HVAC Load Calculation

Thermal Transmittance

March 2026

Program

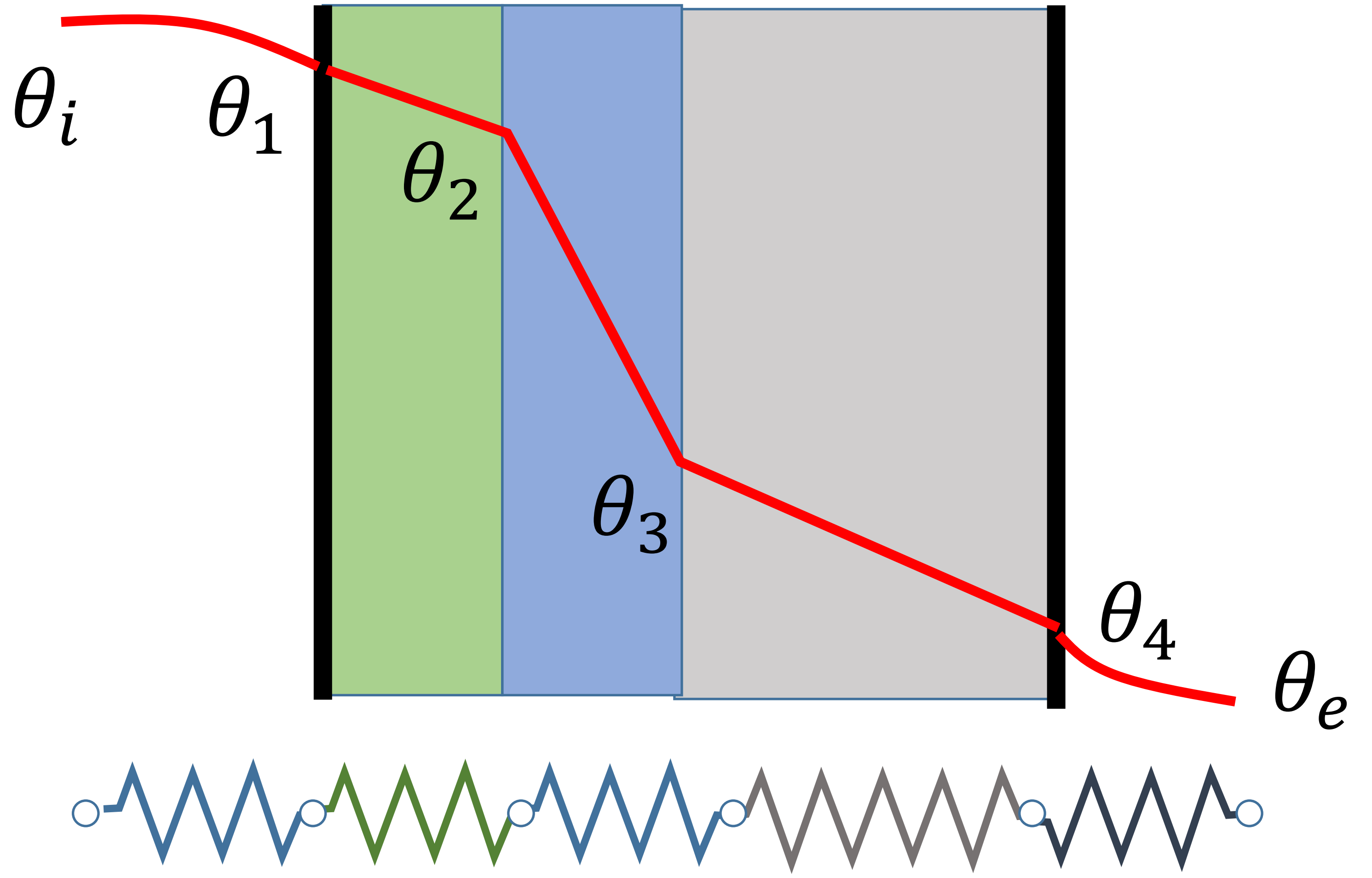
- Non-homogeneous structures
- Equivalent resistive networks
- Resistance calculation
- Equivalent transmittance calculation
- example

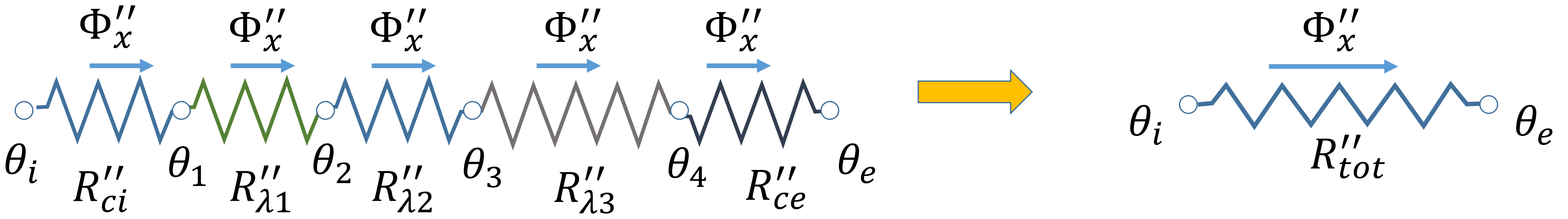
Electrical Net equivalence, composite wall

- Multilayered wall
- Sove the problem with equivalent net

$$\Phi_x'' = \frac{\theta_i - \theta_e}{R_{tot}''}$$

$$R_{tot}'' = R_{ci} + \sum_j R_{\lambda,j} + R_{ce}$$

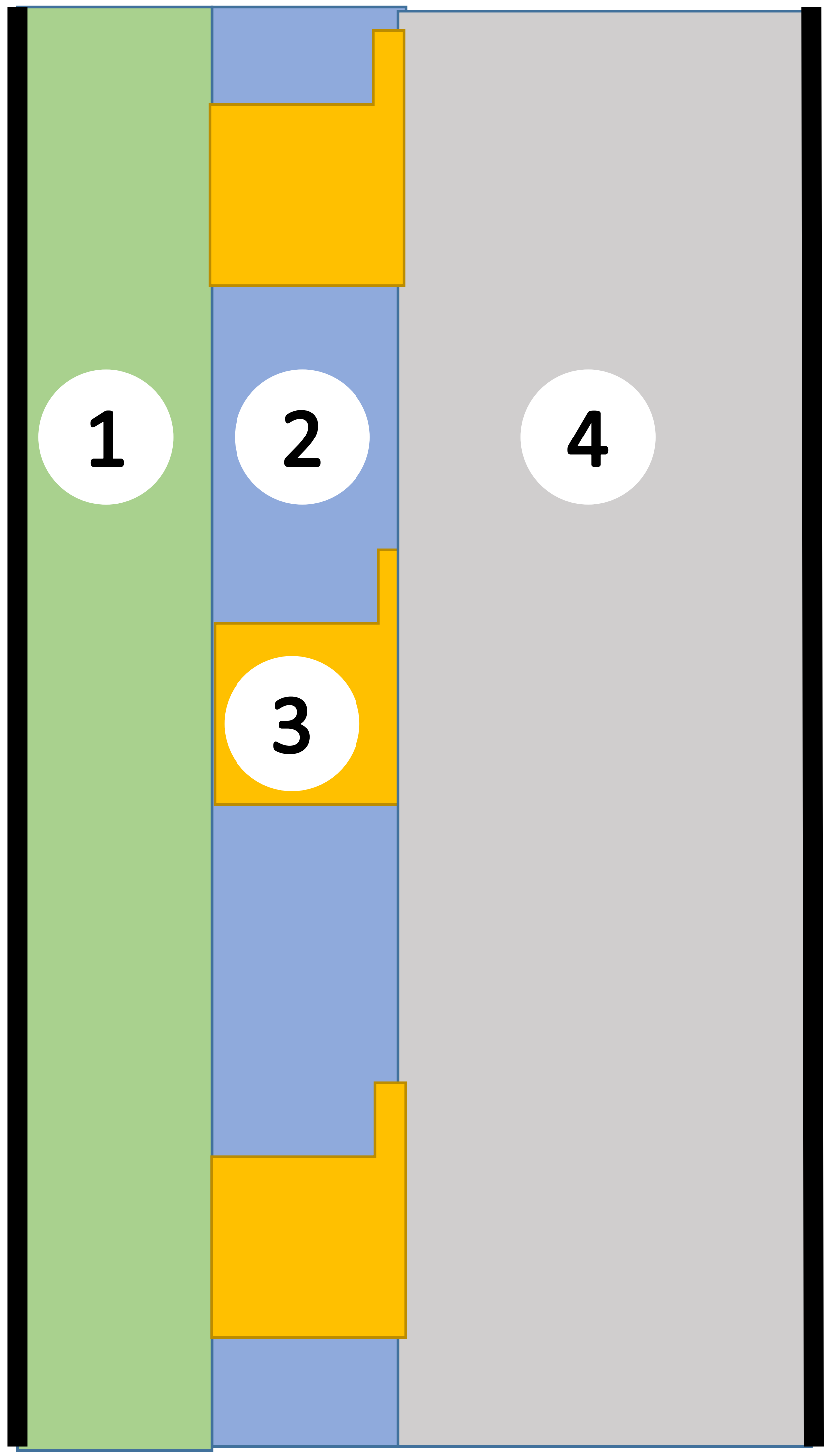




How to deal with uneven walls?

