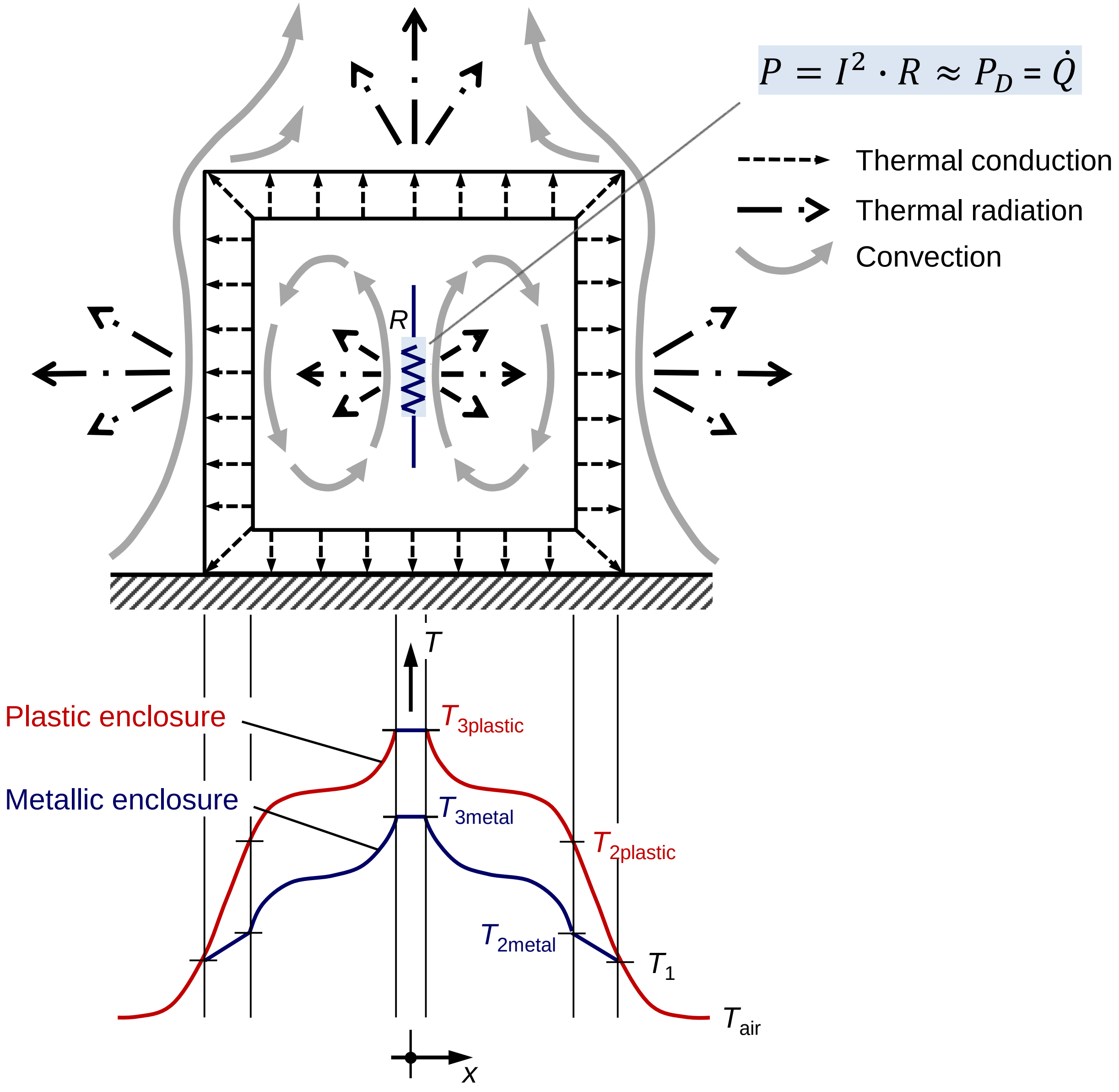
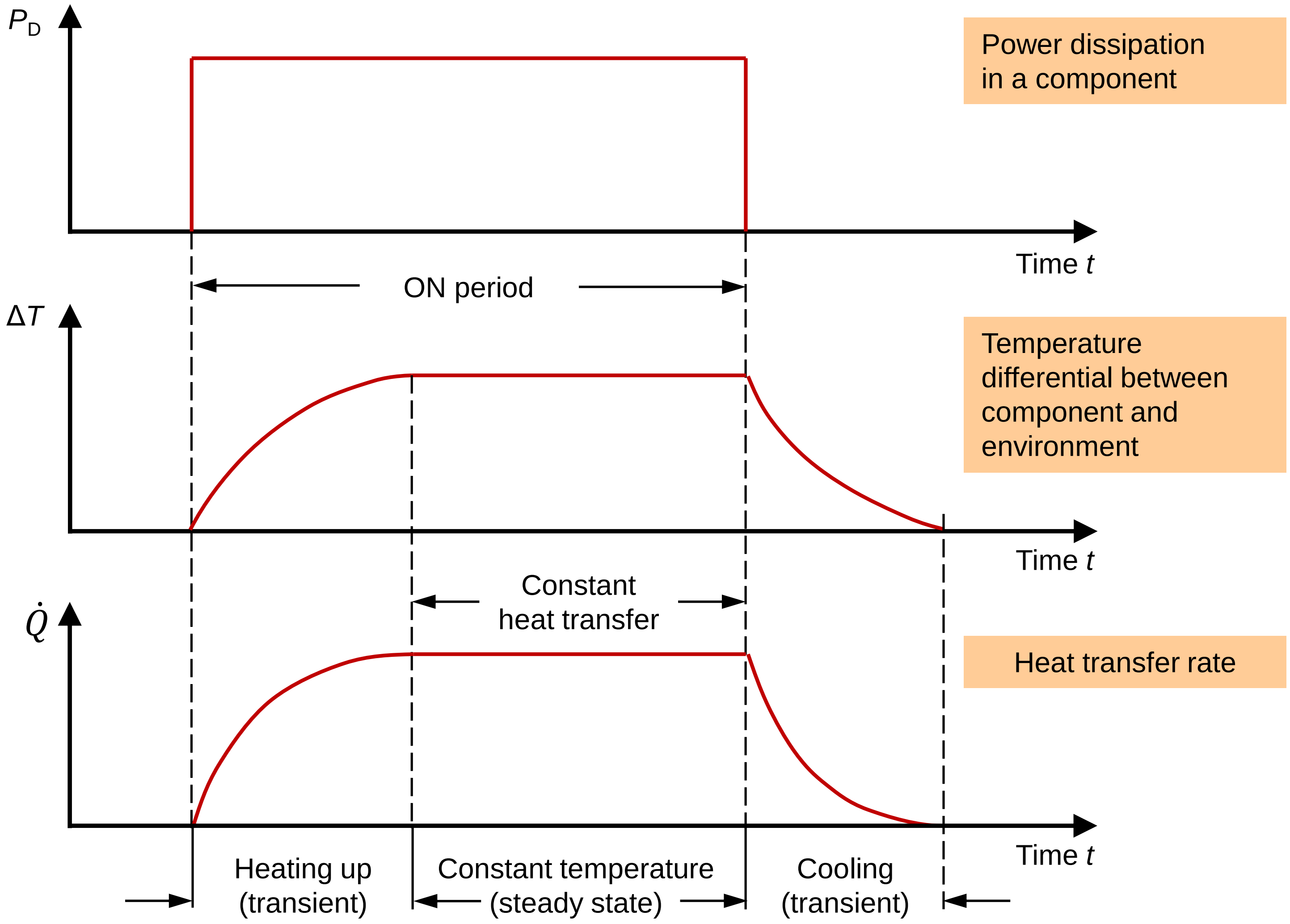


Figures of Chapter 5: Thermal Management and Cooling



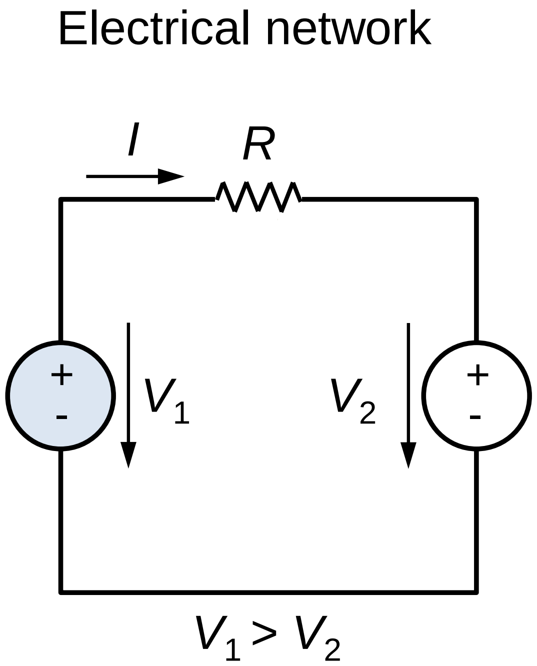
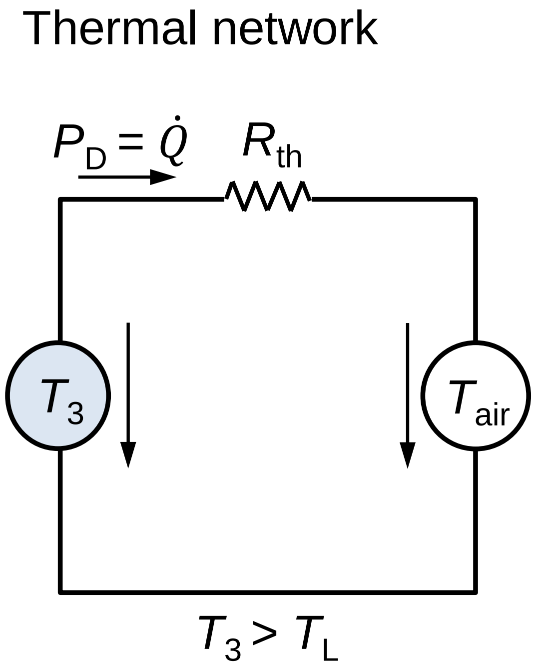
P_D
Power dissipation in a component
Time t
ON period
ΔT
Temperature differential between component and environment
Time t
Constant heat transfer
$\dot{Q}$
Heat transfer rate
Time t
Heating up (transient)
Constant temperature (steady state)
Cooling (transient)

Table 5.1 Main physical quantities in thermal management

Physical quantity	Symbol	Unit
Heat energy, heat, quantity of heat	Q	J
Heat transfer rate, heat flow	$\dot{Q}, q$	W
Power dissipation, heat dissipation, heat loss	P_D	W
Heat flux density, heat flux	$\dot{q}$, $\overrightarrow{\Phi}_q$	W/m^2 (W/m^3)
Temperature	T	K, °C
Thermal resistance	R_{th}	K/W
Thermal capacity, heat capacity	C_{th}	J/K or W·s/K
Thermal conductivity	k	W/mK
Heat transfer coefficient (convection, radiation)	h	W/m^2K

Table 5.2 Theoretical power dissipation P_D for selected electronic components [1]

Component	Power dissipation	Determining parameters
Resistor, conductor (interconnect)	Ohmic losses: $P_D = I^2 \cdot R = I^2 \cdot \rho \cdot \frac{L}{A} = I^2 \cdot \frac{1}{\sigma} \cdot \frac{L}{A}$	I line current R conductor resistance ρ specific electrical resistance σ specific electrical conductance L conductor length A conductor cross section
Capacitor	Dielectric losses with harmonic AC voltage: $P_D = V^2 \cdot \omega \cdot C \cdot \tan\delta$	V r.m.s. value of capacitor voltage ω angular frequency C capacitance $\tan\delta$ dielectric loss angle
Diode	$P_D = V_d \cdot I_d$	V_d diode voltage I_d diode current
CMOS devices	Switching losses (70–90% of losses): $P_D = C \cdot V_{dd} \cdot f$	C load capacitance V_{dd} supply voltage f switching frequency
Bipolar junction transistor	$P_D = V_{CE} \cdot I_C + V_{BE} \cdot I_B \approx V_{CE} \cdot I_C$	V_{CE} collector–emitter voltage I_C collector current V_{BE} base–emitter voltage I_B Base current
Junction field effect transistor, JFET	$P_D = I_D^2 \cdot R_{DS\,(on)}$	I_D drain current $R_{DS(on)}$ drain–source resistance


Electrical network
I
R
+
-
V1
V2
+
-
V1 > V2

Thermal network
PD = Q̇
Rth
T3
Tair
T3 > TL

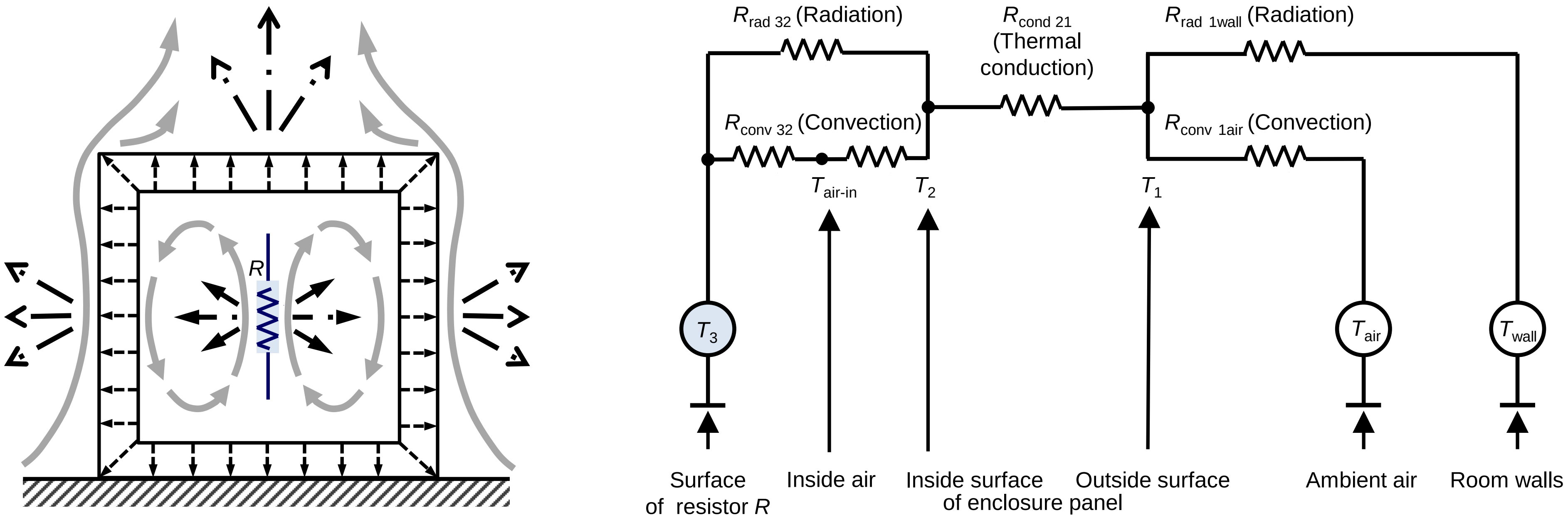
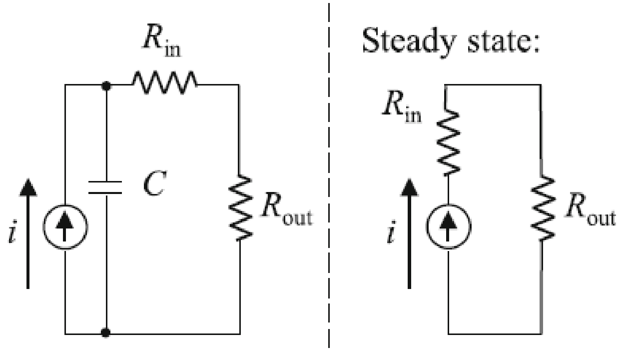
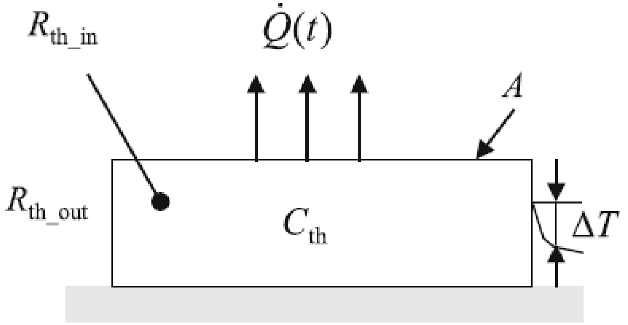

R
R rad 32 (Radiation)
R cond 21 (Thermal conduction)
R rad 1wall (Radiation)
R conv 32 (Convection)
R conv 1air (Convection)
T air-in
T 2
T 1
T 3
T air
T wall
Surface of resistor R
Inside air
Inside surface of enclosure panel
Outside surface
Ambient air
Room walls

Table 5.3 Analogy between electrical and thermal quantities

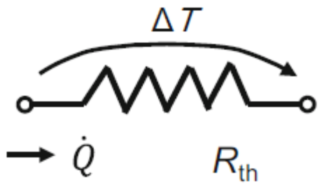
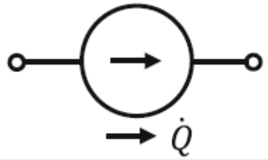
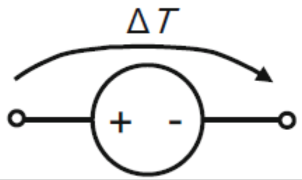
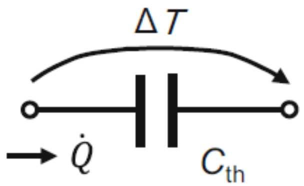
Electrical		Thermal	
			
