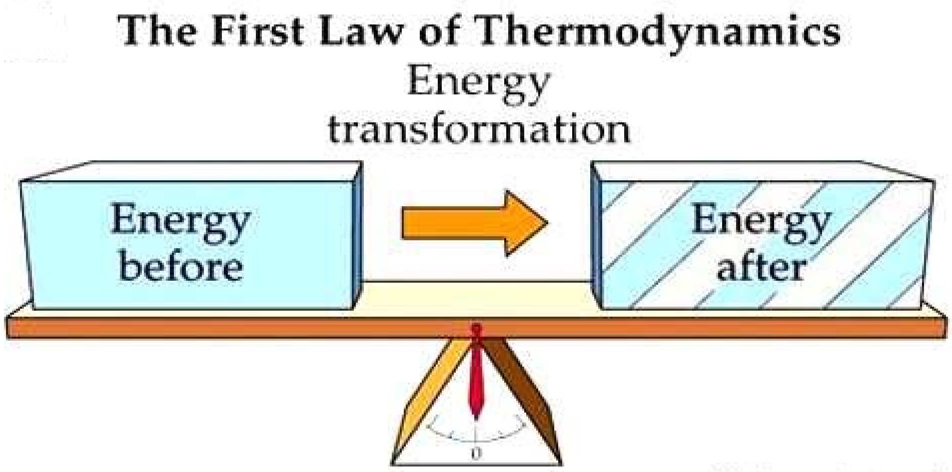
ENERGY BALANCE

- Energy is **always conserved**!

- First law of Thermodynamics:



Energy balance

- Sankey diagram light bulb

LIGHT BULB

Energy balance

Flatscreen

Energy balance

LEARNING OBJECTIVES LECTURE 2

Energy in general

- Using an energy balance
- **Determine efficiency**
- Calculate losses for electric resistors

Conductive heat transfer

- *Explaining* conduction principles
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Efficiency

- Efficiency = fraction of “useful” work/power used
  - What is defined as useful?
  - What is the reference?

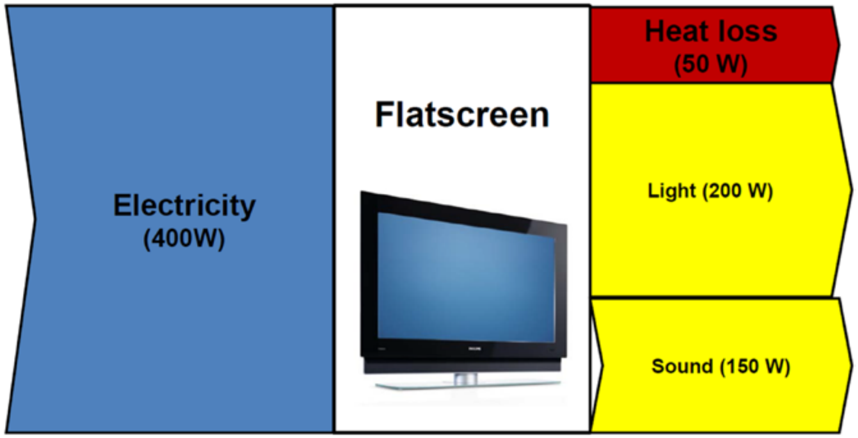
- Efficiency $$\eta = \frac{\text{useful work}}{\text{input energy}} = \frac{\text{useful power}}{\text{input power}}$$ (-)

- Use a Sankey diagram!

Efficiency

Efficiency definition not clear:

- What is useful? What is the input? Give the reasons for the choices made



Flatscreen: useful spent power?

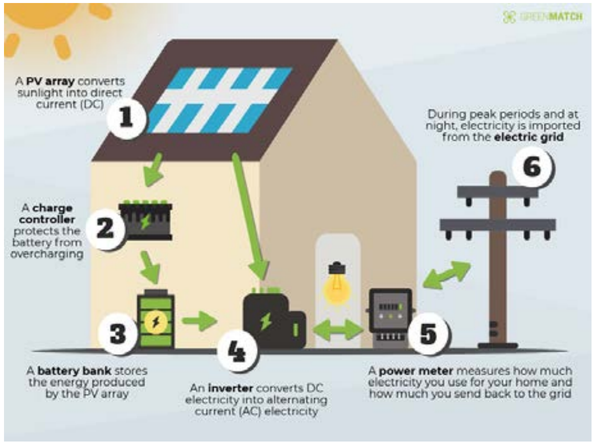
So always explain how you have defined efficiency!

Efficiency – practical values

Product	Efficiency	Remark
Solar panel	12%	Part of sun’s radiation converted to electricity
Vacuum cleaner	20%	Part of electrical power converted to suction power
Petrol engine	35%	Part of chemical energy converted to kinetic energy
Electric kettle	84%	Part of electrical energy converted to useful heat in the water

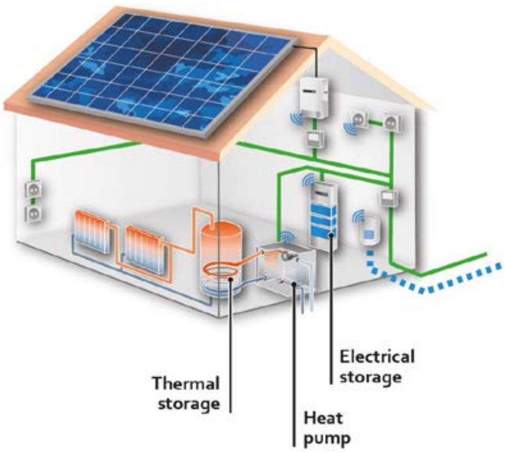
Always state the used definition when talking about efficiency

Solar panel efficiency



PV System

Solar-Thermal System



PV-T System

Part of sun's radiation converted to …….

