The Effect of the Diving/Wet Suit on the Survival Time in Cold Water Immersion

BEE 453
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Executive Summary

In this study, we will compare the effect of normal clothes (assumed as bare skin) with effect of wetsuit in maintaining the core body temperature, produced by metabolic heat generations and blood flow heat generation, using COMSOL. A passenger is immersed in cold water after Titanic has shipwrecked, and the individual is waiting for rescue to come in time before his metabolic functions stop and die. We will compare two cases: with and without wetsuit on the passenger. Skin temperature or wetsuit temperature is assumed to be equal to cold water temperature, which is at 10 degrees Celsius, and the distribution of temperature throughout the body will be graphically shown as the time of body immersion in water increases. It is shown from the results that wetsuit can help maintain the normal core body temperature much longer than normal clothes/bare skin can in cold water immersion.

Introduction and Design Objective

Background and importance of problem:

Hypothermia is the decrease in body temperature due to exposure to colder temperatures, losing bodily heat to the surrounding environment. The first stage of hypothermia occurs when body temperature decreases by one to two degrees Celsius from normal body temperature (37 degrees Celsius). In this stage, shivering and numbness in hands occurs. When hypothermia is continued, the body enters the second stage of hypothermia. Body temperature is dropped by two to four degree Celsius, and bodily movements become uncoordinated. Lips and other body parts may appear pale. When the body temperature reaches below 32 degrees Celsius due to constant exposure to colder temperatures, the body enters the third stage of hypothermia. In this stage, metabolic processes, cellular activities, and organ functions slow down, and eventually stop. This is the minimal temperature for survival and will lead to the death of a person once temperature reaches below this point.

For many divers, hypothermia is of major concern for they are exposed to ocean water for a longer period of time. Thus, divers wear wetsuits to prevent hypothermia from happening quickly. A wetsuit is a protective garment made from neoprene material, which provides thermal protection during immersion in cold water. Wetsuit preserves body heat by trapping a layer of water between the layers of skin and neoprene wetsuit. This layer of water is heated by body heat, and acts as an insulator that slows down body heat from escaping into surrounding water.

In this project, we will consider an average passenger submerged in cold ocean water after a shipwreck such as the case of the Titanic. We will investigate the effect of insulation using the diving suit/wet suit as to how much this suit can prolong the time it takes for the core body temperature to reach 32 degrees Celsius. The wet suit can be a method of increasing the resistance of heat transfer out of the body. And thus, the time allowed for rescues to arrive in time can be increased before the passenger dies.

Design Objective

- Two models will be subject to investigation: Model #1- with wetsuit and Model #2- without wetsuit
- The process of heat transfer (conduction only) from core body to skin tissue/wetsuit to water is modeled as one dimensional heat transfer (top and bottom boundaries are insulated)
- The epidermis/wetsuit temperature is equal to the water temperature (which is at 10 degrees Celsius)
- Model the temperature-time profile of tissue geometry
- Models subject to computer simulations have rectangle geometry divided into the following sections/tissue layers: Core body, inner tissue, subcutaneous fat, dermis, epidermis, and wetsuit (for Model #2 only)
- Determine the core temperature (x = 0) as a function of time for 2 hours. Determine how well the diving suit can insulate the body temperature from the cold water by comparing the core temperature for situations of with and without wetsuit and when the core body temperature gets lower than 32 degrees Celsius.

Assumptions

- Models subject to computer simulations is Axial symmetry (2D) and transient conductive heat transfer
- Heat generated from the body: Basal Metabolic Heat Generation and Heat Generation from Blood Flow
- Heat produced by metabolism is present in the core body and the skin layers
- Heat produced by blood flow is present in the skin layers
- Consider trunk only
- Core body is a lumped parameter
- Change in the cold water temperature is negligible