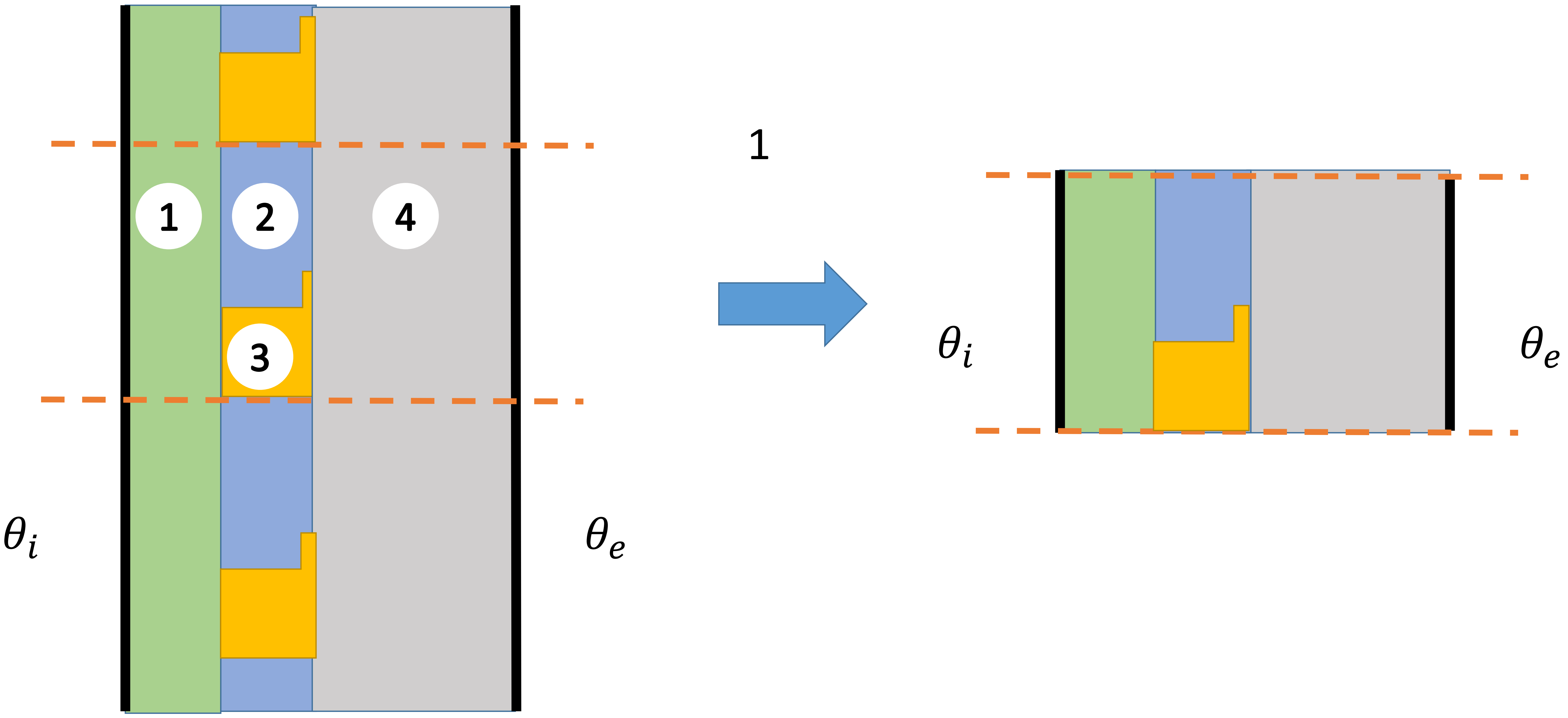
- Typical case with ineven material
- Different materials
- Very common in buildings
- For example: internal insulation systems

θ_i

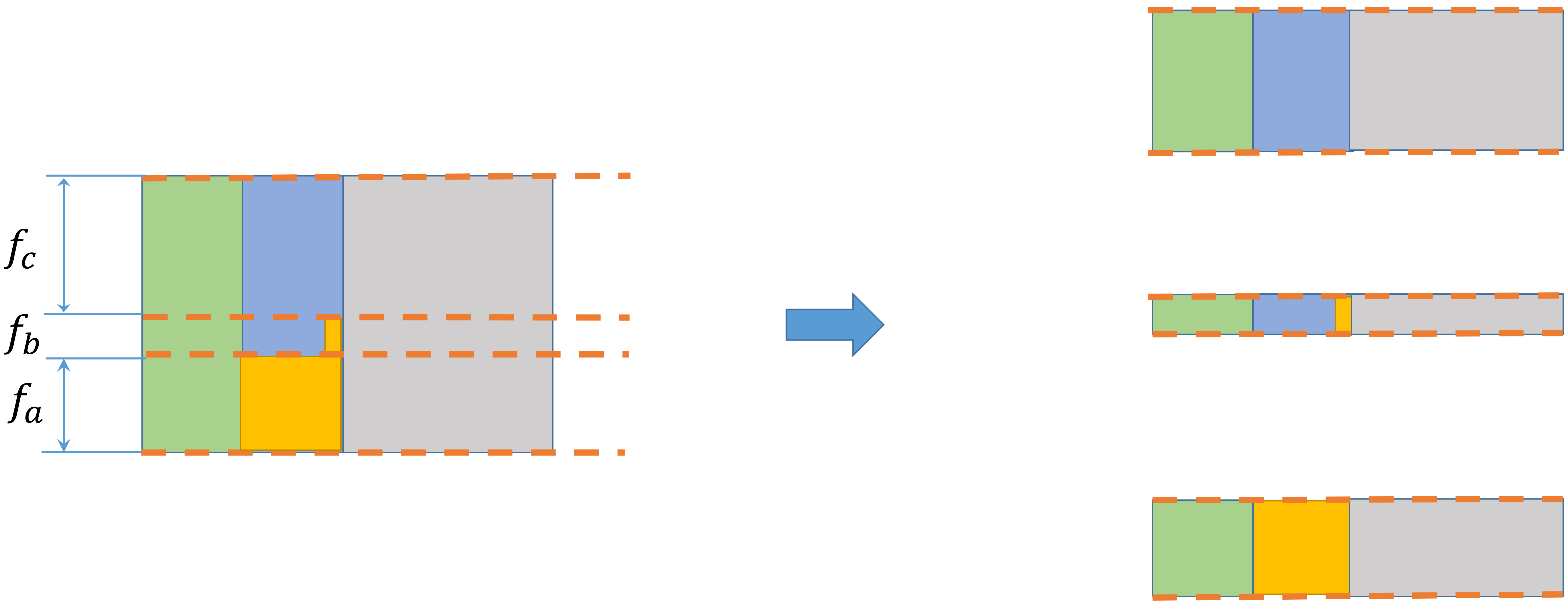


θ_e

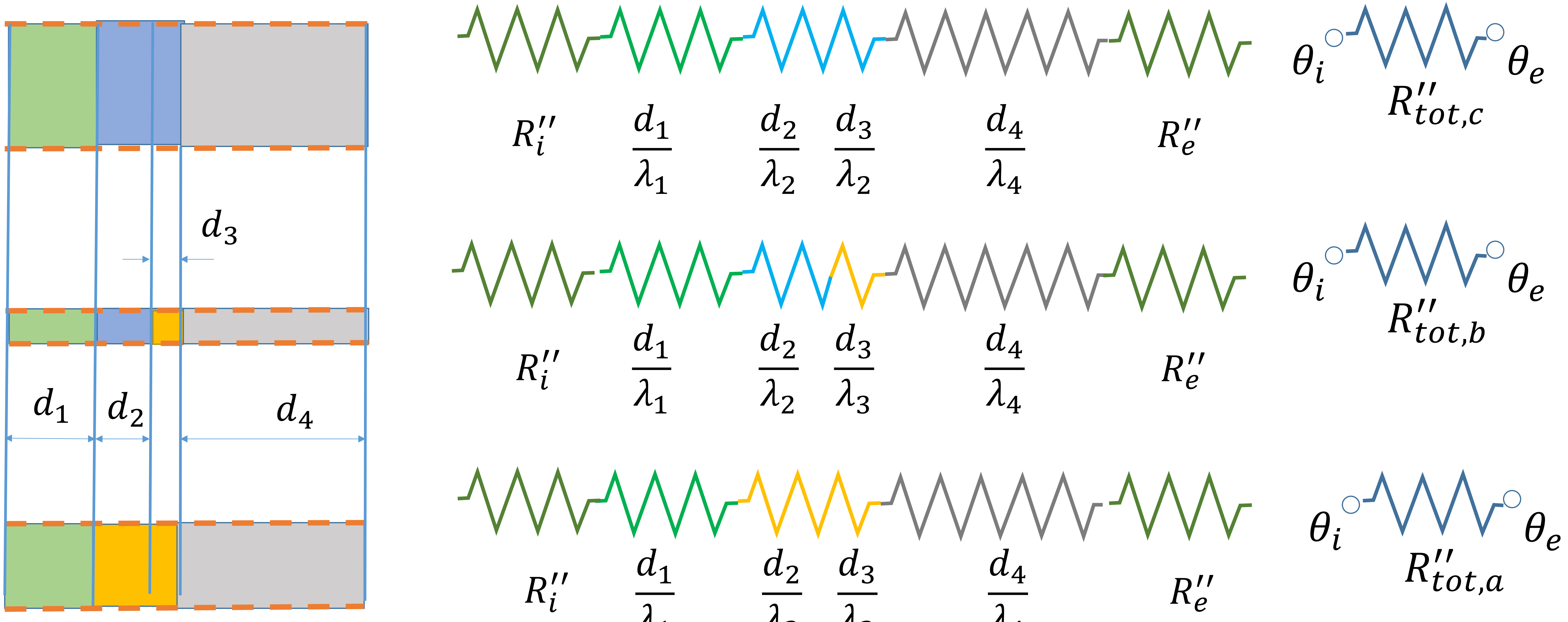
Periodic geometry



Higher limit of thermal resistance

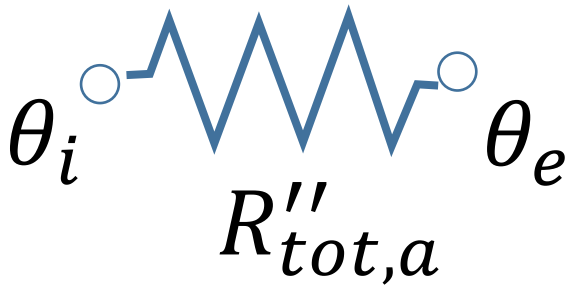


Uneven structures

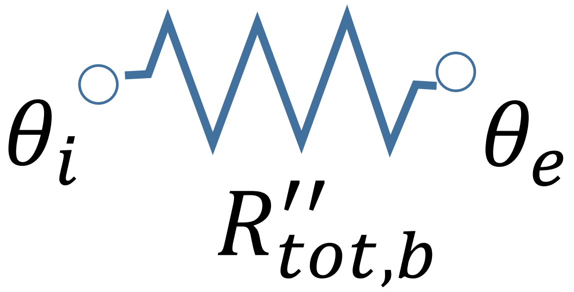


Higher limit of thermal resistance

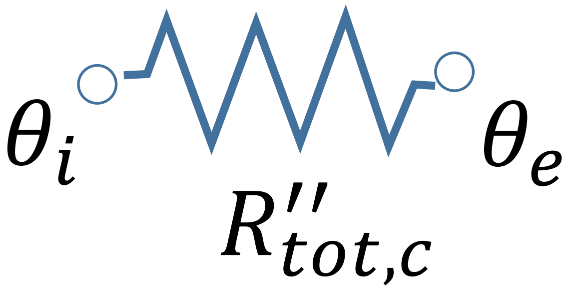
$$R''_{tot,a} = \frac{1}{h_i} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \frac{d_3}{\lambda_2} + \frac{d_4}{\lambda_4} + \frac{1}{h_e}$$



$$R''_{tot,b} = \frac{1}{h_i} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \frac{d_3}{\lambda_3} + \frac{d_4}{\lambda_4} + \frac{1}{h_e}$$