$i(t) = C \cdot \frac{\mathrm{d}V}{\mathrm{d}t} + \frac{V}{R_{in} + R_{out}}$		$\dot{Q}(t) = C_{th} \frac{\mathrm{d}(\Delta T)}{\mathrm{d}t} + \frac{\Delta T}{R_{th\_in} + R_{th\_out}}$	
$i = \frac{V}{R_{in} + R_{out}}$		Steady state: Heat transfer $\dot{Q} = \frac{\Delta T}{R_{th\_in} + R_{th\_out}}$	
Current i	in A	Heat transfer $\dot{Q}$	in W
Current density J	in A/m^2	Heat flux density $\dot{q}$	in W/m^2
Electric potential difference V	in V	Temperature differential ΔT	in K
Resistance $R = \frac{V}{i} = \frac{1}{\beta \cdot A}$ mit $\beta = \frac{\sigma}{L}$	in Ω, V/A	Thermal resistance $R_{th} = \frac{\Delta T}{\dot{Q}} = \frac{1}{h \cdot A}$	in K/W
Capacitance $C = \frac{Q}{V}$	in A·s/V	Thermal capacity $C_{th} = \frac{Q}{\Delta T} = c \cdot m$	in W·s/K
Spec. el. conductance σ	in A/(V m)	Thermal conductivity k	in W/(K m)

h Heat transfer coefficient in W/(K m^2)
c Specific heat capacity in J/(K kg) or W s/(K kg)
Q Heat energy, quantity of heat in J bzw. W s, electrical charge in A s
m Mass in kg

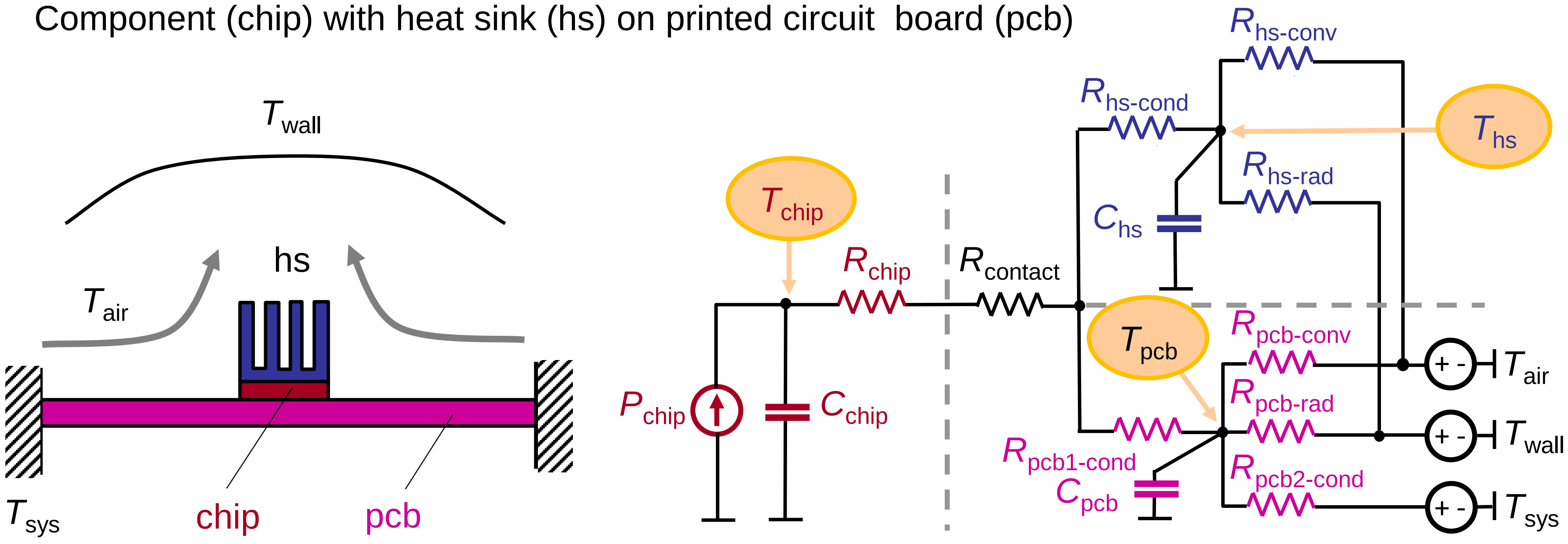
Table 5.4 Variables and parameters in electrical and thermal networks

Electrical network	Thermal network	Symbol
Current in A	Heat transfer in W	$\dot{Q}$
Voltage in V	Temperature in K	T
Charge in A·s	Heat energy in W·s	Q

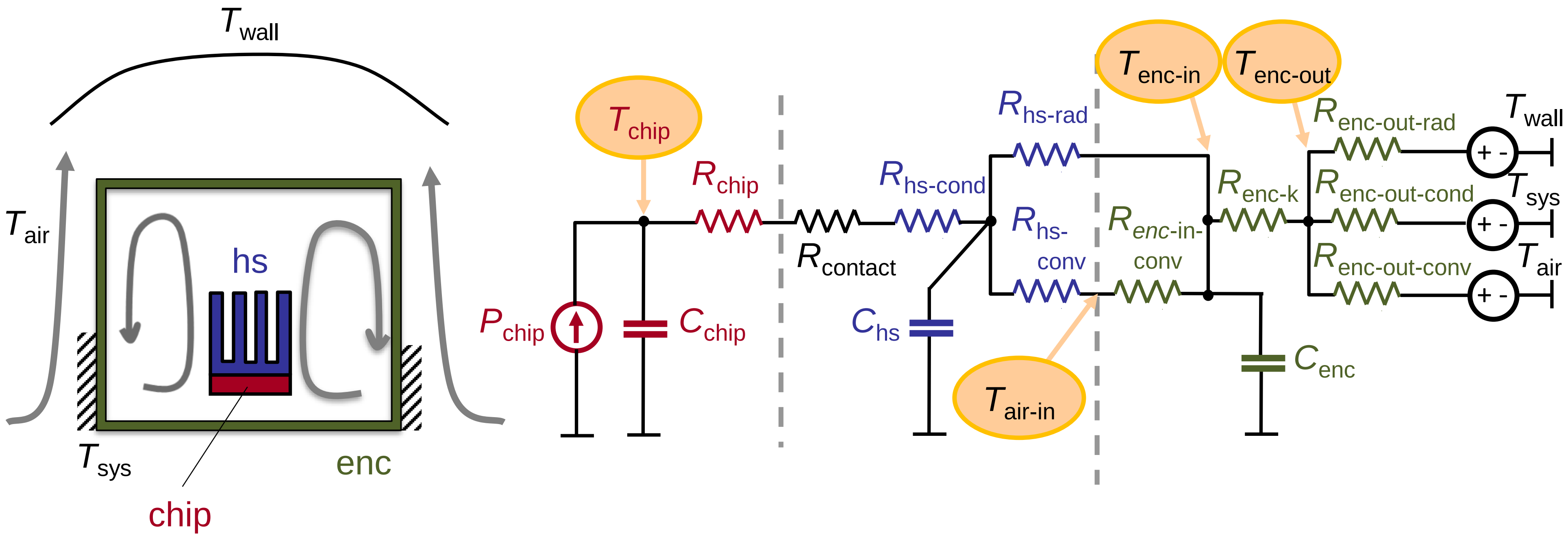
Table 5.5 Elements in thermal networks

Electrical network	Thermal network	Symbol
Ohmic resistance in V/A bzw. Ω	Thermal resistance in K/W	
Current source in A	Heat source in W	
Voltage source in V	Temperature source in K	
Capacitance in A s/V	Thermal capacity in J/K or W·s/K	

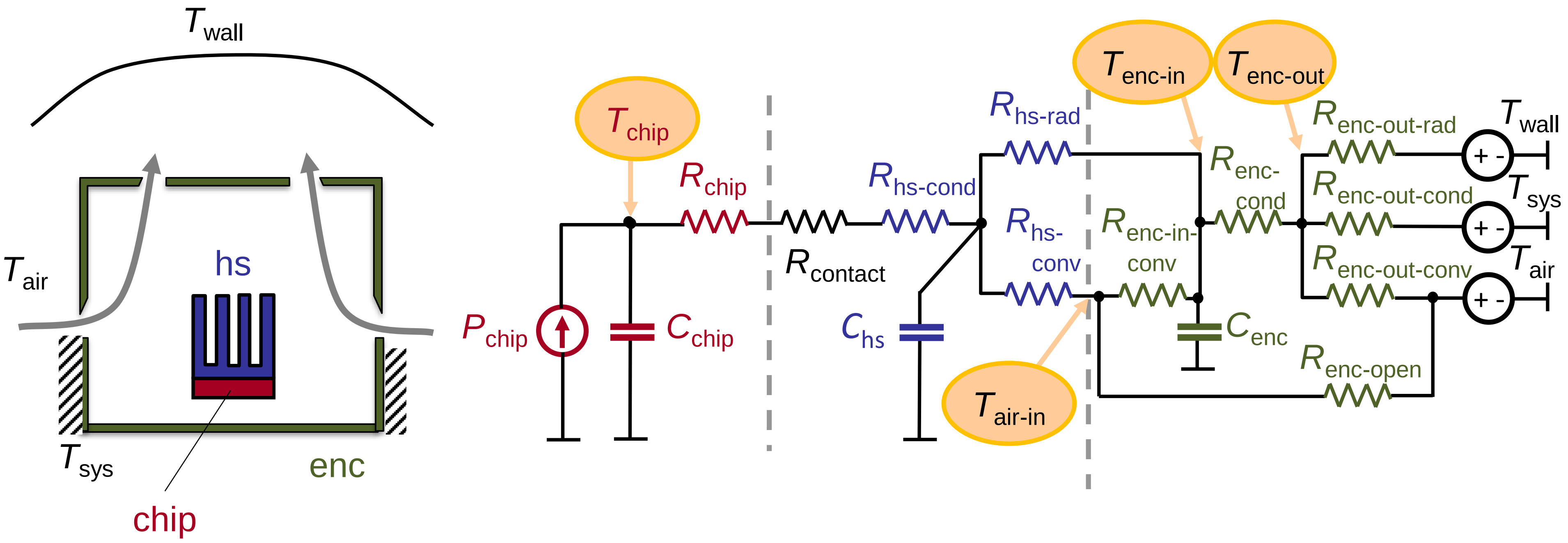
Component (chip) with heat sink (hs) on printed circuit board (pcb)

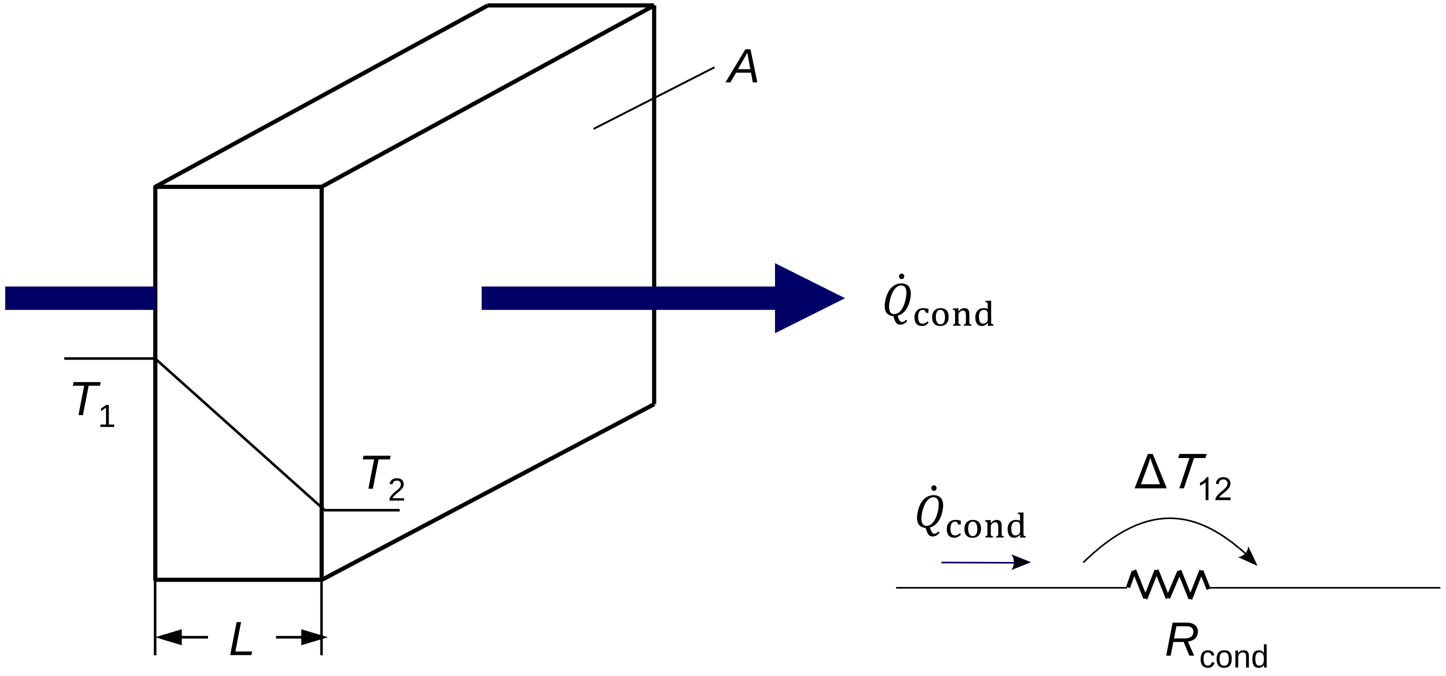


Component with heat sink in sealed enclosure (enc)



Component with heat sink in open (ventilated) enclosure





A
$\dot{Q}_{\text{cond}}$
T_1
T_2
L
$\dot{Q}_{\text{cond}}$
ΔT_{12}
R_{cond}

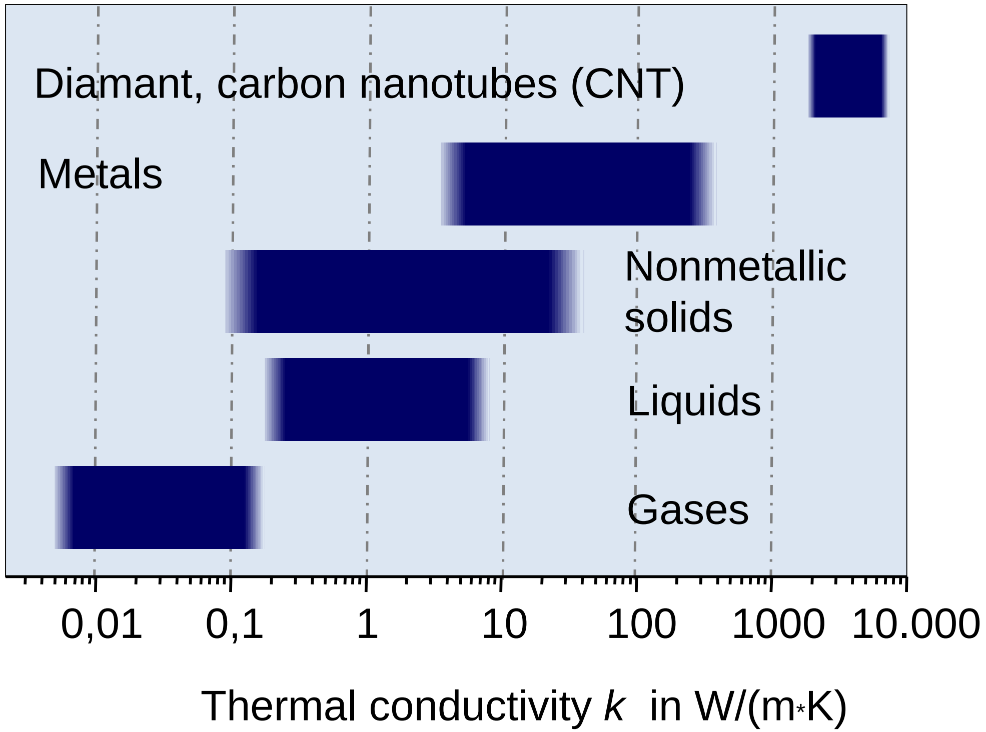
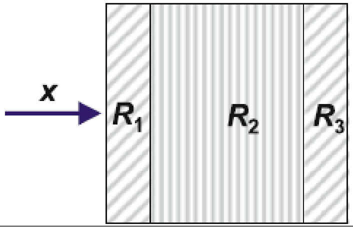
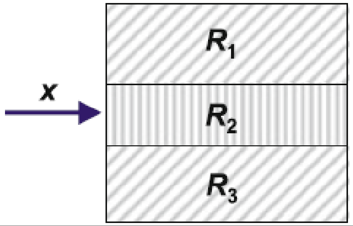
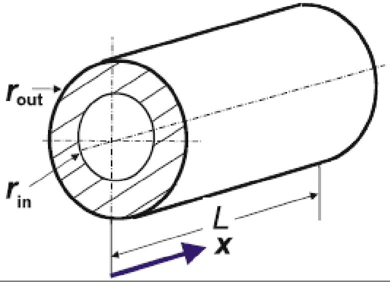
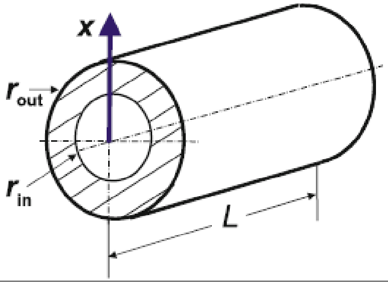
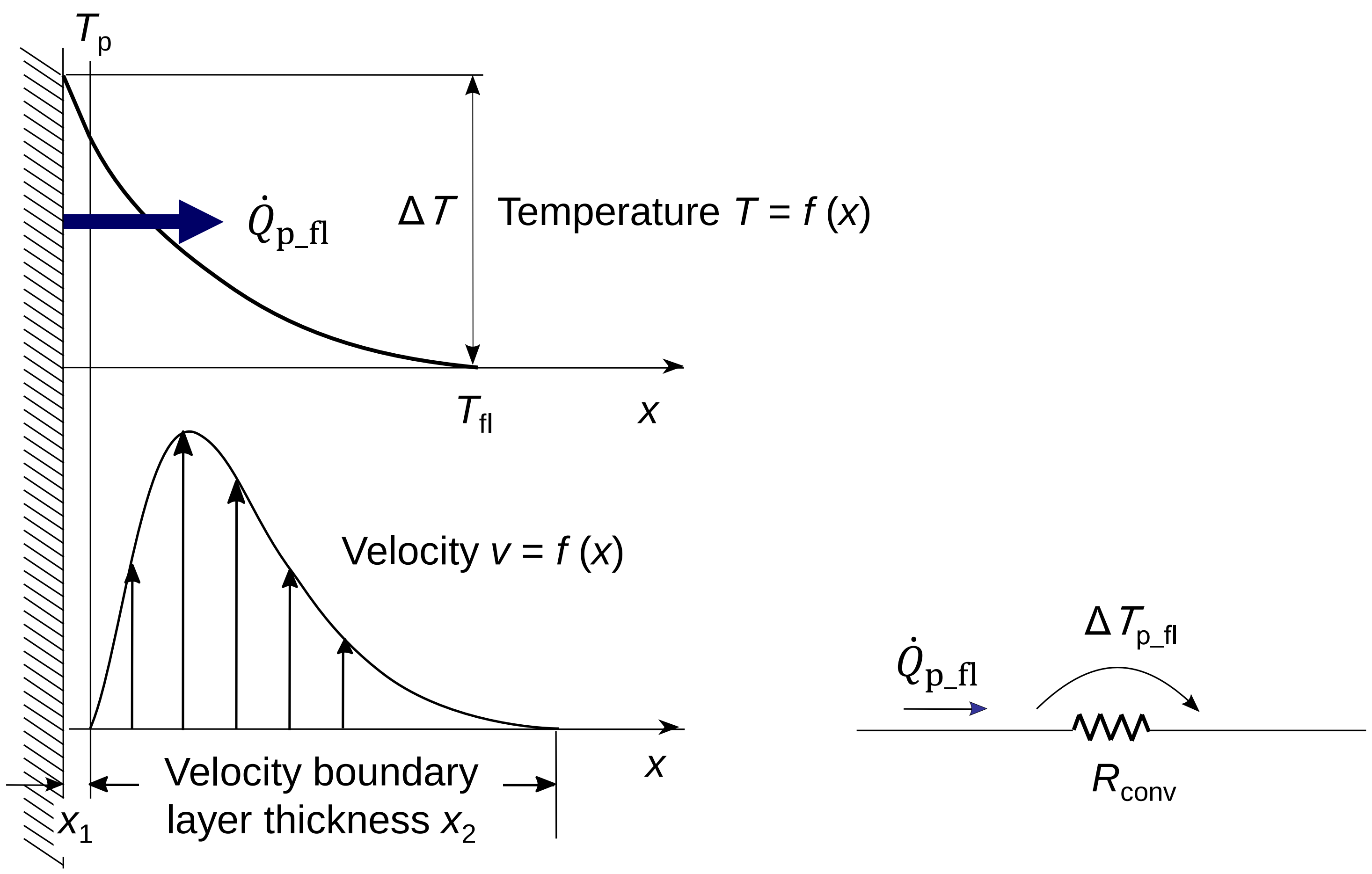