Problem Schematic

Model #1: Diagram of Heat Transfer throughout tissue layers and Diving/Wet Suit

Core Body

Inner Tissue Subcutaneous Fat Dermis Epidermis Wet Suit

Length=150mm

Length=30mm | Length=10mm | Length=2mm

Length=0.08

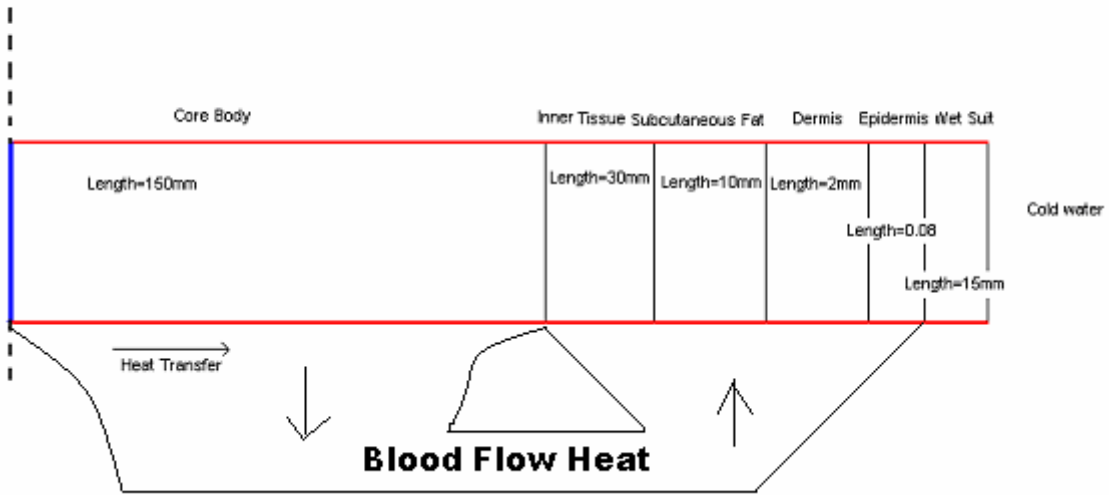Length=15mm

Cold water

Heat Transfer

Blood Flow Heat

Figure 1. Heat is transferred from core body to inner tissue, subcutaneous fat, dermis, epidermis, and wetsuit to cold water in the x-direction. The core body temperature is at 37 degrees Celsius, and the wetsuit is at 25 degrees Celsius. The cold water temperature is at 10 degrees Celsius. The red boundaries indicated insulation (heat flux is zero). The blue line represents the core body temperature where heat flux is zero. The model is axi-symmetric about the dashed line.

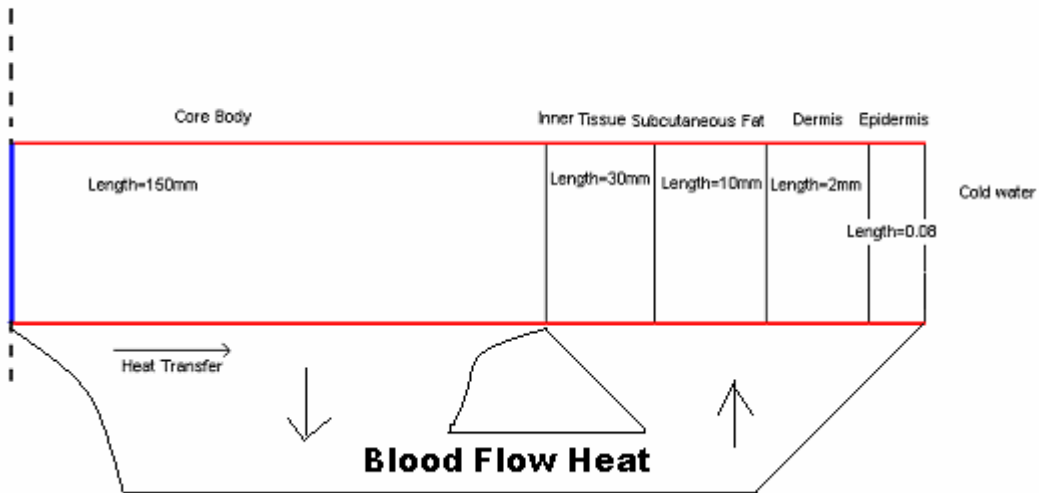Model #2: Diagram of Heat Transfer throughout tissue layers

Core Body

Inner Tissue Subcutaneous Fat Dermis Epidermis

Length=150mm

Length=30mm | Length=10mm | Length=2mm

Length=0.08

Cold water

Heat Transfer

Blood Flow Heat

Figure 2. Heat is transferred from core body to inner tissue, subcutaneous fat, dermis, epidermis, and wetsuit to cold water in the x-direction. The core body temperature is at 37 degrees Celsius, and the skin layers are at 37 degrees Celsius. The cold water temperature is at 10 degrees Celsius. The red boundaries indicated insulation (heat flux

is zero). The blue line represents the core body temperature where heat flux is zero. The model is axi-symmetric about the dashed line.

Results and Discussion

1. Basic Model Design of Human Body

In order to build our model of the human body in cold water immersion, we divided the human body into the core body and the skin layers. Then we determined the geometric properties and thermal properties of the core body and skin layers through literature. Using the COMSOL software, designed our model in 1-dimensional conductive heat transfer and input all the properties including heat generation as a constant.

