University of Twente
Faculty of Engineering Technology (ET)
Research group Thermal Engineering (TE)

Exam Energy & Heat Transfer (E&HT)

22 October 2020, 18:15 - 21:15

- Do not forget to write your name and student number on the provided answer sheets.
- This exam consists of 5 multiple choice questions and 3 open questions.
- A total of 100 points can be earned:
  - 10 points can be earned for the multiple choice questions (2 points each).
  - 25 points can be earned for open question 1.
  - 40 points can be earned for open question 2.
  - 25 points can be earned for open question 3.
- Read each question carefully. If you think you made a mistake in your calculations, please provide an explanation why you think it is wrong.
- The use of a calculator, the lecture slides, your notes and the books '*Heat and Mass Transfer: Fundamental & Application*' and '*Introduction to Heat Transfer*' are allowed.
- On the last page, a table can be found with air properties at different temperatures.

Lecturer: dr. M. Mehrali

Industrial Design Engineering
202000198 Energy & Heat Transfer

UNIVERSITY OF TWENTE.

Multiple choice questions (10 points)

Question 1 (2 points)

You are standing next to a huge camp fire, which makes your body warmer. What will be the dominant heat transfer mechanism in this situation?

a) Conduction

b) Convection

c) Radiation

Question 2 (2 points)

In this course, problems are often solved by using dimensionless numbers, like the Reynolds number. The following two statements are made:

I) Dimensionless numbers are used to reduce the number of variables that describe your system.

II) The Reynolds number gives an indication of the type of flow, which is laminar if Re $< 5 \cdot 10^5$.

Which statements are correct?

a) I and II are both true

b) I is true, II is false

c) I is false, II is true

d) I and II are both false

Question 3 (2 points)

Another dimensionless number is the Nusselt number. Which of the following three statements is true for the Nusselt number in a stagnant (non-moving) fluid?

a) Nu $= 0$. There is no convection in a stagnant fluid, which indicates pure conduction.

b) Nu $= 1$. This indicates pure conduction, where the heat transfer due to convection is equal to the heat transfer with only conduction.

c) Nu $= \infty$. Conduction happens in solid bodies, without a solid body the conduction is equal to 0, giving pure convection.

Question 4 (2 points)

A flat copper plate which dimensions are 1 meter x 1 meter (1 m^2) is subjected to a cold wind flow over its top. The wind flow has a speed of 10 m/s. The temperature of the small plate is 25 °C, whilst the temperature of the wind is 5 °C. Another flat copper plate is placed parallel to the first plate with respect to the wind direction. Its dimensions are 10 meter x 10 meter (100 m^2). Its temperature is also 25 °C. What is the ratio between the small plate's and the large plate's heat transfer coefficient?

a) The heat transfer coefficient of the large plate is about 10 times smaller than the small plate.

b) The heat transfer coefficients are in the same order of magnitude.

c) The heat transfer coefficient of the large plate is about 10 times larger than the small plate.

d) The heat transfer coefficient of the large plate is about 100 times larger than the small plate.

Question 5 (2 points)

When the Biot number is smaller than 0.1, a lumped system can be assumed. What does a lumped system mean in this case?

a) A lumped system means that the system's density is high and that the system lacks a definite or regular shape.

b) Assuming a lumped system means that the convection, conduction and radiation are in the same order of magnitude, meaning they cannot be neglected.

c) A lumped system means that a perfect system can be assumed, for example a completely smooth and round sphere in an ideal air flow.

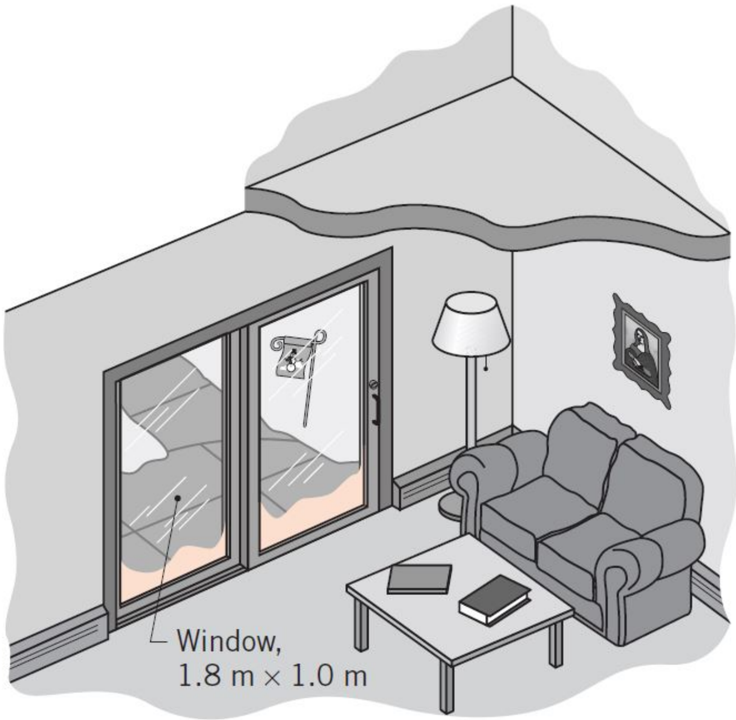
d) A lumped system has a near uniform temperature due to the ratio between the involved heat transfer mechanisms.