Diamant, carbon nanotubes (CNT)
Metals
Nonmetallic solids
Liquids
Gases
0,01
0,1
1
10
100
1000
10.000
Thermal conductivity k in W/(m*K)

Table 5.6 Thermal conductivity k of selected materials at 20 °C in W/(m·K)

Metals	k	Nonmetals	k
Aluminum, pure	237	Plexiglass	0.18
AlSi1MgMn (ENAW-6082)	170	Concrete	
Aluminum oxide	10	Gravel concrete	1.3
Gold	317	Foam concrete	0.35–0.7
Copper (99.9%)	390	Soil	
Sheet copper (merchandise)	372	Coarse gravel	0.52
90% Cu, 10% Al	52	Sand (moist)	0.25–2.0
70% Cu, 30% Zn	110	Glass	1.16
Constantan (55% Cu, 45% Ni)	22	Window glass	0.8–1.1
Magnesium	156	Transparent quartz	1.45
Nickel, pure	90.7	Rubber	0.13–0.24
NiCr (80% Ni, 20% Cr)	12	Phenolic paper (Pertinax)	0.15
Silver	419	Wood (dry)	0.1–0.3
Silicon	148	Paint	0.2
Iron, pure	80.2	Leather	0.15
Steel sheet	59	Air (standard pressure)	0.0257
Low-alloy carbon steel 40Cr1Mo28 (1.7225)	43	Paper, cardboard	0.13–0.18
Austenitic CrNi carbon steel (1.4301)	15–17	Polyvinyl chloride PVC	0.12–0.25
Cast iron	58	Polyamide	0.24–0.3
Tin	67	Porcelain	0.8–1.1
SnCu (99.3% Sn, 0.7% Cu)	65	Chamotte	0.5–1.2
SnAg (96.5% Sn, 3.5% Ag)	78	Teflon	0.25
Zinc	116	Water	0.598
Bismuth	8		

Table 5.7 Application examples of conduction thermal resistances in *x*-direction

Description	Diagram	Conduction thermal resistance
Composite panel, layers in series		$R_{cond\_tot} = \sum_i R_i$
Composite panel, parallel layers		$\frac{1}{R_{cond\_tot}} = \sum_i \frac{1}{R_i}$
Coaxial cylinder, plated-through contact for printed circuit boards		$R_{cond} = \frac{L}{k \cdot \pi \cdot (r_{out}^2 - r_{in}^2)}$
Coaxial cylinder, wire sheathing (insulation)		$R_{cond} = \frac{\ln(r_{out} / r_{in})}{2 \cdot \pi \cdot k \cdot L}$

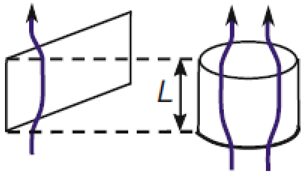
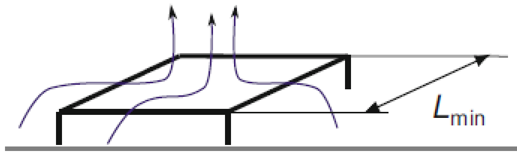
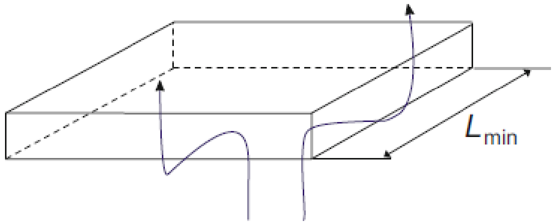


T_p
$\dot{Q}_{p\_fl}$
ΔT
Temperature $T = f(x)$
T_{fl}
x
Velocity $v = f(x)$
x
x_1
Velocity boundary
layer thickness x_2
ΔT_{p_fl}
$\dot{Q}_{p\_fl}$
R_{conv}

Table 5.8 Procedure for determining the convection heat transfer coefficient h_c with dimensionless numbers (see [2] for coefficients c and exponents n, m)

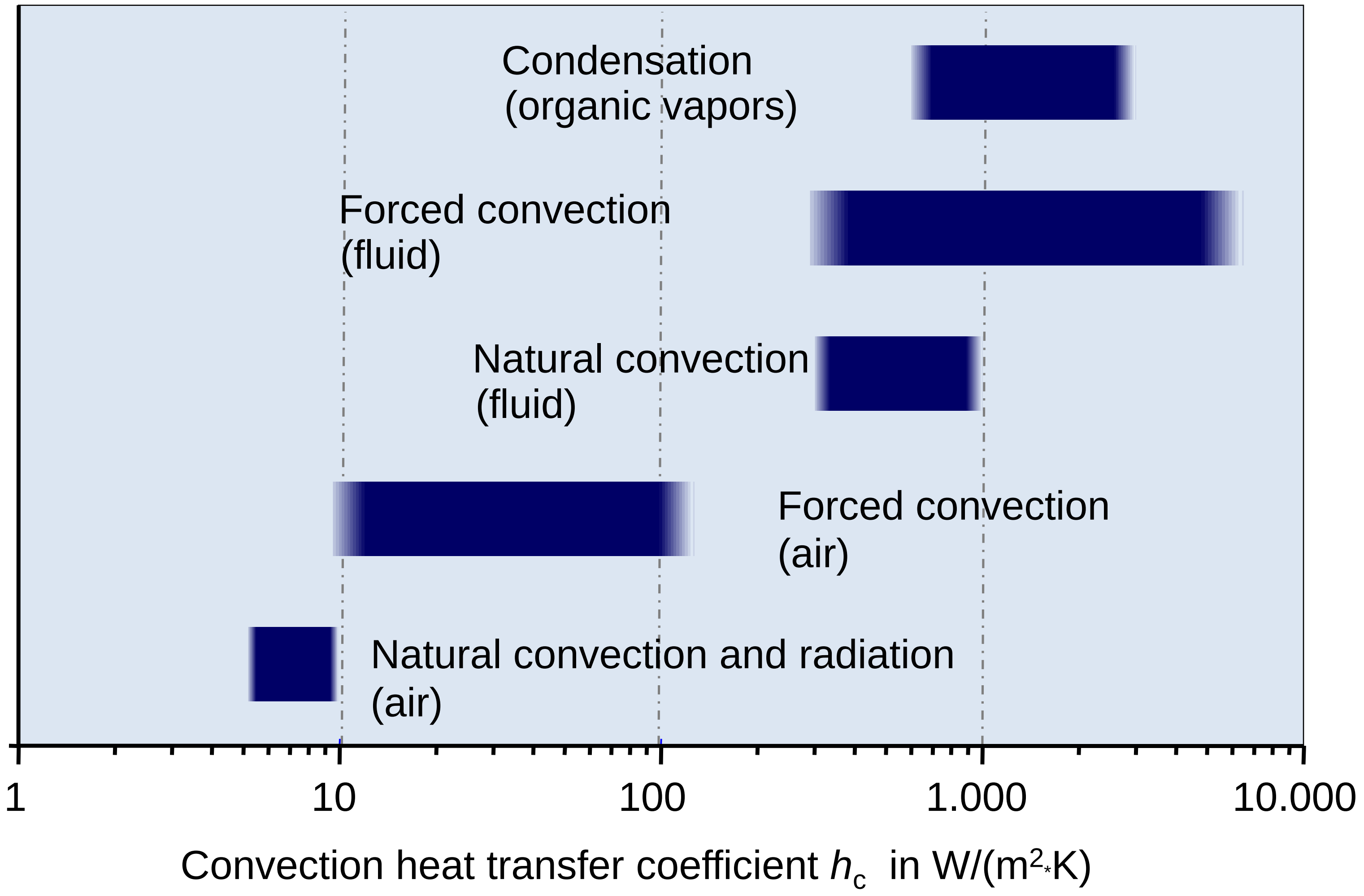
Step	Natural convection	Forced convection
1. Calculate the dimensionless groups	Gr, Pr	Re, Pr
2. Select suitable equation	$Nu = f\,(Gr, Pr)$	$Nu = f\,(Re, Pr)$
3. Calculate Nu	$Nu = c_1 \cdot (Gr \cdot Pr)^{n1}$	$Nu = c_2 \cdot Re^{n2} \cdot Pr^{m}$
4. Calculate h_c	$h_c = \frac{Nu \cdot k}{L}$	$h_c = \frac{Nu \cdot k}{L}$

Table 5.9 Simplified calculation of the convection heat transfer coefficient h_c for the natural convection of air and water at standard pressure and with basic geometries, assuming infinite space [3]

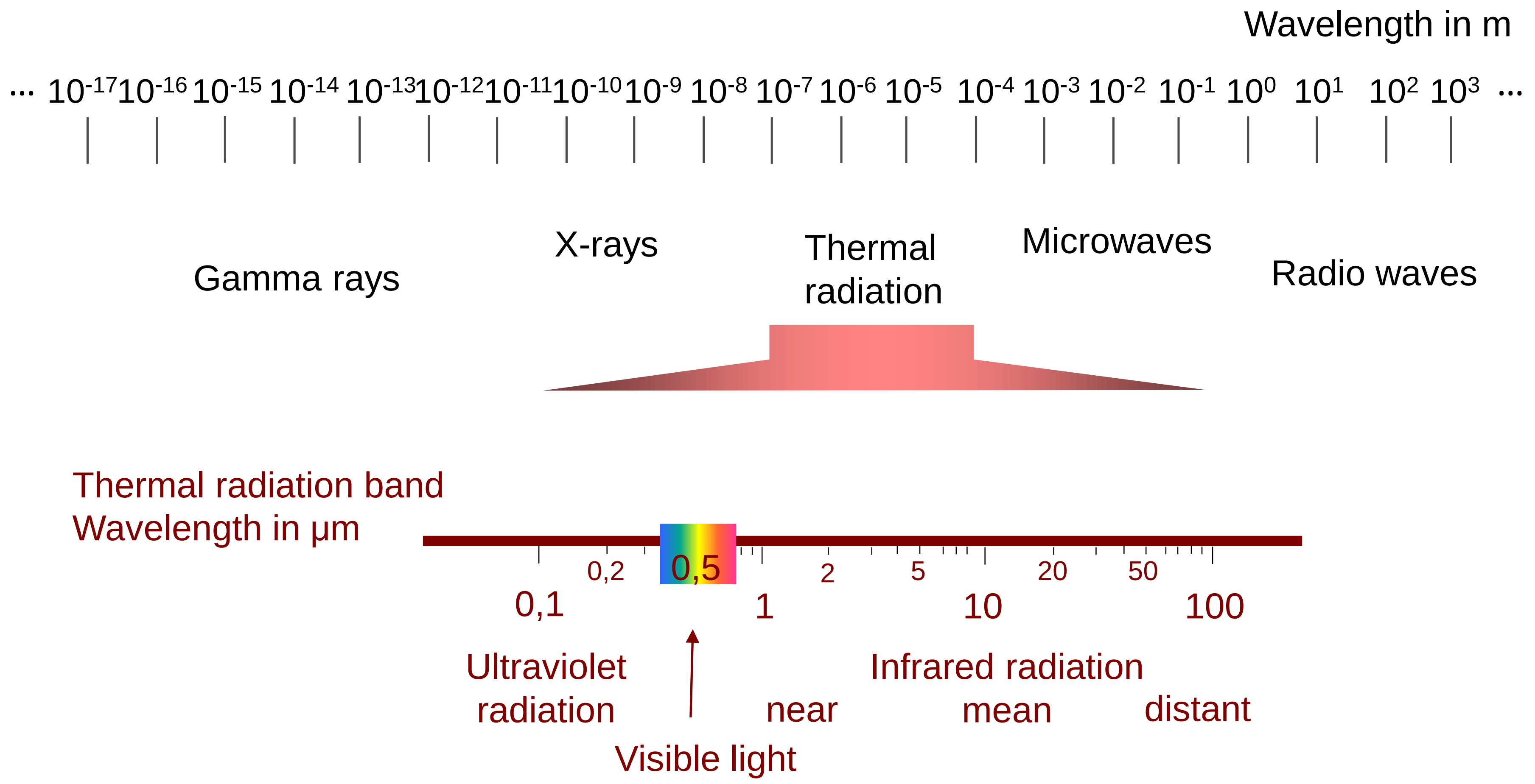
L in m h_c in $W/(m^2\ K)$	Laminar flow $\Delta T \leq (0.84/L)^3$	Turbulent flow $\Delta T > (0.84/L)^3$
Vertical plate or cylinder with height L 	$h_c = c_{lam}\left(\frac{\Delta T}{L}\right)^{0.25}$	$h_c = c_{turb}(\Delta T)^{0.33}$
Horizontal plate, heat dissipation from the top 	$h_c = 1.3 \cdot c_{lam}\left(\frac{\Delta T}{L_{min}}\right)^{0.25}$	$h_c = 1.3 \cdot c_{turb}(\Delta T)^{0.33}$
Horizontal plate, heat dissipation from the bottom 	$h_c = 0.7 \cdot c_{lam}\left(\frac{\Delta T}{L_{min}}\right)^{0.25}$	$h_c = 0.7 \cdot c_{turb}(\Delta T)^{0.33}$

Coefficients c_{lam} and c_{turb} for mean temperature T_m between air and plate surface

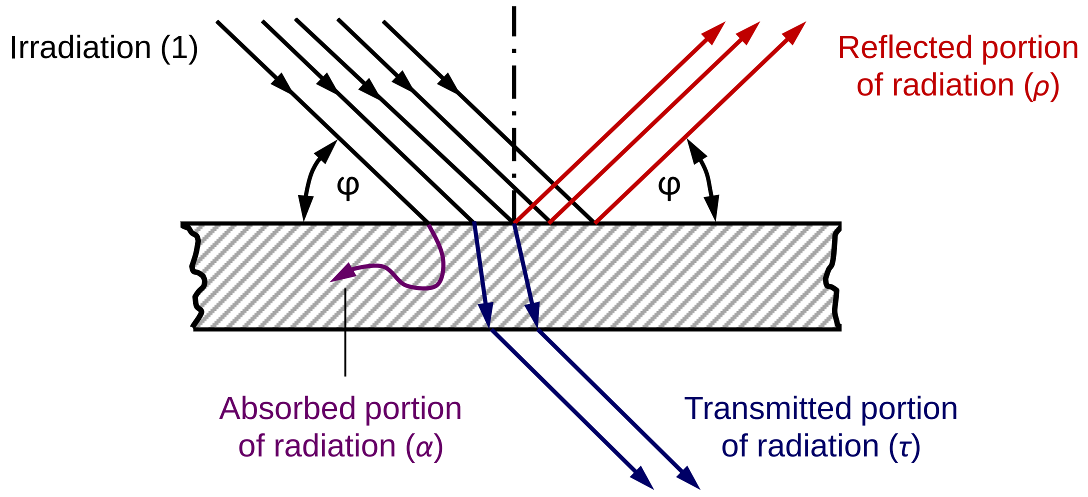
T_m (°C)	0	20	40	60	80	100
c_{lam} (air)		1.38	1.34	1.31	1.29	1.27
c_{lam} (H_2O)		105	149	178	205	227
c_{turb} (air)	1.69	1.61	1.53	1.45	1.39	1.33
c_{turb} (H_2O)	102	198	290	363	425	480



Condensation
(organic vapors)
Forced convection
(fluid)
Natural convection
(fluid)
Forced convection
(air)
Natural convection and radiation
(air)
1
10
100
1.000
10.000
Convection heat transfer coefficient h_c in $W/(m^2 \cdot K)$