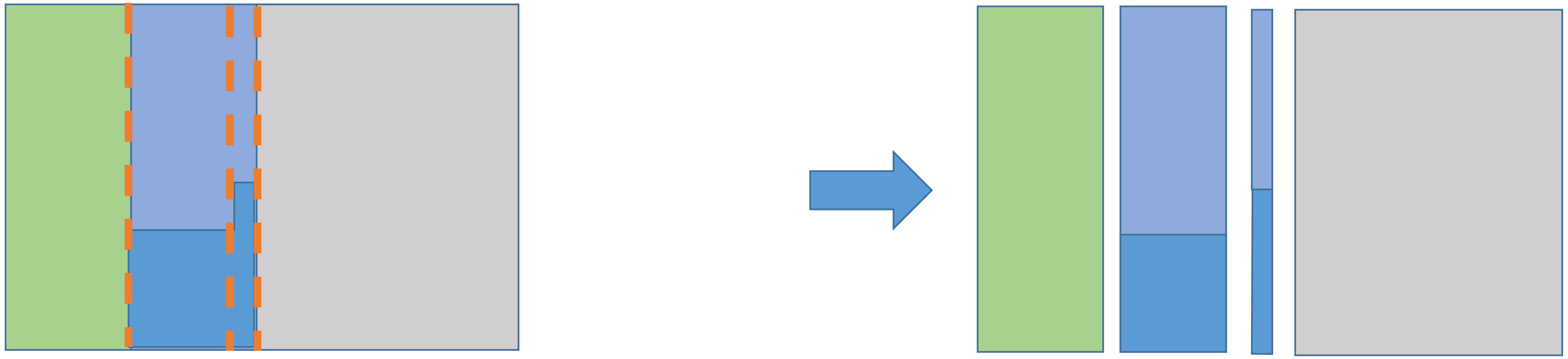


$$R''_{tot,c} = \frac{1}{h_i} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_3} + \frac{d_3}{\lambda_3} + \frac{d_4}{\lambda_4} + \frac{1}{h_e}$$

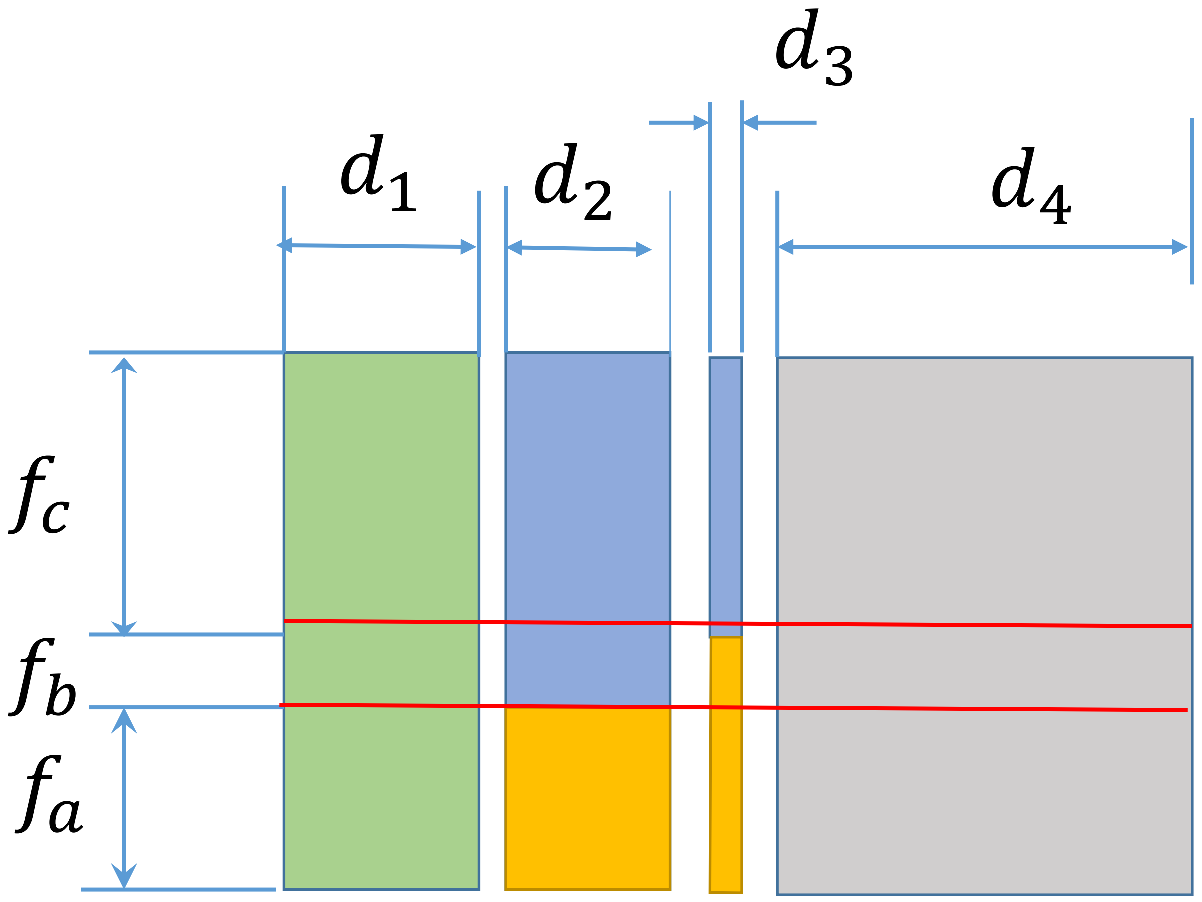


$$\frac{1}{R''_{tot,sup}} = \frac{f_a}{R''_{tot,a}} + \frac{f_b}{R''_{tot,b}} + \frac{f_c}{R''_{tot,c}}$$

