Regular exam

Thermal Energy Conversion (SEE020)

2023-08-22, 08:30 - 12:30

Examiner	David Pallarès (tel.nr. 031 772 1435)
Allowed resources:	calculator, course book, formula sheet
Mark scale	Mark 5: at least 24 p Mark 4: at least 18 p Mark 3: at least 12 p Not passed: less than 12p
Exam review	week 16 (after agreement via e-mail: david.pallares@chalmers.se)

1. Describe the concept of negative CO_2 emissions, and explain a process through which they can be attained. **(2p)**

a) negative CO2 emissions mean that CO2 is in net life cyle terms removed from the atmosphere

b) negative CO2 emissions can be attained by combining biomass combustion with carbon capture and storage (BECCS), or by direct air capture (DAC) and storage

2. Liquid/liquid heat exchangers base their performance on convective heat transfer. Explain:

a) what is the so-called no-slip condition, and why is it important in the study of convective heat transfer **(2p)**

b) why, within the same flow regime region, the convective heat transfer coefficient decreases along the tubes as the flow develops **(2p)**

a) this condition sets the fluid velocity to zero at the convection contact surface. It is important because under this ocnditions, the only mechanism for heat transfer at the particle surface is conduction and thus the heat transfer canbe studied in terms of the temperature gradient normal to the surface

b) because as the flow develops the boundary layer becomes thicker, and thus the temperature gradient normal to the surface decreases – thereby decreasing the heat transfer

3. A stream of hot (50°C) water flowing inside a channel is to be refrigerated by surrounding cold air (10°C). You are given some possibilities regarding the material and thickness for the channel:

	Thermal conductivity [W/m·K]	Thickness [mm]
Steel	13.4	4
Iron	42.3	3
Wood	0.113	11
Plastic	0.33	15

You are also given the possibility to add flanges, both regarding the location (on the water side, or the air side of the channel, or none), and the size of the flanges (small, medium or large).

a) What would be your choice of material and flange location and size? **(3p)**

b) Regarding radiation: would you consider taking any measures to increase the radiative heat exchange between the channel and its surrounding? And any measures to avoid solar irradiation? Explain your answer. **(2p)**

a) As maximized heat transfer is intended, the material set-up providing lowest thermal resistance shall be chosen. Calculating R=L/(k*A) – disregarding A as it is assumed to be the same value for all set-ups – and taking the minimum value gives that iron is the best choice.

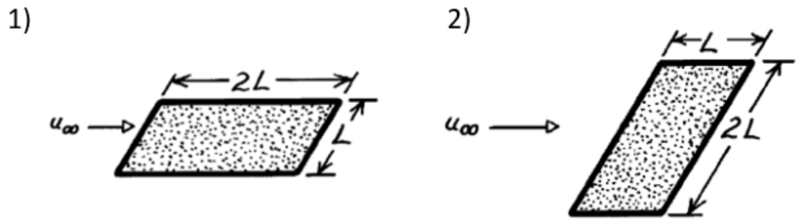
Regarding flanges, these will decrease the convective thermal resistance of the channel side they are placed on. Knowing that forced convection of a liquid has a much better heat transfer than natural convection of a gas, the air side has the higher thermal resistance of the two sides and is thus the one we should attack by using flanges. Large flanges will have a stronger effect than small ones, but also create a higher pressure drop.

b) At such low temperature levels and with such low temperature difference, the theoretical maximum net transfer of radiative heat between the channel surface and the environment is negligible, so no measures are worth considering. On the contrary, avoiding solar radiation to be absorbed by the channel is worth considering, as sun temperature is very high and thus the heat flow can be considerable.

4. A plate surface with dimensions 6m*3m is cooled by means of a forced external gas flow, yielding a heat removal rate of 53 kW. The plate is oriented so that the gas flow along the long side and across the short side (see left drawing below). You are requested to calculate whether a change in the orientation of the plate (as skissed in the right drawing) would yield a higher heat removal than the original (left drawing) one. Assume that laminar conditions are kept all over the plate for both orientations.

a) based exclusively on theory (thus without doing any calculation), what would be your answer: will the alternative orientation provide a higher heat removal rate? **(1p)**

b) how much will be the heat removal with the alternative orientation proposed? **(3p)**



a) The heat transfer will increase as the gas stream will in average travel a shorter distance along the plate and thus experience in average a narrower boundary layer, which enhances the heat transfer.

b) The average heat transfer coefficient for each configuration can be expressed as (eq. 7.30):

$$Nu_1 = \frac{h_1\,2L}{k} = 0.664\;Re_1^{0.5}\,Pr^{0.33} = 0.664\;\left(\frac{u_\infty 2L}{\nu}\right)^{0.5}\;Pr^{0.33}$$

$$Nu_2 = \frac{h_2\,L}{k} = 0.664\;Re_2^{0.5}\,Pr^{0.33} = 0.664\;\left(\frac{u_\infty L}{\nu}\right)^{0.5}\;Pr^{0.33}$$