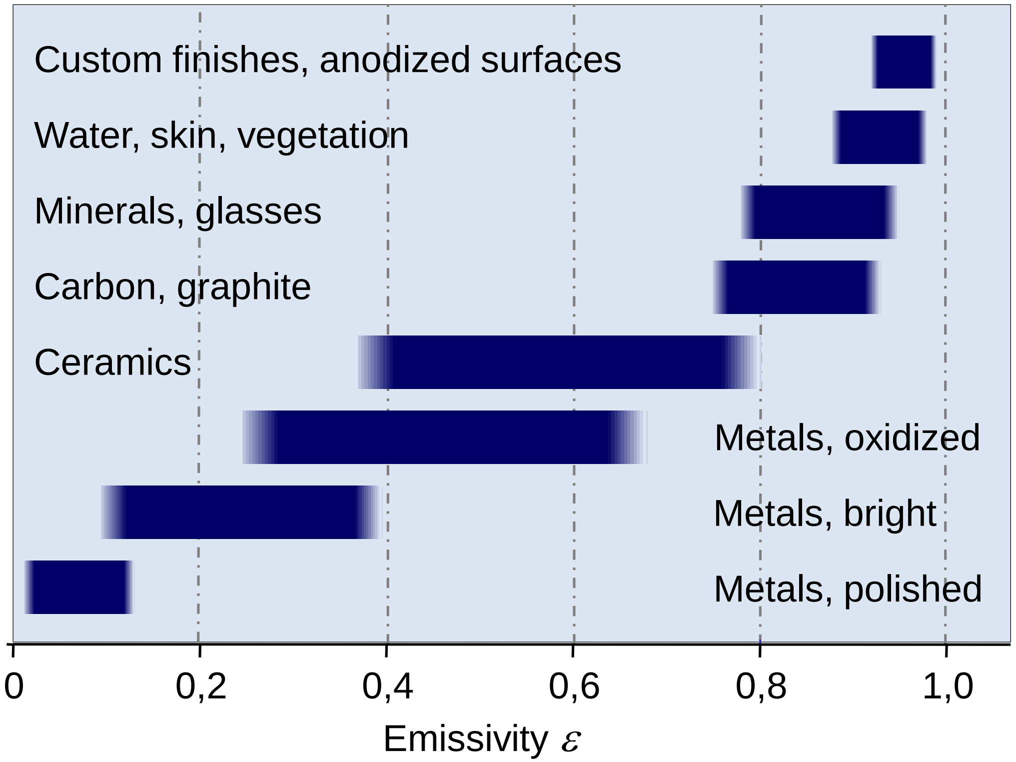
Wavelength in m
... 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} ...
Gamma rays
X-rays
Thermal radiation
Microwaves
Radio waves
Thermal radiation band
Wavelength in µm
0,2
0,5
2
5
20
50
0,1
1
10
100
Ultraviolet radiation
Infrared radiation
near
mean
distant
Visible light

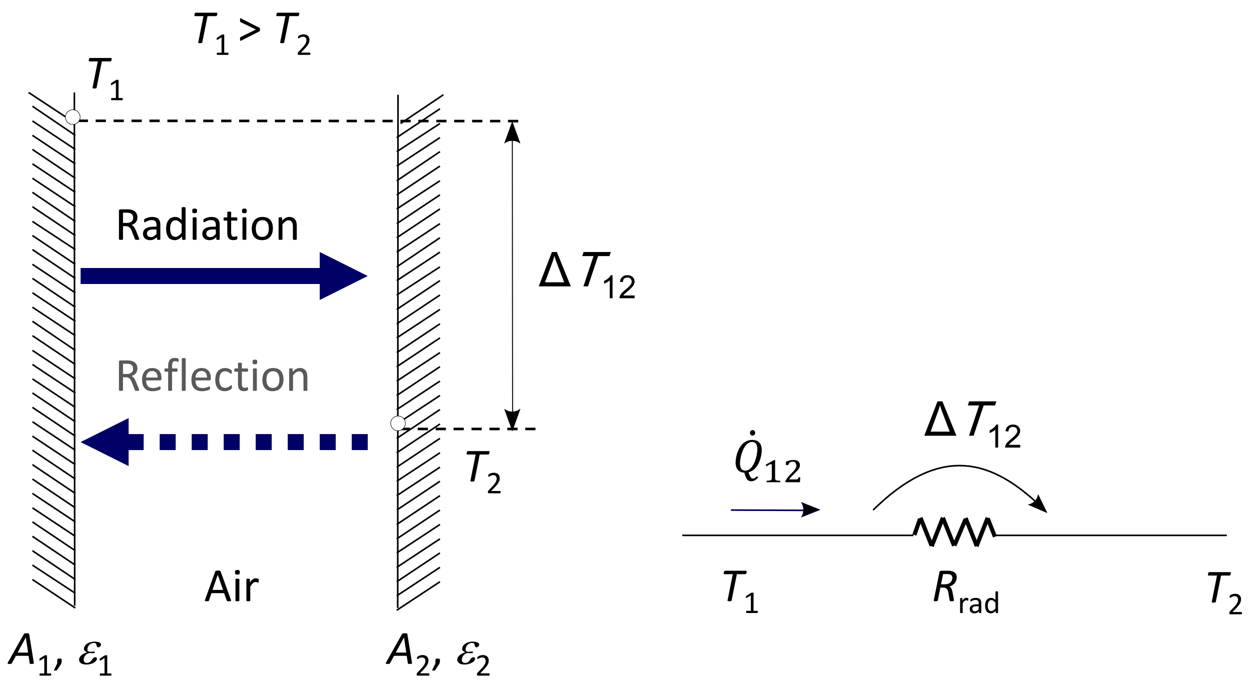


Irradiation (1)
Reflected portion
of radiation (ρ)
φ
φ
Absorbed portion
of radiation (α)
Transmitted portion
of radiation (τ)

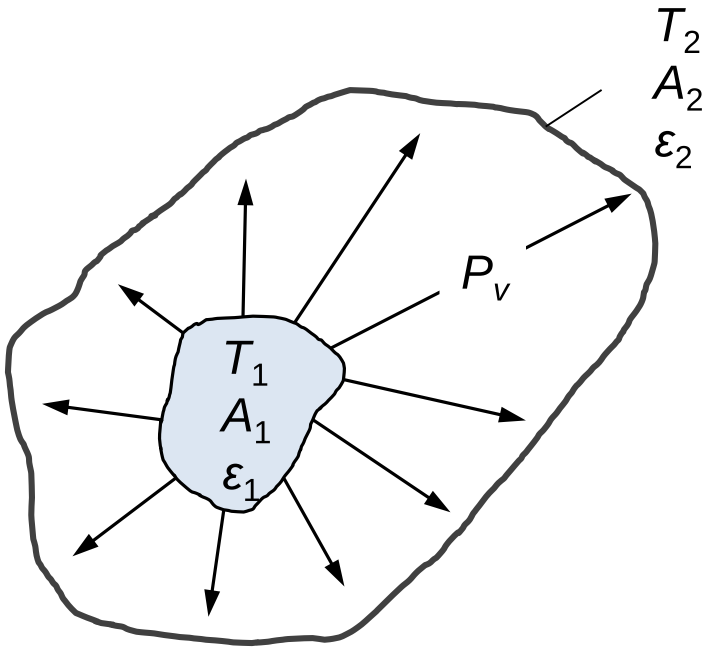
Table 5.10 Emissivity ε for standard radiation (mean values)

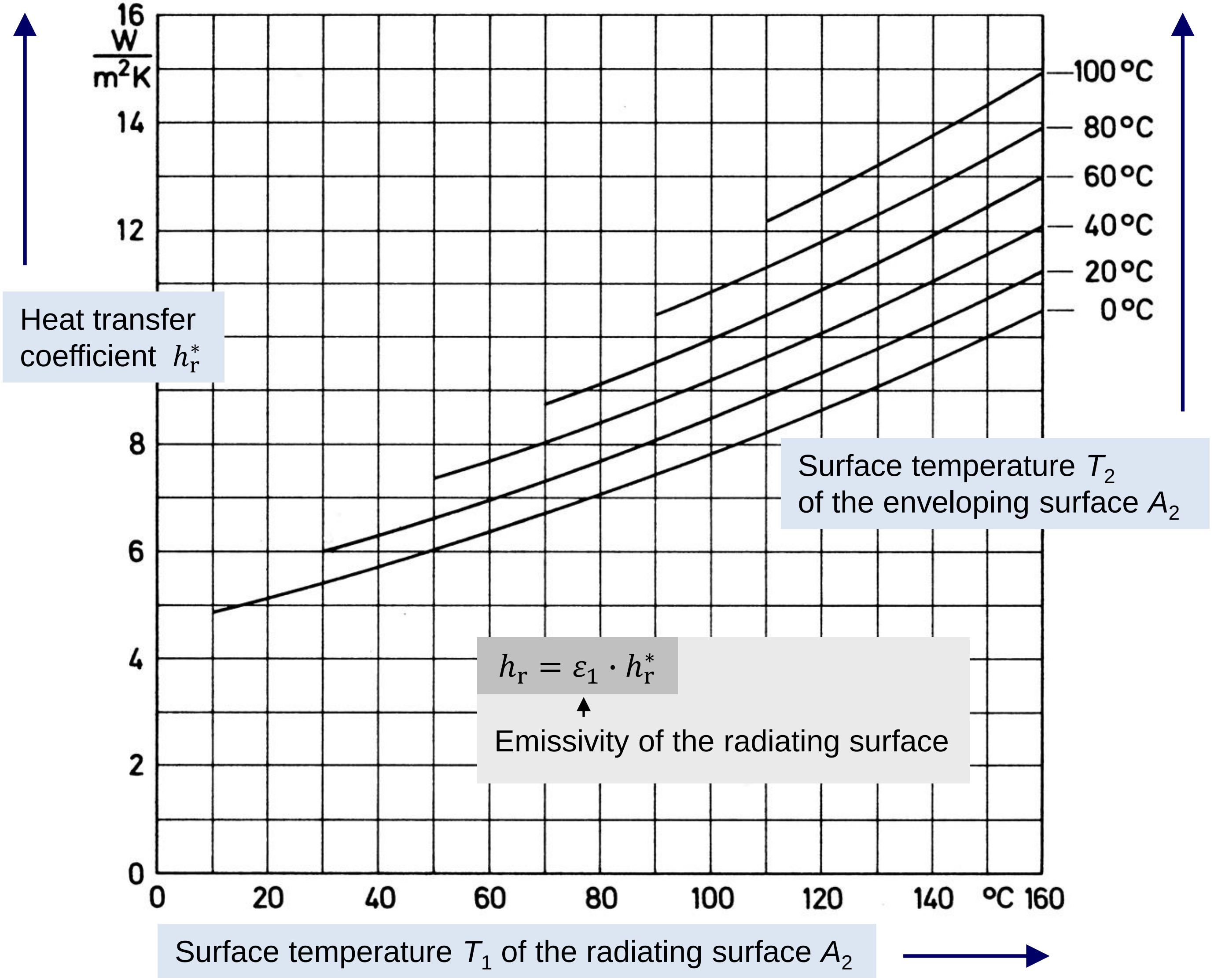
Metals	ε	Nonmetals	ε
Aluminum, rolled, plain	0.04	Ice, water	0.95
Aluminum, oxidized	0.25	Oak, smooth	0.9
Aluminum, anodized, 30 µm layer	0.65	Enamel, white	0.9
Chrome, bright	0.08	Glass	0.94
Cast iron, raw	0.9	Rubber, soft	0.9
Cast iron, treated	0.7	Masonry	0.91
Copper, bright	0.03	Paper	0.92
Copper, slightly/greatly oxidized	0.25/0.76	Porcelain, glazed	0.93
Brass, bright	0.05	Teflon	0.85
Brass, mat	0.22		
Nickel, bright	0.07	Finishes	ε
Nickel, oxidized	0.4	Aluminum paint	0.3
Silver, bright	0.02	Enamel	0.9
Carbon steel, rolled	0.6	Hammer finish	0.35
Carbon steel, slightly rusty	0.7	Paint, black, high-gloss	0.89
Carbon steel, very rusted	0.85	Paint, black, mat	0.96
Carbon steel, brightly sanded	0.24	Paint, white, mat	0.92
Carbon steel, brightly etched	0.13	Red lead	0.92
Steel sheet, wrought	0.6	Oil paint	0.9
Steel sheet, galvanized	0.27	Special aluminum paint	0.2
Steel sheet, nickel-plated, unpolished	0.11		
Tin, bright	0.06		
Zinc, bright	0.05		
Zinc, oxidized	0.11		
Zinc, raw	0.25		


Custom finishes, anodized surfaces
Water, skin, vegetation
Minerals, glasses
Carbon, graphite
Ceramics
Metals, oxidized
Metals, bright
Metals, polished
0
0,2
0,4
0,6
0,8
1,0
Emissivity ε

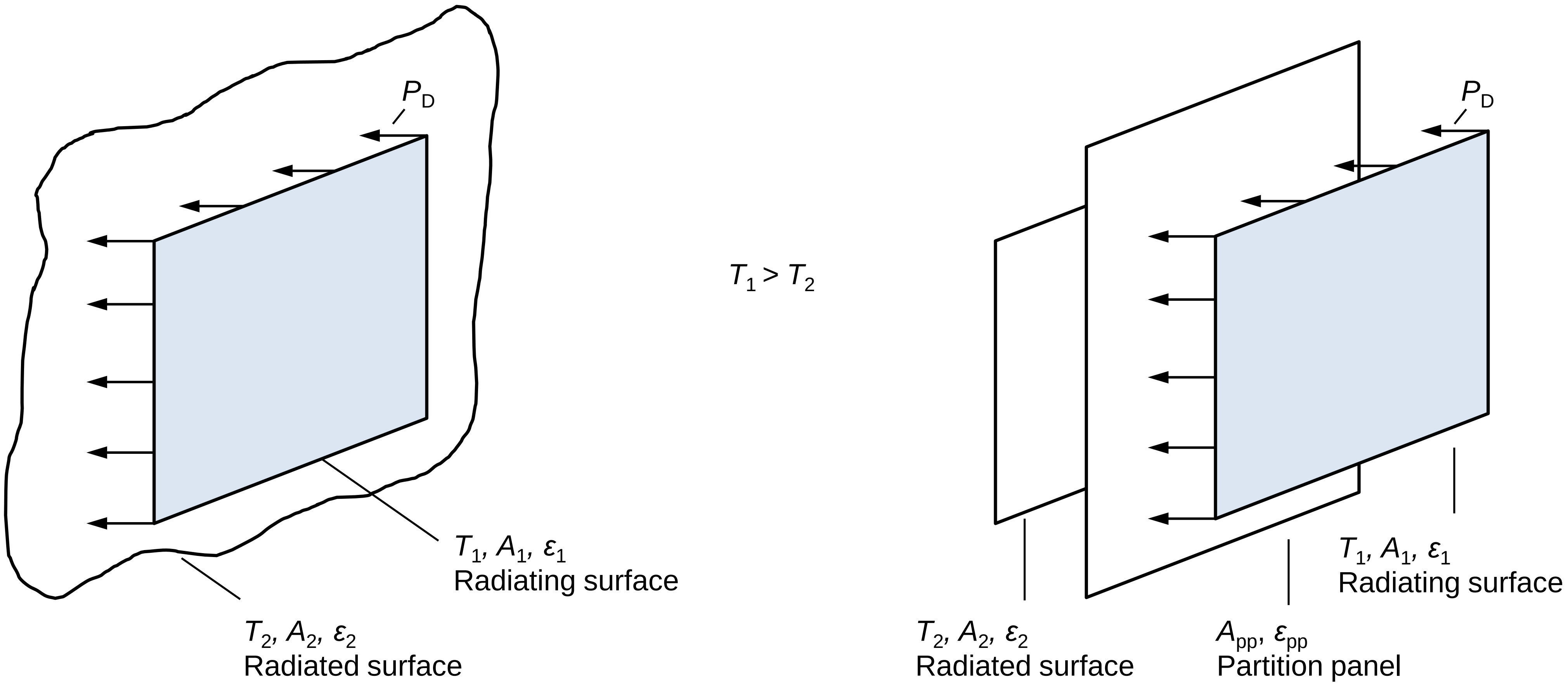


$T_1 > T_2$
T_1
Radiation
Reflection
T_2
ΔT_{12}
Air
A_1, ε_1
A_2, ε_2
$\dot{Q}_{12}$
ΔT_{12}
T_1
R_{rad}
T_2