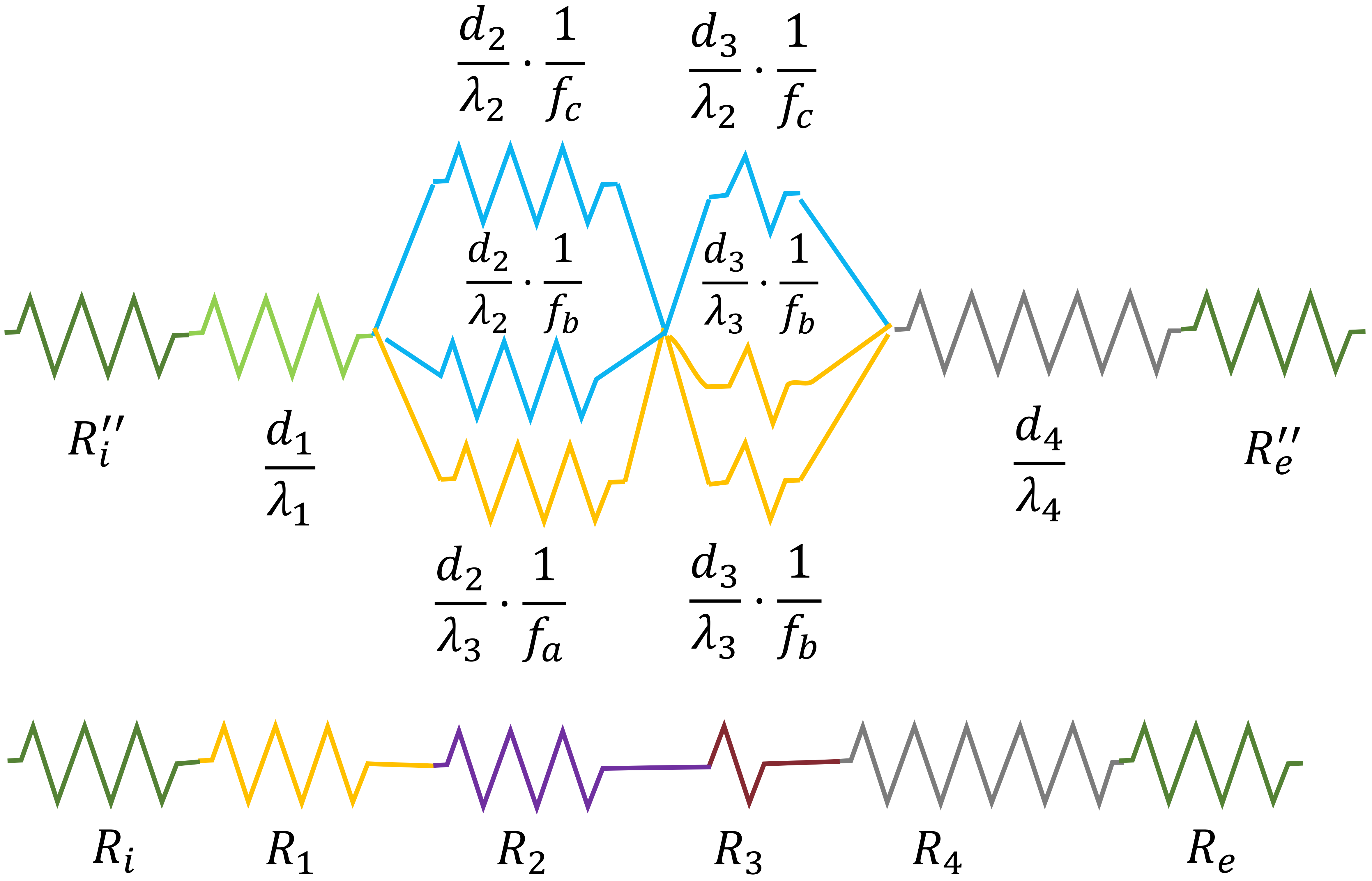
Lower limit of thermal resistance



Lower limit



d_3
d_1
d_2
d_4
f_c
f_b
f_a



$\frac{d_2}{\lambda_2} \cdot \frac{1}{f_c}$
$\frac{d_3}{\lambda_2} \cdot \frac{1}{f_c}$
$\frac{d_2}{\lambda_2} \cdot \frac{1}{f_b}$
$\frac{d_3}{\lambda_3} \cdot \frac{1}{f_b}$
R_i''
$\frac{d_1}{\lambda_1}$
$\frac{d_4}{\lambda_4}$
R_e''
$\frac{d_2}{\lambda_3} \cdot \frac{1}{f_a}$
$\frac{d_3}{\lambda_3} \cdot \frac{1}{f_b}$
R_i
R_1
R_2
R_3
R_4
R_e

Lower limit

$$R_1 = \left(\frac{1}{d_1/\lambda_1}\right)^{-1}$$

$$R_2 = \left(\frac{f_c}{d_2/\lambda_2} + \frac{f_b}{d_2/\lambda_2} + \frac{f_a}{d_2/\lambda_3}\right)^{-1}$$

$$R_3 = \left(\frac{f_c}{d_3/\lambda_2} + \frac{f_b}{d_3/\lambda_3} + \frac{f_a}{d_3/\lambda_3}\right)^{-1}$$

$$R_4 = \left(\frac{1}{d_4/\lambda_4}\right)^{-1}$$

$$R_{tot,inf} = \mathrm{R_i} + \mathrm{R_1} + \mathrm{R_2} + \mathrm{R_3} + \mathrm{R_4} + \mathrm{R_e}$$

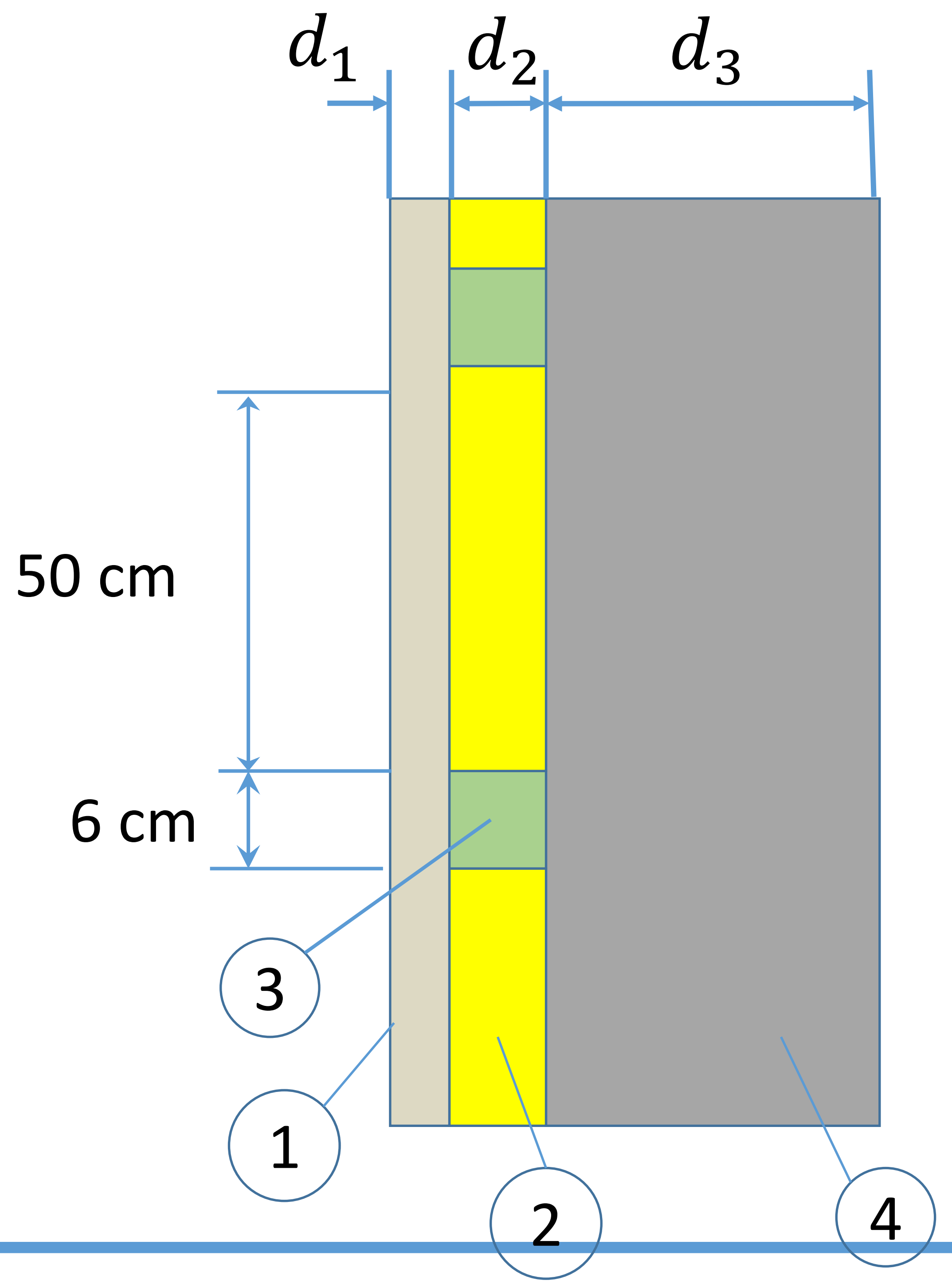
$$R_{tot,} = \frac{R_{tot,inf} + R_{tot,sup}}{2}$$

Problem

$d_1 = 0{,}0125\ m;\ d_2 = 0{,}03\ m\ ;\ d_3$=0,32 m

$\lambda_1 = 0{,}2,\ \lambda_2 = 0{,}032\ ,\ \lambda_3 = 0{,}12\ ,\ \lambda_4 = 0{,}8\ \frac{W}{m \cdot K}$

Compute the transmittance



Example

$d_1 = 0{,}0125\ m;\ d_2 = 0{,}03\ m\ ;\ d_3$=0,32 m

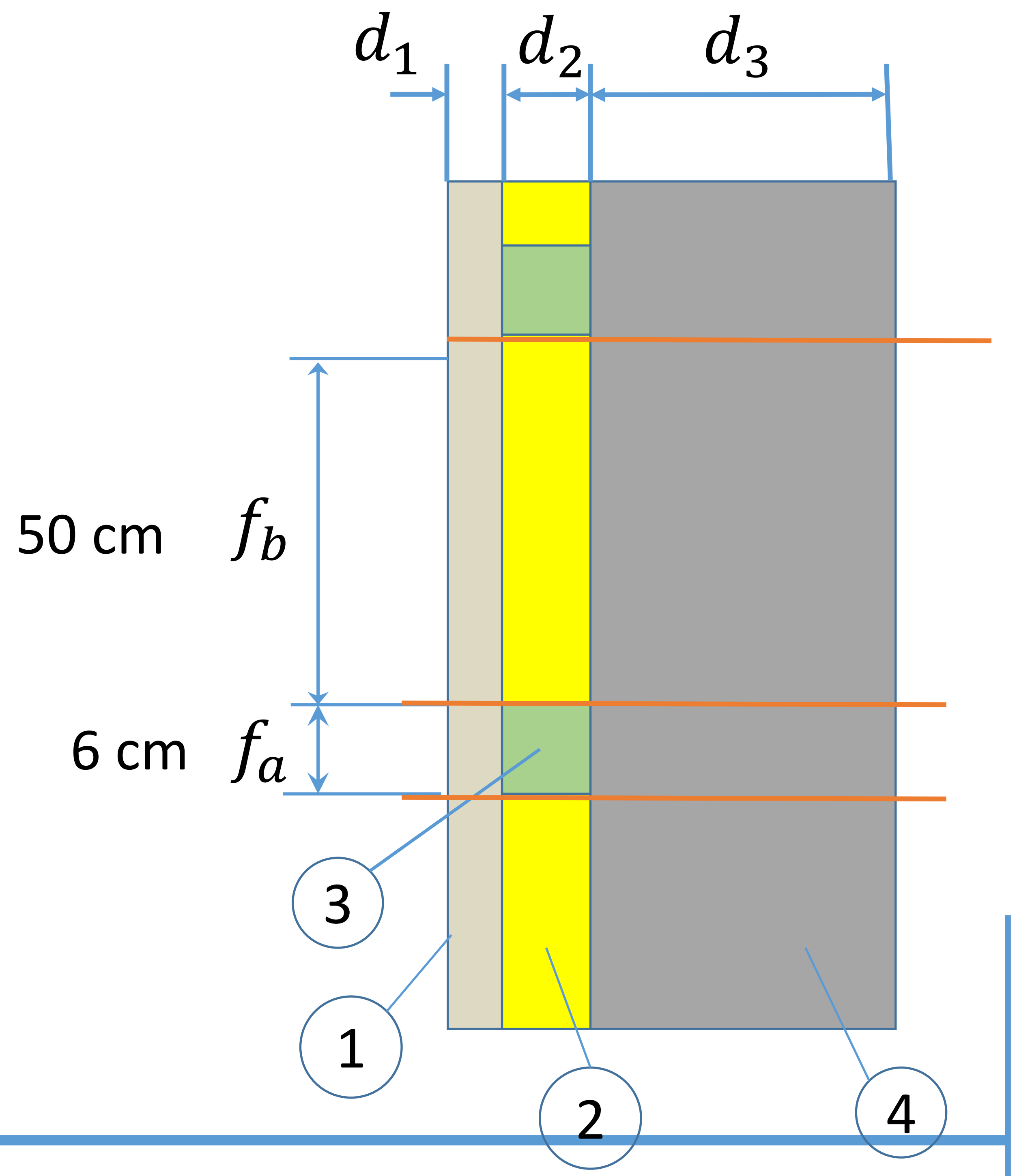
$\lambda_1 = 0{,}2,\ \lambda_2 = 0{,}032\ ,\ \lambda_3 = 0{,}12\ ,\ \lambda_4 = 0{,}8\ \frac{W}{m \cdot K}$

