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P5 8 How clothing keeps us warm

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Abstract

In this paper, we investigate how humans keep warm by wearing clothes in a cold environment, assuming an 18°C room to maintain a body temperature of 34°C , where heat is lost to the surroundings via conduction, convection, radiation, and evaporation. We are taking into account a forearm as a cylinder of radius $r = 0.04\text{m}$, and length, $L = 0.6\text{m}$, covered by a 1cm thick wool layer having thermal conductivity $k = 0.04\text{Wm}^{-2}\text{K}^{-1}$. From the results, the heat loss without clothing is 50.5W and with clothing is 7.96W , which means the clothing is able to trap 85% of the heat from escaping to the surrounding .

Introduction

There are four main mechanisms through which the human body constantly loses heat [1]:

Conduction is a mechanism that conducts heat through direct contact from a warmer object, such as skin, to a colder one, such as air or clothing. One thing to note is that when the colder object is air, conduction is minimal, unless the air is still in contact with the skin. Clothing materials such as wool and cotton have lower thermal conductivity than skin or air motion.

Convection occurs when heat is transferred by a liquid or gas. For example, the warm air surrounding the skin increases as a result of its decreasing density and is replaced by cold air, becoming a continuous heat-loss cycle. What clothing does is trap a layer of warm air near the skin, which can reduce convection loss.

Radiation in this situation would be infrared, as all electromagnetic waves above absolute zero emit a certain thermal radiation. Wearing clothing reduces the area that is emitted and increases the time it takes to emit radiation from the skin.

Evaporation occurs when the body heats up, producing sweat. Due to the sweat that absorbs the latent heat from the skin, it turns into vapor that escapes into the air.

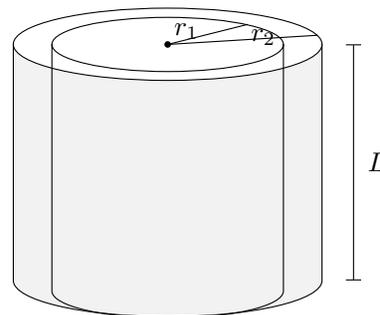


Figure 1: Example diagram for assuming forearm as cylinder covered by another cylinder represent 1cm thick wool layer(jumper). Where the radius of forearm is $r_1 = 0.04\text{m}$, the radius of forearm covered by wool layer is $r_2 = 0.05\text{m}$, the length of forearm is $L = 0.6\text{m}$.

Method

To calculate the heat loss of the body with clothing on compared to the body without clothing, we assume the forearm as a cylinder of radius, $r = 0.04m$; length, $L = 0.6m$; Forearm temperature, $T_{arm} = 307K$ and ambient temperature, $T_{amb} = 291K$ in a room.

To begin with, we calculate the heat loss without clothes, as no thermal resistance is applied[2] and use the Stefan-Boltzmann equation[3].

$$P_{without} = k_{air}A(T_{arm} - T_{amb}) + \epsilon\sigma A(T_{arm}^4 - T_{amb}^4) \quad (1)$$

which

$$P_{without} = P_{cond} + P_{rad}$$

Where P_{cond} is the heat loss from convection, k_{air} is the cooling constant of average $k = 15Wm^{-2}K^{-1}$ [4], and A is the total surface area of the forearm ; where ϵ is the skin emissivity = 0.98 [5] , σ is Stefan's constant $k = 5.67 \times 10^{-8}Wm^{-2}K^{-4}$

The next part is to determine the heat loss with clothing using the thermal resistance equation [3].

$$R_{total} = \frac{\Delta x}{k_{wool}A_{arm}} + \frac{\Delta x}{(k_{air} + k_{wool})A_{arm}} \quad (2)$$

which

$$R_{total} = R_{cond} + R_{outer}$$

that led to

$$P_{with} = \frac{\Delta T}{R_{total}} \quad (3)$$

Where R_{cond} and R_{outer} are the thermal resistance of the conductive and outer surface, respectively, k_{wool} and k_{air} are the thermal conductivity of wool and air, respectively , $0.04Wm^{-2}K^{-1}$ [6]and $15Wm^{-2}K^{-1}$. Where (3) use the thermal current equation[3] :

Lastly, calculate the amount of heat that remained and the percentage by wearing the wool jumper:

$$\delta P = P_{without} - P_{with} \quad (4)$$

$$Percentage = \left(1 - \frac{P_{with}}{P_{without}}\right) \times 100\% \quad (5)$$

Results

For (1), total heat loss without clothing :

$$P_{without} = 50.5W$$

For (2), the total thermal resistance is :

$$R_{total} = 2.01KW^{-1}$$

For (3), the total heat loss with clothing is :

$$P_{with} = 7.96W$$

For (4) and (5) = the heat loss difference is

$$\delta P = 42.6W$$

$$Percentage = 85\%$$

Discussion

As convection is the main source, the bare-skin loses heat, about 72% of the 50.5 W in the results. A thin layer of fabric can almost stop this process. Wool, for example, traps a layer of still air next to the skin, which replaces the fast-moving cold air in the room.

The conduction through the wool is small due to low conductivity $0.04Wm^{-2}K^{-1}$ which, in an indoor condition, direct conductive loss to solid objects is negligible compared to convection and radiation.

For radiation, roughly 28% of the bare-skin loss. By slightly increasing the outer surface area larger and the exterior temperature of the jumper quickly approaches room temperature, the net radiated power becomes smaller.

Evaporation is neglected in this model because significant sweating does not occur at an ambient temperature of 18 °C when the body is insulated.

Conclusion

As the warmth maintained by clothing mainly traps still air, which has very low thermal conductivity, it also increases the path length and the time it takes for heat to escape. A 1 cm wool layer reduces the heat loss from a forearm by 85%, from 50.5 W to 7.96 W at 18 °C. The calculation also confirms the effectiveness of air-trapping materials such as wool in a cold environment.

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