Open question 1 (25 points)

During a winter day, the window of a patio door with a height of 1.8 m and width of 1.0 m shows a frost line near its base. The room wall and air temperatures are 15 °C.

a) Explain why the window would show a frost layer at the base rather than at the top.

b) Estimate the heat loss through the window due to free convection and radiation. Assume the window has a uniform temperature of 0 °C and the emissivity of the glass surface is 0.94. If the room has electric baseboard heating, estimate the corresponding daily cost of the window heat loss for a utility rate of €0.18 per kWh.



Open question 2 (40 points)

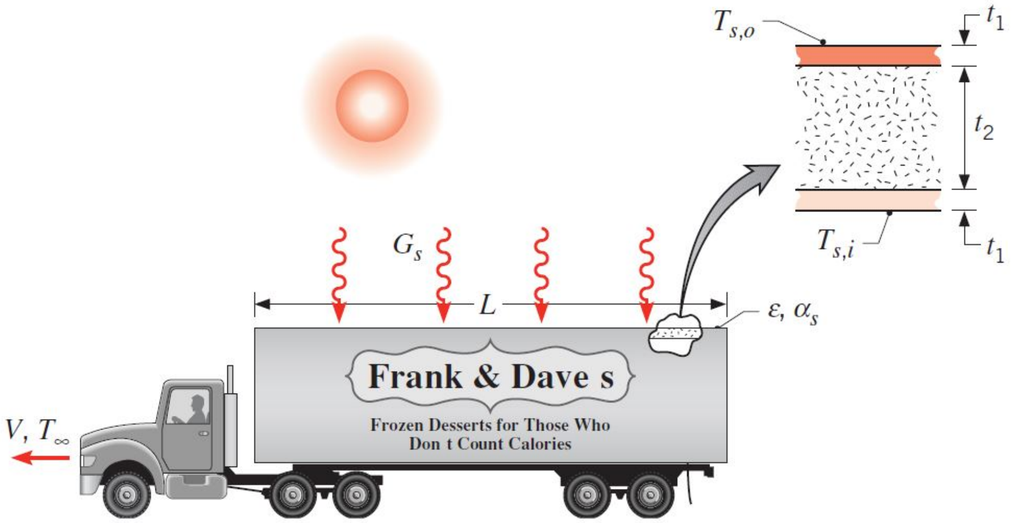
The roof of a refrigerated truck compartment is of composite construction, consisting of a layer of foamed urethane insulation (t_2 = 50.00 mm, $k_i = 0.0260\ W/m \cdot K$) sandwiched between aluminum alloy panels (t_1 = 5.00mm, $k_p = 180.00\ W/m \cdot K$). The length and width of the roof are L = 10.00 m and W = 3.50 m, respectively, and the temperature of the inner surface is $T_{s,i}$ = -10.00°C. Consider conditions for which the truck is moving at a speed of V = 105.00 km/h, the air temperature is T_∞ = 32.00°C, and the solar irradiation is G_S = 750.00 $\mathrm{W\,m^{-2}}$. Turbulent flow may be assumed over the entire length of the roof. Hint: you may assume that the irradiation from the sky is negligible. To solve the equilibrium equation, you can use that $T_{s,o}^4 = T_{s,o}^2 * T_\infty^2$

a) For equivalent values of the solar absorptivity and the emissivity of the outer surface ($\alpha_S = \varepsilon = 0.500$), estimate the average temperature $T_{s,o}$ of the outer surface. What is the corresponding heat load imposed on the refrigeration system? The refrigeration has to compensate for this heat load to keep the system in equilibrium.

b) A special finish ($\alpha_S = 0.150, \varepsilon = 0.800$) may be applied to the outer surface. What effect would such an application have on the surface temperature and the heat load?

c) If, with $\alpha_S = \varepsilon = 0.500$, the roof is not insulated ($t_2 = 0$), what are the corresponding values of the surface temperature and the heat load?

Compare the different cases to eachother and report your results.