2. Metabolic Heat Generation

We found through literature the basal metabolism rate as a function of temperature and included this equation in the source term of the core body and skin layers. This term was divided by the human body volume which was calculated as a function of human body weight and height.

3. Heat generated from Blood Flow

We included an equation of heat generated from blood flow as a function of core temperature and skin temperature in the source term of the skin layers. Since the blood flows in a cycle from the core body to the skin layers, the heat generated by blood flow in the skin layers was integrated and divided by the volume of the core body to include the loss of heat by the blood flow in the source term of the core body region.

4. Change in Blood Flow Rate

Then we included the change in blood flow rate as a function of core temperature and skin temperature (Parsons K., 2003). This term accounts for the decrease in blood flow rate as the core temperature or skin temperature decreases.

5. Sensitivity Analysis and Mesh Convergence

We did a sensitivity analysis of four variables: the surrounding cold water temperature, human body weight, human body height and the heat conductivity of the wet suit. The cold water temperature is varied from situation to situation and the human body weight and human body height are different for each individual. The heat conductivity of the wetsuit was found in literature as a range from 0.15-0.45 W/mK. The Mesh was refined to see if the time it takes for the core body temperature to reach 32 degrees Celsius changed by an increase in the number of elements. The figures of mesh convergence for both cases are shown below.
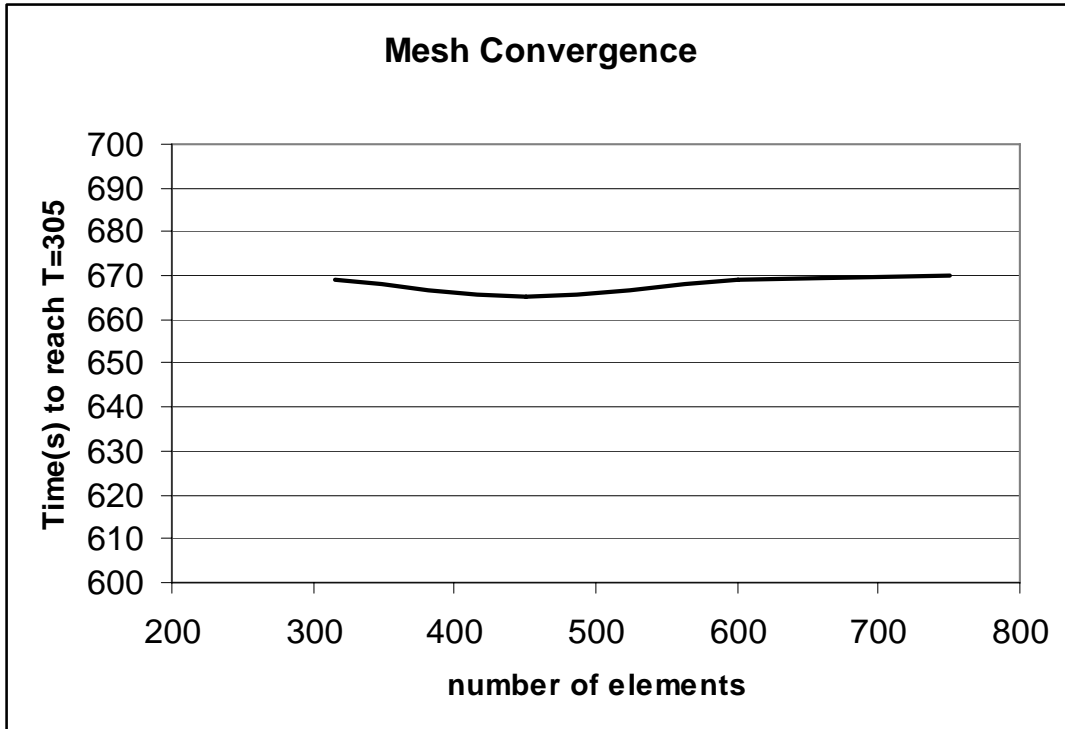
Figure 3. Plot of time taken for core temperature to reach 32 degrees Celsius with increasing number of elements.
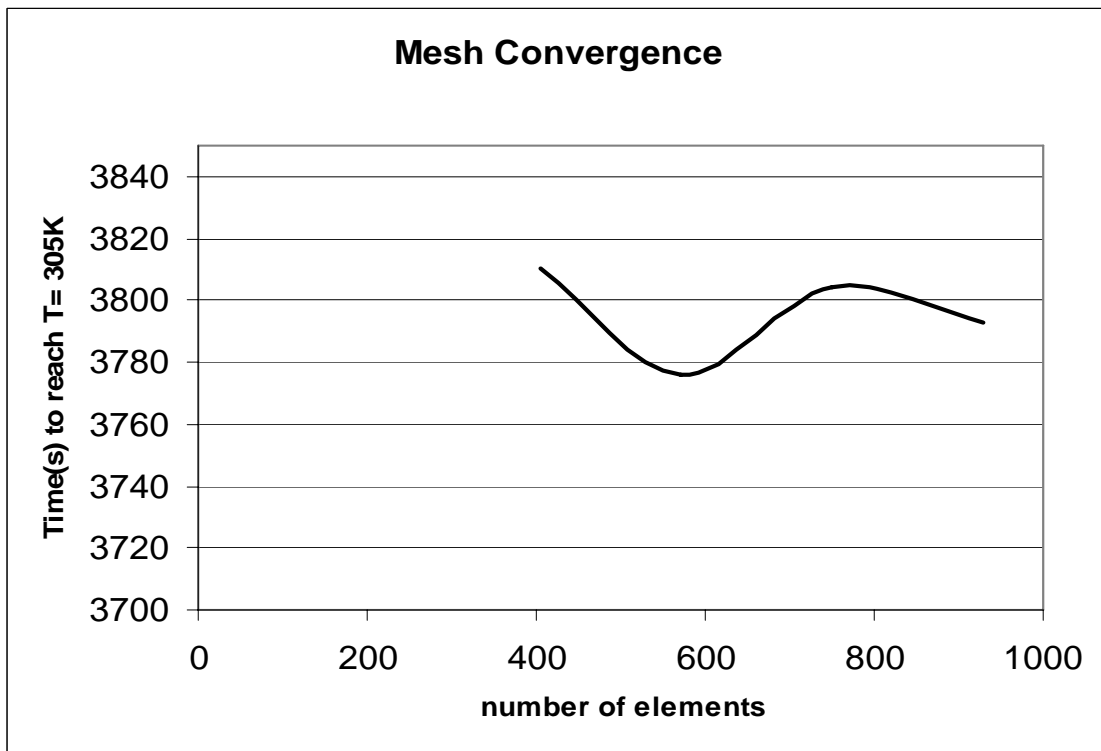
Figure 4. Plot of time taken for core temperature to reach 32 degrees Celsius with increasing number of elements for the case with wetsuit.