Solar Collector	Efficiency	Remark
PV	≈ 12%	Part of sun's radiation converted to electricity
Solar-Thermal	≈ 30 – 45 %.	Part of sun's radiation converted to heat
PV-T	≈ 30%	Part of sun's radiation converted to heat and electricity

Learning objectives lecture 2

Energy in general

- Using an energy balance
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- **Calculate losses for electric resistors**

Conductive heat transfer

- *Explaining* conduction principles
- *Calculate* conductive heat transfer
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Resistors

Electric resistors: barrier in electric circuit

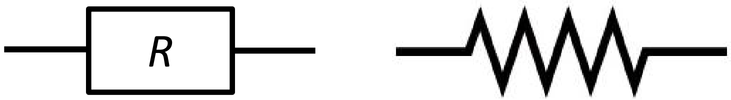
→ heat generation

Heat: purpose

Heat: "byproduct"

Resistors

Schematical symbols:



Resistance *R* determined by:

- Length of the wire (*L*)
- Through-flow area (*A*)
- Material (resistivity ρ)

Compare: flow through straw

Pouillet's law: $$R = \rho \frac{L}{A}$$

Not density:
$\Omega \cdot m \neq kg/m^3$

Resistor as heat source

Resistor converts electic energy into thermal energy:

$$E = I^2 R \Delta t = Q \qquad [\mathrm{J}]$$

So electric power becomes thermal power:

Notation: $\dot{Q}$ ("Heat-flow" or heat transfer rate)

$$P = I^2 R = \dot{Q} \qquad [\mathrm{J/s}] = [\mathrm{W}]$$

SIDESTEP

Dot sign means: per unit time (time derivative)

$$\text{Power} = \frac{\text{Energy change}}{\text{Time}}$$

$$P = \frac{dE}{dt} \approx \frac{\Delta E}{\Delta t}$$

$$\dot{Q} = \frac{dQ}{dt} \approx \frac{\Delta Q}{\Delta t}$$

$$(\text{Velocity } v = \frac{dx}{dt} = \dot{x} \approx \frac{\text{displacement } \Delta x}{\Delta t})$$

$$(\text{Acceleration } a = \frac{dv}{dt} = \dot{v} = \ddot{x} \approx \frac{\text{velocity change } \Delta v}{\Delta t})$$

Resistivity

$$R = \rho \frac{L}{A}$$

Material	**ρ ($\Omega \cdot$ m) at 20 °C**
Copper	$1{,}67 \cdot 10^{-8}$
Tungsten	$5{,}5 \cdot 10^{-8}$
Aluminum	$2{,}65 \cdot 10^{-8}$
Glass	$1 \cdot 10^{12}$
PVC	$1 \cdot 10^{14}$
Rubber	$1 \cdot 10^{15}$

Conductors

Insulators

Conductors / insulators

Also thermal!

Insulators?

Conductors?

LEARNING OBJECTIVES LECTURE 2

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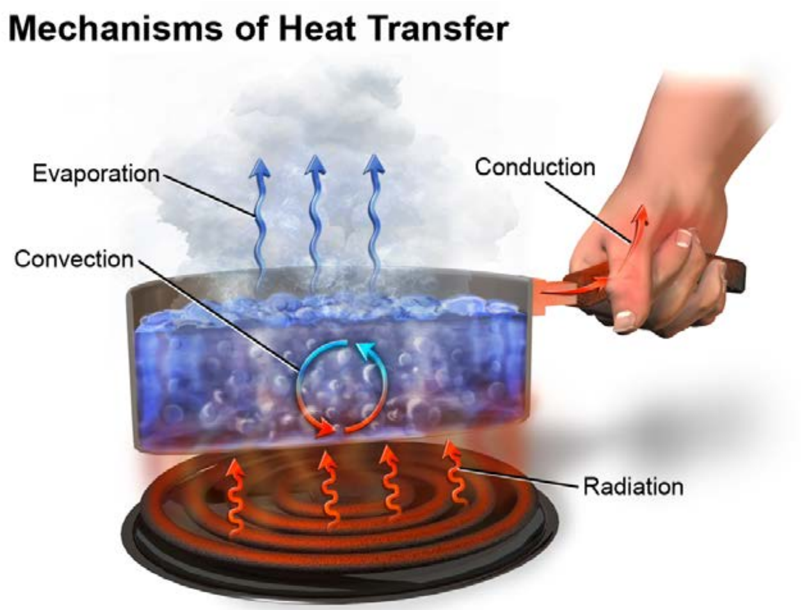
Heat transfer mechanisms

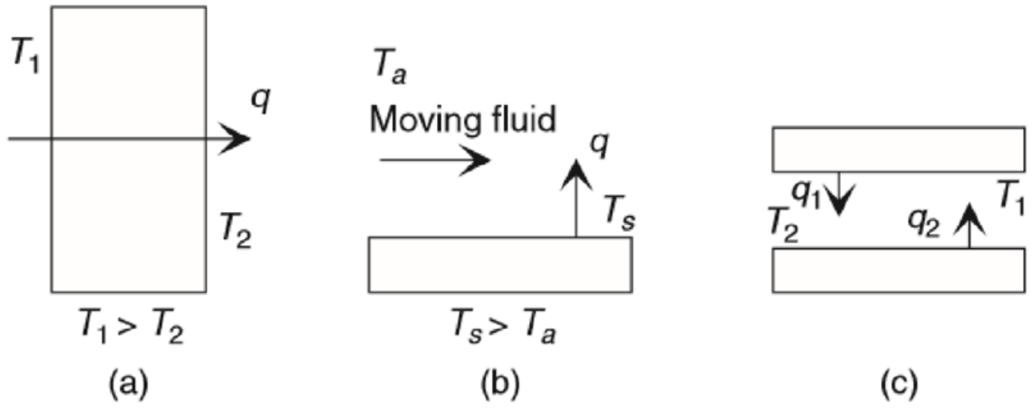
Representations of heat transfer modes:

(a) conduction through a solid, liquid or gas,

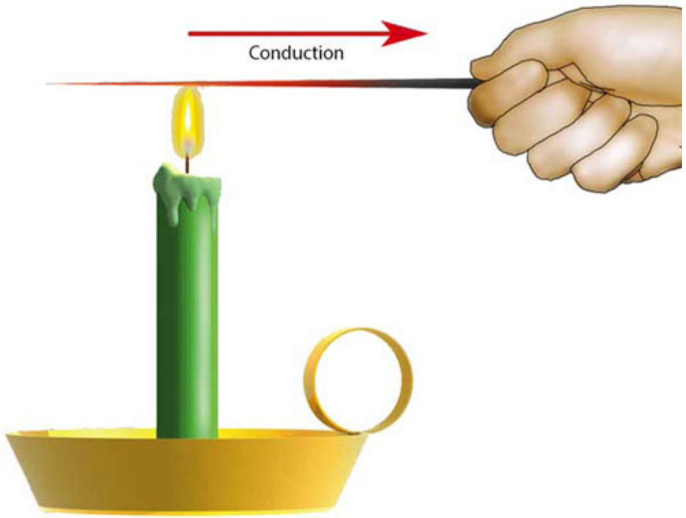
(b) convection from a surface to a moving fluid,