Dividing the two expressions yields:

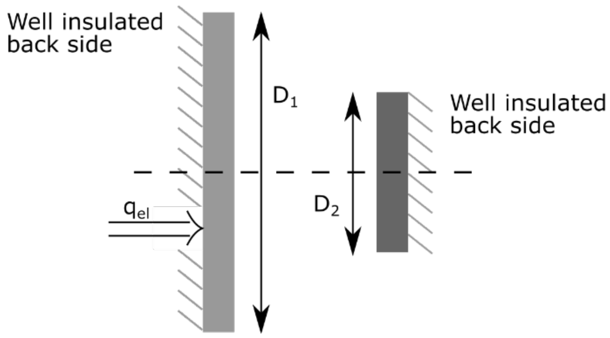
$$\frac{h_1\,2}{h_2} = 2^{0.5}\quad \rightarrow h_2 = h_1\,\sqrt{2}$$

Thus, the heat transfer is improved with a factor sqrt(2): q_2=53 kW * sqrt(2) = 74.95 kW

5. Two discs are placed so that they are parallell and coaxial (have the same axis), according to the figure below. The larger disc (1), with a diameter of 0.25 m, is electrically heated so that it reaches a temperature of 150°C. Heat is transferred due to radiation from the larger disc to the opposite, smaller disc (2), which has a diameter of 0,10 m. The back side of both discs are well insulated and the large surrounding surfaces and air holds a temperature of 27°C. The view factor F_{12} is determined as 0.09 and disc 1 can be considered as a blackbody.

a) What will be the temperature of the smaller disc at steady state conditions if all heat transfer can be considered to be due to radiation? State the assumptions that you make. (**4p**)

b) In an attempt to determine the emissivity of the smaller disc you force air over the surface of the smaller disc, receiving a convective heat transfer coefficient of 25 W/m²K. In your experiment you measure the temperature of the smaller disc as 70°C, while the temperature of the larger disc is not affected. Determine the emissivity of the smaller disc. (**2p**)



a) Index: Large disc = 1, Small disc = 2, Surrounding (and air) = 3

Given: $D_1 = 0{,}25\ m \quad ; \quad D_2 = 0{,}10\ m \quad ; \quad \varepsilon_1 = 1{,}0$

$$T_1 = 150°C = 423\ K \quad ; \quad T_3 = 27°C = 300\ K \quad ; \quad F_{12} = 0.09$$

Energy balance at surface 2, In = Out:

$$\alpha_2(A_1F_{12}J_1 + A_3F_{32}J_3) = A_2\varepsilon_2\sigma T_2^4$$

$$\alpha_2(F_{21}J_1 + F_{23}J_3) = \varepsilon_2\sigma T_2^4$$

We assume surface 2 to be grey and diffuse: $\alpha_2 = \varepsilon_2$. Since surface 1 is a blackbody and the surrounding 3 is large in comparison to 1 and 2:

$$J_1 = E_{b1} = \sigma T_1^4 \quad ; \quad J_3 = \varepsilon_3\sigma T_3^4 + \rho_3\sigma T_3^4 = \sigma T_3^4.$$

Using the reciprocity relation, summation rule and the fact that the discs don't see themselves and the surrounding is much larger than the discs:

$$F_{11} = F_{22} = 0$$

$$F_{21} = \frac{A_1F_{12}}{A_2} = \frac{D_1^2F_{12}}{D_2^2} = \frac{0.25^2 * 0.09}{0.10^2} = 0.5625$$

$$F_{23} = 1 - F_{21} - F_{22} = 0.4375$$

We can now determine the temperature of disc 2:

$$T_2 = (F_{21}T_1^4 + F_{23}T_3^4)^{1/4} = (0.5625 * 423^4 + 0.4375 * 300^4)^{1/4} = 383K = 110°C$$

b) Given: $h_2 = 25\ W/m^2K \quad ; \quad T_2 = 61°C = 334\ K$

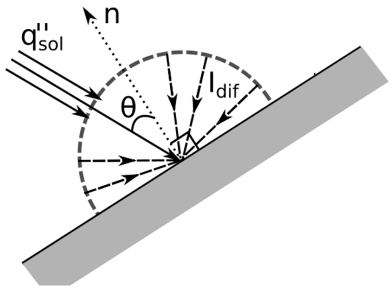
Forcing air over the disc changes the energy balance:

$$\alpha_2(A_2F_{21}J_1 + A_2F_{23}J_3) = A_2\varepsilon_2\sigma T_2^4 + h_2A_2(T_2 - T_3)$$

$$\varepsilon_2 = \frac{h_2(T_2 - T_3)}{\sigma(F_{21}T_1^4 + F_{23}T_3^4 - T_2^4)} = \frac{25(61 - 27)}{5.67 * 10^{-8}(0.5625 * 523^4 + 0.4375 * 300^4)} = 0.6956 \approx 0.70$$