For the case without wetsuit, after 700 elements the mesh converged to 670 seconds. For the case with wetsuit, after 900 elements the mesh converged to about 3800 seconds.

Results

       According to our model, if an individual of height 175cm and of weight 70kg stays in cold water of about 10 degrees Celsius the following are the results that we got. In the case without the wetsuit, when the skin is directly in contact with the cold water, the time it takes for the core body temperature to reach the fatal temperature of 32 degrees Celsius is 670 seconds, which is 11.1 minutes, which is shown below.
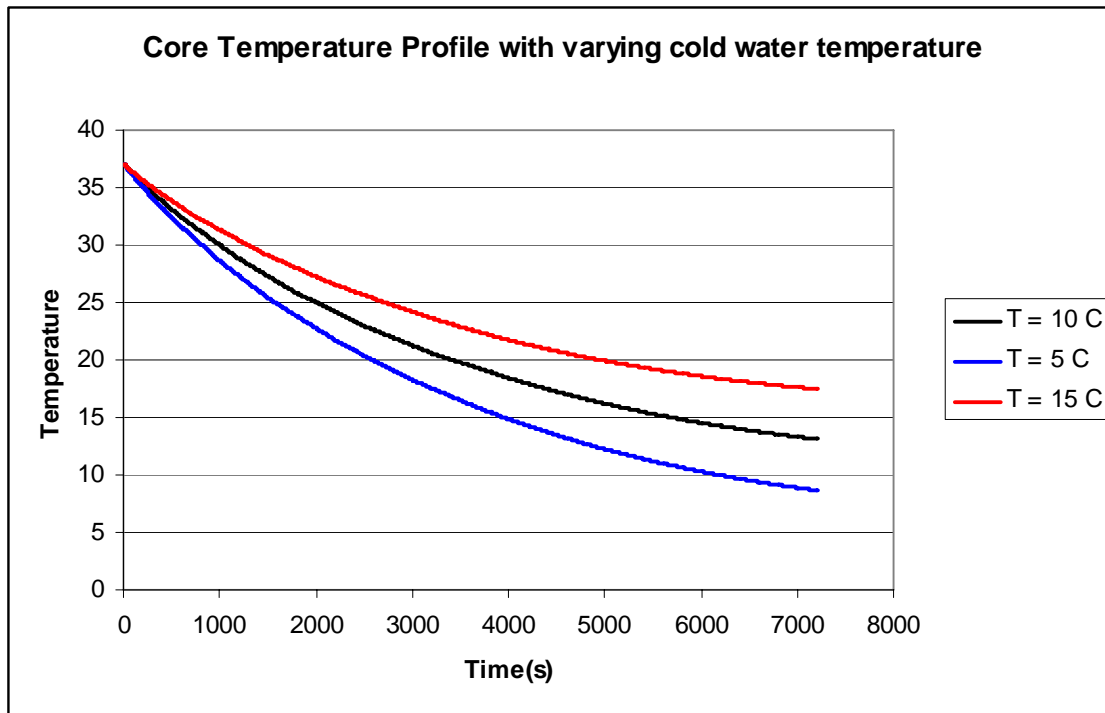