T_2
A_2
ε_2
P_v
T_1
A_1
ε_1

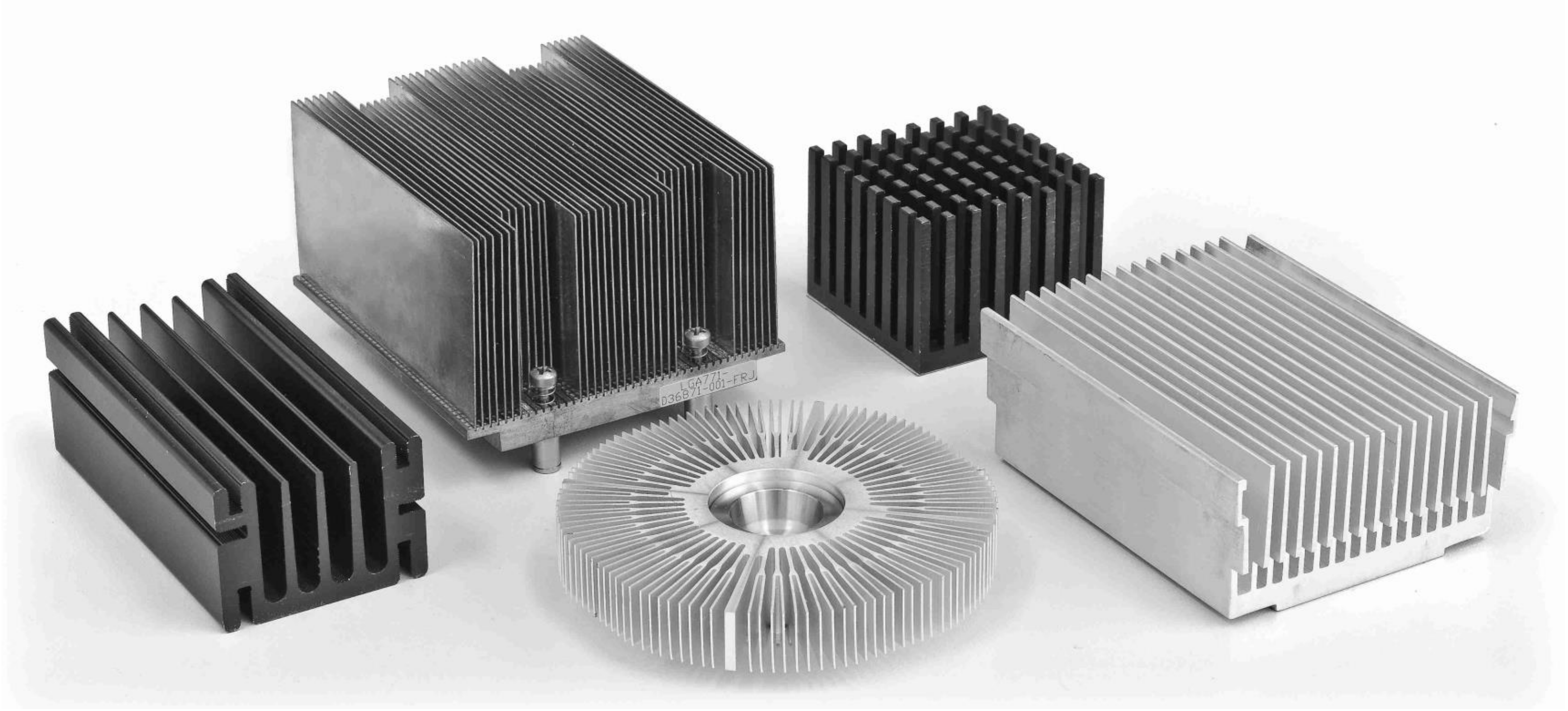


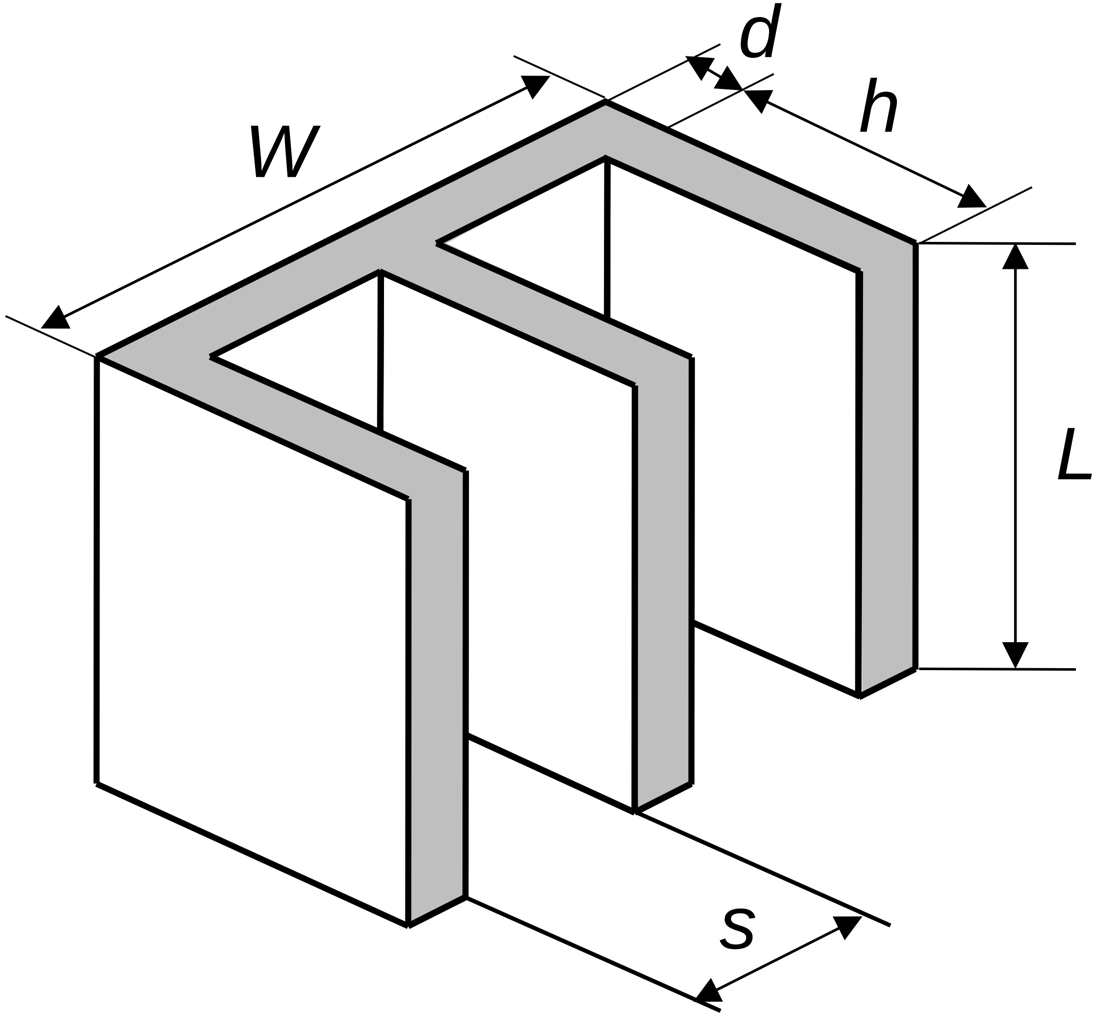
Heat transfer coefficient h_r^*
16
W/m²K
14
12
8
6
4
2
0
0
20
40
60
80
100
120
140
°C 160
100 °C
80 °C
60 °C
40 °C
20 °C
0 °C
Surface temperature T_2 of the enveloping surface A_2
$h_r = \varepsilon_1 \cdot h_r^*$
Emissivity of the radiating surface
Surface temperature T_1 of the radiating surface A_2



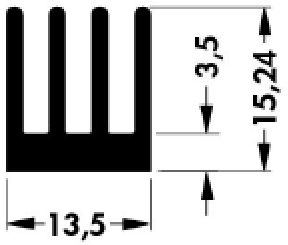
Special case (c)

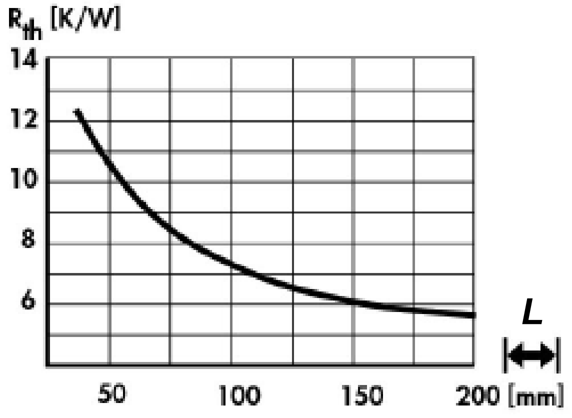
Special case (d)

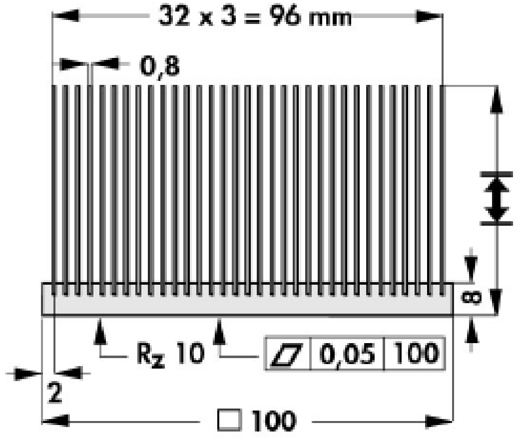

LGA771-
D36B71-001-FRJ

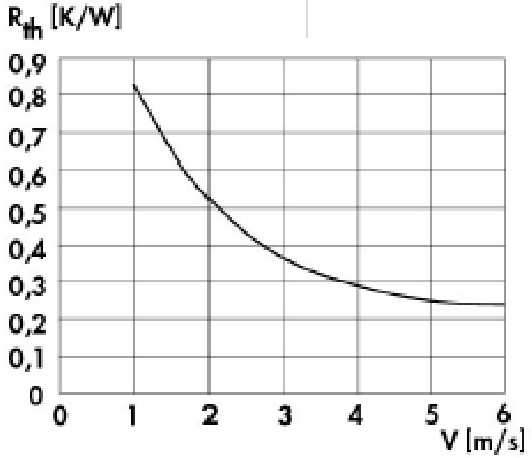


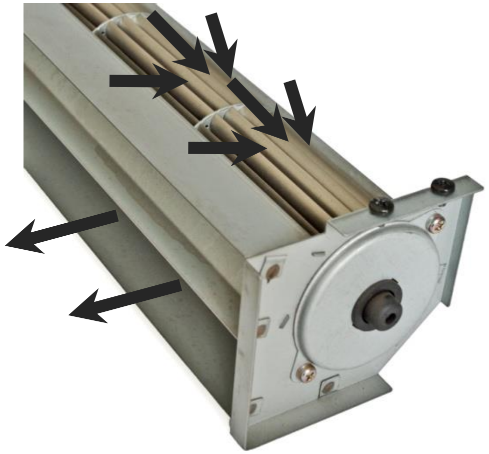
W
d
h
L
s

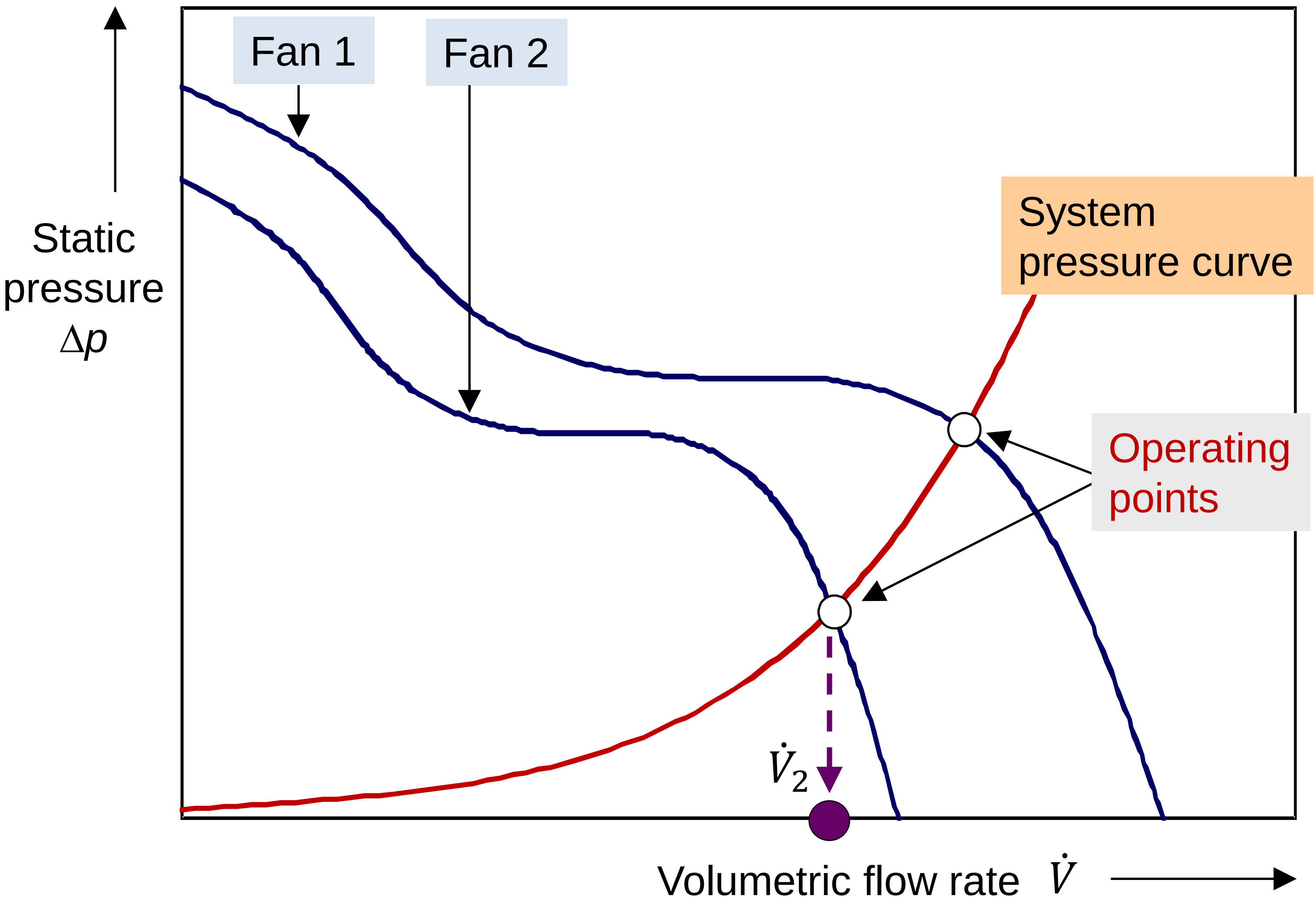

3,5
15,24
13,5

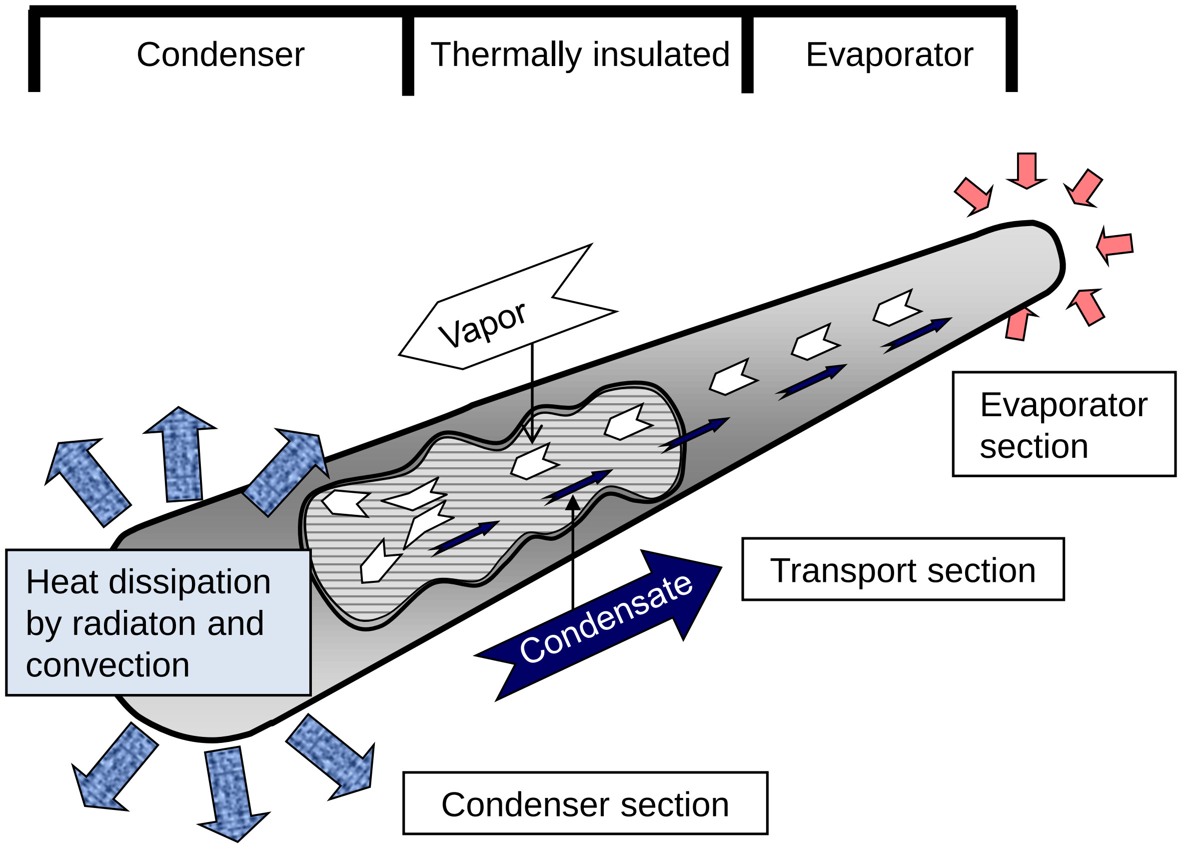

Rth [K/W]
14
12
10
8
6
50
100
150
200 [mm]
L

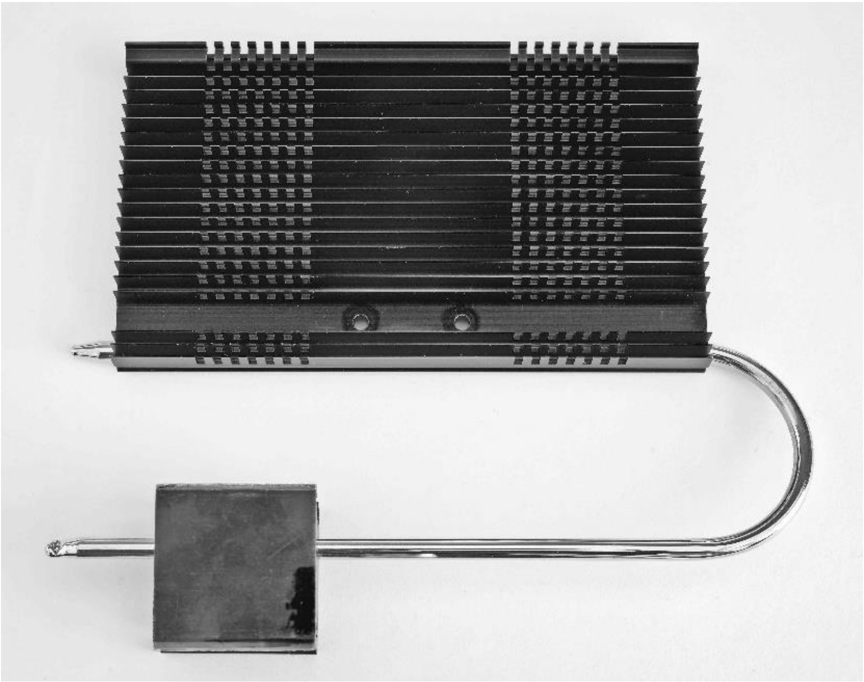

32 x 3 = 96 mm
0,8
8
Rz 10
0,05
100
2
□ 100

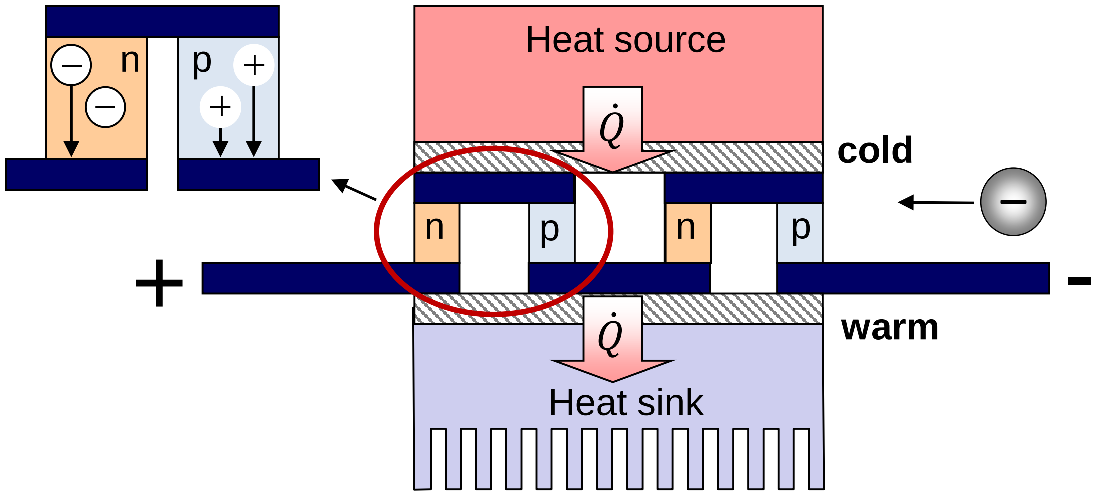

Rth [K/W]
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
1
2
3
4
5
6
V [m/s]

