Lecture 4 – Exercises

Exercise 1: Convective heat transfer by forced convection

Consider a cobblestone pavement from Exercise 1 in Lect. 2. In the afternoon, its surface reached 70°C while air temperature was 35°C. What was the rate of convective heat transfer from the surface of the pavement at a wind speed of U=4.6 m/s? The characteristic length is the width of the pavement equal to 2 m. Air properties at average temperature are provided.

Properties of air at 52.5°C, atmospheric pressure	
Density ρ ($\frac{kg}{m^3}$)	1.084
Dynamic viscosity μ ($\frac{N \cdot s}{m^2}$)	$19.75 \cdot 10^{-6}$
Thermal diffusivity $\boldsymbol{\alpha}$ (m^2/s)	$25.89 \cdot 10^{-6}$
Thermal conductivity $\boldsymbol{k}$ ($\frac{W}{m \cdot K}$)	0.0283

[see Exercises 2-3 in the following pages]

Exercise 2: Combined modes of heat transfer (convection and radiation)

Imagine the building located in Lausanne (temperate climate) having the Wall 1 structure from Exercise 1 in Lect.3. Total conductive thermal resistance was found as $R_{k,tot} = 0.166\,\frac{W}{m^2\cdot K}$.

Considering the given indoor and outdoor conditions, determine thermal resistances due to convection ($R_{c,e}$ and $R_{c,i}$) and due to radiation ($R_{r,e}$ and $R_{r,i}$), as shown in Fig. 1. Compare indoor and outdoor surface thermal resistances R_{si} and R_{se} with conductive thermal resistance $R_{k,tot}$.

- Indoor height of the wall is H=2.5m, the length of the wall is 5 m.
- Indoor air conditions: $t_i = 22$°C and $U_i < \ 0.05\ m/s$ (air flow is negligible, along the wall)
- Outdoor air conditions: $t_e = -5$°C and $U_e = \ 1.2\ m/s$ (wind is tangential to the wall)
- Surface temperatures: $t_{si} = 20$°C, and $t_{se} = 0$°C
- Emissivity of both surfaces is $\varepsilon = 0.9$
- Sky temperature for temperate areas can be estimated as $t_{sky} = \ t_e - 11$ (per ISO 13790)

Air properties are provided in the table below:

t (°C)	$\rho\ (\frac{kg}{m^3})$	$k\ (\frac{W}{m\cdot K})$	$\alpha \cdot 10^{-6}\ (\frac{m^2}{s})$	$\mu \cdot 10^{-6}\ (\frac{N\cdot s}{m^2})$
-5	1.317	0.02398	18.11	16.97
-2.5	1.305	0.02417	18.42	17.09
0	1.293	0.02436	18.74	17.22
20	1.204	0.02588	21.36	18.21
21	1.2	0.02595	21.49	18.26
22	1.196	0.02603	21.63	18.31

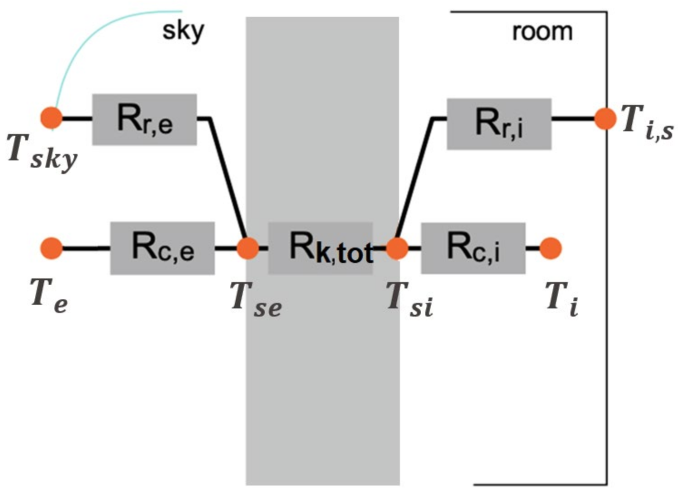

Figure 1: Network of thermal resistance through a building wall

Exercise 3: Evaporation rate, latent vs. sensible heat

The city of Chicago is located in the North of the United States, on the coast of Great Lake Michigan. The local climate is humid continental with hot summers. Although the downtown area is full of skyscrapers, most of Chicago's parts are considered to be *open low-rises* (local climatic zone LCZ6).

Considering the following parameters given, answer the questions posed below.

- The average Bowen ratio is 1.08.
- The parameters at a reference height of 6 m are:
  - air temperature $t_a = 10.2\ °C$
  - relative humidity $\varphi = 71\ \%$
  - air density $\rho = 2.45\ \ kg/m^3$
  - average wind speed $U = 4.5\ \ m/s$
  - air pressure is $p_a = 1.01 \times 10^5\ Pa$
- The specific heat capacity of air at 10.2 °C is $c_p = 1005\ J/kg \cdot K$ and the latent heat of vaporization at this temperature is $L_v = 2477\ \ kJ/kg$.
- The bulk transfer coefficient for water vapor is $C_w = 1.32 \times 10^{-3}$.
- The net radiative heat flux $Q^* = 545\ \ W/m^2$

1. Name the main drivers of evaporation in the summertime. Would the evaporation be strong in Chicago? Comment on your results considering the Bowen ratio.
2. Calculate the *potential evaporation rate* using the Penman method, considering that the ground heat flux Q_G is negligible. Compare the contribution of the radiation and the aerodynamic terms.
3. Determine the *latent heat flux* Q_E and *sensible heat flux* Q_H using the surface energy balance method.
4. Compare the actual evaporation rate determined by knowing Q_E in (3) with the 4.5 m/s potential evaporation rate determined in (2).

Figure 2: Aerial photo of Chicago at sunset (image from the webpage)