

W03

A refrigeration truck is in motion at a speed of 80 km/h. The truck's depiction is presented in the image below.



Figure 1: Refrigeration truck

The dimensions of the truck's upper section measure 3 meters in length and 2.1 meters in width. The truck interior houses stored ice cream, requiring temperature regulation. The internal air maintains a temperature of $-7\text{ }^{\circ}\text{C}$, featuring a heat transfer coefficient of $h_i = 10\text{ W/m}^2\text{K}$. To insulate the roof, a sandwiched arrangement employs insulation ($t_2 = 40\text{ mm}$, $k_2 = 0.0320\text{ W/mK}$) nestled between two aluminum sheets ($t_1 = t_3 = 3\text{ mm}$, $k_1 = k_3 = 180\text{ W/mK}$). The ambient external temperature stands at $28\text{ }^{\circ}\text{C}$.

- Determine the Reynolds number for the roof of the passenger truck. Assume the average fluid properties to be $T_f = 25\text{ }^{\circ}\text{C}$. Please clearly indicate what properties or air are used and which assumptions have been made.
- Determine at which length the laminar flow becomes turbulent.
- Find an expression for the heat transfer coefficient h_o outside the truck. Also, explain what the heat transfer coefficient tells us.
- Provide a sketch of the thermal network. Include all known temperatures, resistances, and the direction of the flow of heat. Explain each component.
- Determine the rate of heat transfer from the ambient through the top of the truck.
- Determine the temperature T_s of the top surface of the truck roof. What would have been a good estimate for T_f in task a)?
- Give a sketch of the temperature profile. The domain drawn should cover the inside temperature of $-7\text{ }^{\circ}\text{C}$ as well as the outside temperature of $28\text{ }^{\circ}\text{C}$.

Solution W03

- a) Determine the Reynolds number for the roof of the passenger truck. Assume the average fluid properties to be $T_f = 25^\circ\text{C}$. Please clearly indicate what properties or air are used and which assumptions have been made.

The assumptions that are being made are:

- The roof is perfectly flat.

(0.5) Correctly stated assumption

The properties of air are:

- $\rho = 1.184 \text{ kg/m}^3$
- $k = 0.02551 \text{ W/mK}$
- $\mu = 1.849 \cdot 10^{-5} \text{ kg/m} \cdot \text{s}$
- $\text{Pr} = 0.7296$

(0.5) Correct air properties

The Reynolds number can be determined as:

$$\text{Re}_L = \frac{\rho \cdot V \cdot L}{\mu} = \frac{1.184 \cdot 22.22 \cdot 3}{1.849 \cdot 10^{-5}} = 4.269 \cdot 10^6$$

where $V = 22.22 \text{ m/s}$ and the characteristic length is $L = 3 \text{ m}$.

(0.5) Correct Reynolds number

- b) Determine at which length the laminar flow becomes turbulent.

The flow becomes turbulent for a flat plate when $\text{Re}_{\text{crit}} = 5 \cdot 10^5$.

Rewriting the expression of the Reynolds number yields:

$$x_{\text{crit}} = \frac{\text{Re}_{\text{crit}} \cdot \mu}{\rho \cdot V} = \frac{(5 \cdot 10^5) \cdot (1.849 \cdot 10^{-5})}{1.184 \cdot 22.22} = 0.35 \text{ m}$$

(0.5) Correct critical length

- c) Find an expression for the heat transfer coefficient h_o outside the truck. Also, explain what the heat transfer coefficient tells us.

The heat transfer coefficient, often denoted as "h," is a crucial parameter in the field of heat transfer. It quantifies the rate of heat transfer between a solid surface and a fluid (liquid or gas) that is in contact with that surface. Essentially, the heat transfer coefficient tells us how efficiently heat is being exchanged between the surface and the fluid.

In more technical terms, the heat transfer coefficient is defined as the amount of heat transferred per unit area per unit temperature difference between the surface and the fluid.

(1) Correct definition heat transfer coefficient

Having determined the Reynolds number, it yields that the following correlation for the Nusselt number is applicable:

$$\text{Nu} = 0.037 \cdot \text{Re}_L^{4/5} \cdot \text{Pr}^{1/3} = 0.037 \cdot (4.269 \cdot 10^6)^{4/5} \cdot (0.7296)^{1/3} = 6.71 \cdot 10^3$$

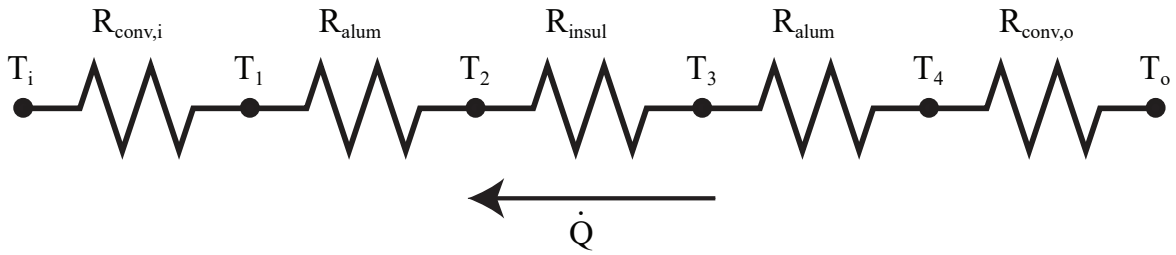
(1) Correct correlation Nusselt number and value

Which yields the heat transfer coefficient:

$$h_o = \frac{\text{Nu} \cdot k}{L} = \frac{(6.71 \cdot 10^3) \cdot 0.02551}{3} = 57.07 \text{ W/m}^2\text{K}$$