Figure 5. Plot of change in core temperature with varying cold water temperatures of 5, 10, and 15 degrees Celsius in the case without wetsuit.

In the case with the wetsuit, the time it takes for the core body temperature to reach the fatal temperature of 32 degrees Celsius is 3796 seconds, which is 63.3 minutes, shown below.
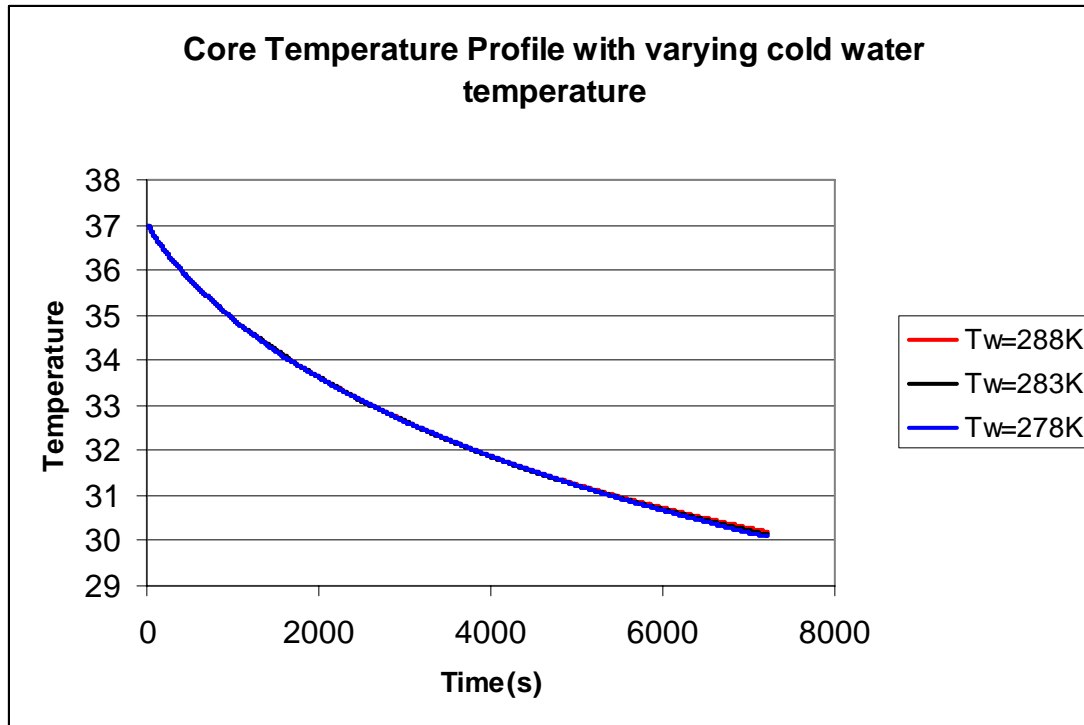
Figure 6. Plot of change in core temperature with varying cold water temperature: 5, 10, 15 degrees Celsius in the case with wetsuit.

Comparing both data, it is shown that to it takes about 50 minutes more to reach 32 degree Celsius for the case with wetsuit than the case without wetsuit. Such difference in time shows wetsuit works as a good insulator in keeping the body heat from dissipating into surrounding water. Thus, when the wetsuit is present, the rate of heat transfer out of the body is slower than when there is no wetsuit. The heat transfer through the wetsuit gives more time of heat generation in the body and heat delivered through blood flow because the wetsuit has low heat conductivity and high heat capacity.

