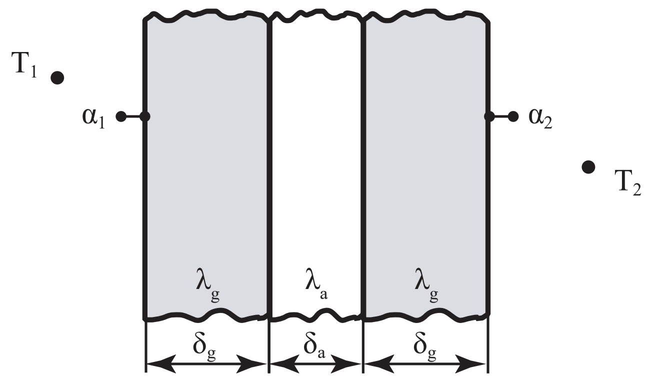
Exercise II.4 (Window insulation ⋆):

Consider a 1.2-m-height and 2-m-wide double-pane window consisting of two layers of glass separated by a stagnant air space. Convection occurs at the inside and outside of the pane window. Disregard any heat transfer by radiation.



Given parameters:

- Conductivity of glass: $\lambda_g = 0.78$ W/mK
- Conductivity of air: $\lambda_a = 0.026$ W/mK
- Thickness of glass layer: $\delta_g = 3$ mm
- Thickness of air layer: $\delta_a = 15$ mm
- Inside convection coefficient: $\alpha_1 = 10$ W/m^{2}K
- Outside convection coefficient: $\alpha_2 = 25$ W/m^{2}K
- Inside temperature: $T_1 = 22$ °C
- Outside temperature: $T_2 = -7$ °C

Tasks:

a) Determine the steady heat transfer rate through this double-pane window and the temperature of its inner surface.

b) Compare your results with a three-layer glass (3-mm-thickness) with two stagnant air spaces filled with krypton ($\delta_k = 8\,\text{mm}$, $\lambda_k = 0.00949\,{}^{\text{W}}/_{\text{m K}}$).

c) Discuss the reason for choosing a three-layer glass and scrutinize all assumptions made in tasks a) and b).

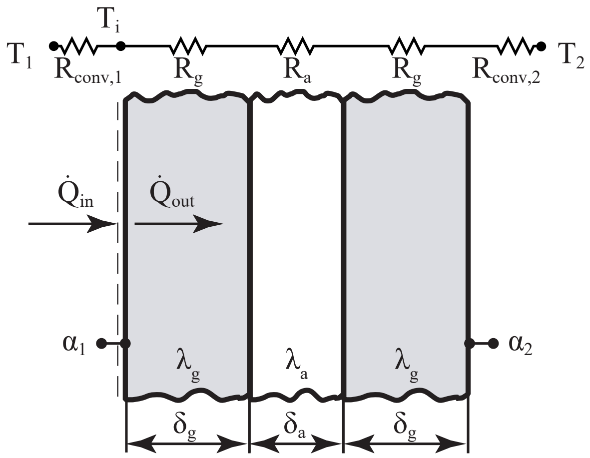
Solution II.4 (Window insulation ⋆):

Task a)

The provided problem can be resolved by establishing the energy balance of the system, akin to delineating the thermal resistance network for a multi-layer wall scenario. Subsequently, the thermal resistances can be ascertained, allowing for the determination of the rate of heat loss in both situations.

1 **Setting up the balance:**

Before commencing the calculations, it is crucial to have a clear understanding of the thermal resistance network. In the provided scenario, we are working with 5 resistors connected in series.



The energy balance at the interface between the ambient and the glass on the left side reads:

$$0 = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}} \tag{II.4.1}$$

2 **Defining the elements within the balance:**

The ingoing rate of heat transfer can be defined as:

$$\dot{Q}_{\text{in}} = \frac{T_1 - T_{\text{i}}}{R_{\text{conv},1}} \tag{II.4.2}$$

The outgoing rate of heat transfer can be defined as:

$$\dot{Q}_{\text{out}} = \frac{T_{\text{i}} - T_2}{2R_{\text{g}} + R_{\text{a}} + R_{\text{conv},2}} \tag{II.4.3}$$

Before calculating the overall thermal resistance, it is necessary to ascertain the cross-sectional area:

$$A = 1.2\ [\text{m}] \cdot 2\ [\text{m}] = 2.4\ [\text{m}^2] \tag{II.4.4}$$

The conductive thermal resistances within the system can be calculated as follows:

$$R_{\text{g}} = \frac{\delta_{\text{g}}}{\lambda_{\text{g}} A} = \frac{0.003\ [\text{m}]}{0.78\ [\text{W/mK}] \cdot 2.4\ [\text{m}^2]} = 0.002\ [\text{K/W}] \tag{II.4.5}$$

$$R_{\text{a}} = \frac{\delta_{\text{a}}}{\lambda_{\text{a}} A} = \frac{0.015\ [\text{m}]}{0.026\ [\text{W/mK}] \cdot 2.4\ [\text{m}^2]} = 0.240\ [\text{K/W}] \tag{II.4.6}$$