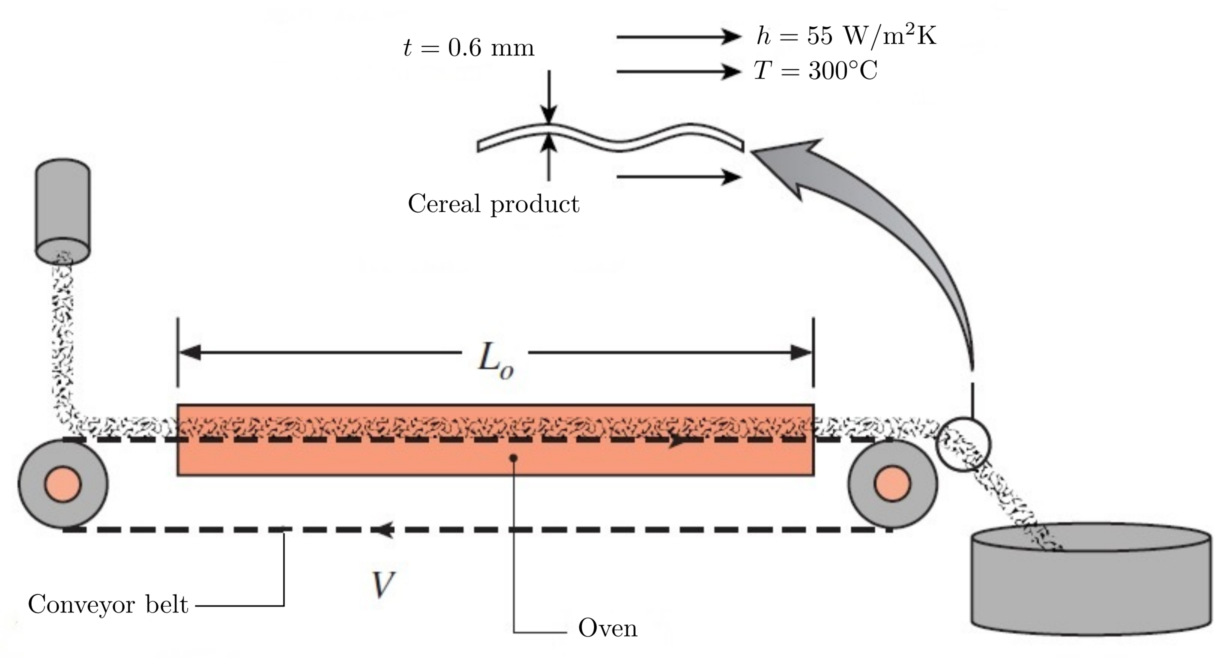
Open question 3 (25 points)

A flaked cereal is of thickness $t = 0.6$ mm. The density, specific heat and thermal conductivity of the flake are $\rho = 700\ \mathrm{kg\,m^{-3}}$, $c_p = 2400\ \mathrm{J\,kg^{-1}\,K^{-1}}$ and $k = 0.34\ \mathrm{W\,m^{-1}\,K^{-1}}$ respectively. The product is to be baked by increasing its temperature from $T_i = 20$ °C to $T_f = 220$ °C in a convection oven, through which the product is carried on a conveyor. The oven is $L_0 = 3$ m long and the convection heat transfer coefficient at the product surface and oven air temperature are $h = 55\ \mathrm{W\,m^{-2}\,K^{-1}}$ and $T_\infty = 300$ °C respectively.

a) Determine the required conveyor velocity V.

An engineer suggests that the productivity can be increased if the flake thickness is reduced to $t = 0.4$ mm.

b) Determine the required conveyor velocity and the percentual change in productivity when a flake with a reduced thickness is used. Is the engineer correct?



Tables

Below, the properties of air at atmospheric pressure have been listed for different temperatures.

Properties of air at 1 atm pressure

Temp. T, °C	Density ρ, kg/m³	Specific Heat c_p, J/kg · K	Thermal Conductivity k, W/m · K	Thermal Diffusivity α, m²/s	Dynamic Viscosity μ, kg/m · s	Kinematic Viscosity ν, m²/s	Prandtl Number Pr
−150	2.866	983	0.01171	4.158×10^{-6}	8.636×10^{-6}	3.013×10^{-6}	0.7246
−100	2.038	966	0.01582	8.036×10^{-6}	1.189×10^{-5}	5.837×10^{-6}	0.7263
−50	1.582	999	0.01979	1.252×10^{-5}	1.474×10^{-5}	9.319×10^{-6}	0.7440
−40	1.514	1002	0.02057	1.356×10^{-5}	1.527×10^{-5}	1.008×10^{-5}	0.7436
−30	1.451	1004	0.02134	1.465×10^{-5}	1.579×10^{-5}	1.087×10^{-5}	0.7425
−20	1.394	1005	0.02211	1.578×10^{-5}	1.630×10^{-5}	1.169×10^{-5}	0.7408
−10	1.341	1006	0.02288	1.696×10^{-5}	1.680×10^{-5}	1.252×10^{-5}	0.7387
0	1.292	1006	0.02364	1.818×10^{-5}	1.729×10^{-5}	1.338×10^{-5}	0.7362
5	1.269	1006	0.02401	1.880×10^{-5}	1.754×10^{-5}	1.382×10^{-5}	0.7350
10	1.246	1006	0.02439	1.944×10^{-5}	1.778×10^{-5}	1.426×10^{-5}	0.7336
15	1.225	1007	0.02476	2.009×10^{-5}	1.802×10^{-5}	1.470×10^{-5}	0.7323
20	1.204	1007	0.02514	2.074×10^{-5}	1.825×10^{-5}	1.516×10^{-5}	0.7309
25	1.184	1007	0.02551	2.141×10^{-5}	1.849×10^{-5}	1.562×10^{-5}	0.7296
30	1.164	1007	0.02588	2.208×10^{-5}	1.872×10^{-5}	1.608×10^{-5}	0.7282
35	1.145	1007	0.02625	2.277×10^{-5}	1.895×10^{-5}	1.655×10^{-5}	0.7268
40	1.127	1007	0.02662	2.346×10^{-5}	1.918×10^{-5}	1.702×10^{-5}	0.7255
45	1.109	1007	0.02699	2.416×10^{-5}	1.941×10^{-5}	1.750×10^{-5}	0.7241
50	1.092	1007	0.02735	2.487×10^{-5}	1.963×10^{-5}	1.798×10^{-5}	0.7228
60	1.059	1007	0.02808	2.632×10^{-5}	2.008×10^{-5}	1.896×10^{-5}	0.7202
70	1.028	1007	0.02881	2.780×10^{-5}	2.052×10^{-5}	1.995×10^{-5}	0.7177
80	0.9994	1008	0.02953	2.931×10^{-5}	2.096×10^{-5}	2.097×10^{-5}	0.7154
90	0.9718	1008	0.03024	3.086×10^{-5}	2.139×10^{-5}	2.201×10^{-5}	0.7132
100	0.9458	1009	0.03095	3.243×10^{-5}	2.181×10^{-5}	2.306×10^{-5}	0.7111
120	0.8977	1011	0.03235	3.565×10^{-5}	2.264×10^{-5}	2.522×10^{-5}	0.7073
140	0.8542	1013	0.03374	3.898×10^{-5}	2.345×10^{-5}	2.745×10^{-5}	0.7041
160	0.8148	1016	0.03511	4.241×10^{-5}	2.420×10^{-5}	2.975×10^{-5}	0.7014
180	0.7788	1019	0.03646	4.593×10^{-5}	2.504×10^{-5}	3.212×10^{-5}	0.6992
200	0.7459	1023	0.03779	4.954×10^{-5}	2.577×10^{-5}	3.455×10^{-5}	0.6974
250	0.6746	1033	0.04104	5.890×10^{-5}	2.760×10^{-5}	4.091×10^{-5}	0.6946
300	0.6158	1044	0.04418	6.871×10^{-5}	2.934×10^{-5}	4.765×10^{-5}	0.6935