Sensitivity Analysis

It is very important to see how change in heat conductivity affects core body temperature over time. For the change in heat conductivity of the wetsuit, as the heat conductivity increases the change in the core body temperature is higher and reaches lower core body temperature faster as shown below.
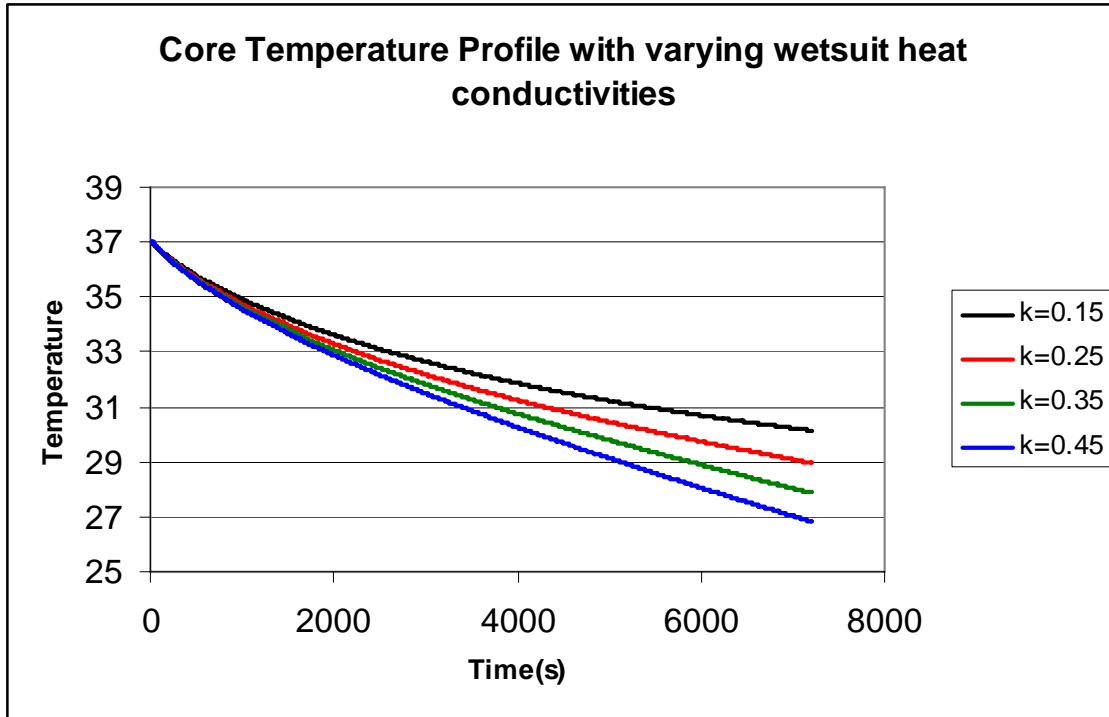
Figure 7. Plot of change in core temperature with varying wetsuit heat conductivity (k = 0.15, 0.25, 0.35, 0.45).

The change in heat conductivity of wetsuit greatly affects the survival time of the passenger, and it is important to wear wetsuit with smaller heat conductivity to extend survival time. Additional sensitivity analyses have been done on change in cold water temperature, body height and weight. For the change in the cold water temperature, in the case without the wetsuit where the skin has direct contact with the cold water, there is sufficient amount of change in the core body temperature. The time it takes for the core body temperature to reach 32 degrees for each cold water temperature of 5,10,15 degrees Celsius is 548, 670, 854 seconds (Figure 5.). However, in the case with the wetsuit, there is not much change in the core body temperature after only 2 hours (Figure 6.), which implies that the wetsuit works as insulation for the body. According to the sensitivity analysis we have done, the height and weight have not much effect on the change in core body temperature in both case without and with the wetsuit (Figure 8.& 9. and Figure 10. & 11.).

Conclusions and Design Recommendations

Design Recommendations

Although our model shows the temperature variations throughout the layers of tissues and core body, we assumed the core body to be a lumped parameter, uniform in its structure. We assumed that organs and bones are considered to be a part of the core body. To make our model more accurate in determining the time it takes for the immersed body to reach

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32 degrees Celsius and below, although very difficult it would be better if we could incorporate organs as well as bones into our model.

Moreover, our model only represents the trunk, and do not consider any other parts of the body. Our model will better simulate the actual human body if the models of the other parts of the body and their correlation with the core body are included. Thus, instead of using just one rectangular geometry, we could design models of other body parts and relate these models with how the core body temperature varies and how the heat is distributed to the various body parts from the core body. Otherwise we could design an axi-symmetric model of the entire body but this will be very difficult to accomplish.

In our model, we had the equation of blood flow rate which takes into account for the blood vessel dilation and contraction due to temperature change. However, in this equation after the core body temperature was lower than 36.8 and the skin temperature was higher than 33.7, there was no change in the blood flow rate. If we could discover an equation that could better describe the blood flow rate change outside this range our current model can be improved.

We could further analyze our model using different kinds of insulation materials such as normal clothing, dry suits or life vests. Thus by comparing the efficiency of other insulation materials with that of the wetsuit we can determine whether the wetsuit is a great insulating material for cold water immersion or find the best insulating material for the human body.