(c) radiation between two surfaces





Heat transfer mechanisms



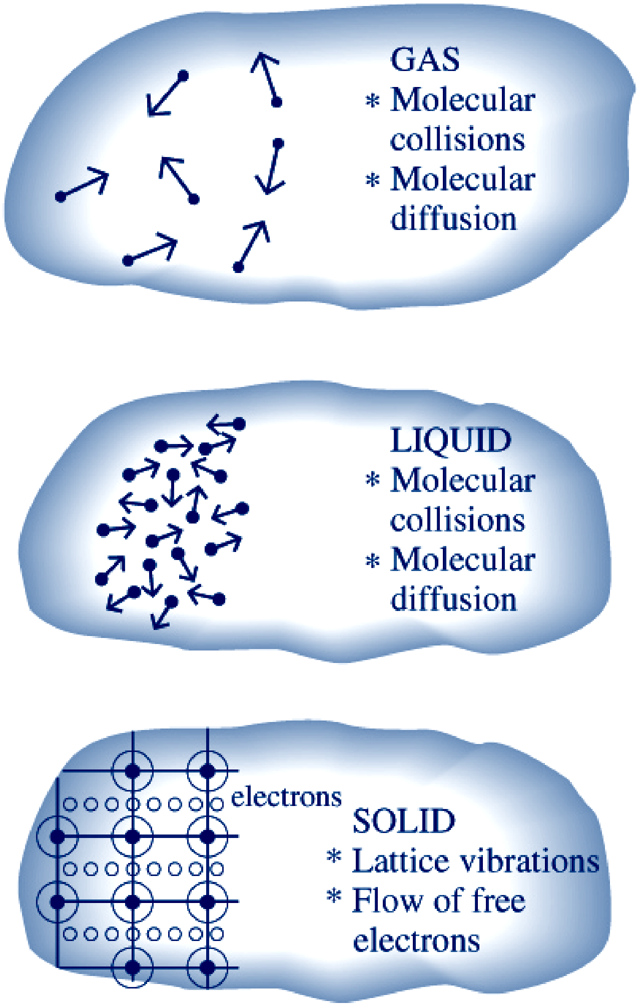
- Conduction
- Convection
- Radiation

CONDUCTION

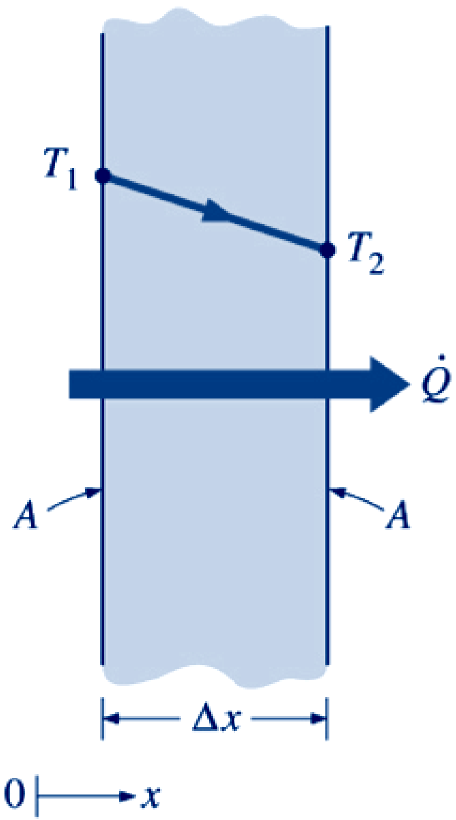
Conduction:

Transfer of thermal energy between (non flowing) molecules

- Always from more energetic (warm) to less energetic (cold) particles!



Conduction(Fourier's Law)



x_1 x_2

Cross section of part of a wall (almost flat)

Heat transfer rate : $\dot{Q}$

- **Steady state condition-1D**
- Proportional to area A
- Proportional to temp. Difference : $T_2 - T_1$
- Inversely proportional to thickness: $\Delta x = x_2 - x_1$
- Dependent on material → thermal conductivity: k

$$\dot{Q} = -k\,A\frac{T_2 - T_1}{x_2 - x_1} = -k\,A\frac{\Delta T}{\Delta x} \quad (\mathrm{W})$$

Negative sign since heat flow is positive at a negative temperature gradient.

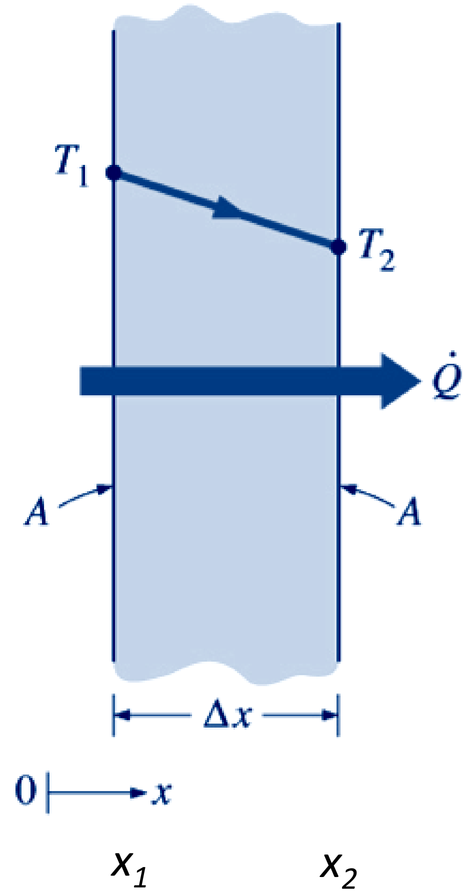
Conduction(Fourier's Law)

$$\dot{Q} = -kA\frac{T_2 - T_1}{x_2 - x_1} = -kA\frac{\Delta T}{\Delta x}(\mathrm{W})$$