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A flat copper plate which dimensions are 1 meter x 1 meter (1 m^2) is subjected to a cold wind flow over its top. The wind flow has a speed of 10 m/s. The temperature of the small plate is 25 °C, whilst the temperature of the wind is 5 °C. Another flat copper plate is placed parallel to the first plate with respect to the wind direction. Its dimensions are 10 meter x 10 meter (100 m^2). Its temperature is also 25 °C. What is the ratio between the small plate's and the large plate's heat transfer coefficient?

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Open question 1 (25 points)

a) total points=4, b) total points=21

a.) For these winter conditions, a frost line could appear and it would be at the bottom of the window. The boundary layer is thicker at the top of the window, and hence the heat flux from the warmer room is greater than compared to that at the bottom portion of the window where the boundary layer is thinner. Also, the air in the room may be stratified and cooler near the floor compared to near the ceiling.

Correct reasoning - 4 pt.

b.) The heat loss from the room to the window, having a temperature $T_s = 0°C$ by convection and radiation:

Correct sketch- 2 pt.

$$\begin{aligned} Q_{loss} &= Q_{conv} + Q_{rad} \\ Q_{loss} &= Ah(T_\infty - T_s) + A\epsilon\sigma(T_\infty^4 - T_4^s) \end{aligned} \tag{2.1}$$

Correct equation for Q_{loss}- 2 pt.

Calculating T_f:

$$T_f = \frac{T_s + T\infty}{2} = 7.5°C \tag{2.2}$$

Correct T_f - 1.pt

Values taken at 5 degrees C

Taking values at 5°C:

$$\begin{aligned} \nu &= 1.382 \cdot 10^{-5} \mathrm{m^2\,s^{-1}} \\ k &= 0.02401 \mathrm{W\,m^{-1}\,K^{-1}} \\ \alpha &= 1.880 \cdot 10^{-5} \mathrm{m^2\,s^{-1}} \\ Pr &= 0.7350 \end{aligned} \tag{2.3}$$

Correct values - 1 pt.

Substituting in the Grasshoff equation

$$Gr = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2}$$

where

$$\beta = \frac{2}{T_s + T_\infty} = \frac{1}{T_f} = 0.00356 \tag{2.4}$$

Correct beta- 1 pt.

$$\mathrm{Gr} = \frac{9.81 \cdot 0.00356 \cdot (15)1.8^3}{(1.382 \cdot 10^{-5})^2} = 1.6018 \cdot 10^{10}$$

Correct calculations for Grasshof- 2 pt.

The Grashoff and Prandtl number can be substituted for the Rayleigh number

$$\mathrm{Ra} = \mathrm{Gr} \cdot \mathrm{Pr} = 1.1773 \cdot 10^{10} \tag{2.5}$$

Correct Rayleigh number- 1 pt.

There are now two possibilities for the Nusselt number.

Using the complex Nusselt relation

$$\mathrm{Nu} = \left[0.825 + \frac{0.387 \cdot \mathrm{Ra}^{1/6}}{\left(1 + (0.492/\mathrm{Pr})^{9/16}\right)^{8/27}}\right] = 241.5 \tag{2.6}$$

Correct expression and calculation of Nusselt- 2 pt.

We then get:

$$h = \frac{\mathrm{Nu}_{large} \cdot k}{L} = 3.23\mathrm{W\,m^{-2}\,K} \tag{2.7}$$

Correct calculation of h- 2 pt.

$$Q_{conv} = A \cdot h_{large} \cdot (T_s - T_\infty) = 87.083\mathrm{W} \tag{2.8}$$

Correct calculation of convection part- 1 pt.

$$Q_{rad} = A\epsilon\sigma(T_\infty^4 - T_s^4) = 127.2\mathrm{W} \tag{2.9}$$

Correct calculation of radiative part- 2pt.