Realistic Constraints

Experiments that deal with the matter of life or death of humans cannot be conducted in real life. Our model if improved can be used to test the survival time and efficiency of insulation materials in the case of the cold water immersion of the human body without any further actual experiments on humans. This model can be responsible for the health and safety of humans.

Appendix A

Governing equations

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial x^2} + \frac{Q}{\rho c_p}$$

The governing equation includes only the conduction and heat generation term without the convection term; since in our model it is assumed that there is no convective heat transfer from the core body/skin layers to the surrounding cold water. The heat transfers only in one direction, and thus, the governing equation is written in terms of x. The heat generation term represents the sum of the heat generated by basal metabolism and the heat delivered by blood flow.

Other Equations used

- Source Term Q = Metabolic Rate + Heat generation from blood flow

- Basal Metabolic rate: $B = \dfrac{b_0 M^{3/4} e^{-E/kT}}{V}$, where B is metabolic rate, $e^{-E/kT}$ is Boltzmann-Arrhenius factor, b_0 is taxa-specific normalization constant, M is body mass, E is activation energy, k is Boltzmann's constant, T is absolute temperature, and V is the body volume.

  - Body Surface Area: $BSA(m^2) = \left(\dfrac{Height \bullet Weight}{3600}\right)^{1/2}$

  - Body Volume: $V = BSA \times 50.6 \times \left(\dfrac{Weight}{Height}\right)^{0.436}$

- Blood Flow: $BF = m_b \bullet C_b \bullet (T_c - T_s)$, where m_b is blood flow rate, C_b is heat capacity of blood, T_c is core body temperature, and T_s is temperature of skin layers. $W_{SIG_{cr}}$ represents the effector controlling signal for vasodilation, and $C_{SIG_{sk}}$ represents effector controlling signal for vasoconstriction. Change in blood flow rate with time is shown in Figure 12.

  - Blood Flow Rate: $m_b = \left(\dfrac{1}{3600}\right) \bullet \left[6.3 + \dfrac{200 W_{SIG_{cr}}}{1 + 0.5 C_{SIG_{sk}}}\right]$

$$W_{SIG_{cr}} = 0 \quad for \quad T_c \leq 36.8$$
$$= T_c - 36.8 \quad for \quad T_c > 36.8$$

$$C_{SIG_{cr}} = 33.7 - T_s \quad for \quad T_s < 33.7$$
$$= 0 \quad for \quad T_s \geq 33.7$$

Initial Conditions

Temperature of the cold water = $10\,°C$
Temperature of the wetsuit = $25\,°C$
Temperature of the core body and the skin layers = $37\,°C$

Boundary conditions

$$\frac{\partial T}{\partial x}\bigg|_{x=0,t} = 0$$

$T_{coldwater,t} = 10\,°C$

The sides are thermally insulated since this model is a one dimensional flow.

Geometric Properties

Table 1. List of geometric properties (thickness) of core body, tissue layers, and wetsuit

Subdomain	Thickness (m)
Core Body	0.15
Inner Tissue	0.03
Subcutaneous Fat	0.01
Dermis	0.002
Epidermis	0.00008
Wetsuit	0.015

Thermal- Properties

Table 2. List of thermal properties, densities, and heat capacities of core body, tissue layers, and wetsuit

Subdomain	Thermal conductivity (W/m K)	Density (kg/m^3)	Heat capacity (J/kg K)
Core Body	0.519	985	3470
Inner Tissue	0.24	1200	3590
Subcutaneous Fat	0.45	1200	3300
Dermis	0.19	1000	2500
Epidermis	0.5	1000	4000
Wetsuit	0.15-0.45	1230	188000

Constants

Table 3. Values of constants used to calculate metabolic rate, and blood flow rate