- Fourier's law simplified for **plane surface**

- Per m²: **Heat flux**

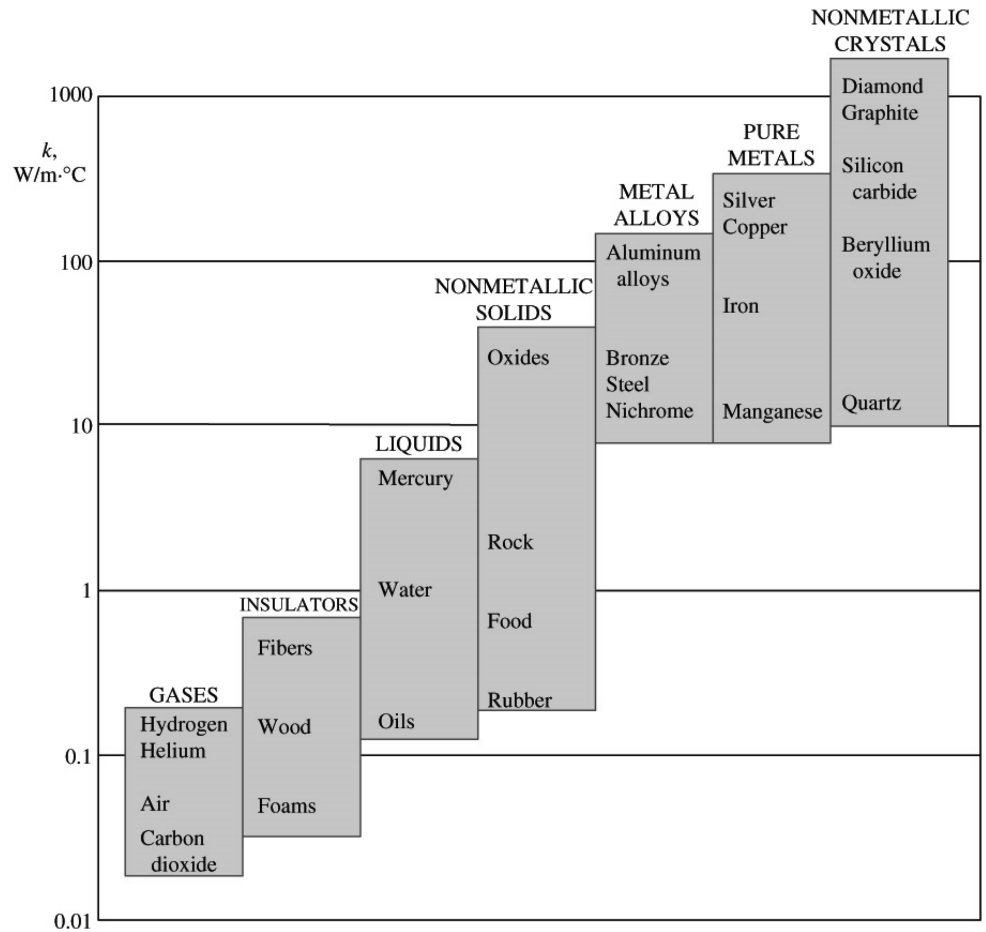
$$\dot{q} = \frac{\dot{Q}}{A} = -k\frac{T_2 - T_1}{x_2 - x_1} = -k\frac{\Delta T}{\Delta x}\ (\mathrm{W/m^2})$$



Thermal conductivity (k)

Unit: $$\frac{\mathrm{W}}{\mathrm{m} \cdot \mathrm{K}}$$

$\Rightarrow$ The amount of power conducted through 1 m of material at a 1 K temperature difference



High k: Conductor

Low k: Insulator

Give reason : Birds puff up their feathers in winter

A. So that they can trap more air

B. So that can develop charge

C. So that they can reduce the frictions

D. So that they can dry them faster

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ASSIGNMENT: ELECTRIC KETTLE

*What is the **efficiency** of an electric kettle when the water is almost boiling (T=100 ^oC)?*

Data/assumptions/simplifications:

- Wall temperature outside 50^{o}C
- Diameter 10 cm
- Height 20 cm
- Plastic wall:
  - Thickness 2,7 mm
  - k = 0,20 W / (m · K)
- Neglect losses through top and bottom
- Electric power P_{el} = 930 W

$$\dot{Q} = -k\,A\frac{\Delta T}{\Delta x}$$

Conduction flat wall- summarized

- Fourier's law for plane surface:
  - Temperature difference $\Delta T = T_2 - T_1$ (K)
  - Thickness $\Delta x = x_2 - x_1$ (m)
  - Surface area A (m^2)
  - Thermal conductivity k (W / (m · K))

Heat transfer rate: $\dot{Q} = -k\, A \frac{\Delta T}{\Delta x}$ (W)

Heat flux: $\dot{q} = -k \frac{\Delta T}{\Delta x}$ (W / m^2)

Next: model heat flow as thermal resistance network

(Make it easier for calculations)

CONDUCTION FLAT WALL- SUMMARIZED

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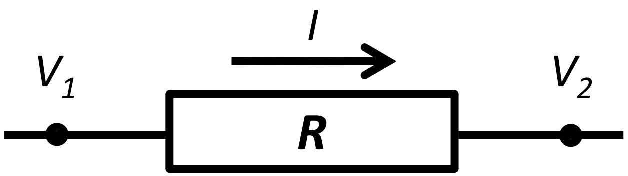
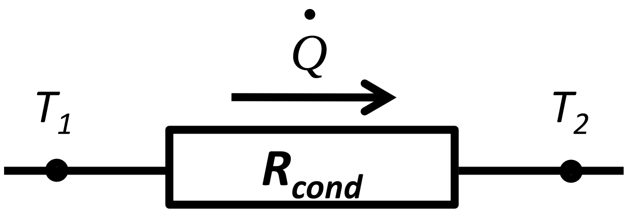
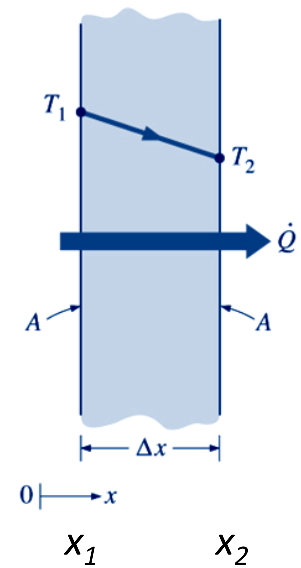
ANALOGY ELECTRICITY - HEAT