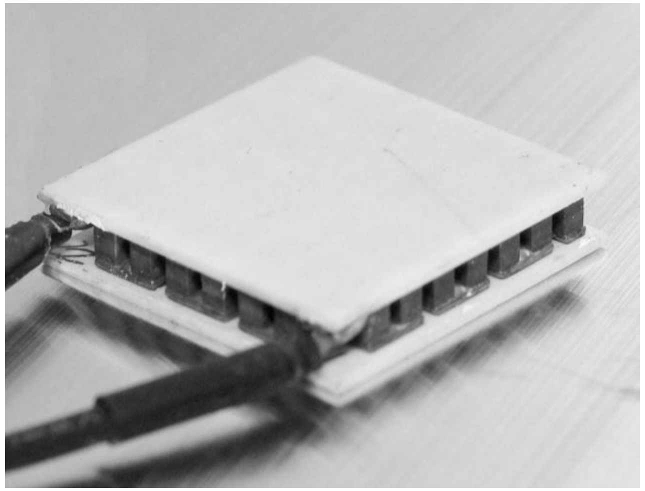


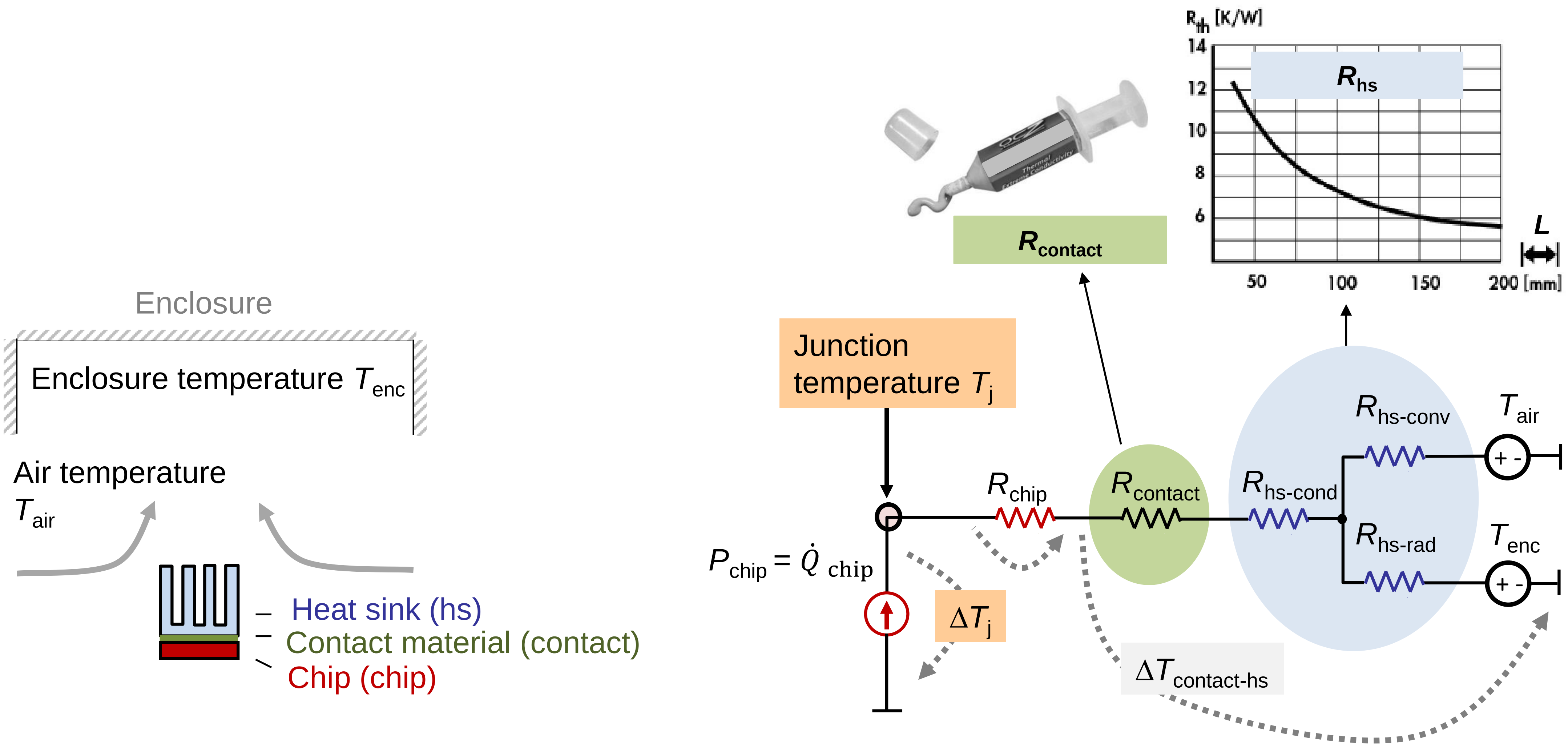

Fan 1
Fan 2
Static pressure Δp
System pressure curve
Operating points
$\dot{V}_2$
Volumetric flow rate $\dot{V}$

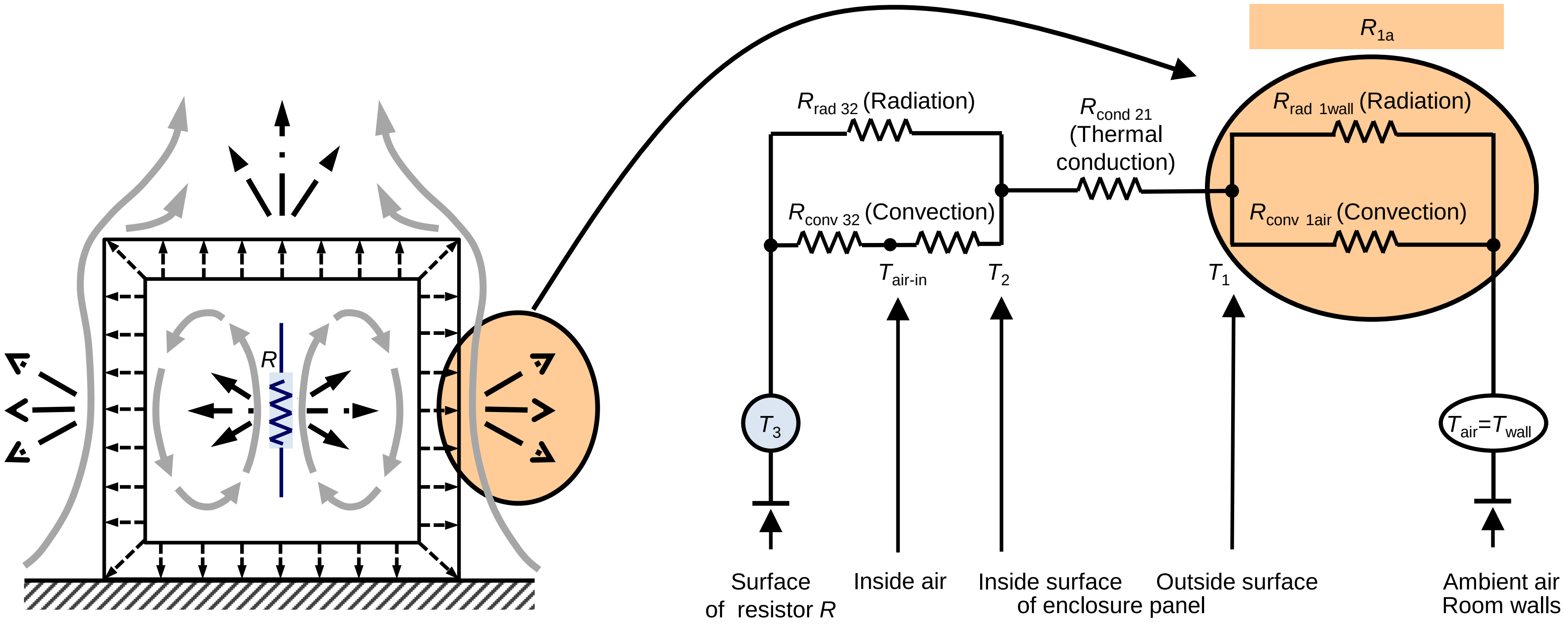

Condenser
Thermally insulated
Evaporator
Vapor
Evaporator section
Transport section
Condensate
Heat dissipation by radiaton and convection
Condenser section



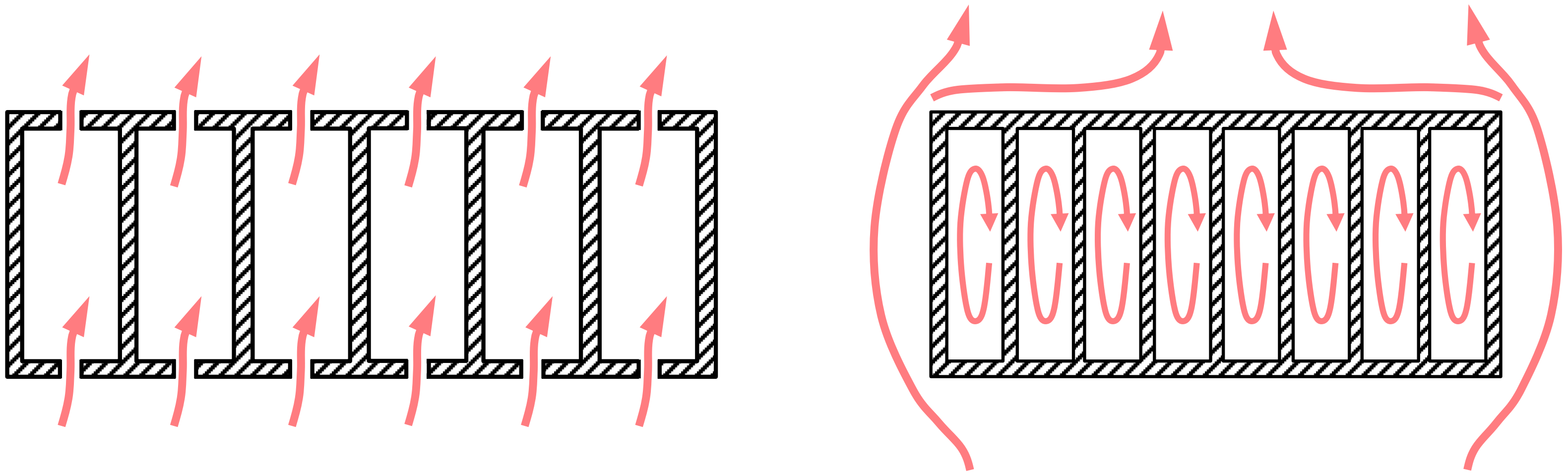

n
p
Heat source
$\dot{Q}$
cold
n
p
n
p
+
-
$\dot{Q}$
warm
Heat sink

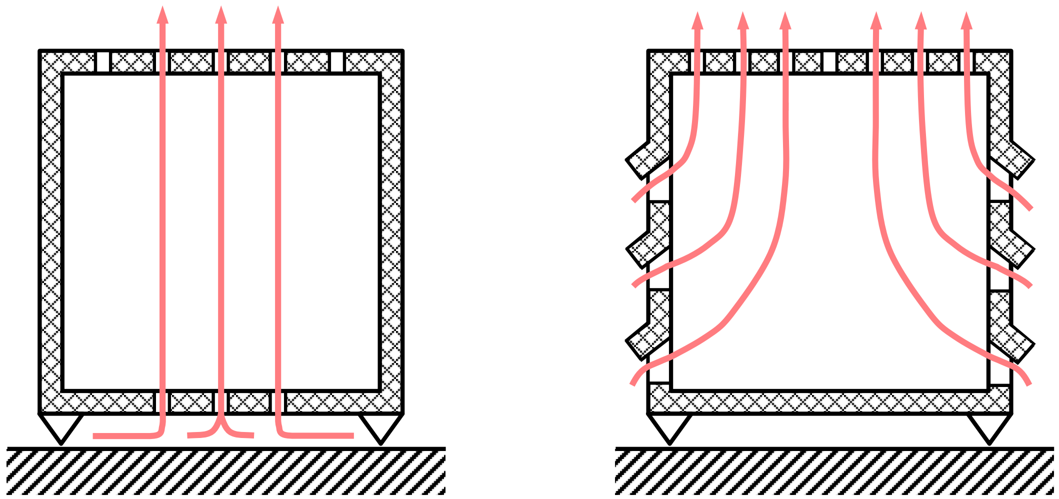


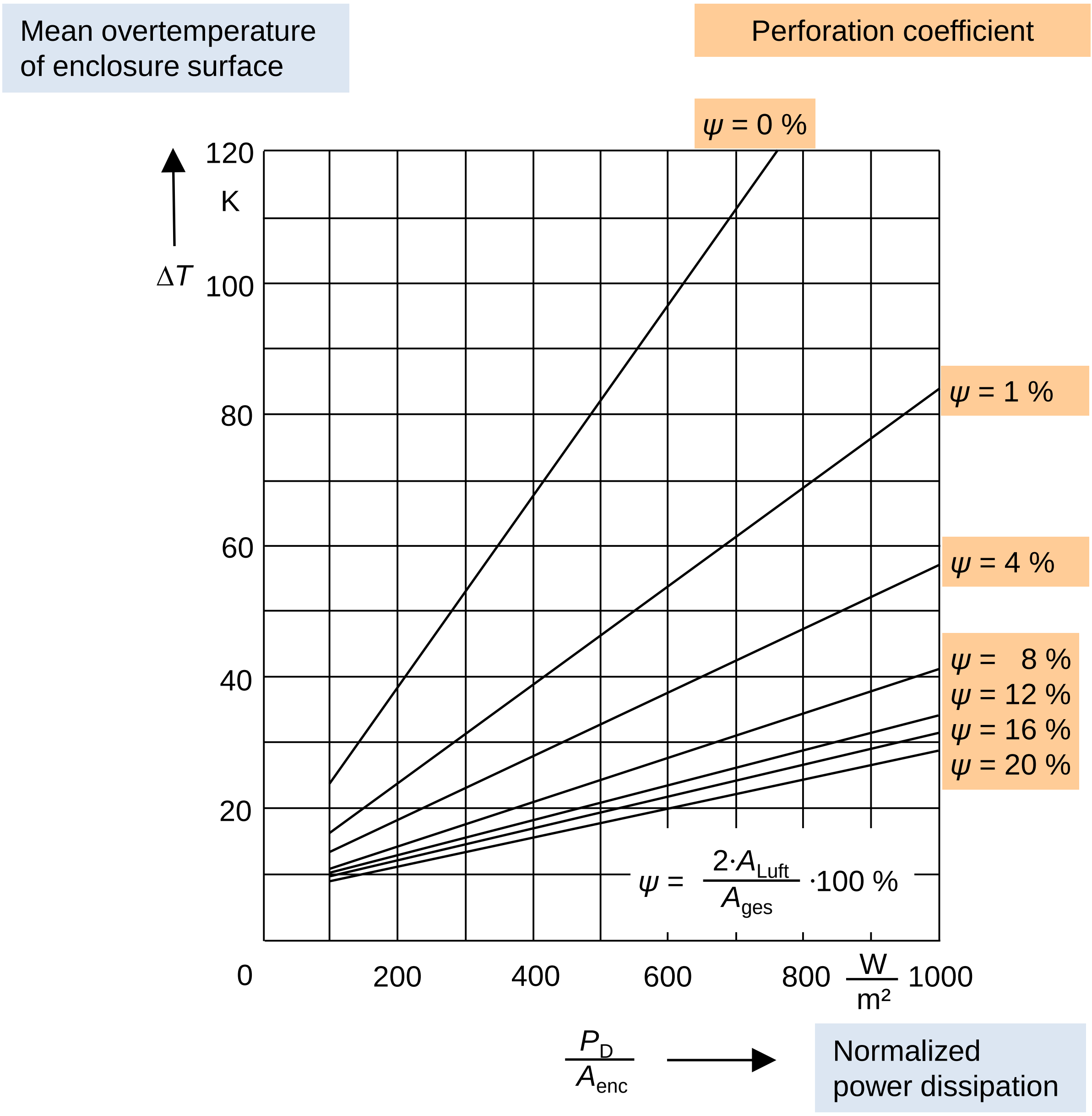

Enclosure
Enclosure temperature T_{enc}
Air temperature T_{air}
Heat sink (hs)
Contact material (contact)
Chip (chip)
Junction temperature T_j
$P_{chip} = \dot{Q}_{chip}$
R_{chip}
$R_{contact}$
$R_{hs\text{-}cond}$
$R_{hs\text{-}conv}$
$R_{hs\text{-}rad}$
T_{air}
T_{enc}
+ -
+ -
ΔT_j
$\Delta T_{contact\text{-}hs}$
$R_{contact}$
R_{th} [K/W]
14
12
10
8
6
R_{hs}
L
50
100
150
200 [mm]