So

$$Q_{loss} = 214.212\mathrm{W} \tag{2.10}$$

Correct calculation of total heat loss- 1 pt.

Now, the daily costs can be calculated. The equation is

$$\mathrm{costs} = Q_{loss} \cdot 10^{-3} \cdot 0.18 \cdot 24h \tag{2.11}$$

Correct equation for costs- 2 pt.

' Which gives

$$\mathrm{costs} = 0.925\,\mathrm{euro}$$

Correct calculation of costs- 1.pt

Using the simplified Nusselt relation

$$\mathrm{Nu} = 0.1 \cdot \mathrm{Ra}^{1/3} = 227.5 \tag{2.12}$$

Correct expression and calculation of Nusselt- 2 pt.

$$h = \frac{\mathrm{Nu}_{small} \cdot k}{L} = 3.038\mathrm{W\,m^{-2}\,K} \tag{2.13}$$

Correct calculation of h- 2 pt.

$$Q_{conv} = A \cdot h_{short} \cdot (T_s - T_\infty) = 82.0347\mathrm{W} \tag{2.14}$$

Correct calculation of convection part- 1 pt.

$$Q_{rad} = A\epsilon\sigma(T_\infty^4 - T_s^4) = 127.2\mathrm{W} \tag{2.15}$$

Correct calculation of radiative part- 2pt.

So the Q is :

$$Q_{loss} = 209.163 \tag{2.16}$$

Correct calculation of total heat loss- 1 pt.

Now, the daily costs can be calculated. The equation is

$$\mathrm{costs} = Q_{loss} \cdot 10^{-3} \cdot 0.18 \cdot 24h \tag{2.17}$$

Correct equation for costs- 2 pt.

Which gives

$$\mathrm{costs} = 0.903\,\mathrm{euro}$$

Correct calculation of costs- 1.pt

Values taken at 10 degrees C

Taking values at 10°C:

$$\begin{aligned}\nu &= 1.426 \cdot 10^{-5}\mathrm{m^2\,s^{-1}} \\ k &= 0.02439\mathrm{W\,m^{-1}\,K^{-1}} \\ \alpha &= 1.994 \cdot 10^{-5}\mathrm{m^2\,s^{-1}} \\ Pr &= 0.7336\end{aligned} \tag{2.18}$$

Correct values - 1 pt.

Substituting in the Grasshoff equation

$$Gr = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2}$$

where

$$\beta = \frac{2}{T_s + T_\infty} = \frac{1}{T_f} = 0.00356\mathrm{K^{-1}} \tag{2.19}$$

Correct beta- 2 pt.

$$\mathrm{Gr} = \frac{9.81 \cdot 0.00356 \cdot (15)1.8^3}{(1.462 \cdot 10^{-5})^2} = 1.504 \cdot 10^{10}$$

Correct calculations for Grasshof- 2 pt.

The Grashoff and Prandtl number can be substituted for the Rayleigh number

$$\mathrm{Ra} = \mathrm{Gr} \cdot \mathrm{Pr} = 1.10374 \cdot 10^{10} \tag{2.20}$$

Correct Rayleigh number- 2 pt.

There are now two possibilities for the Nusselt number.

Using the complex Nusselt relation

$$\mathrm{Nu} = \left[0.825 + \frac{0.387 \cdot \mathrm{Ra}^{1/6}}{\left(1 + (0.492/\mathrm{Pr})^{9/16}\right)^{8/27}}\right] = 236.3 \tag{2.21}$$

Correct expression and calculation of Nusselt- 2 pt.

We then get:

$$h = \frac{\mathrm{Nu}_{large} \cdot k}{L} = 3.20\mathrm{W\,m^{-2}\,K} \tag{2.22}$$

Correct calculation of h- 2 pt.

$$Q_{conv} = A \cdot h_{large} \cdot (T_s - T_\infty) = 86.45\mathrm{W} \tag{2.23}$$

Correct calculation of convection part- 1 pt.

$$Q_{rad} = A\epsilon\sigma(T_\infty^4 - T_s^4) = 127.2\mathrm{W} \tag{2.24}$$

Correct calculation of radiative part- 2pt.

So

$$Q_{loss} = 213.5\mathrm{W} \tag{2.25}$$

Correct calculation of total heat loss- 1 pt.

Now, the daily costs can be calculated. The equation is

$$\mathrm{costs} = Q_{loss} \cdot 10^{-3} \cdot 0.18 \cdot 24h \tag{2.26}$$

Correct equation for costs- 2 pt.

Which gives

$$\mathrm{costs} = 0.922\,\mathrm{euro}$$

Correct calculation of costs- 1.pt

Using the simplified Nusselt relation

$$\mathrm{Nu} = 0.1 \cdot \mathrm{Ra}^{1/3} = 222.6 \tag{2.27}$$

Correct expression and calculation of Nusselt- 2 pt.

$$h = \frac{\mathrm{Nu}_{small} \cdot k}{L} = 3.017\mathrm{W\,m^{-2}\,K} \tag{2.28}$$

Correct calculation of h- 2 pt.

$$Q_{conv} = A \cdot h_{short} \cdot (T_s - T_\infty) = 81.45\mathrm{W} \tag{2.29}$$

Correct calculation of convection part- 1 pt.

$$Q_{rad} = A\epsilon\sigma(T_\infty^4 - T_s^4) = 127.2\mathrm{W} \tag{2.30}$$

Correct calculation of radiative part- 2pt.