Electric resistor ↔ Flat wall as thermal resistor







Voltage difference	$V_1 - V_2$	↔	Temperature difference	$T_1 - T_2$
Current flow	I	↔	Heat flow	$\dot{Q}$
Electrical resistance	R	↔	Thermal resistance	R_{cond}

unit: Ω

unit: K/W

Analogy electricity - heat

Heat conduction through plane wall

Fourier's law:

$$\dot{Q} = -k\,A\frac{T_2 - T_1}{\Delta x}$$

$$= +k\,A\frac{T_1 - T_2}{\Delta x}$$

$$= \frac{T_1 - T_2}{\dfrac{\Delta x}{k\,A}}$$

$$\dot{Q} = \frac{T_1 - T_2}{R_{cond}} \text{ with } R_{cond} = \frac{\Delta x}{kA} \quad \text{(K/W)}$$

Heat transfer in "Ohmic way"!

Electrical resistance

Ohm's law:

$$I = \frac{V_1 - V_2}{R}$$

$V_1 - V_2$	$\leftrightarrow$	$T_1 - T_2$
I	$\leftrightarrow$	$\dot{Q}$
R	$\leftrightarrow$	R_{cond}

$$\Rightarrow \dot{Q} = \frac{T_1 - T_2}{R_{cond}}$$

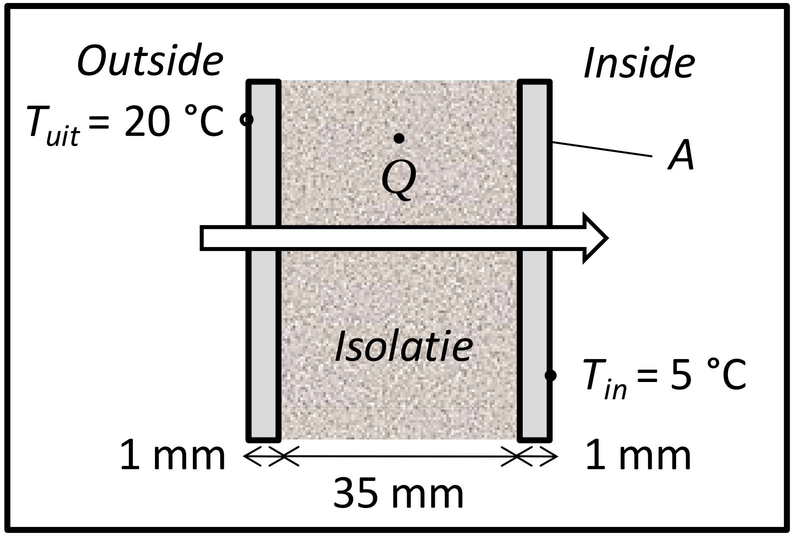
Thermal resistance networks

Fridge wall: heat flow $\dot{Q}$ through three resistors

Thermal resistance networks

Fridge wall: heat flow $\dot{Q}$ through three resistors

- Outer wall (R_1)
- Insulation (R_2)
- Inner wall (R_3)



Thermal resistance networks

Fridge wall: heat flow $\dot{Q}$ through three resistors

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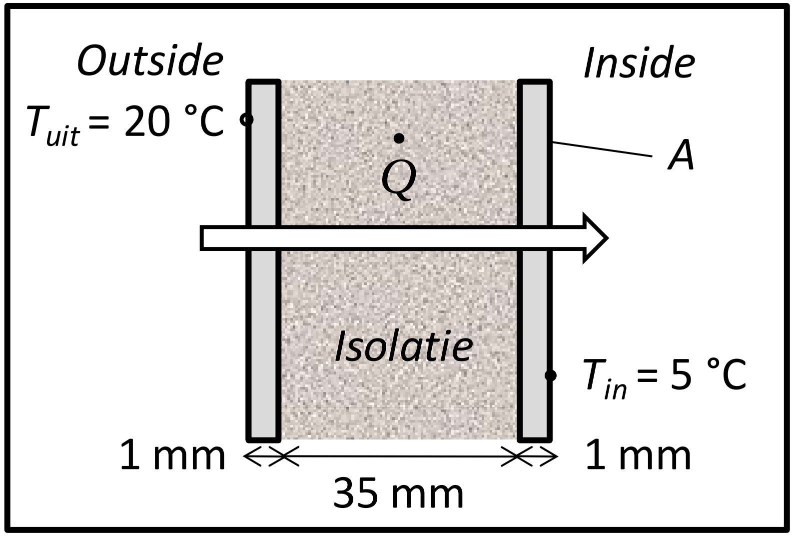
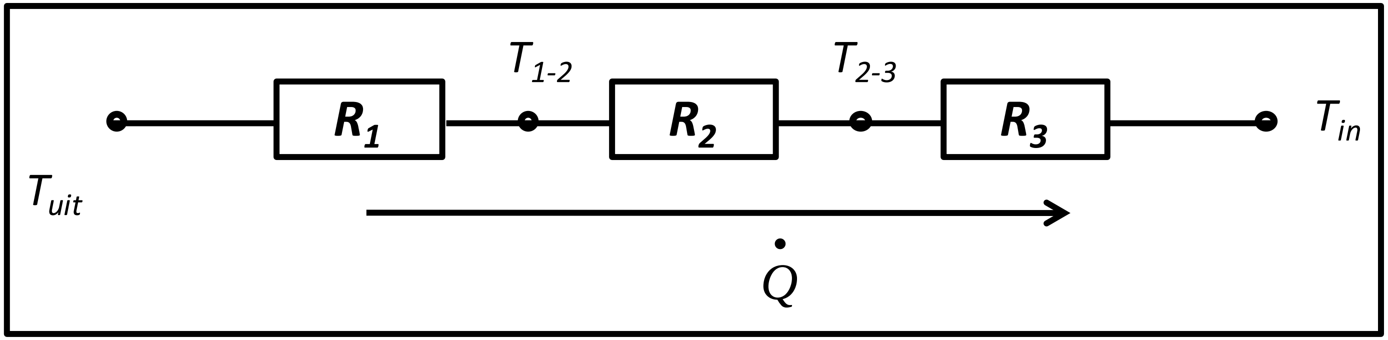
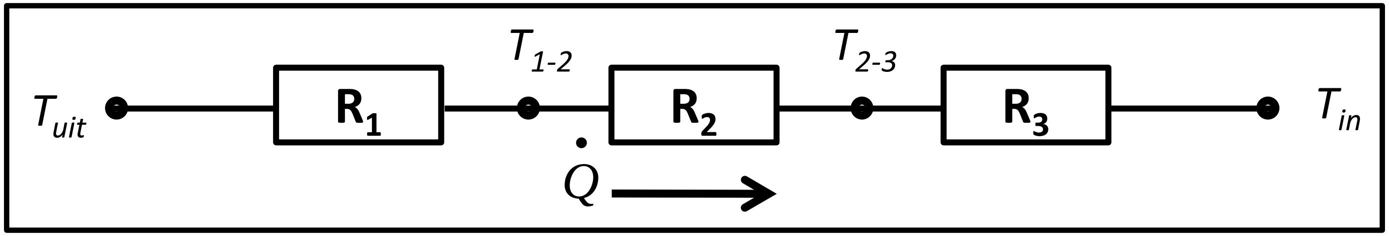