6. Consider the following conditions at a mirror in CSP park. The sky is clear and the direct irradiation from the sun to the mirror is $q''_{sol} = 1100\ W/m^2$ and it is incident at $\theta = 25°$, according to the figure below. The diffuse intensity incident to the mirror, I_{dif}, is $75\ W/m^2 sr$.

a) Determine the total irradiation to the mirror. (**2p**)
b) Discuss the different contributions of direct and diffuse irradiation to a CSP plant and how these changes if a clear day becomes cloudy. (**1p**)



a) Given: $q''_{sol} = 1100\ W/m^2$; $I_{dif} = 75\ W/m^2 sr$; $\theta = 25°$

The total irradiation is the sum of the direct and diffuse contributions: $G_{tot} = G_{dir} + G_{dif}$

The direct contribution is incident at an angle from the mirror normal: $G_{dir} = q''_{sol}\cos(\theta)$

The diffuse contribution is given as the diffuse intensity. We assume that the diffuse intensity is the same in all directions over a hemisphere: $G_{dif} = I_{dif}\pi$

$$G_{tot} = q''_{sol}\cos(\theta) + I_{dif}\pi = 1100 * \cos(25°) + 75 * \pi \approx 1233\ W/m^2$$

c) Direct irradiation is what can be redirected using a mirror, the diffuse radiation will be as diffuse after being reflected and won't contribute to the irradiation at the absorber surface. During a clear day, the dominant portion of the irradiation is direct, but if the sky becomes cloudy, most of the irradiation will instead become diffuse. This will lower the effectiveness of the CSP plant.
d)

7. You are to design a heat exchanger for a currently build vessel (ship) cooling the refrigerant with the seawater. You have narrowed down the type of heat exchanger to wo types, a shell and tube and a plate heat exchanger.

Discuss the advantages and disadvantages for each option and go through all aspects relevant for the design. **(2p)**

Material/Price/Footprint/Fouling/cleaning

8. The design for a boiler requires the calculation of the involved gas volumes to design the fan capacities. The fuel to be combusted is specified as below.

Calculate the air demand m3/kg_{fuel}, the humid flue gas formed in m3/kg_{fuel} and the amount of water formed in kg water/kg_{fuel}. **(4p)**

Use the conditions of 25 °C and 10MPa for the calculations of the gas volumes and an air ratio of 1 (stoichiometric)

Fuel composition	kg_i/kg_{fuel}
C	0,857
H	0,143

Molar mass	kg_i/mol_i
C	0,012
H	0,001
CO2	0,044
H2O	0,018
O2	0,032
N2	0,028

Facit:

Air demand:
$C+1O_2 \rightarrow CO_2$
0,857[kg_C/kg_{fuel}]/0,012 [kg_C/mol_C] *1[mol_{O2}/mol_C]*4,77[mol_{air}/mol_{O2}]*0,0248[$m3_{air}/mol_{air}$]= =8,45 [$m3_{air}/kg_{fuel}$]

$H+0,25O_2 \rightarrow 0,5H_2O$
0,143[kg_H/kg_{fuel}]/0,001[kg_H/mol_H]*0,25[mol_{O2}/mol_H]*4,77[mol_{air}/mol_{O2}]*0,0248[$m3_{air}/mol_{air}$]= =4,23 [$m3_{air}/kg_{fuel}$]

Total air demand: 12,68 $m3_{air}/kg_{fuel}$]= 10 [$m3_{N2}/kg_{fuel}$]+ 2,68 [$m3_{O2}/kg_{fuel}$]

Water formed:
$H+0,25O_2 \rightarrow 0,5H_2O$
0,143[kg_H/kg_{fuel}]/0,001[mol_H/kg_H]*0,5[mol_{H2O}/mol_H]*0,018[mol_{H2O}/kg_{H2O}]= 1,29 [kg_{H2O}/kg_{fuel}]

Flue gas flow:
0,857[kg_C/kg_{fuel}]/0,012[kg_C/mol_C] *0,0248[$m3_{air}/mol_{air}$]= 1,77 [$m3_{CO2}/kg_{fuel}$]
0,143[kg_H/kg_{fuel}]/0,001[kg_H/mol_H]*0,5[mol_{H2O}/mol_H]*0,0248[$m3_{air}/mol_{air}$]= 1,77 [$m3_{H2O}/kg_{fuel}$]

Total flue gas flow:
1,77[$m3_{CO2}/kg_{fuel}$] +1,77[$m3_{H2O}/kg_{fuel}$] +10 [$m3_{N2}/kg_{fuel}$]= 13,54[$m3_{fluegas}/kg_{fuel}$]