So the Q is :

$$Q_{loss} = 208.58W \tag{2.31}$$

Correct calculation of total heat loss- 1 pt.

Now, the daily costs can be calculated. The equation is

$$\mathrm{costs} = Q_{loss} \cdot 10^{-3} \cdot 0.18 \cdot 24h \tag{2.32}$$

Correct equation for costs- 2 pt.

Which gives

$$\mathrm{costs} = 0.901\,\mathrm{euro}$$

Correct calculation of costs- 1.pt

Deduction of points

Specific:
Not using T_f : -8 pt.
Using wrong value for β: - 5 pt.
Using wrong characterstic length: -5 pt.
Standard:
Missing/wrong units: -0.5pt per time, -3 pt. total
Missing/wrong assumptions: -0.5pt per time, -3 pt. total
Missing/wrong conclusion/discussion: -0.5pt per time, -3 pt. total
Missing/wrong description: -0.5pt per time, -3 pt. total

Open question 2 (40 points)

26 points can be earned for part a). 8 points can be earned for part b). 6 points can be earned for part c).

a.) Estimate the average temperature $T_{s,o}$ of the outer surface. What is the corresponding heat load imposed on the refrigeration system? :

The physical phenomena which are important are conduction, convection and radiation. It is a steady state problem, resulting in the following equilibrium equation:

$$q''_{radiation} + q''_{convection} - E_{loss} = q''_{conduction} \tag{3.1}$$

Correct equilibrium equation- 4 pt.

The sketch below displays the situation, with different values for cases a, b and c.

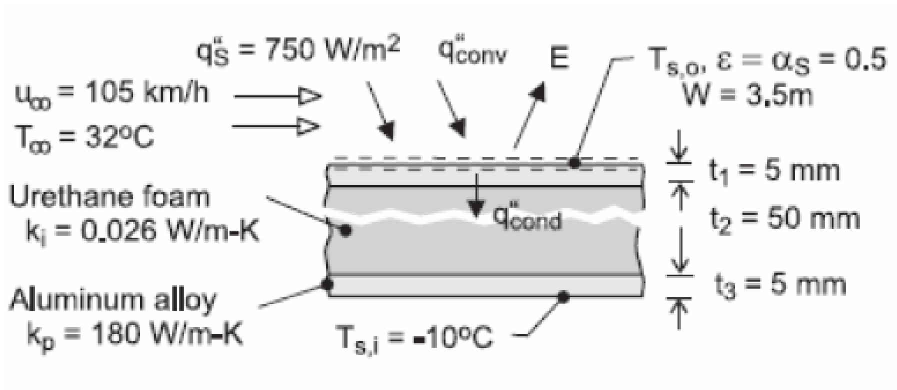

Figure 3.1: Sketch of the problem

Correct sketch- 4 pt.

Layer of foamed urethane insulation: t_2 = 50.00 mm, k_i = 0.0260 $W/m \cdot K$
Aluminum alloy panels: t_1 = 5.00 mm, k_p = 180.00 $W/m \cdot K$
Length roof = L = 10.00 m
Width roof = W = 3.50 m
Temperature of the inner surface = $T_{s,i}$ = -10°C = 263.00 K
Speed truck = V = 105.00 km/h = 29.20 m/s
Air temperature = T_∞ = 32.00°C = 305.00 K
Solar irradiation = G_S = 750.00 W m^{-2}
Stefan-Boltzmann constant = $\sigma = 5.670 * 10^{-8} W * m^{-2} * K^{-4}$
Solar absorptivity = α_S = 0.500
Emissivity = ε = 0.500

From tables:
Film temperature = $T_f \approx 300K$
Dynamic viscosity = ν = 15.89 $*10^{-6} m^2 s^{-1}$
Thermal conductivity = k_{air} = 0.0263 $W m^{-1} K^{-1}$

Correct values from table- 1 pt.

Assumptions:

- Irradiation from the sky is negligible
- The flow is turbulent over the entire outer surface
- The average convection coefficient may be used to estimate the average surface temperature
- The properties which are given are constant
- To translate Celsius to Kelvin, 273K is added

The equation which has to be solved is:

$$q''_{radiation} + q''_{convection} - E_{loss} = q''_{conduction} = \frac{T_{s,o} - T_{s,i}}{R''_{tot}} \tag{3.2}$$

Start by solving components of this equation. R_{tot} and $q_{radiation}$ are given by:

$$\begin{aligned} R''_{tot} &= 2R_p + R_i && (3.3) \\ &= 2\frac{t_1}{k_p} + \frac{t_2}{k_i} && (3.4) \\ &= 2 * 2.78 * 10^{-5} + 1.923 && (3.5) \\ &= 1.923 \frac{m^2 K}{W} && (3.6) \end{aligned}$$

Correct calculation R_{tot}- 2 pt.

$$\begin{aligned} q''_{radiation} &= \alpha_S G_S && (3.7) \\ &= 0.500 * 750.00 && (3.8) \\ &= 375.00 \frac{W}{m^2 K} && (3.9) \end{aligned}$$

Correct radiation- 1 pt.