The two convective thermal resistances can be calculated as follows:

$$R_{\text{conv},1} = \frac{1}{\alpha_1 A} = \frac{1}{10\ [\text{W/m}^2\text{K}] \cdot 2.4\ [\text{m}^2]} = 0.042\ [\text{K/W}] \tag{II.4.7}$$

$$R_{\text{conv},2} = \frac{1}{\alpha_2 A} = \frac{1}{25\ [\text{W/m}^2\text{K}] \cdot 2.4\ [\text{m}^2]} = 0.017\ [\text{K/W}] \tag{II.4.8}$$

3 **Inserting and rearranging:**

Inserting and rearranging yields:

$$\begin{aligned} T_\text{i} &= \frac{T_1\,(2R_\text{g} + R_\text{a} + R_{\text{conv},2}) + T_2 R_{\text{conv},1}}{R_{\text{conv},1} + 2R_\text{g} + R_\text{a} + R_{\text{conv},2}} \\ &= \frac{22\ [^\circ\text{C}]\,(2 \cdot 0.002 + 0.240 + 0.017)\ [\text{K/W}] + -7\ [^\circ\text{C}] \cdot 0.042\ [\text{K/W}]}{(0.042 + 2 \cdot 0.002 + 0.240 + 0.017)\ [\text{K/W}]} = 18\ [^\circ\text{C}] \end{aligned} \tag{II.4.9}$$

Substitution of the interface temperature into the ingoing rate of heat transfer yields the heat transfer rate:

$$\dot{Q}_\text{in} = \frac{T_1 - T_\text{i}}{R_{\text{conv},1}} = \frac{22\ [^\circ\text{C}] - 18\ [^\circ\text{C}]}{0.042\ [\text{K/W}]} = 96\ [\text{W}] \tag{II.4.10}$$

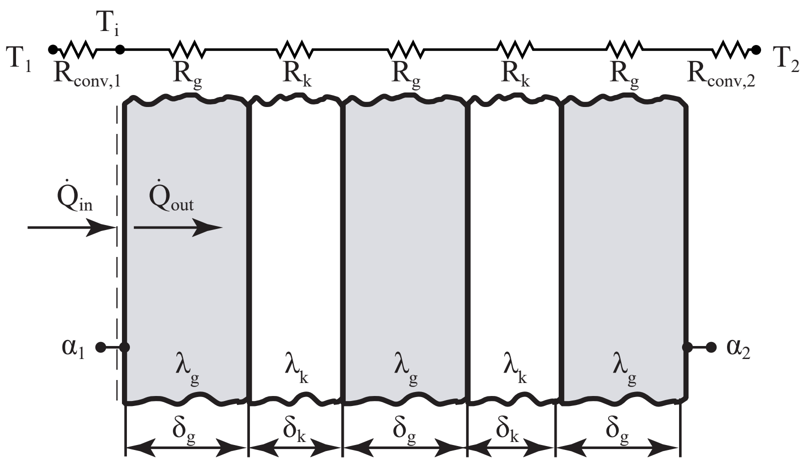
Conclusion

The heat transfer rate through the double-pane window is 96 W, and the temperature of its inner surface is 18 °C.

Task b)

1 **Setting up the balance:**

The same approach as previously can be applied. However, in this instance, there are three layers instead of two, and the enclosures are thinner, now filled with krypton. This results in a scenario where 7 resistors are arranged in series.



The energy balance at the interface still reads the same:

$$0 = \dot{Q}_\text{in} - \dot{Q}_\text{out} \tag{II.4.11}$$

2 Defining the elements within the balance:

The ingoing rate of heat transfer can be defined as:

$$\dot{Q}_{\mathrm{in}} = \frac{T_1 - T_\mathrm{i}}{R_{\mathrm{conv},1}} \tag{II.4.12}$$

The outgoing rate of heat transfer can be defined as:

$$\dot{Q}_{\mathrm{out}} = \frac{T_\mathrm{i} - T_2}{3R_\mathrm{g} + 2R_\mathrm{k} + R_{\mathrm{conv},2}} \tag{II.4.13}$$