$f_a = \frac{6}{56} = 0{,}107;\ f_b = \frac{50}{56} = 0{,}893$

$$R_{tot,a} = R_{si} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_3} + \frac{d_3}{\lambda_4} + R_{se} = 0.883\ \frac{m^2 K}{W}$$

$$R_{tot,b} = R_{si} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \frac{d_3}{\lambda_4} + R_{se} = 1.570\ \frac{m^2 K}{W}$$

$$R_{tot,sup} = \left(\frac{f_a}{R_{tot,,a}} + \frac{f_b}{R_{tot,b}}\right)^{-1} = 1.449\ \frac{m^2 \cdot K}{W}$$



Example

$$f_a = \frac{6}{56} = 0{,}107;\ f_b = \frac{50}{56} = 0{,}893$$

$$R_{tot,1} = \frac{d_1}{\lambda_1} = 0{,}0625\,\frac{m^2K}{W}$$

$$R_{tot,2} = \left(\frac{f_a}{\frac{d_2}{\lambda_3}} + \frac{f_b}{\frac{d_2}{\lambda_2}}\right)^{-1} = 0.724\ \frac{m^2K}{W}$$

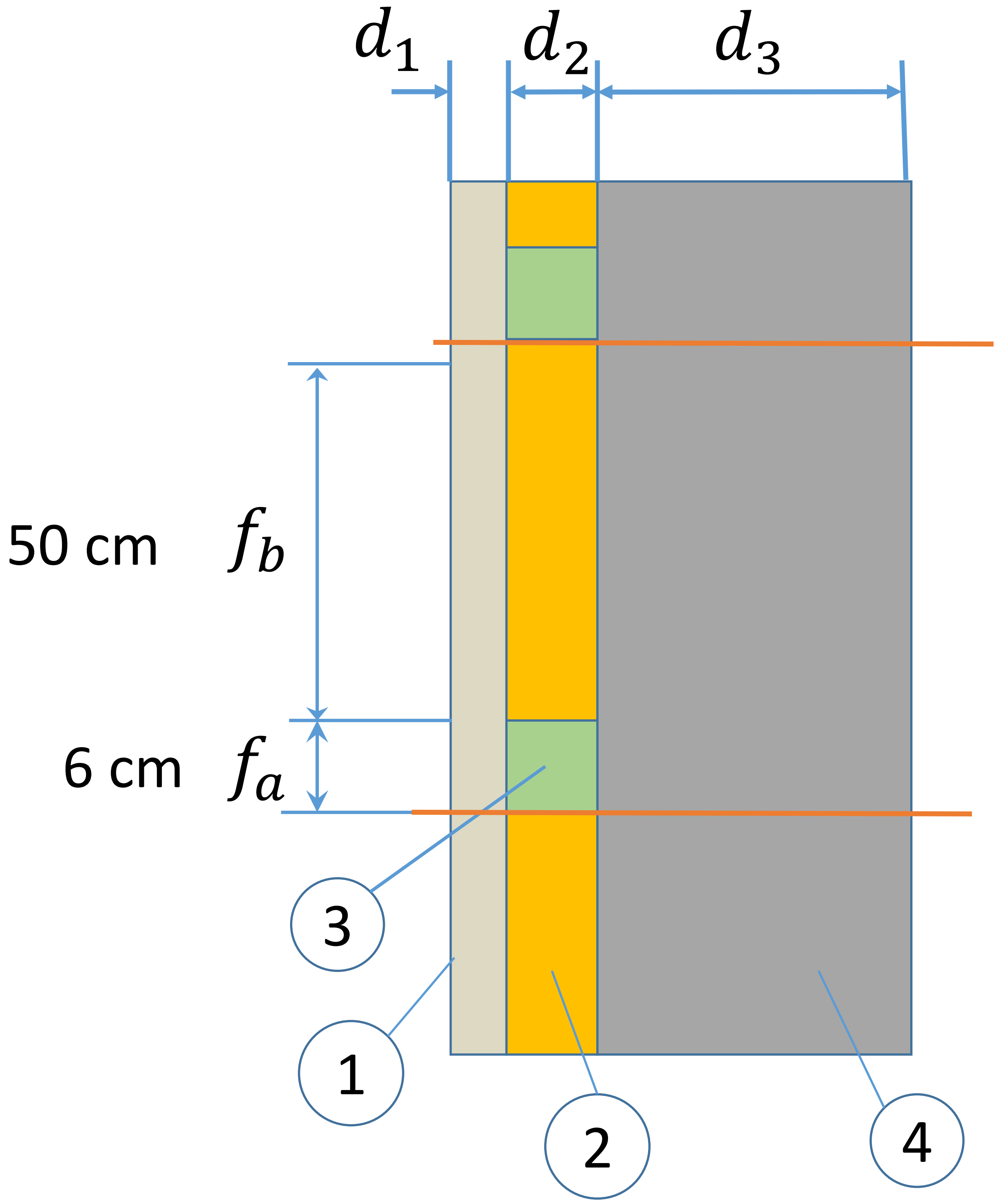
$$R_{tot,3} = \frac{d_3}{\lambda_4} = 0{,}400\ \frac{\mathrm{m}^2\cdot\mathrm{K}}{\mathrm{W}}$$

$$R_{tot,inf} = R_{si} + R_{tot,1} + R_{tot,2} + R_{tot,3} + R_{se} = 1.357\,\frac{\mathrm{m}^2\cdot\mathrm{K}}{\mathrm{W}}$$

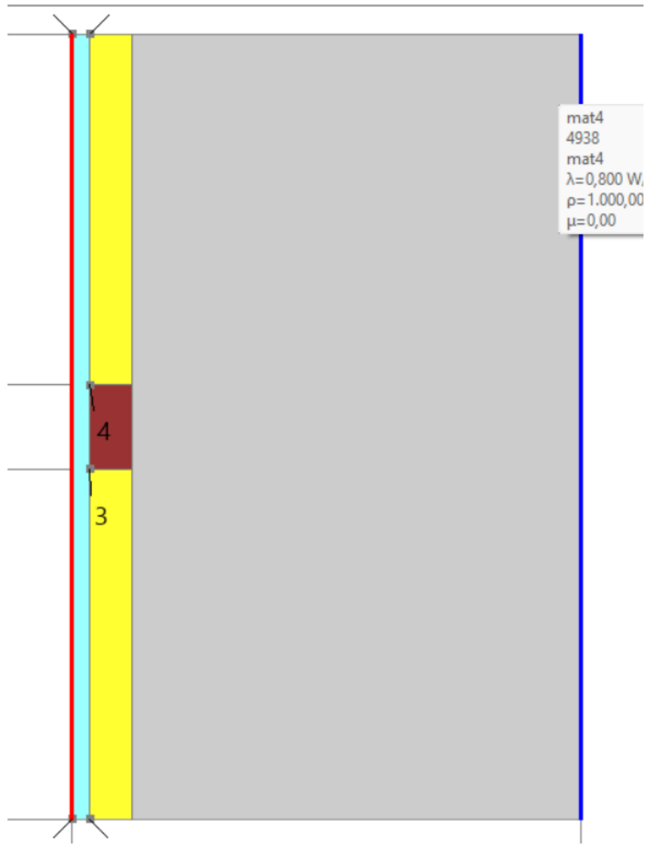
$$R_{tot} = \frac{R_{tot,sup}+R_{tot,inf}}{2} = 1.403\ \frac{\mathrm{m}^2\cdot\mathrm{K}}{\mathrm{W}}$$