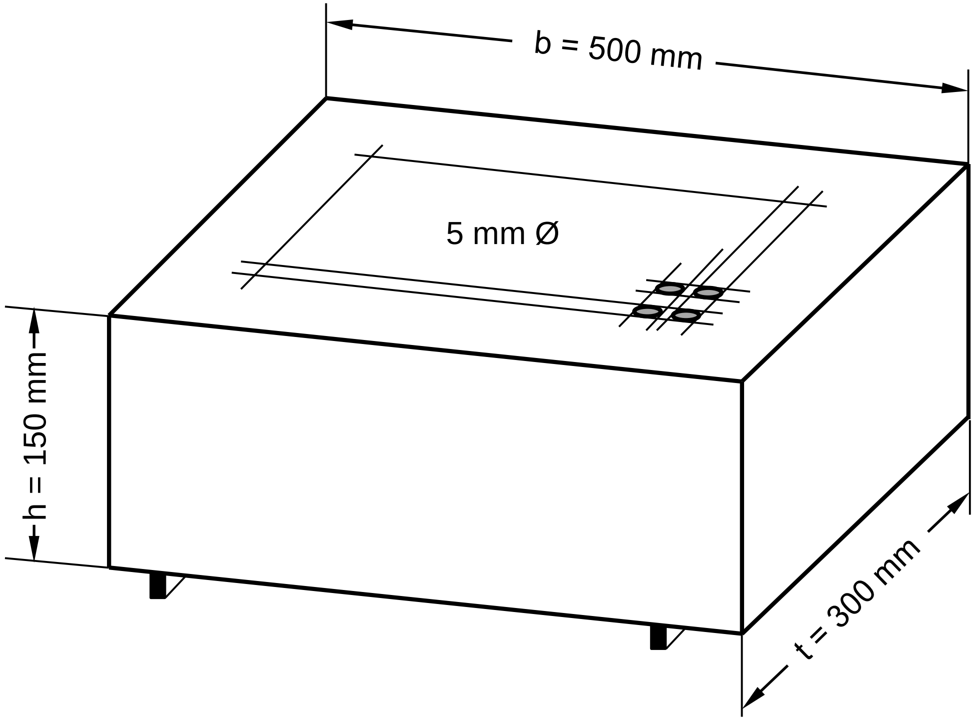


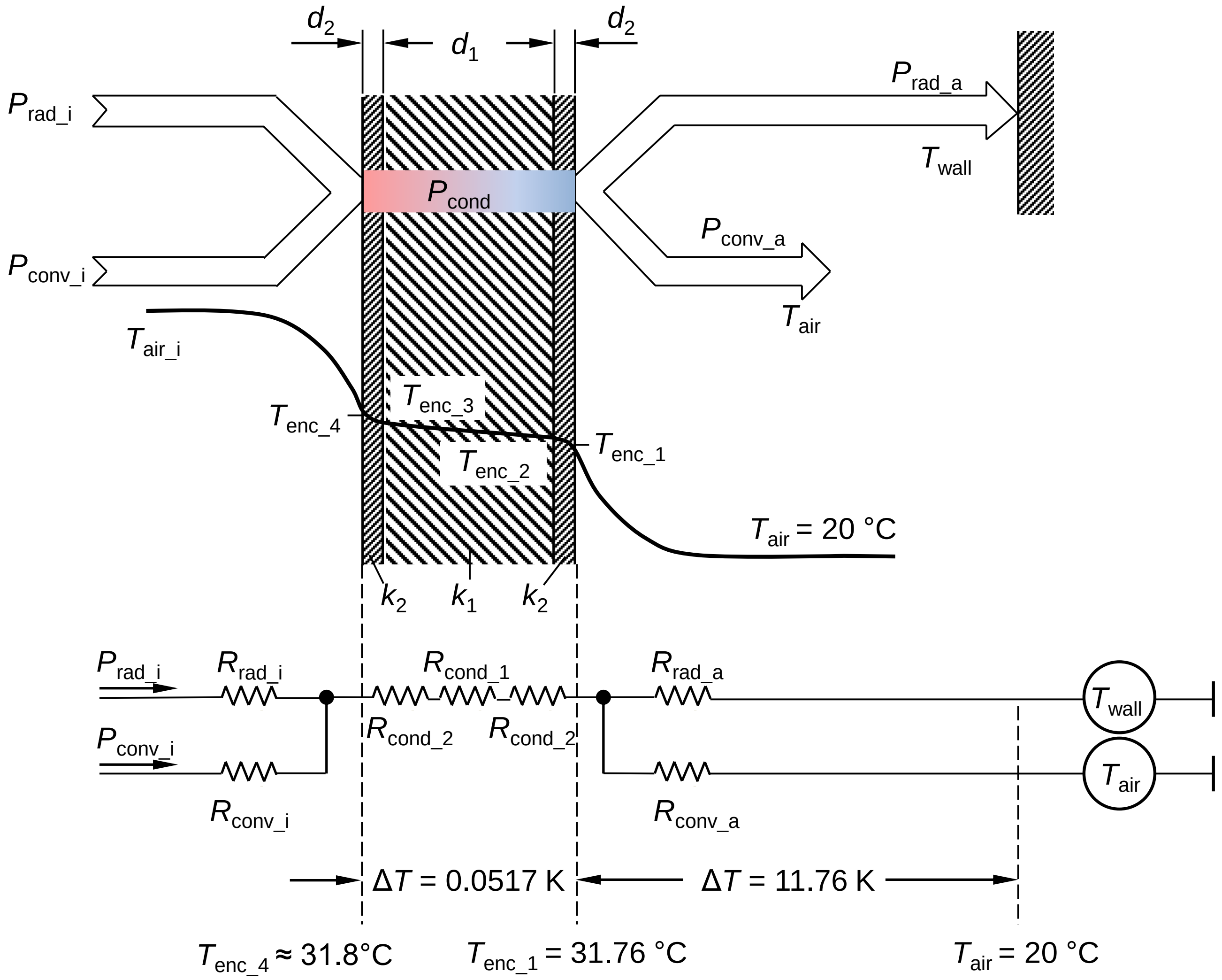
R
R_{1a}
$R_{rad\ 32}$ (Radiation)
$R_{cond\ 21}$ (Thermal conduction)
$R_{rad\ 1wall}$ (Radiation)
$R_{conv\ 32}$ (Convection)
$R_{conv\ 1air}$ (Convection)
$T_{air\text{-}in}$
T_2
T_1
T_3
$T_{air}=T_{wall}$
Surface of resistor R
Inside air
Inside surface of enclosure panel
Outside surface
Ambient air Room walls



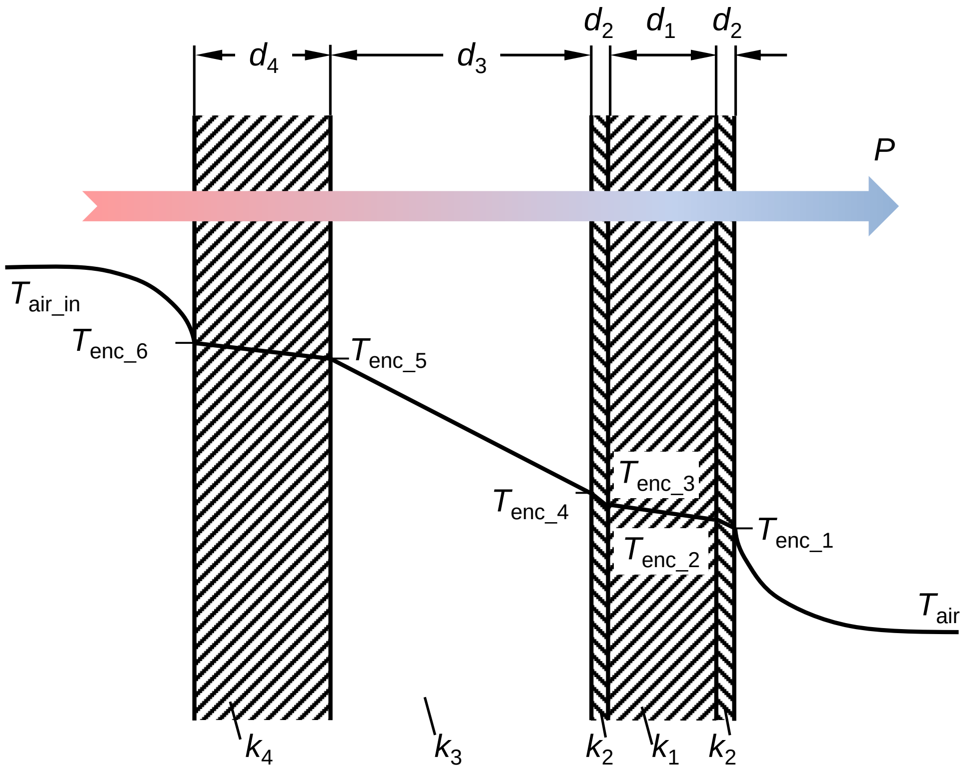



Mean overtemperature
of enclosure surface
Perforation coefficient
ψ = 0 %
ψ = 1 %
ψ = 4 %
ψ = 8 %
ψ = 12 %
ψ = 16 %
ψ = 20 %
120
K
ΔT
100
80
60
40
20
0
200
400
600
800
W/m²
1000
ψ = 2·A_Luft / A_ges ·100 %
P_D / A_enc
Normalized
power dissipation

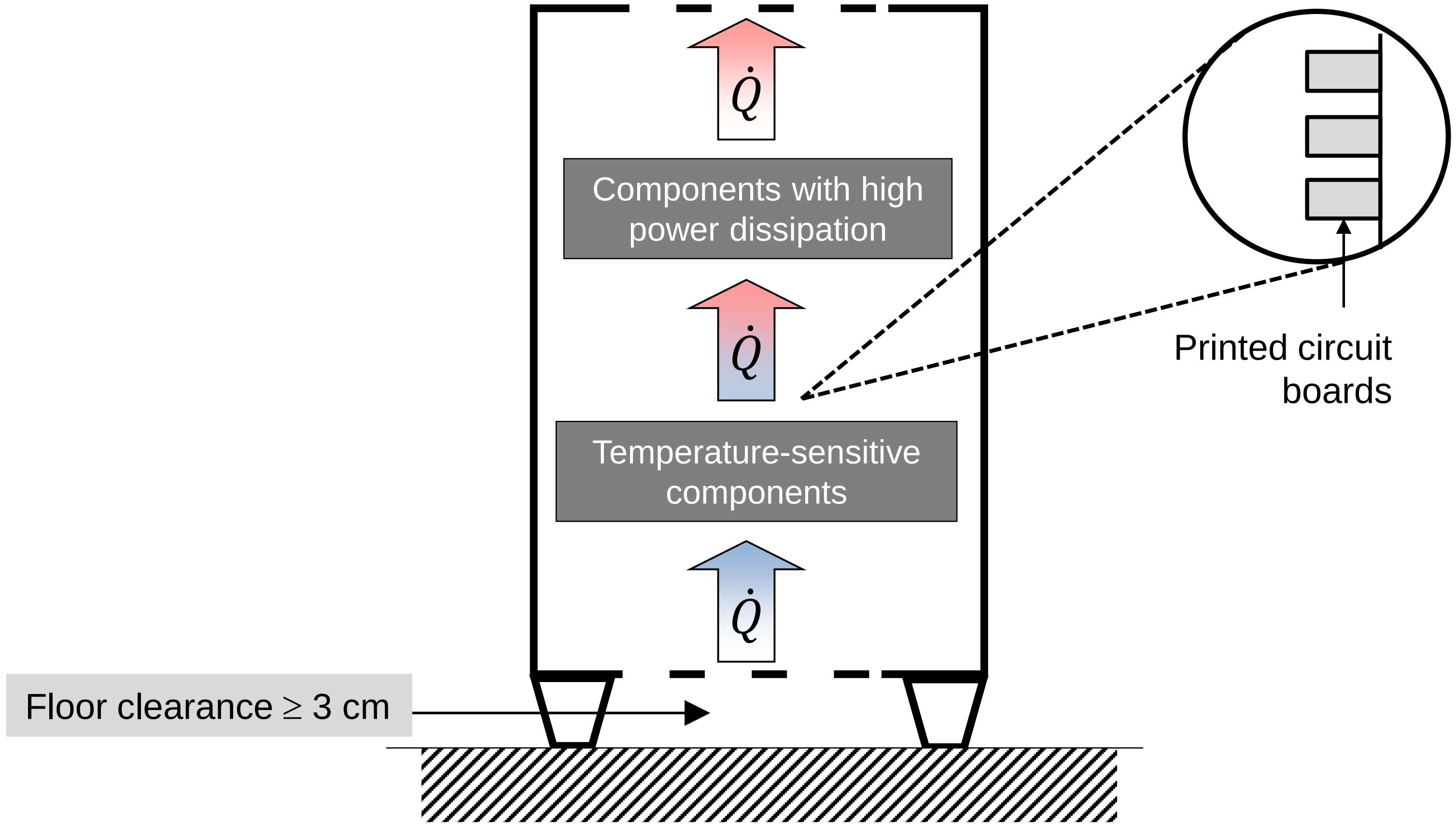

b = 500 mm
5 mm Ø
h = 150 mm
t = 300 mm

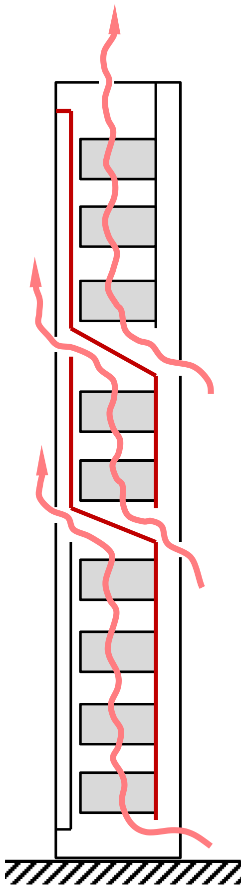


d2
d1
d2
P rad_i
P conv_i
P cond
P rad_a
T wall
P conv_a
T air
T air_i
T enc_3
T enc_4
T enc_1
T enc_2
T air = 20 °C
k2
k1
k2
P rad_i
R rad_i
R cond_1
R rad_a
R cond_2
R cond_2
T wall
P conv_i
T air
R conv_i
R conv_a
ΔT = 0.0517 K
ΔT = 11.76 K
T enc_4 ≈ 31.8°C
T enc_1 = 31.76 °C
T air = 20 °C

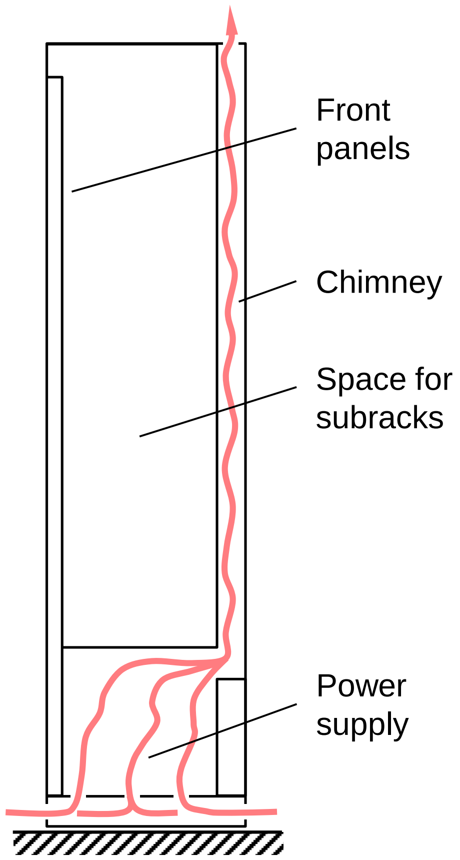


d4
d3
d2
d1
d2
P
T_air_in
T_enc_6
T_enc_5
T_enc_4
T_enc_3
T_enc_2
T_enc_1
T_air
k4
k3
k2
k1
k2

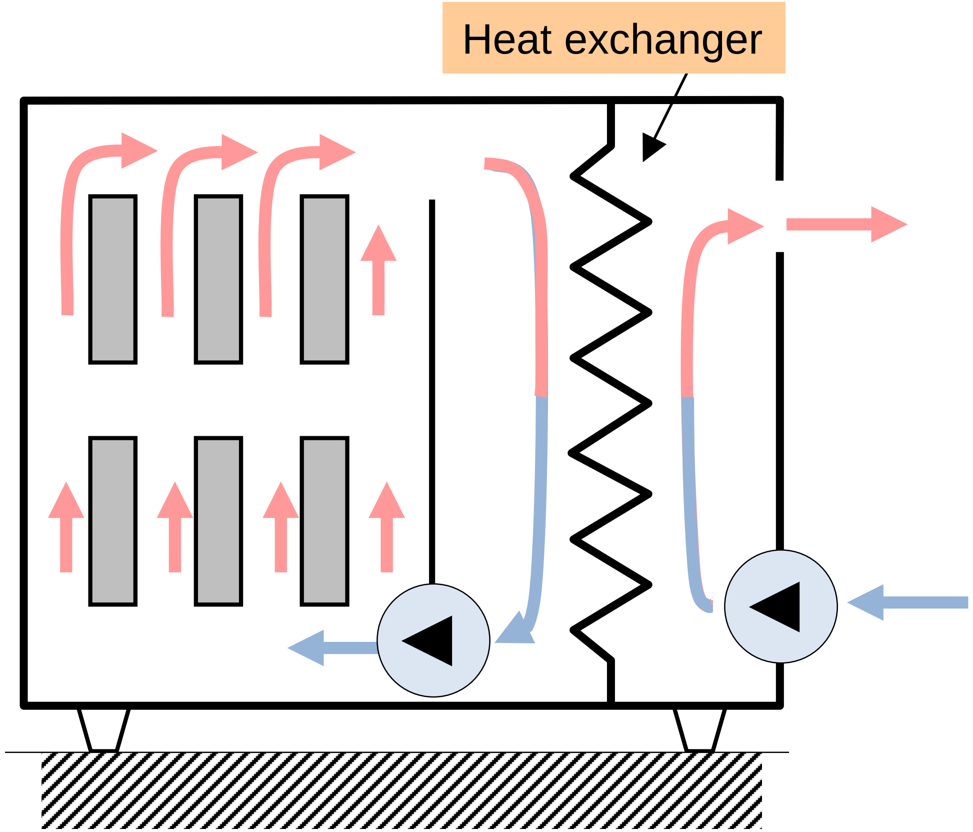

$\dot{Q}$
Components with high power dissipation
$\dot{Q}$
Temperature-sensitive components
$\dot{Q}$
Floor clearance ≥ 3 cm
Printed circuit boards