The two convective thermal resistances can be calculated as follows:

$$R_{\mathrm{conv},1} = \frac{1}{\alpha_1 A} = \frac{1}{10\ [\mathrm{W/m^2K}] \cdot 2.4\ [\mathrm{m^2}]} = 0.042\ [\mathrm{K/W}] \tag{II.4.14}$$

$$R_{\mathrm{conv},2} = \frac{1}{\alpha_2 A} = \frac{1}{25\ [\mathrm{W/m^2K}] \cdot 2.4\ [\mathrm{m^2}]} = 0.017\ [\mathrm{K/W}] \tag{II.4.15}$$

The conductive thermal resistances within the system can be calculated as follows:

$$R_\mathrm{g} = \frac{\delta_\mathrm{g}}{\lambda_\mathrm{g} A} = \frac{0.003\ [\mathrm{m}]}{0.78\ [\mathrm{W/mK}] \cdot 2.4\ [\mathrm{m^2}]} = 0.002\ [\mathrm{K/W}] \tag{II.4.16}$$

$$R_\mathrm{k} = \frac{\delta_\mathrm{k}}{\lambda_\mathrm{k} A} = \frac{0.008\ [\mathrm{m}]}{0.00949\ [\mathrm{W/mK}] \cdot 2.4\ [\mathrm{m^2}]} = 0.351\ [\mathrm{K/W}] \tag{II.4.17}$$

3 Inserting and rearranging:

Inserting and rearranging yields:

$$\begin{aligned} T_\mathrm{i} &= \frac{T_1\left(3 \cdot R_\mathrm{g} + 2 \cdot R_\mathrm{k} + R_{\mathrm{conv},2}\right) + T_2 R_{\mathrm{conv},1}}{R_{\mathrm{conv},1} + 3 \cdot R_\mathrm{g} + 2 \cdot R_\mathrm{k} + R_{\mathrm{conv},2}} \\ &= \frac{22\ [^\circ\mathrm{C}]\left(3 \cdot 0.002 + 2 \cdot 0.351 + 0.017\right)\ [\mathrm{K/W}] + -7\ [^\circ\mathrm{C}] \cdot 0.042\ [\mathrm{K/W}]}{\left(0.042 + 3 \cdot 0.002 + 2 \cdot 0.351 + 0.017\right)\ [\mathrm{K/W}]} = 20\ [^\circ\mathrm{C}] \end{aligned} \tag{II.4.18}$$

Substitution of the interface temperature into the ingoing rate of heat transfer yields the heat transfer rate:

$$\dot{Q}_{\mathrm{in}} = \frac{T_1 - T_\mathrm{i}}{R_{\mathrm{conv},1}} = \frac{22\ [^\circ\mathrm{C}] - 20\ [^\circ\mathrm{C}]}{0.042\ [\mathrm{K/W}]} = 38\ [\mathrm{W}] \tag{II.4.19}$$

Conclusion

The heat transfer rate through the triple-pane window is 38 W, and the temperature of its inner surface is 18 °C. In comparison to the two-pane window, the heat loss has decreased by 60%, while the interface temperature has risen by 2 °C.

Task c)

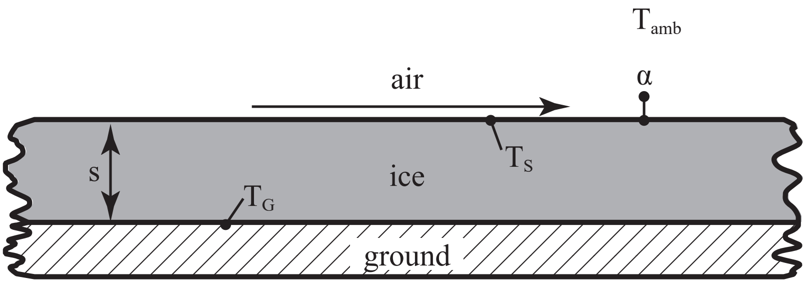
Conclusion

Selecting a three-layer glass configuration serves several purposes in thermal insulation. Firstly, the addition of an extra layer introduces an additional thermal barrier, further impeding heat transfer. This results in a reduction in the overall heat loss through the window. Secondly, the use of thinner enclosures filled with krypton is a deliberate choice to enhance thermal resistance. The lower thermal conductivity of krypton compared to air contributes to improved insulation performance.

> Calculations assume ideal behavior in terms of thermal conductivity and neglect potential non-idealities that may exist in real-world scenarios. Furthermore, the assumptions of steady-state conditions and uniform temperature distribution are inherent in the analysis.
>
> These assumptions, while simplifying the calculations, should be acknowledged, and their limitations considered in the context of real-world applications.