$q_{convection}$ is given by the following formula, where h can be determined by using the Reynolds, Prandtl and Nusselt number.

$$\begin{aligned} Re &= \frac{u_\infty L}{\nu} && (3.10) \\ &= \frac{29.2 * 10}{15.89 * 10^{-6}} && (3.11) \\ &= 1.84 * 10^7 && (3.12) \\ Pr &= 0.707 && (3.13) \\ & && (3.14) \end{aligned}$$

Correct Reynolds and Prandtl - 1 pt.

$$\begin{aligned} Nu &= 0.037 * Re^{4/5} * Pr^{1/3} && (3.15) \\ &= 0.037 * (1.84 * 10^7)^{4/5} * 0.707^{1/3} && (3.16) \\ &= 2.1373 * 10^4 && (3.17) \\ & && (3.18) \end{aligned}$$

Correct Nusselt correlation and number- 2 pt.

$$h = \frac{Nu * k_{air}}{L} \tag{3.19}$$
$$= \frac{2.1373 * 10^4 * 0.0263}{10} \tag{3.20}$$
$$= 56.2 \frac{W}{m^2 K} \tag{3.21}$$

Correct convection- 1 pt.

The radiation loss, denoted by E_{loss} and the convection loss are given by:

$$E_{loss} = \epsilon \sigma T_{s,o}^4 \tag{3.22}$$
$$= 0.5 * 5.670 * 10^{-8} * T_{s,o}^4 \tag{3.23}$$
$$\tag{3.24}$$

Correct E_{loss} and convection - 1 pt.

$$q''_{convection} = \bar{h}(T_\infty - T_{s,o}) \tag{3.25}$$
$$= 56.2 * (305 - T_{s,o}) \tag{3.26}$$

Correct E_{loss} and convection - 1 pt.

Substituting in the total formula gives one equation with one unknown, which can be solved:

$$375 + 56.2 * (305 - T_{s,o}) - 0.500 * 5.670 * 10^{-8} * T_{s,o}^4 = \frac{T_{s,o} - 263.00}{1.923} \tag{3.27}$$

Correct (solvable) equation - 2 pt.

Solving by using the correlation $T_{s,o}^4 = T_{s,o}^2 * T_\infty^2$ gives:

$$T_{s,o} = 306.9K = 33.9°\text{C} \tag{3.28}$$

Correct surface temperature - 4 pt.

Note that this temperature is higher than the outer air due to radiation. The heat loss of the refrigeration system is given by the conduction loss of the total area. It is given by:

$$Q_{loss} = q''_{conduction} * A \tag{3.29}$$
$$= \frac{\Delta T}{R_{tot}} * W * L \tag{3.30}$$
$$= \frac{33.9 - -10}{1.923} * 3.5 * 10 = 799W \tag{3.31}$$

Correct Q_{loss} - 2 pt.

b.) Estimate the average temperature $T_{s,o}$ of the outer surface and its corresponding heat load for the changed values. :

The following values have changed:
Solar absorptivity = α_S = 0.15
Emissivity = ε = 0.8
When looking at the equilibrium state:

$$q''_{radiation} + q''_{convection} - E_{loss} = q''_{conduction} = \frac{T_{s,o} - T_{s,i}}{R''_{tot}} \tag{3.32}$$

The values for $q''_{radiation}$ and E_{loss} will change.

Only calculating relevant parts - 1 pt.

Solving $q''_{radiation}$ and E_{loss} gives:

$$\begin{aligned} q''_{radiation} &= \alpha_S G_S &(3.33)\\ &= 0.15 * 750 &(3.34)\\ &= 112.5 \frac{W}{m^2 K} &(3.35)\\ & &(3.36) \end{aligned}$$

Correct radiation - 1 pt.

$$\begin{aligned} E_{loss} &= \epsilon \sigma T_{s,o}^4 &(3.37)\\ &= 0.8 * 5.670 * 10^{-8} * T_{s,o}^4 &(3.38)\\ & &(3.39) \end{aligned}$$

Correct E_{loss} - 1 pt.

Substituting the new values in the equilibrium equation gives:

$$112.5 + 56.2 * (305 - T_{s,o}) - 0.800 * 5.670 * 10^{-8} * T_{s,o}^4 = \frac{T_{s,o} - 263.00}{1.923} \tag{3.40}$$

And solving for $T_{s,o}$ by using the correlation $T_{s,o}^4 = T_{s,o}^2 * T_\infty^2$ gives:

$$T_{s,o} = 299.9K = 26.9°\text{C} \tag{3.41}$$

Correct surface temperature - 2 pt.

The heat loss is again given by the conduction over the total area, which is given by:

$$\begin{aligned} Q_{loss} &= q''_{conduction} * A &(3.42)\\ &= \frac{\Delta T}{R_{tot}} * W * L &(3.43)\\ &= \frac{27.1 - -10.00}{1.923} * 3.50 * 10.00 = 675W &(3.44) \end{aligned}$$

Correct Q_{loss} - 2 pt.