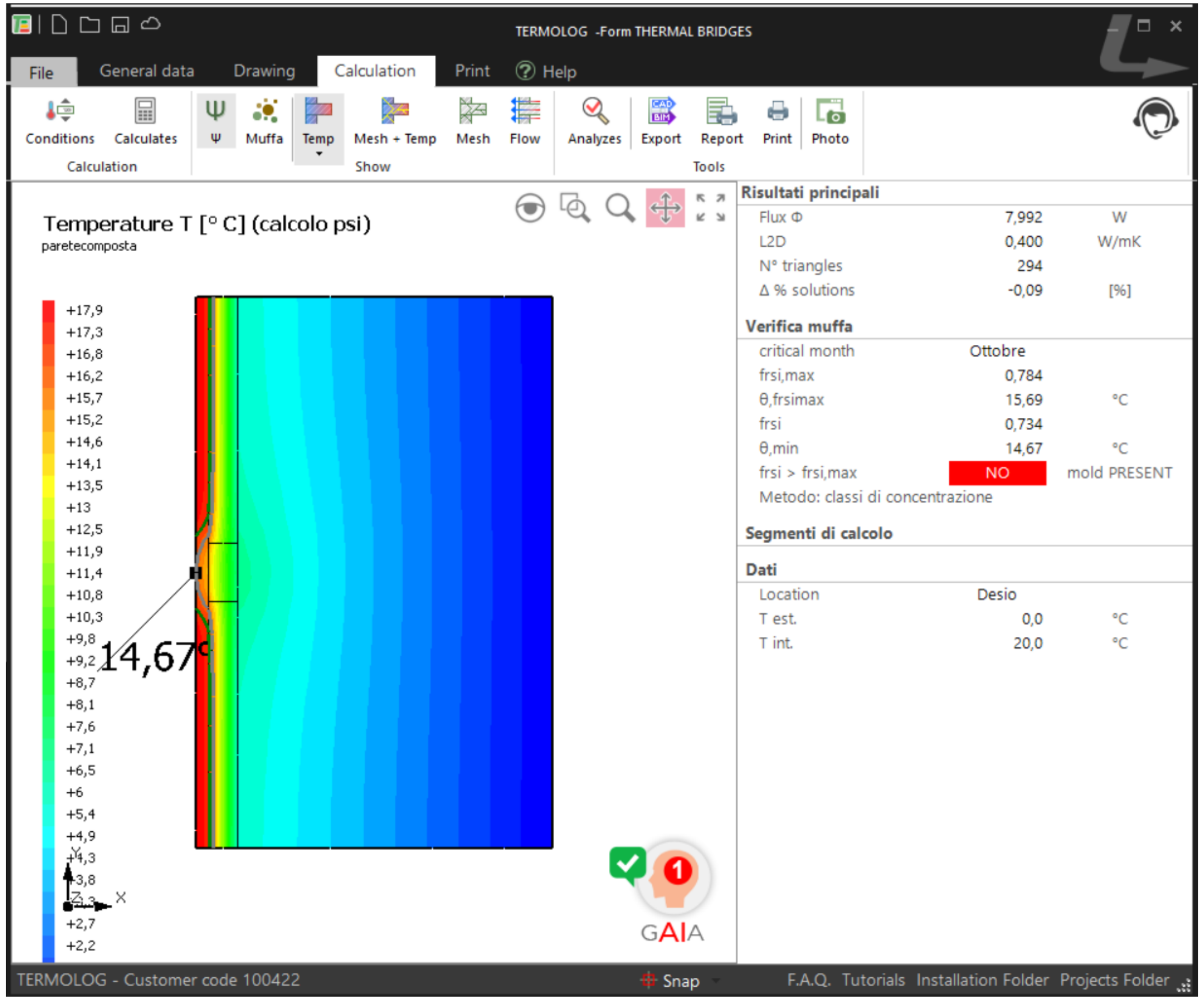
$$U = \frac{1}{R_{tot}} = 0{,}713\,\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{K}} \quad U_{1d} = \frac{1}{R_{tot,b}} = 0{,}637\,\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{K}}$$

$$\Delta U\% = \frac{U_{1d}-U}{U}\cdot 100 = -10.65\ \%$$



Calcolo 2D





$$\theta_{int} = 20\,°C \quad ; \quad \theta_{ext} = 0\,°C$$

$$\Phi_{2d} = 7.992\ W/m$$

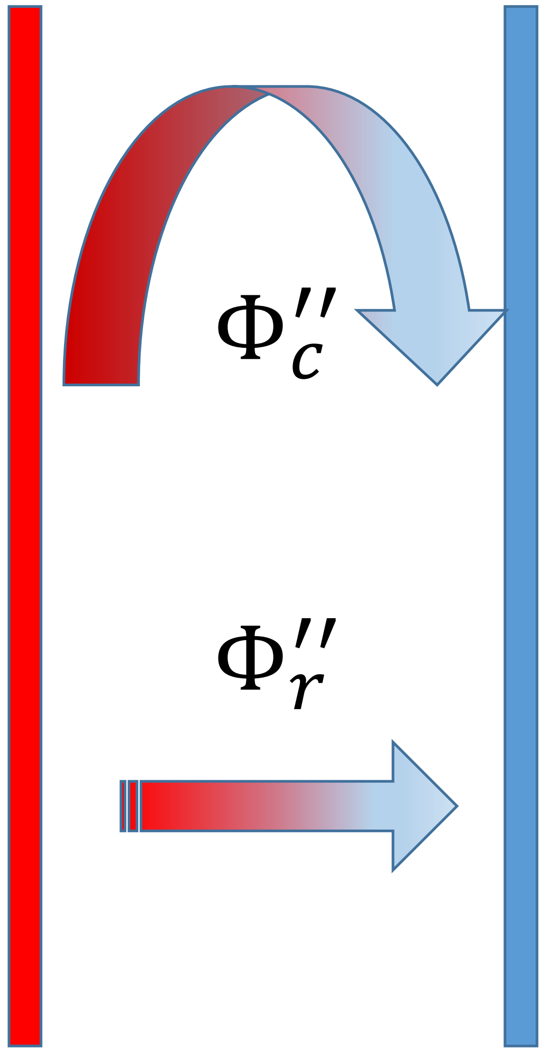
$$\overline{U} = \frac{\Phi_{2d}}{\Delta\theta \cdot H} = \frac{7.992}{20 \cdot 0.56} = 0.7136\,\frac{W}{m^2 \cdot K}$$

Air gaps

- In building structures, both closed and open cavities are very common
- Closed cavities
- Hollow-box walls
- Internal and external thermal insulation
- Double or triple glazing (with other gases)
- Open cavities
- Attics
- Ventilated insulation

Calcolo della trasmittanza

- Heat exchange occurs by convection and radiation
- Convection exchange is linear
- Radiation exchange is non-linear
- Radiation exchange is linearizable

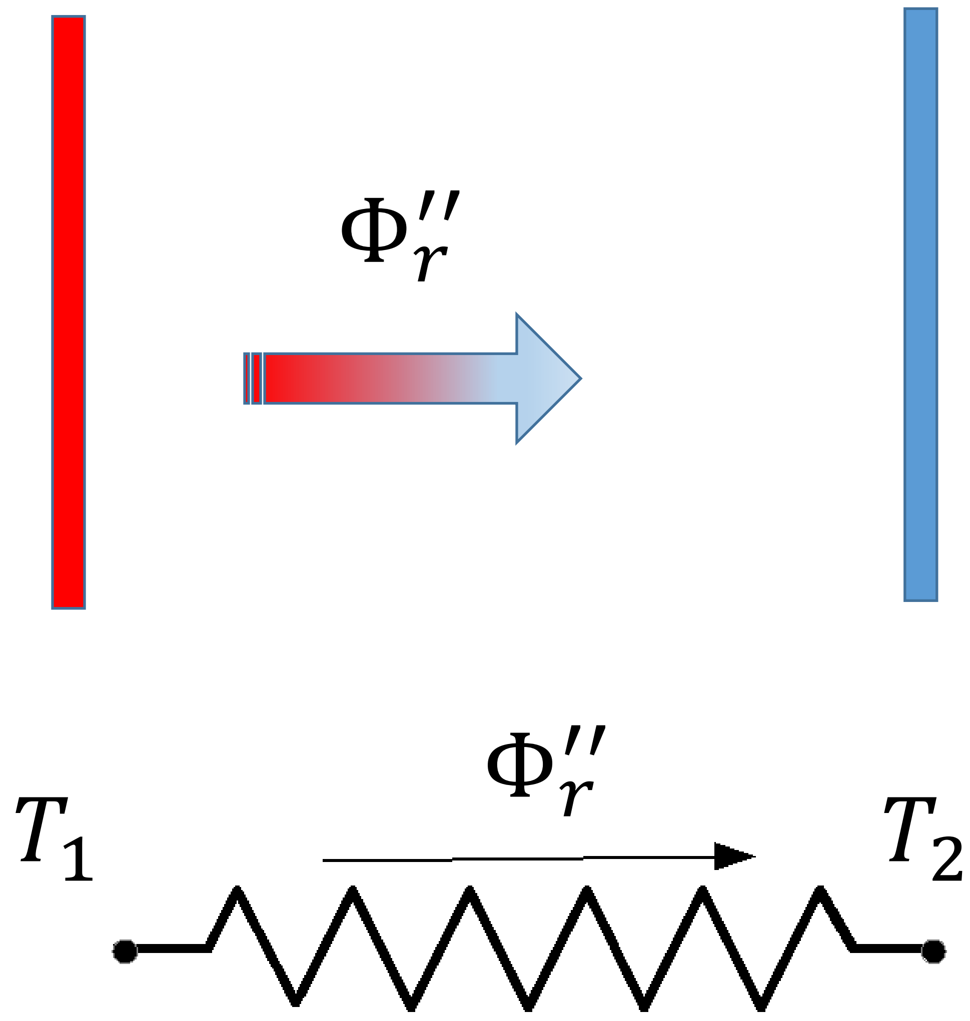


Radiant heat exchange

- Simple geometry parallel walls
- Specific heat transfer

$$\Phi_r'' = \sigma_0 \cdot \frac{(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