Exercise II.5 (Ice layer ⋆⋆):

During a cold winter day, the ground is covered with an ice layer of thickness s. Air is flowing over the ice layer. The problem is one-dimensional and steady-state. No layer of water is forming on top of the ice.



Given parameters:

- Conductivity of ice: $\lambda = 2.2$ W/mK
- Heat transfer coefficient at the ice surface: $\alpha = 10$ W/m^{2}K
- Temperature of the air: $T_{\mathrm{amb}} = 5$ °C
- Temperature of the ice at the surface: $T_{\mathrm{S}} = -3$ °C
- Temperature of the ice at the ground: $T_{\mathrm{G}} = -10$ °C
- Temperature of the air: $T_{\mathrm{amb}} = 5$ °C

Tasks:

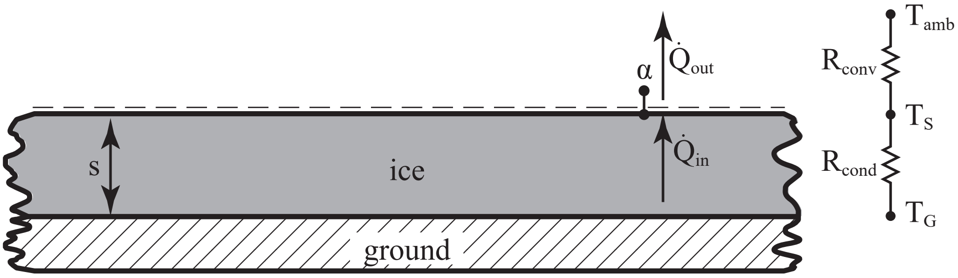
a) Determine the thickness s of the ice layer.

Solution II.5 (Ice layer ⋆⋆):

Task a)

1 **Setting up the balance:**

Before starting the calculations, it is required to possess an understanding of the thermal resistance network. In the given scenario, we are dealing with 2 resistors connected in series.



We are dealing with one-dimensional steady-state heat transfer without sources/sinks. Therefore, the energy balance at the interface with the ambient reads:

$$0 = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}} \tag{II.5.1}$$

2 **Defining the elements within the balance:**

The ingoing rate of heat transfer can be described by use of the conductive resistance:

$$\dot{Q}_{\text{in}} = \frac{T_\text{S} - T_\text{G}}{R_\text{cond}} \tag{II.5.2}$$

and the outgoing rate of heat transfer:

$$\dot{Q}_{\text{out}} = \frac{T_\text{amb} - T_\text{S}}{R_\text{conv}} \tag{II.5.3}$$

The conductive resistance can be written as:

$$R_\text{cond} = \frac{s}{\lambda A} \tag{II.5.4}$$

and the convective resistance: The conductive resistance can be written as:

$$R_\text{conv} = \frac{1}{\alpha A} \tag{II.5.5}$$

3 **Inserting and rearranging:**

Inserting the terms into the energy balance and rewriting yields the ice thickness s:

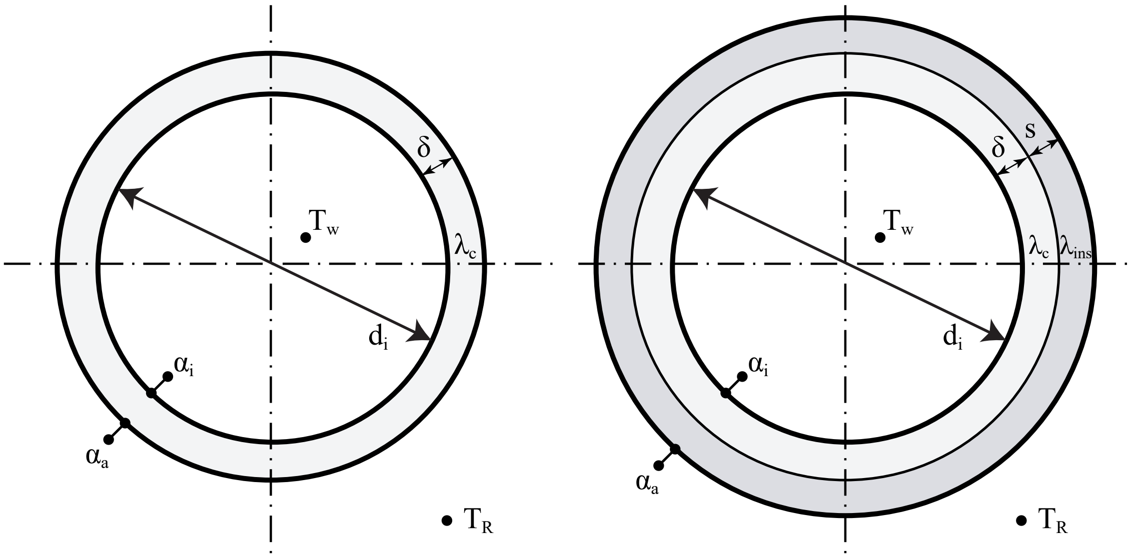
$$\begin{aligned} s &= \frac{\lambda}{\alpha} \cdot \frac{T_\text{S} - T_\text{G}}{T_\text{amb} - T_\text{S}} \\ &= \frac{2.2\ [\text{W/mK}]}{10\ [\text{W/m}^2\text{K}]} \cdot \frac{(-3+10)\ [^\circ\text{C}]}{(5+3)\ [^\circ\text{C}]} = 0.19\ [\text{m}] \end{aligned} \tag{II.5.6}$$