(0.5) Correct heat transfer coefficient

- d) Provide a sketch of the thermal network. Include all known temperatures, resistances, and the direction of the flow of heat. Explain each component



(1) Correct sketch of thermal resistance network

- T_i : Temperature at the inside of the truck. Known to be -7°C .
- T_o : Temperature at the outside ambient. Known to be 28°C .
- T_1, T_2, T_3, T_4 : Interface temperatures between different resistances. All are unknown at this point.
- $R_{\text{conv},i}$: Thermal resistance induced by convection happening inside the truck. Not known yet.
- R_{alum} : Thermal resistance induced by the aluminum layer due to conductive heat transfer. Not known yet.
- R_{insul} : Thermal resistance induced by the insulating layer due to conductive heat transfer. Not known yet.
- $R_{\text{conv},o}$: Thermal resistance induced by convection happening outside the truck. Not known yet.
- \dot{Q} : Rate of heat transfer from the outside ambient to the inside of the truck. Not known yet.

(1) Correct explanation of all components, (-0.5) per missing criteria

- e) Determine the rate of heat transfer from the ambient through the top of the truck. First, all resistances should be determined:

$$R_{\text{conv},i} = \frac{1}{h_i \cdot A} = \frac{1}{10 \cdot (3 \times 1.8)} = 0.0185 \text{ K/W}$$

$$R_{\text{alum}} = \frac{t_1}{k_1 \cdot A} = \frac{0.003}{180 \cdot (3 \times 1.8)} = 3.086 \cdot 10^{-6} \text{ K/W}$$

$$R_{\text{insul}} = \frac{t_2}{k_2 \cdot A} = \frac{0.04}{0.032 \cdot (3 \times 1.8)} = 0.2315 \text{ K/W}$$

$$R_{\text{conv},o} = \frac{1}{h_o \cdot A} = \frac{1}{57.0705 \cdot (3 \times 1.8)} = 0.0032 \text{ K/W}$$

(1) Correct thermal resistances, (-0.5) per missing criteria

The total thermal resistance yields from:

$$R_{\text{total}} = R_{\text{conv},i} + R_{\text{alum}} + R_{\text{insul}} + R_{\text{alum}} + R_{\text{conv},o} = 0.2533 \text{ K/W}$$

(0.5) Correct total thermal resistance

Using the thermal resistance theorem, one finds the rate of heat transfer:

$$\dot{Q} = \frac{T_o - T_i}{R_{\text{total}}} = \frac{28 - (-7)}{0.2533} = 138.21 \text{ W}$$

(1) Correct rate of heat transfer

- f) Determine the temperature T_s of the top surface of the truck roof. The top surface $T_s = T_4$ yields from using the thermal resistance theorem:

$$\dot{Q} = \frac{T_o - T_s}{R_{\text{conv},o}}$$

Where rewriting gives:

$$T_s = T_o - \dot{Q} \cdot R_{\text{conv},o} = 27.55^\circ\text{C}.$$

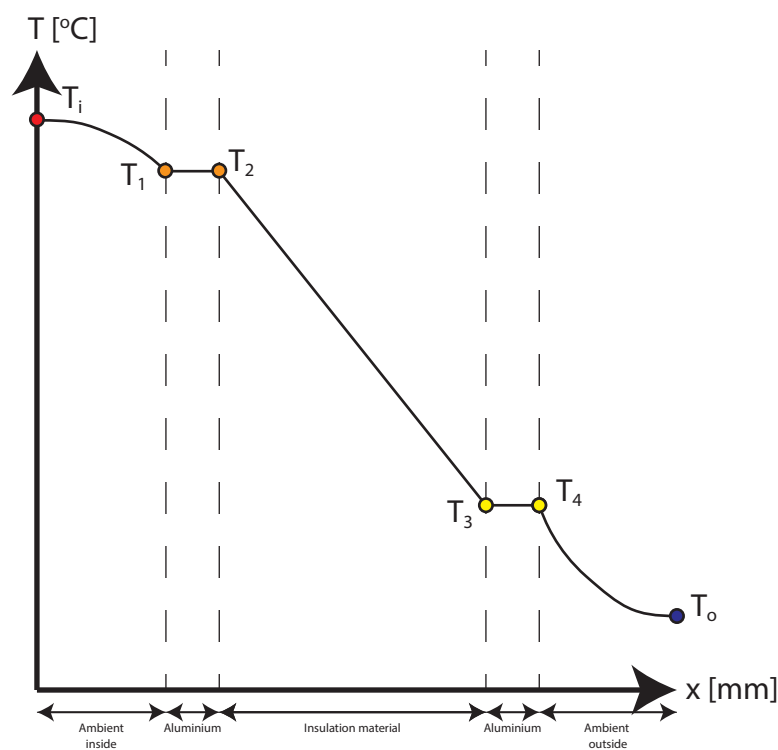
(1) Correct surface temperature

A good estimate for T_f would have been:

$$T_f = \frac{T_o + T_s}{2} = \frac{28 + 27.55}{2} = 27.78^\circ\text{C}.$$

(1) Correct average fluid temperature

g) Give a sketch of the temperature profile. The domain drawn should cover the inside temperature of $-7\text{ }^{\circ}\text{C}$ as well as the outside temperature of $28\text{ }^{\circ}\text{C}$.



The temperature in the ambient inside should start with a horizontal slope, which increases when moving in the positive x-direction.

The temperature drop in the aluminum layers is negligible.

The temperature drop in the insulation layer is the largest of all, with the steepest slope.

The temperature in the ambient outside should have a decrease in slope until it reaches the ambient temperature where the slope becomes horizontal.

(2) For all correct criteria, (-0.5) per missing criteria