Conclusion - 1 pt.

c.) Estimate the average temperature $T_{s,o}$ of the outer surface and its corresponding heat load for the changed values. :

The following values have changed:
Solar absorptivity $= \alpha_S = 0.500$
Emissivity $= \varepsilon = 0.500$
Thickness isolation $= t_2 = 0m$
When looking at the equilibrium state:

$$q''_{radiation} + q''_{convection} - E_{loss} = q''_{conduction} = \frac{T_{s,o} - T_{s,i}}{R''_{tot}} \tag{3.45}$$

The situation is the same as a), but with a different R''_{tot}:

$$\begin{aligned}
R''_{tot} &= 2R_p + R_i && (3.46)\\
&= 2\frac{t_1}{k_p} + \frac{t_2}{k_i} && (3.47)\\
&= 2 * 2.78 * 10^{-5} + 0 && (3.48)\\
&= 5.56 * 10^{-5}\frac{m^2K}{W} && (3.49)
\end{aligned}$$

Correct R_{tot} - 1 pt.

Substituting this in the total equilibrium equation gives:
Substituting in the total formula gives one equation with one unknown, which can be solved:

$$375 + 56.2 * (305.00 - T_{s,o}) - 0.500 * 5.670 * 10^{-8} * T_{s,o}^4 = \frac{T_{s,o} - 263.00}{5.56 * 10^{-5}} \tag{3.50}$$

Solving by using the correlation $T_{s,o}^4 = T_{s,o}^2 * T_\infty^2$ gives:

$$T_{s,o} = 263.14K = -9.86°\text{C} \tag{3.51}$$

Correct surface temperature - 2 pt.

The heat loss of the refrigeration system is given by the conduction loss of the total area. It is given by:

$$\begin{aligned}
Q_{loss} &= q''_{conduction} * A && (3.52)\\
&= \frac{\Delta T}{R_{tot}} * W * L && (3.53)\\
&= \frac{-9.86 - -10.00}{5.56 * 10^{-5}} * 3.50 * 10.00 = 8.81 * 10^4 W && (3.54)
\end{aligned}$$

Correct Q_{loss} - 2 pt.

Correct conclusion - 1 pt.

Open question 3 (25 points)

a.) Conveyor belt velocity:
The characteristic length of the flake cereal can be calculated by using that convection only takes place at the top surface:

$$L_c = \frac{V}{A_s} = \frac{t * A_s}{A_s} = t = 0.6\text{mm} \tag{4.1}$$

5 pt. Use correct length and get characteristic length

This characteristic length gives a Biot number of:

$$Bi = \frac{hL_c}{k} = \frac{55 * 0.6 * 10^{-3}}{0.34} = 0.097 < 0.1 \tag{4.2}$$

So we can assume a lumped system.

2 pt. Correct Biot and conclusion

Therefore the lumped capacitance approximation is valid and the time will be:

$$\begin{aligned} t &= \frac{\rho V c_p}{hA_s} \ln\left(\frac{\theta_i}{\theta}\right) \\ &= \frac{\rho L_c c_p}{h} \ln\left(\frac{T_i - T_\infty}{T - T_\infty}\right) \\ &= \frac{700 * 0.0006 * 2400}{55} \ln\left(\frac{20 - 300}{220 - 300}\right) \\ &= 22.96\text{s} \end{aligned} \tag{4.3}$$

5 pt. Correct time to reach the required temperature

The conveyor velocity then becomes:

$$V = \frac{L_o}{t} = \frac{3}{22.96} = 0.13 m/s \tag{4.4}$$

3 pt. Correct velocity

b.) Conveyor belt velocity for reduced flake and productivity:
With a flake thickness of 0.4 mm, the conveyor velocity becomes:

$$L_c = 0.4\text{mm} \tag{4.5}$$

$$Bi = \frac{hL_c}{k} = \frac{55 * 0.4 * 10^{-3}}{0.34} = 0.065 < 0.1 \tag{4.6}$$

$$\begin{aligned} t &= \frac{\rho V c_p}{hA_s} \ln\left(\frac{\theta_i}{\theta}\right) \\ &= \frac{\rho L_c c_p}{h} \ln\left(\frac{T_i - T_\infty}{T - T_\infty}\right) \\ &= \frac{700 * 0.0004 * 2400}{55} \ln\left(\frac{20 - 300}{220 - 300}\right) \\ &= 15.31\text{s} \end{aligned} \tag{4.7}$$

$$V = \frac{L_o}{t} = \frac{3}{15.31} = 0.20 m/s \tag{4.8}$$

5 pt. Correct velocity

The percentual increase in productivity is:

$$\eta = \frac{V_{0.4} - V_{0.6}}{V_{0.6}} \cdot 100\% = \frac{0.20 - 0.13}{0.13} \cdot 100\% = 54\% \tag{4.9}$$

So the engineer is right, the productivity is increased by 54%.

5 pt. Correct increase and conclusion

Deduction of points

Standard: Missing/wrong units: -0.5pt per time, -3 pt. total Missing/wrong assumptions: -0.5pt per time, -3 pt. total Missing/wrong conclusion/discussion: -0.5pt per time, -3 pt. total Missing/wrong description: -0.5pt per time, -3 pt. total