- Heat exchanged depends on the emissivities of the walls



Linearizzazione dello scambio radiativo

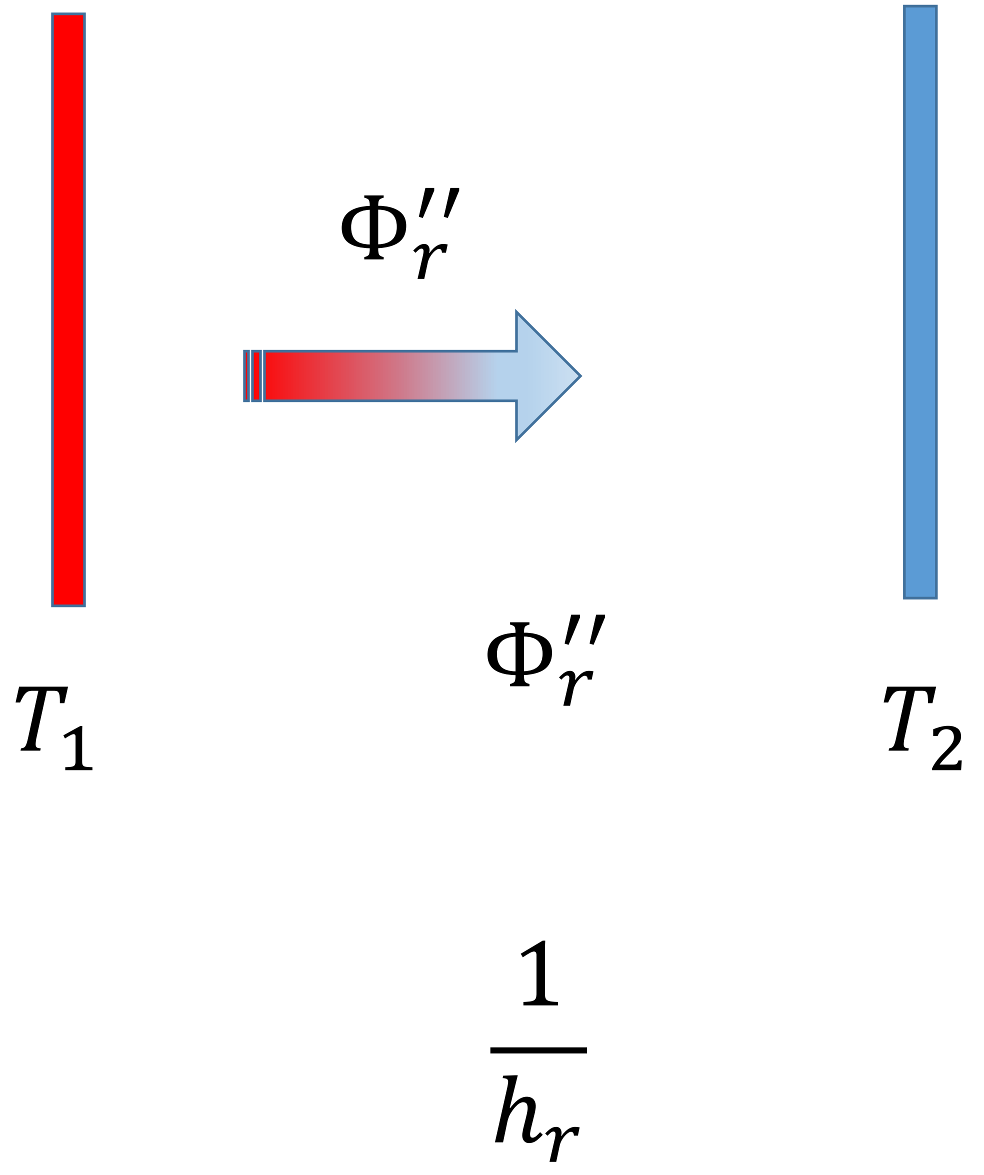
- The nonlinear term is given by the difference of temperatures at the fourth power
- Temperatures are expressed in [K]
- The difference of temperatures is small

$$(T_1^4 - T_2^4) = (T_1^2 + T_2^2) \cdot (T_1^2 - T_2^2) =$$

$$= (T_1^2 + T_2^2) \cdot (T_1 + T_2) \cdot (T_1 - T_2)$$

$$\cong 2 \cdot T_m^2 \cdot 2 \cdot T_m \cdot (\theta_1 - \theta_2) = 4 \cdot T_m^3 \cdot (\theta_1 - \theta_2)$$

$$T_m = \frac{T_1 + T_2}{2} \text{ [K]}$$

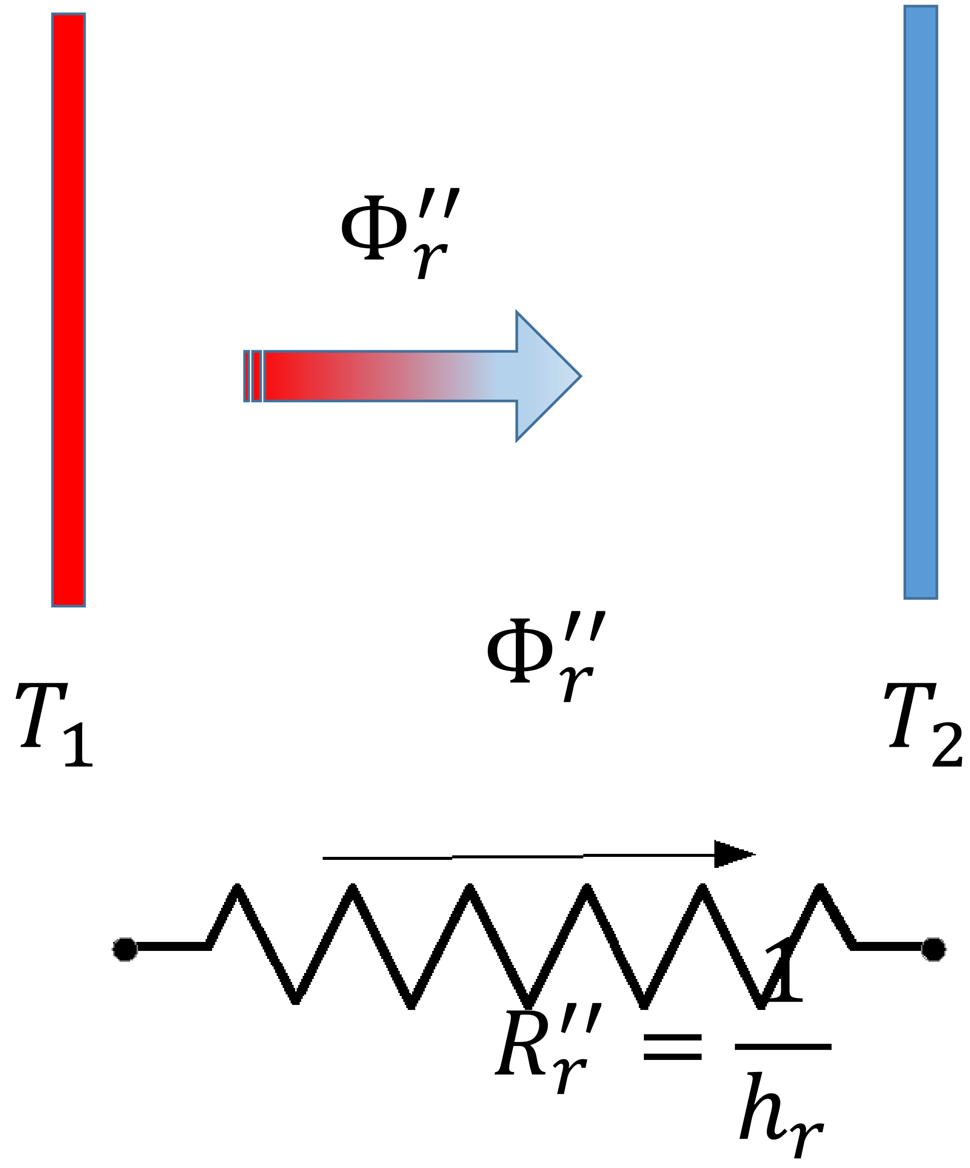


Radiation heat trasfer linearization

$$\phi_r'' = \sigma_0 \cdot 4 \cdot T_m^3 \cdot \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \cdot (\theta_1 - \theta_2)$$

$$\phi_r'' = h_r \cdot (\theta_1 - \theta_2)$$

$$\Phi_r'' = \frac{\theta_1 - \theta_2}{R_r''}$$



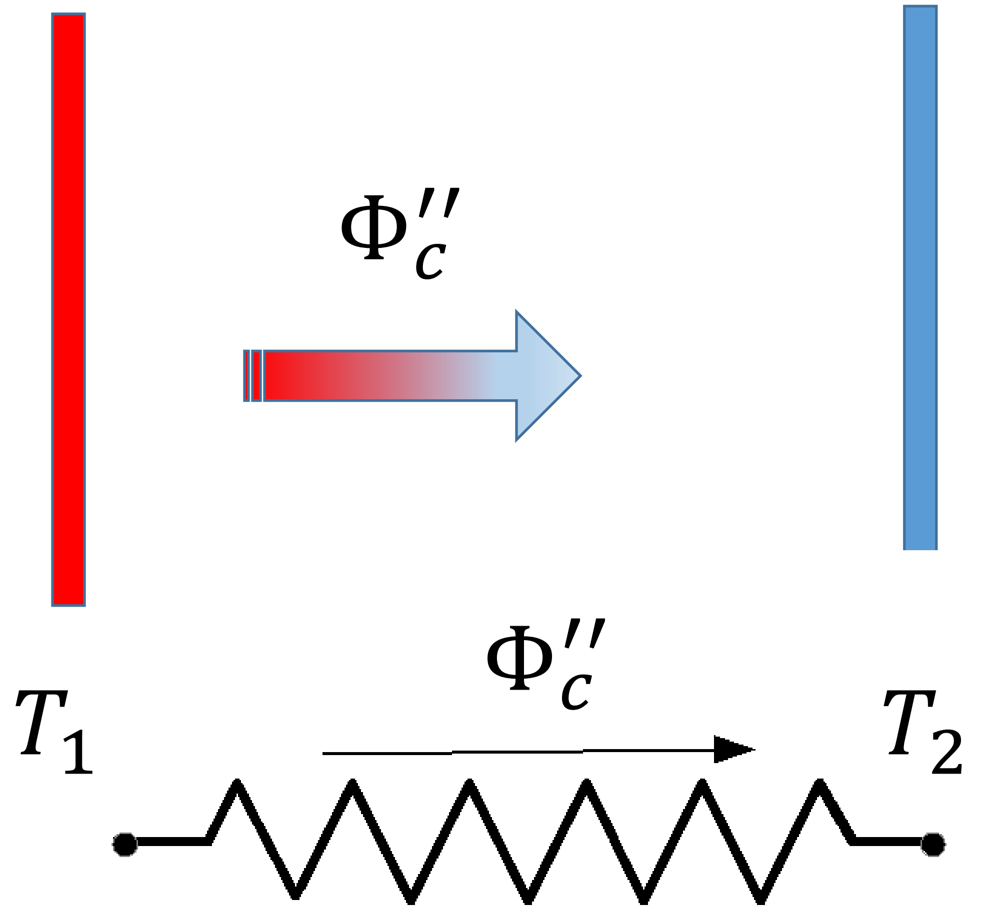
$\varepsilon_1, \varepsilon_2$ ↓ h_r ↓ R_r'' ↑ Φ_r'' ↓