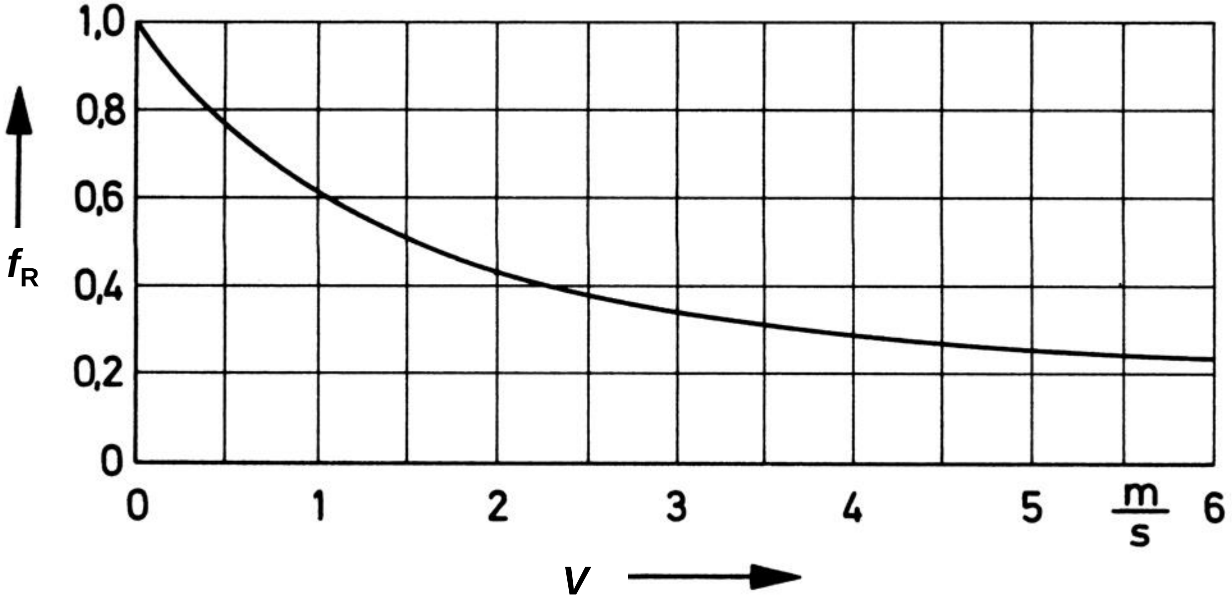


Baffles

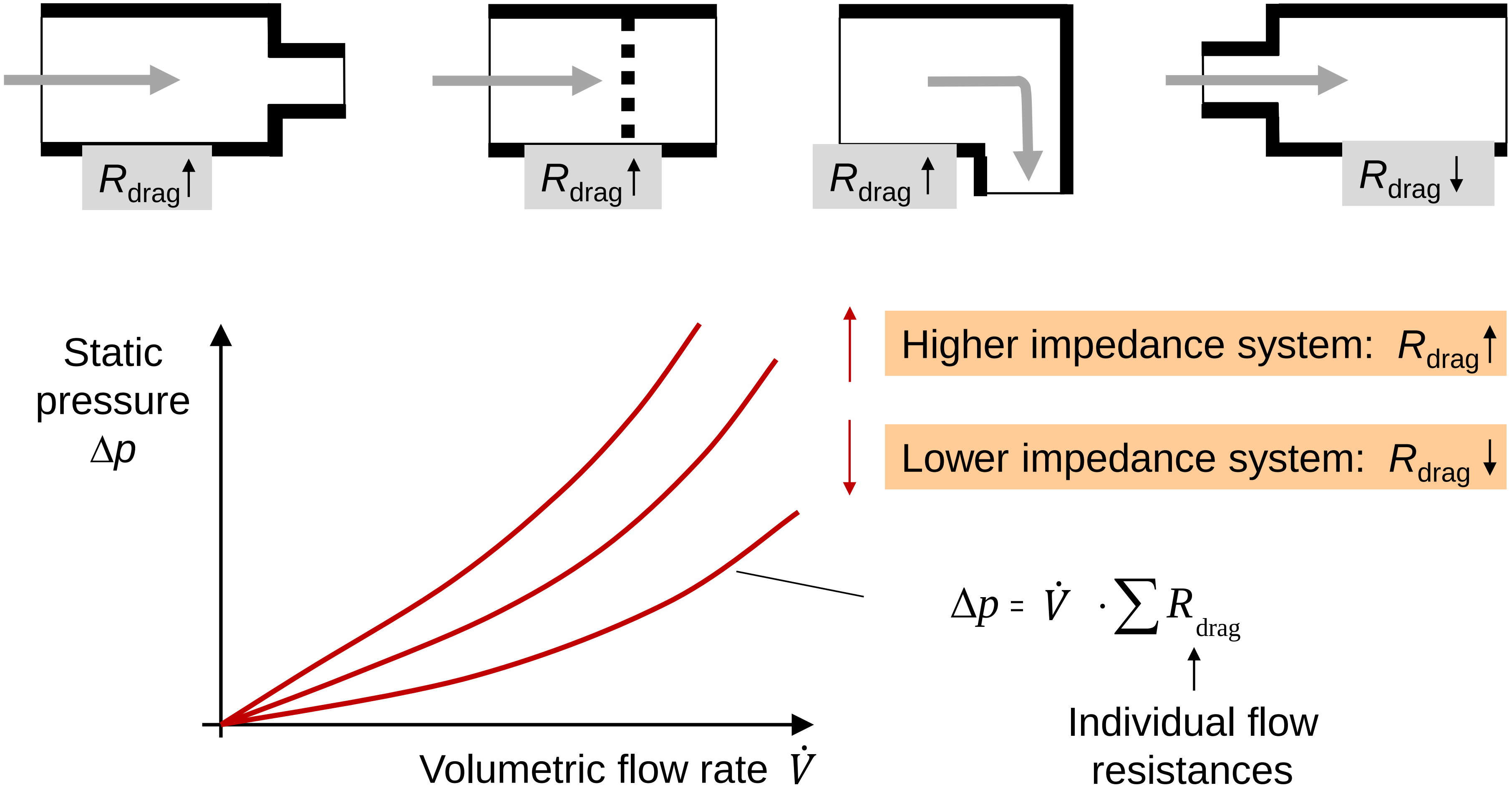


Chimney effect

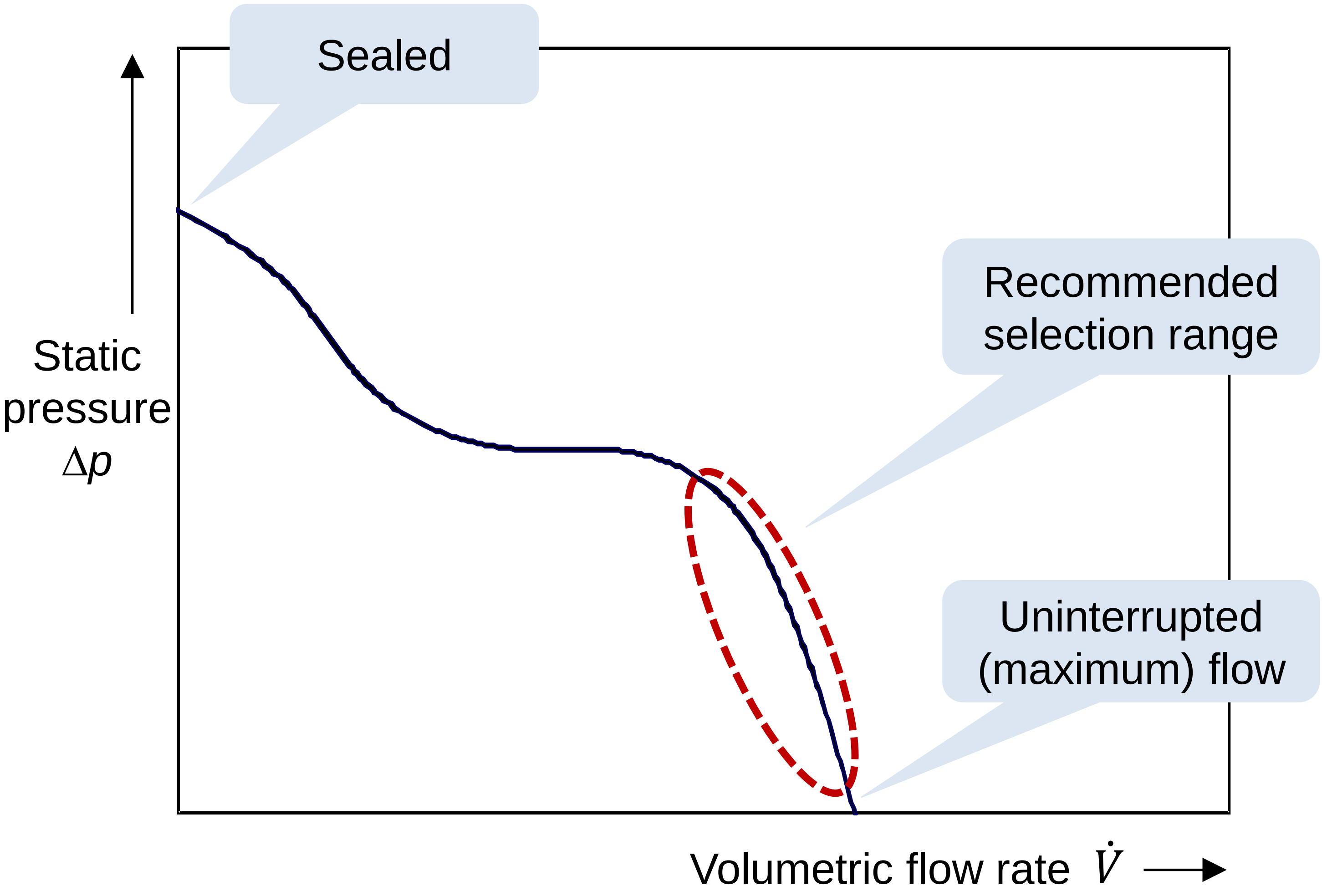

Heat exchanger

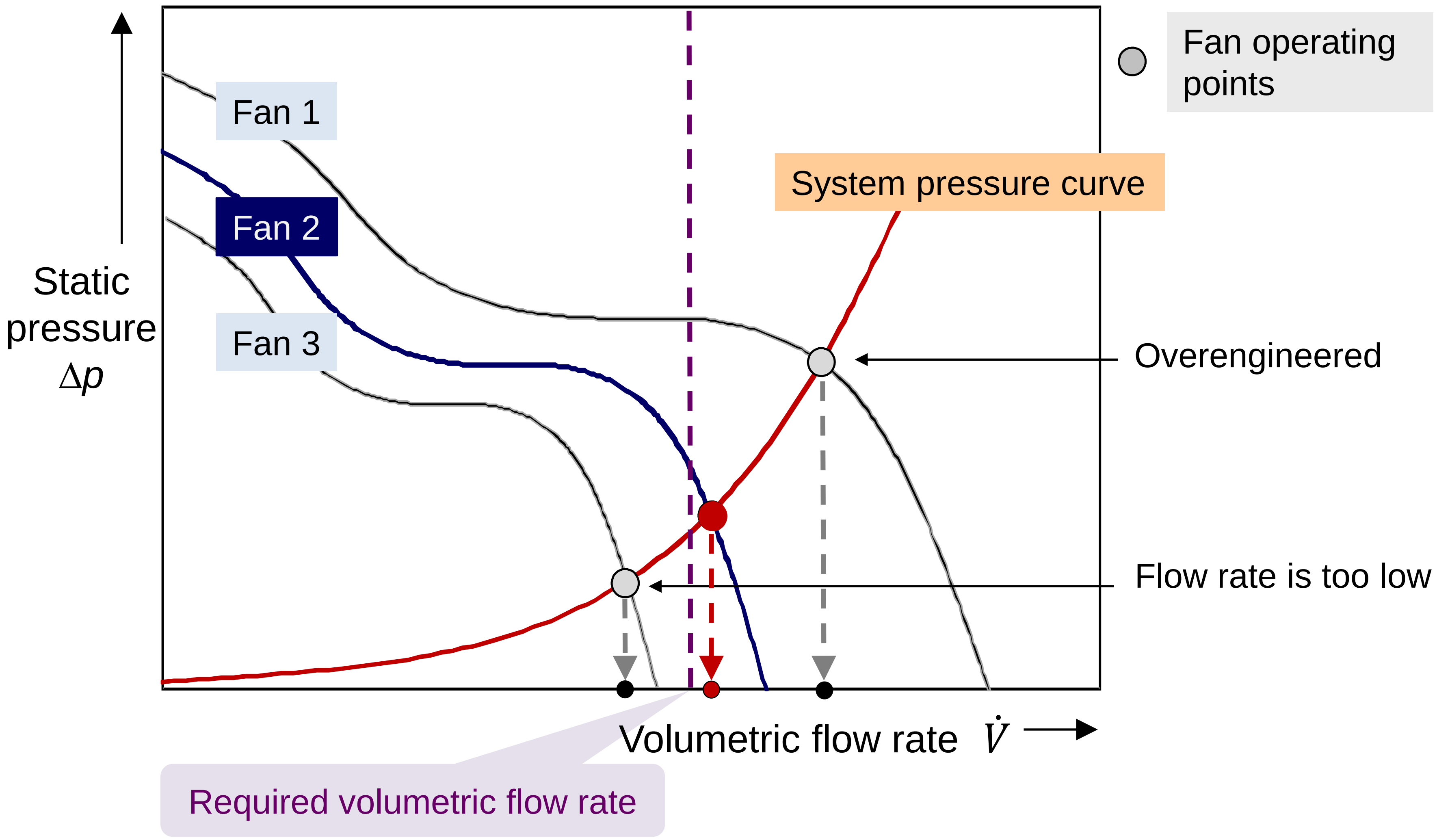


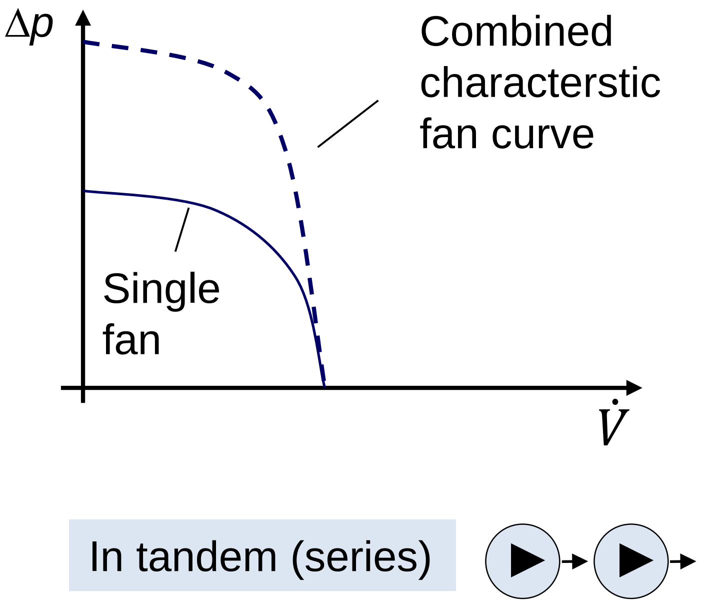
1,0
0,8
0,6
0,4
0,2
0
f_R
0
1
2
3
4
5
6
m/s
V



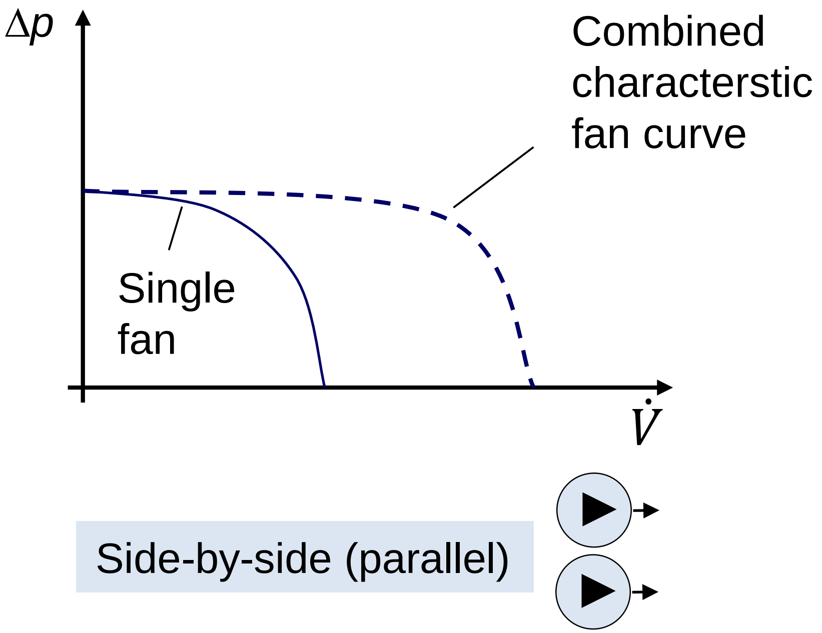
$R_{drag}\uparrow$
$R_{drag}\uparrow$
$R_{drag}\uparrow$
$R_{drag}\downarrow$
Static pressure Δp
Volumetric flow rate $\dot{V}$
Higher impedance system: $R_{drag}\uparrow$
Lower impedance system: $R_{drag}\downarrow$
$\Delta p = \dot{V} \cdot \sum R_{drag}$
Individual flow resistances


Sealed
Static pressure Δp
Recommended selection range
Uninterrupted (maximum) flow
Volumetric flow rate $\dot{V}$


Fan operating points
Fan 1
Fan 2
Fan 3
System pressure curve
Static pressure Δp
Overengineered
Flow rate is too low
Volumetric flow rate $\dot{V}$
Required volumetric flow rate



Δp
Combined
characterstic
fan curve
Single
fan
V̇
In tandem (series)



Δp
Combined
characterstic
fan curve
Single
fan
V̇
Side-by-side (parallel)