THERMAL RESISTANCE NETWORKS



$T_{1\text{-}2}$, $T_{2\text{-}3}$? Use: $\dot{Q}$ = constant throughout the resistors

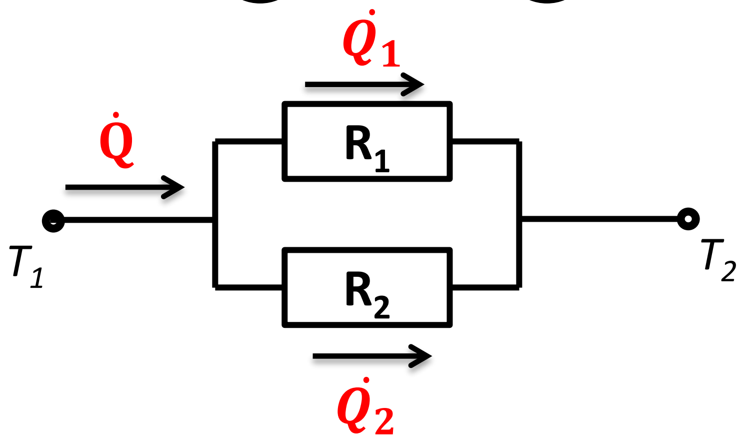
$$\dot{Q} = \frac{T_{uit} - T_{in}}{R_{tot}}$$

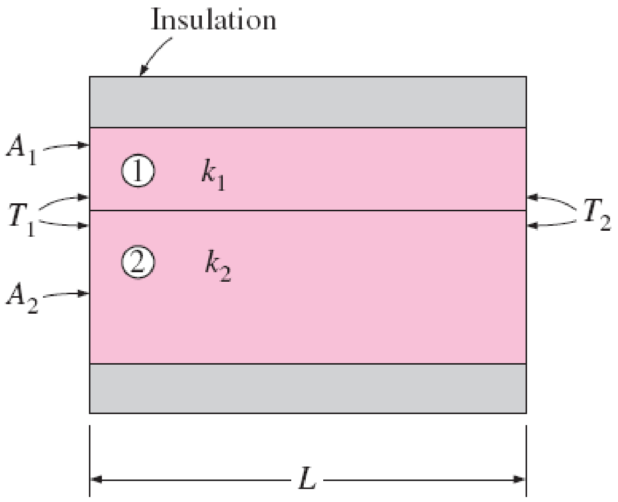
$$= \frac{T_{uit} - T_{1-2}}{R_1} = \frac{T_{1-2} - T_{2-3}}{R_2} = \frac{T_{2-3} - T_{in}}{R_3} = \frac{T_{uit} - T_{2-3}}{R_1 + R_2} = \frac{T_{1-2} - T_{in}}{R_2 + R_3}$$

$\Rightarrow$ Solve all unknown temperatures by comparing total and partial resistors in series, similar to voltage in an electrical circuit

$\Rightarrow$ **Next: parallel thermal resistors**

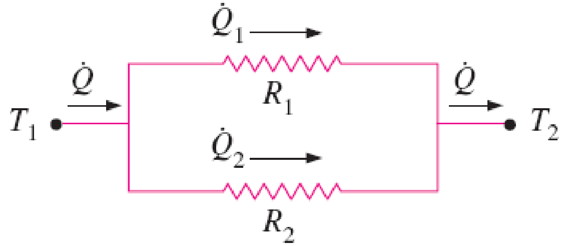
Thermal resistance networks





$$\dot{Q} = \dot{Q}_1 + \dot{Q}_2 = \frac{T_1 - T_2}{R_{\text{total}}}$$

$$\dot{Q} = \dot{Q}_1 + \dot{Q}_2 = \frac{T_1 - T_2}{R_1} + \frac{T_1 - T_2}{R_2} = (T_1 - T_2)\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

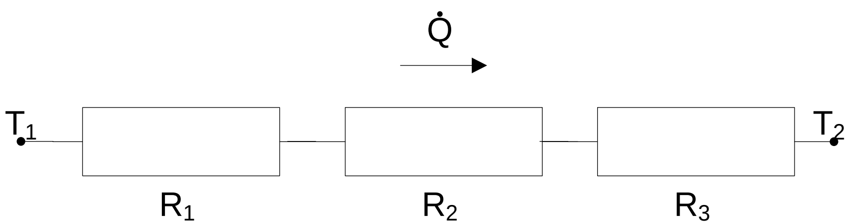


$$\dot{Q} = \dot{Q}_1 + \dot{Q}_2$$

$$\Rightarrow \frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} \longrightarrow R_{\text{total}} = \frac{R_1 R_2}{R_1 + R_2}$$