Conclusion

The thickness of the ice layer is 19 cm.

Exercise II.6 (Warm-water pipe ⋆⋆⋆)**:**

In a room, a copper warm-water pipe is utilized to contain water. This copper pipe features an inner diameter of d_i and a wall thickness denoted as δ. During a chilly winter day, insulation measures are taken, involving the addition of an extra insulation layer with a thickness of s.



Given parameters:

- Heat transfer coefficient at the inner side of the pipe: α_i = 2300 W/m^{2}K
- Heat transfer coefficient at the outer side of the pipe: α_a = 6 W/m^{2}K
- Temperature of the room: T_R = 20 °C
- Temperature of the water: T_W = 80 °C
- Conductivity of copper: λ_c = 372 W/mK
- Conductivity of insulation material: λ_ins = 0.042 W/mK
- Inner diameter of the copper pipe: d_i = 6 mm
- Thickness of the copper pipe: δ = 1 mm
- Thickness of the insulation layer: s = 4 mm

Hints:

- Changes to the heat transfer coefficient at the outer side of the pipe as a function of the diameter are disregarded.

Tasks:

a) Calculate the heat transferred per unit length of the pipe, denoted as $\dot{q}'$, for both an uninsulated pipe and an insulated pipe. What noteworthy observations can be made from your findings?

b) Qualitatively sketch the heat emission profile $\dot{q}'$ as a function of the insulation thickness for different thermal conductivities of the insulation material. Explain the underlying physical principles.

c) Calculate the required thermal conductivity for the insulating material to always achieve a reduction in heat loss, regardless of the thickness of the insulation.

Solution II.6 (Warm-water pipe ⋆⋆⋆):

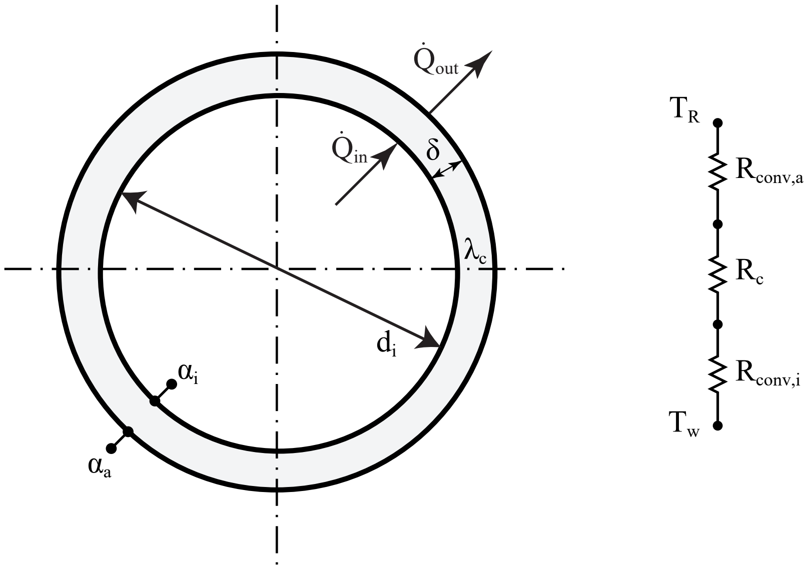
Task a)

To calculate the heat transferred per unit length, denoted as $\dot{q}'$, we will consider the length of the pipe to be precisely one unit, i.e., $L = 1$ m. In this instance, $\dot{Q} = \dot{q}'$.

System without insulation:

1 **Setting up the balance:**

Before doing the calculations, it is required to have an understanding of the thermal resistance network. In the given uninsulated scenario, we are dealing with 3 resistors connected in series.



The energy balance through the pipe wall reads:

$$0 = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}} \tag{II.6.1}$$

2 **Defining the elements within the balance:**

From the energy balance, it follows that $\dot{Q}_{\text{in}} = \dot{Q}_{\text{out}}$. Both can be expressed using the total thermal resistance between the two specified reference temperatures.