Coupled heat transfer

- Convective coefficient is obtained from tables UNI EN ISO 6946

$\Delta T \leq 5\ K$	
Direction	h_a [W/(m^2·K)]
horizontal	1,25
upwards	1,95
downwards	$0{,}12 \cdot d^{-0{,}44}$

$\Delta T > 5\ K$	
Direction	h_a [W/(m^2·K)]
horizontal	$0{,}73 \cdot \Delta T^{\frac{1}{3}}$
upwards	$1{,}14 \cdot \Delta T^{\frac{1}{3}}$
downwards	$0{,}09 \cdot \Delta T^{0{,}187} \cdot d^{-0{,}44}$



$$R''_c = \frac{1}{h_c}$$

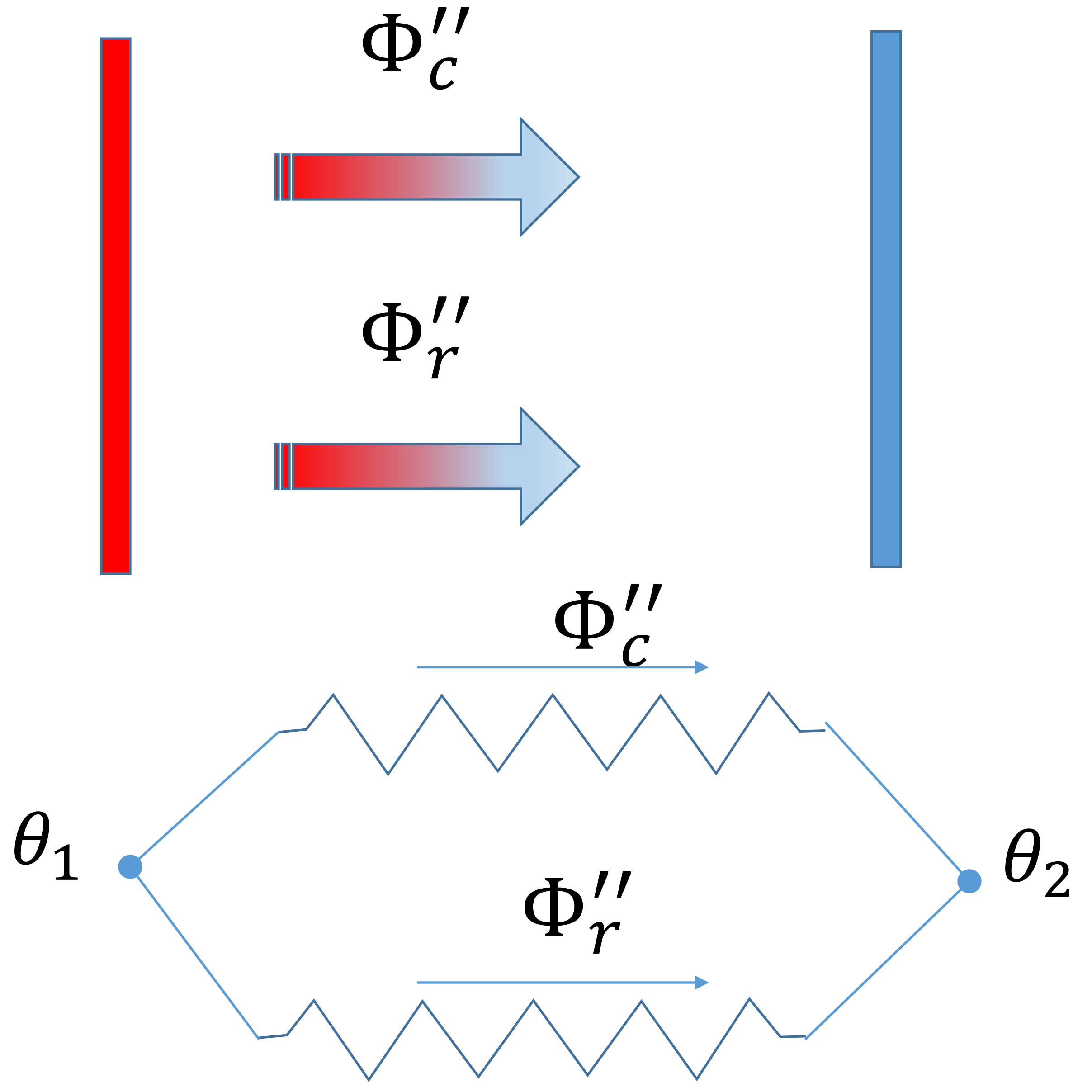
Convective and radiative heat transfer

- Consider both heat exchange

$$\Phi''_g = (h_a + h_r) \cdot (\theta_1 - \theta_2)$$

$$\phi''_g = \frac{(\theta_1 - \theta_2)}{R_g}$$

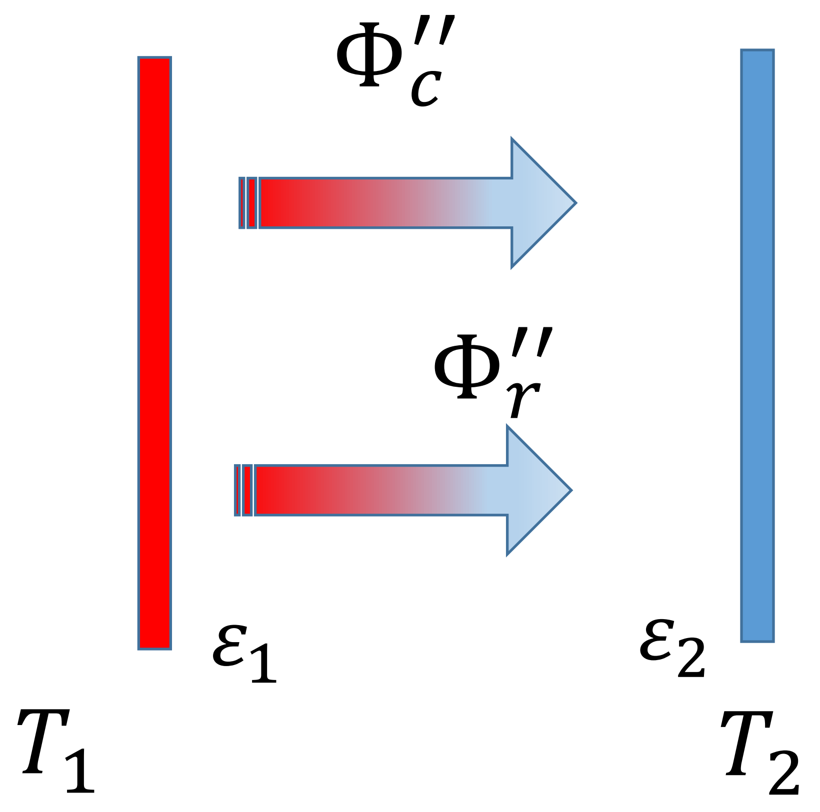
$$R_g = \frac{1}{h_a + h_r}$$



Example

- $\theta_1 = 19\ °C$
- $\theta_2 = 15\ °C$
- $T_m = 290{,}15\ \mathrm{K}$
- $\varepsilon_1 = 0{,}9$
- $\varepsilon_2 = 0{,}95$
- $h_c = 1{,}25\ \mathrm{W/(m^2 \cdot K)}$
- $\mathrm{h}_r = 4{,}76\ \mathrm{W/(m^2 \cdot K)}$
- $h = h_c + h_r = 6{,}01\ \mathrm{W/(m^2 K)}$
- $\Phi = h \cdot (E_{n1} - E_{n2}) = 24{,}04\ \mathrm{W/m^2}$

- $\theta_1 = 19\ °C$
- $\theta_2 = 15\ °C$
- $T_m = 290{,}15\ \mathrm{K}$
- $\varepsilon_1 = 0{,}9$
- $\varepsilon_2 = 0{,}1$
- $h_c = 1{,}25\ \mathrm{W/(m^2 \cdot K)}$
- $\mathrm{h}_r = 0{,}548\ \mathrm{W/(m^2 \cdot K)}$
- $h = h_c + h_r = 1{,}797\ \mathrm{W/(m^2 K)}$
- $\Phi = h \cdot (E_{n1} - E_{n2}) = 7{,}19\ \mathrm{W/m^2}$



Convection heat transfer in enclosures

- Old Italian standard UNI 10345 reported formulas for computing the heat transfer in enclosures

$$h_g = Nu \cdot \frac{\lambda}{s}$$

s gap thickness

λ gas conductivity

$$Nu = a \cdot \, (Gr \cdot \, \mathrm{Pr})^b$$

Vertical surfaces:	a=0.035,	b=0.38
Horizontal surfaces	a=0.16,	b=0.28
Inclined surfaces	a=0.10,	b=0.31

Non dimensional parameters

$$Gr = \frac{\rho^2 \cdot s^3 \cdot 9.81 \cdot \Delta T}{T_m \cdot \mu^2}$$

$$Pr = \frac{c \cdot \mu}{\lambda}$$

Gas properties

Prospetto III — Proprietà termofisiche dei gas usati nelle intercapedini

Gas	Temperatura di riferimento °C	Massa volumica kg/m^3	Viscosità dinamica* $\cdot 10^5$ kg/(ms)	Conduttività termica** $\cdot 10^2$ W/(mK)	Capacità termica massica kJ/(kgK)
Aria	– 10	1,326	1,661	2,336	1,008
	0	1,277	1,711	2,416	
	10	1,232	1,761	2,496	
	20	1,189	1,811	2,576	
Argon	– 10	1,829	2,038	1,584	0,519
	0	1,762	2,101	1,634	
	10	1,699	2,164	1,684	
	20	1,640	2,228	1,734	
SF	– 10	6,844	1,383	1,119	0,614
	0	6,602	1,421	1,197	
	10	6,360	1,459	1,275	
	20	6,118	1,497	1,354	
Kripton	– 10	3,832	2,020	0,842	0,245
	0	3,690	2,340	0,870	
	10	3,560	2,670	0,900	
	20	3,430	2,500	0,926	

* Dividere i valori per 10^5.

** Dividere i valori per 10^2.