Thermal resistance networks

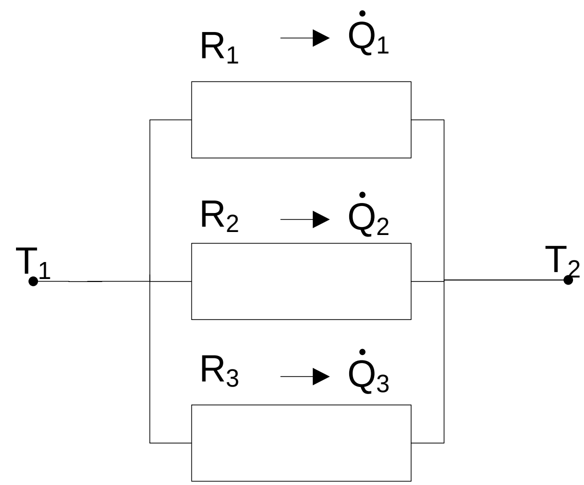
Series Resistors



$$R_{tot} = \sum_i R_i$$

(Add Resistors)

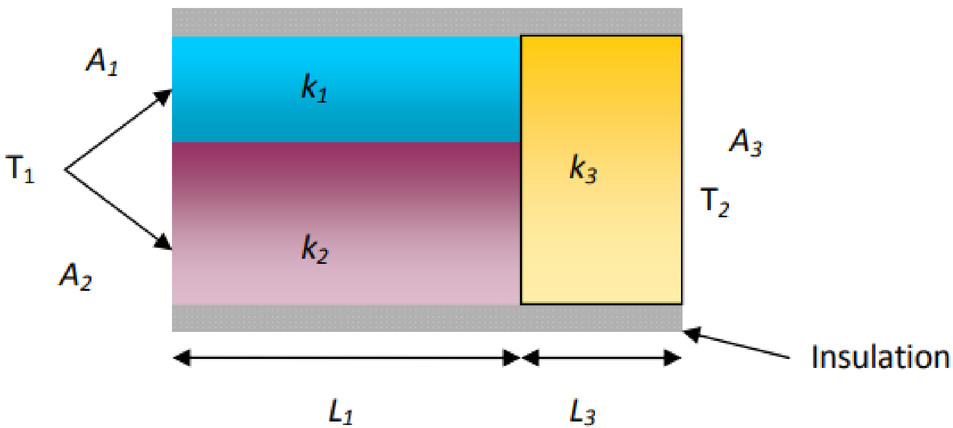
Parallel Resistors

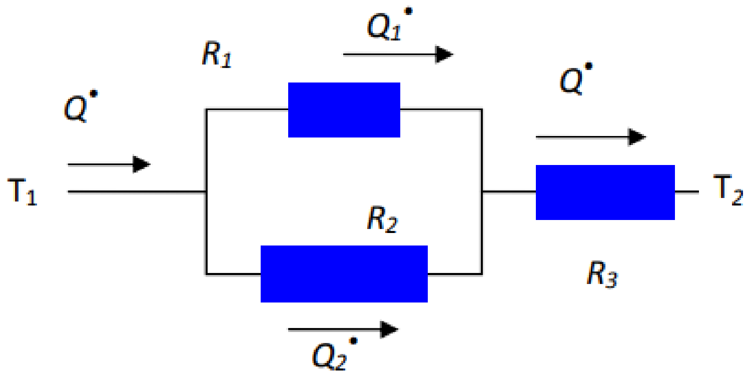


$$\frac{1}{R_{tot}} = \sum_i \frac{1}{R_i}$$

(Add Heat Flows)

Thermal resistance networks





$$\dot{Q} = \frac{T_1 - T_\infty}{R_{total}}$$

$$R_{total} = R_{12} + R_3 = \frac{R_1 R_2}{R_1 + R_2} + R_3$$

Resistance and insulation

Thermal resistance plane surface:

$$R = \frac{\Delta x}{kA} \qquad (\frac{\mathrm{K}}{\mathrm{W}})$$

Alternative concept: insulation value (building materials):

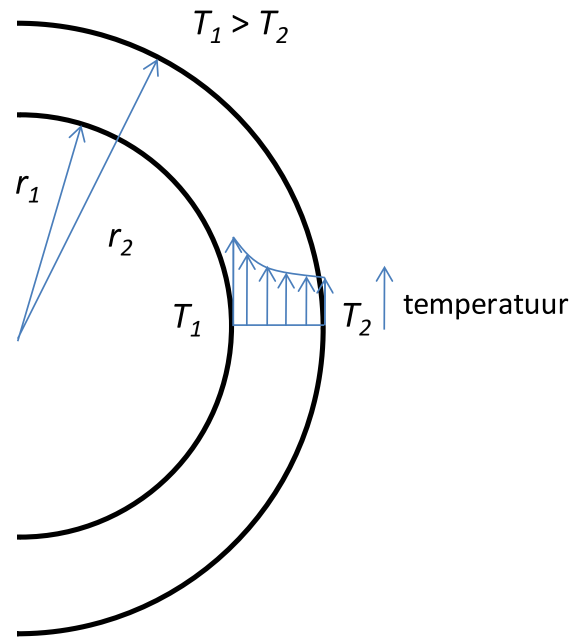
$$R - value = \frac{\Delta x}{k} = R \cdot A \qquad (\frac{\mathrm{m}^2 \cdot \mathrm{K}}{\mathrm{W}})$$

$\Rightarrow$ Insulation value is the heat resistance of 1 m^2 of material

Material	***R*-value ($\mathrm{m}^2 \cdot \mathrm{K}$ / W)**
Bricks (wall)	0,26
Rockwool 5 cm thick	1,45
Glasswool 11 cm thick	2,50

NB: Often the symbol *R* is used for both concepts. Look at the units!