The rate of heat transfer reads:

$$\dot{Q}_{\text{in}} = \dot{Q}_{\text{out}} = \frac{T_{\text{W}} - T_{\text{R}}}{R_{\text{conv,i}} + R_{\text{c}} + R_{\text{conv,a}}} \tag{II.6.2}$$

Calculation of the thermal resistance due to convection on the inside:

$$\begin{aligned} R_{\text{conv,i}} &= \frac{1}{\alpha_{\text{i}} \pi d_{\text{i}} L} \\ &= \frac{1}{2300\ [\text{W/m}^2\text{K}] \cdot \pi \cdot 0.006\ [\text{m}] \cdot 1\ [\text{m}]} = 0.02\ [\text{K/W}] \end{aligned} \tag{II.6.3}$$

Thermal resistance of the copper layer:

$$R_c = \frac{1}{2\pi L\lambda_c}\ln\left(\frac{d_i+2\delta}{d_i}\right) \tag{II.6.4}$$
$$= \frac{1}{2\cdot\pi\cdot 1\ [\mathrm{m}]\cdot 372\ [\mathrm{W/mK}]}\ln\left(\frac{(0.006+2\cdot 0.001)\ [\mathrm{m}]}{0.006\ [\mathrm{m}]}\right) = 0.0001\ [\mathrm{K/W}]$$

Thermal resistance convection on the outside:

$$R_{\mathrm{conv,a}} = \frac{1}{\alpha_a\pi\left(d_i+2\delta\right)\cdot L} \tag{II.6.5}$$
$$= \frac{1}{6\ [\mathrm{W/m^2K}]\cdot\pi\cdot(0.006+2\cdot 0.001)\ [\mathrm{m}]\cdot 1\ [\mathrm{m}]} = 6.63\ [\mathrm{K/W}]$$

3 **Inserting and rearranging:**

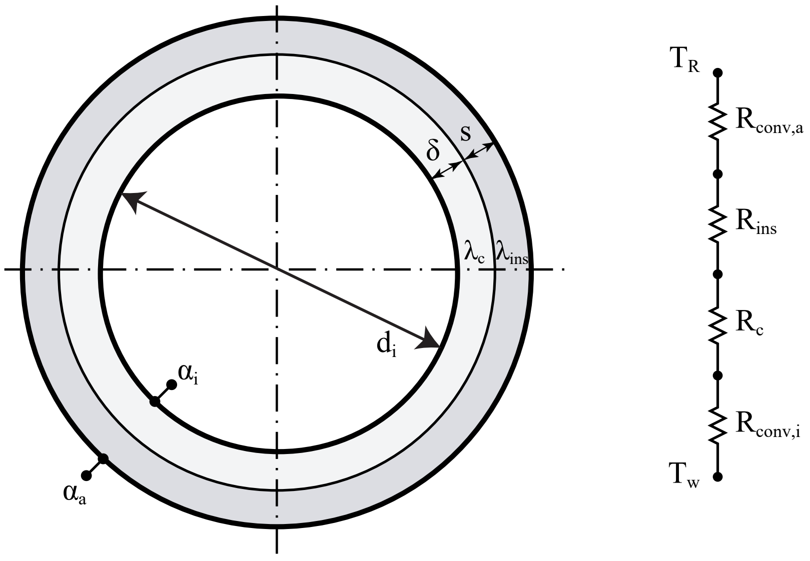
Inserting yields:

$$\dot{Q} = \frac{(80-20)\ [^\circ\mathrm{C}]}{(0.02+0.0001+6.63)\ [\mathrm{K/W}]} = 9\ [\mathrm{W}] \tag{II.6.6}$$

System with insulation:

1 **Setting up the balance:**

It is important to have an idea of what the thermal resistance network in the given problem looks like. In the described situation we are dealing with 4 resistances that are connected in series.



$$0 = \dot{Q}_{\mathrm{in}} - \dot{Q}_{\mathrm{out}} \tag{II.6.7}$$

2 **Defining the elements within the balance:**

From the energy balance, it follows that $\dot{Q}_{\mathrm{in}} = \dot{Q}_{\mathrm{out}}$. Both can be expressed using the total thermal resistance between the two specified reference temperatures.