CONDUCTION IN NON-PLANAR SURFACE



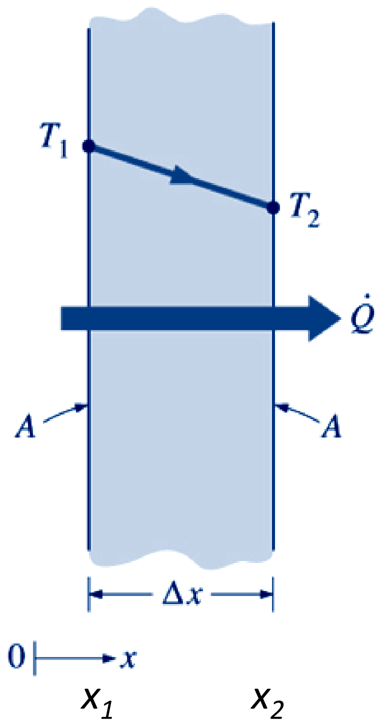
Small radius: small flow-through surface→ high resistance→ large temperature *gradient*

(In areas with a high resistance the temperature decreases more in the direction of the heat flow)

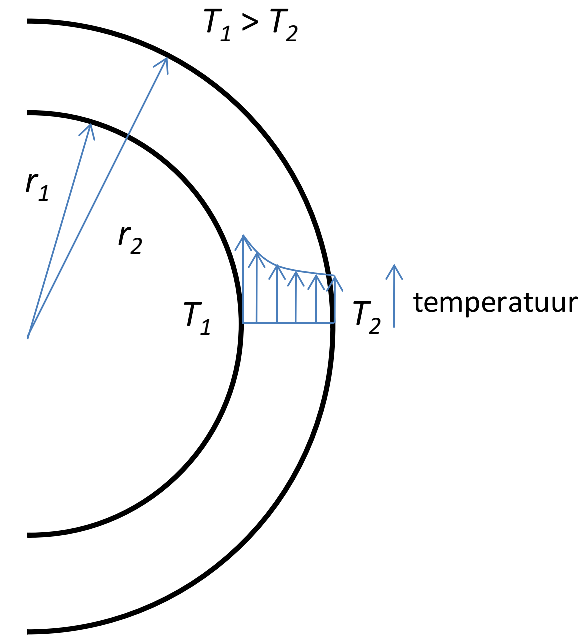
$$\dot{Q} = \frac{T_1 - T_2}{R}$$

Conduction in non-planar surface

Plane wall



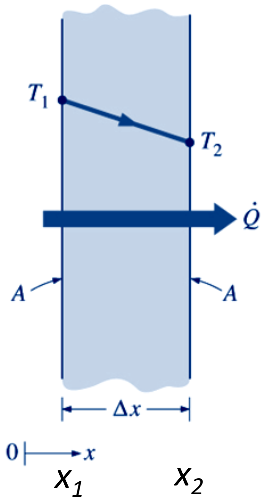
Curved wall



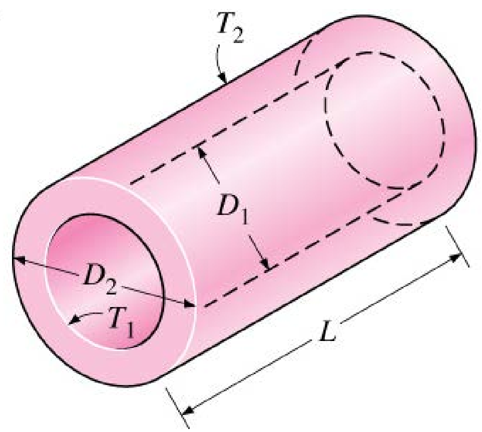
- Surface area constant over *x*
- Temperature profile linearly decreasing (Fourier's law)
- Temperature gradient (= 'slope') constant

- Surface area increases with *r*
- Temperature profile decreasing concave up
- Temperature gradient smaller with increasing radius *r*

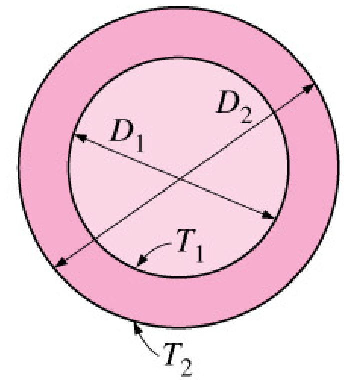
Various conduction resistances



Plane wall



Cilindrical pipe



Spherical shell

$$R = \frac{\Delta x}{kA}$$

$$R = \frac{\ln\left(\frac{D_2}{D_1}\right)}{2\pi L k}$$

$$R = \frac{D_2 - D_1}{2\pi k D_1 D_2}$$

$$\boxed{\dot{Q} = \frac{T_1 - T_2}{R}}$$

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Summary Lecture 2 (1/2)

- Efficiency $$\eta = \frac{\text{useful work}}{\text{inputted energy}} = \frac{\text{useful power}}{\text{inputted power}}$$

  Justify the applied definition!

- Heat transfer rate $\dot{Q}$ (W); Heat flux: $\dot{q} = \dot{Q}/A$ (W/m^2)

  ↑

  "Q-flux"

- Heat dissipation electric resistor

  $$\dot{Q} = I^2 R \quad (\text{W}) \qquad \text{with} \qquad R = \rho \frac{L}{A} \qquad (\Omega)$$

Summary Lecture 2 (2/2)

- Conduction: heat transfer between molecules
- Different appearances of Fourier's law
  - Plane surface: $\dot{Q} = -k\,A\dfrac{T_2 - T_1}{x_2 - x_1} = \dfrac{T_1 - T_2}{R}$ with $R = \dfrac{\Delta x}{kA}$ $\quad (\dfrac{\mathrm{K}}{\mathrm{W}})$
  - Cylindrical tube: $\dot{Q} = \dfrac{T_1 - T_2}{R}$ with $R = \dfrac{\ln(\dfrac{D_2}{D_1})}{2\pi\,L\,k}$
  - Spherical shell: $\dot{Q} = \dfrac{T_1 - T_2}{R}$ with $R = \dfrac{D_2 - D_1}{2\pi\,kD_1 D_2}$
- Thermal resistors: for ease of calculation
- Insulation value: *R*-value = $R \cdot A \quad (\dfrac{\mathrm{m}^2 \cdot \mathrm{K}}{\mathrm{W}})$

LECTORIAL 1

- Lectorial : Friday, 9th September,13:45 - 15:30

⇒ Assignments: Check HEATQUIZ

⇒ Deadlines: schedule on Canvas & Manual

Ready, set,

GO!...