The rate of heat transfer reads:

$$\dot{Q}_{\mathrm{in}} = \dot{Q}_{\mathrm{out}} = \frac{T_W - T_R}{R_{\mathrm{conv,i}} + R_c + R_{\mathrm{ins}} + R_{\mathrm{conv,a}}} \tag{II.6.8}$$

The thermal resistance insulation layer can be calculated as follows:

$$R_{\text{ins}} = \frac{1}{2\pi L\lambda_{\text{ins}}} \ln\left(\frac{d_{\text{i}} + 2\delta + 2s}{d_{\text{i}} + 2\delta}\right) \tag{II.6.9}$$
$$= \frac{1}{2 \cdot \pi \cdot 1\ [\text{m}] \cdot 0.042\ [\text{W/mK}]} \ln\left(\frac{(0.006 + 2 \cdot 0.001 + 2 \cdot 0.004)\ [\text{m}]}{(0.006 + 2 \cdot 0.001)\ [\text{m}]}\right) = 2.63\ [\text{K/W}]$$

With the increased thickness of the pipe, there is a corresponding increase in the surface area of the outer wall. Consequently, the thermal resistance of the convection layer on the exterior has also changed. The thermal resistance of convection on the outside can be computed now as follows:

$$R_{\text{conv,a}} = \frac{1}{\alpha_{\text{a}}\pi\left(d_{\text{i}} + 2\delta + 2s\right) \cdot L} \tag{II.6.10}$$
$$= \frac{1}{6\ [\text{W/m}^2\text{K}] \cdot \pi \cdot (0.006 + 2 \cdot 0.001 + 2 \cdot 0.004)\ [\text{m}] \cdot 1\ [\text{m}]} = 3.32\ [\text{K/W}]$$

3 **Inserting and rearranging:**

Filling in:

$$\dot{Q} = \frac{(80 - 20)\ [^{\circ}\text{C}]}{(0.02 + 0.0001 + 2.63 + 3.32)\ [\text{K/W}]} = 10\ [\text{W}] \tag{II.6.11}$$

Conclusion

It is evident that in the uninsulated scenario, the heat transferred per unit length is 9 W/m, while for the insulated scenario, it is 10 W/m. This might initially seem counterintuitive, as one would anticipate a decrease in the heat transfer rate for the insulated pipe, given the expectation of reduced heat losses.

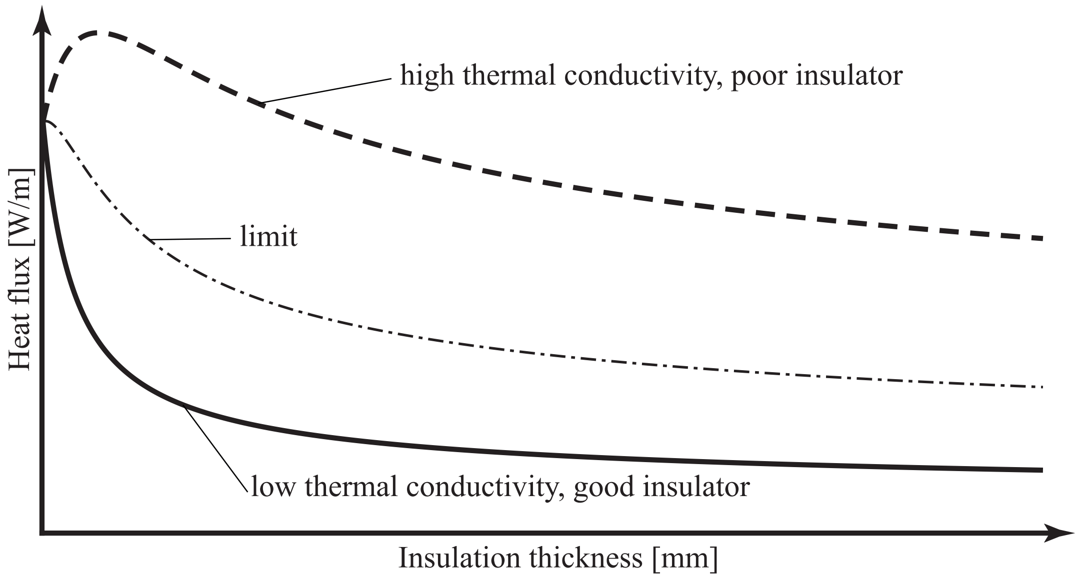
However, this can be explained by considering that the additional resistance introduced by insulation serves to further diminish the thermal resistance caused by convection on the outside. Consequently, the overall thermal resistance of the system is reduced due to this modification, resulting in a larger heat loss for the insulated pipe.

Task b)

As noted in the previous task, the heat flux increased despite the addition of an insulating layer. This phenomenon was attributed to the reduction in convective thermal resistance on the outside being more substantial than the increase in thermal resistance resulting from the insulation. This behavior persists until a critical insulating thickness is reached, beyond which the rise in thermal resistance from the insulator consistently outweighs the decrease in convective thermal resistance on the outside. Notably, this behavior is characteristic of "poor insulators" characterized by relatively high thermal conductivity.

If the thermal conductivity of our insulator were low enough, we would have a "good insulator," and in such a case, the added thermal resistance from the insulator would consistently be greater than the reduction in convective resistance on the outside. Consequently, for all insulation thicknesses, the addition of an insulator would result in a reduction in heat flux.

Conclusion



Task c)

Insulation is beneficial only when the rate of heat transfer, denoted as $\dot{q}'$, experiences a decline. As previously discussed, in certain scenarios, the addition of an insulation layer may lead to an increase in the rate of heat transfer instead of a decrease. The rate of heat transfer, $\dot{q}'$, begins to decrease beyond a critical point where the thickness of the insulation layer reaches a crucial value. This critical value, where the rate of heat transfer $\dot{q}'$ is at its maximum, corresponds to the minimum value of the total thermal resistance. Following this point, the rate of heat transfer will consistently decrease, regardless of the insulation thickness.

By taking the derivative of the total thermal resistance with respect to the outer diameter D_o and setting it equal to zero, we can identify the critical condition where R_total is minimized:

$$\frac{d}{dD_\mathrm{o}}\left[R_\mathrm{conv,i} + R_\mathrm{c} + R_\mathrm{ins} + R_\mathrm{conv,a}\right] = 0 \tag{II.6.12}$$

Setting the derivatives of $R_\mathrm{conv,i}$ and R_c equal to zero, as both resistances are independent of the outer diameter:

$$\frac{d}{dD_\mathrm{o}}\left[R_\mathrm{ins} + R_\mathrm{conv,a}\right] = 0 \tag{II.6.13}$$

Inserting the definitions of the thermal resistances yields:

$$\frac{d}{dD_\mathrm{o}}\left[\frac{1}{2\pi L\lambda_\mathrm{ins}}\ln\left(\frac{d_\mathrm{i} + 2\delta + 2s}{d_\mathrm{i} + 2\delta}\right) + \frac{1}{\alpha_\mathrm{a}\pi\left(d_\mathrm{i} + 2\delta + 2s\right)\cdot L}\right] = 0 \tag{II.6.14}$$

For simplicity, we will substitute $D_\mathrm{o} = d_\mathrm{i} + 2\delta + 2s$ and $d_\mathrm{o} = d_\mathrm{i} + 2\delta$, and then eliminate the constants πL:

$$\frac{d}{dD_\mathrm{o}}\left[\frac{1}{2\lambda_\mathrm{ins}}\ln\left(\frac{D_\mathrm{o}}{d_\mathrm{o}}\right) + \frac{1}{\alpha_\mathrm{a}D_\mathrm{o}}\right] = 0 \tag{II.6.15}$$

Differentiating everything in between brackets with respect to D_o gives:

$$\frac{1}{2\cdot\lambda_\mathrm{ins}}\cdot\frac{1}{D_\mathrm{o}} - \frac{1}{\alpha_\mathrm{a}D_\mathrm{o}^2} = 0 \tag{II.6.16}$$

This provides the critical diameter beyond which the heat flux will always decrease:

$$D_{\mathrm{o,crit}} = \frac{2 \cdot \lambda_{\mathrm{ins}}}{\alpha_{\mathrm{a}}} \tag{II.6.17}$$

We can reformulate this expression to derive an expression for the thermal conductivity as a function of the outer diameter:

$$\lambda_{\mathrm{ins}} = \frac{\alpha_{\mathrm{a}} \cdot D_{\mathrm{o,crit}}}{2} \tag{II.6.18}$$

In this context, we aim for the outer diameter without any insulation to be equal to the critical diameter. Hence, $D_{\mathrm{o,crit}} = d_{\mathrm{i}} + 2\delta$. Substituting and filling in provides the minimum required thermal conductivity of the insulation layer to consistently achieve a reduction in heat loss, regardless of the thickness of the insulation:

$$\begin{aligned} \lambda_{\mathrm{ins}} &= \frac{\alpha_{\mathrm{a}} \cdot (d_{\mathrm{i}} + 2\delta)}{2} \\ &= \frac{6\ [\mathrm{W/m^2K}] \cdot (0.006 + 2 \cdot 0.001)\ \ [\mathrm{m}]}{2} = 0.024\ [\mathrm{W/mK}] \end{aligned} \tag{II.6.19}$$

Conclusion

Hence, for the insulating material to always achieve a reduction in heat loss, irrespective of the insulation thickness, the thermal conductivity must not exceed 0.024 W/mK. Otherwise, an initial addition of insulation material may increase the rate of heat loss, and only after reaching a critical outer diameter will it subsequently lead to a decrease in heat losses.