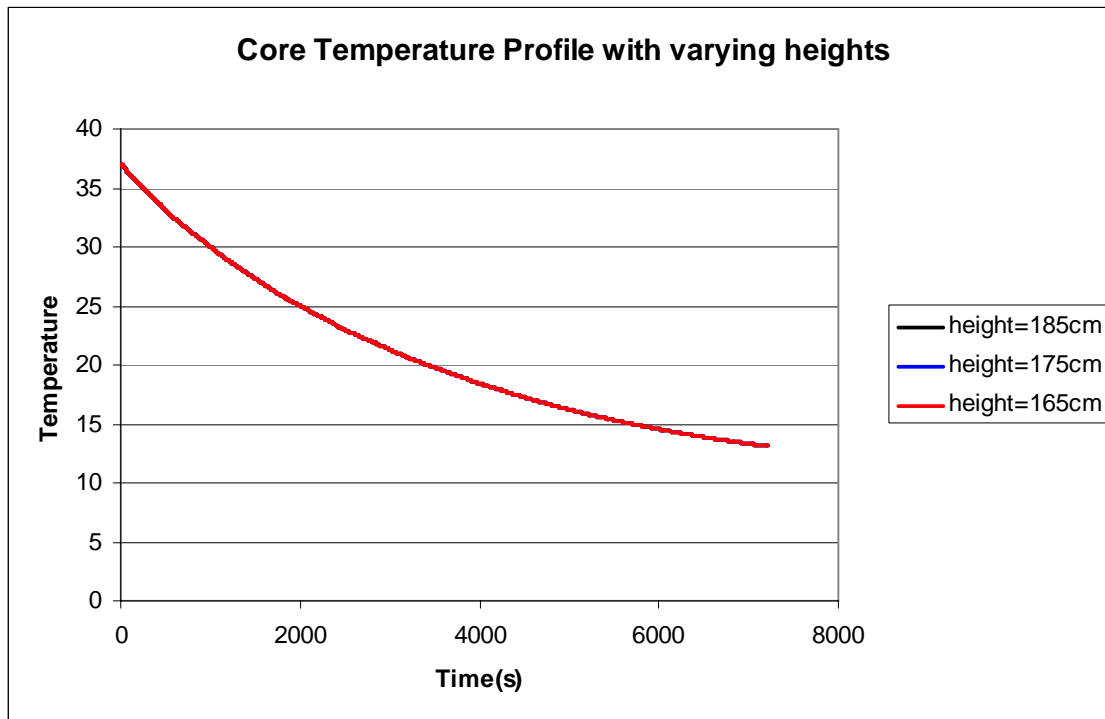| Constants	Value
b_0	3085563081 W/g$^{3/4}$
E	0.65 eV
k	8.62 x 10^{-5} eV/K

C_b	4180 J/Kg K

Appendix B

Figures of Sensitivity Analysis

Without Wetsuit

Figure 8. Plot of change in core temperature with varying body heights: 165cm, 175cm, 185cm in the case without wetsuit.
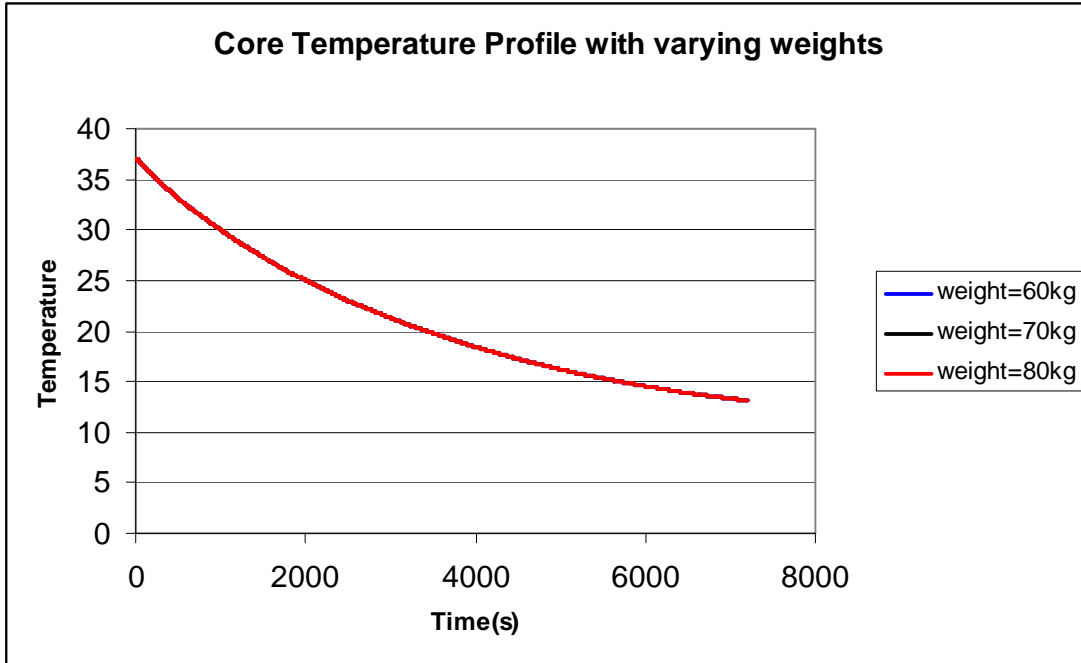
Figure 9. Plot of change in core temperature with varying body weights: 60kg, 70kg, 80kg in the case without wetsuit.
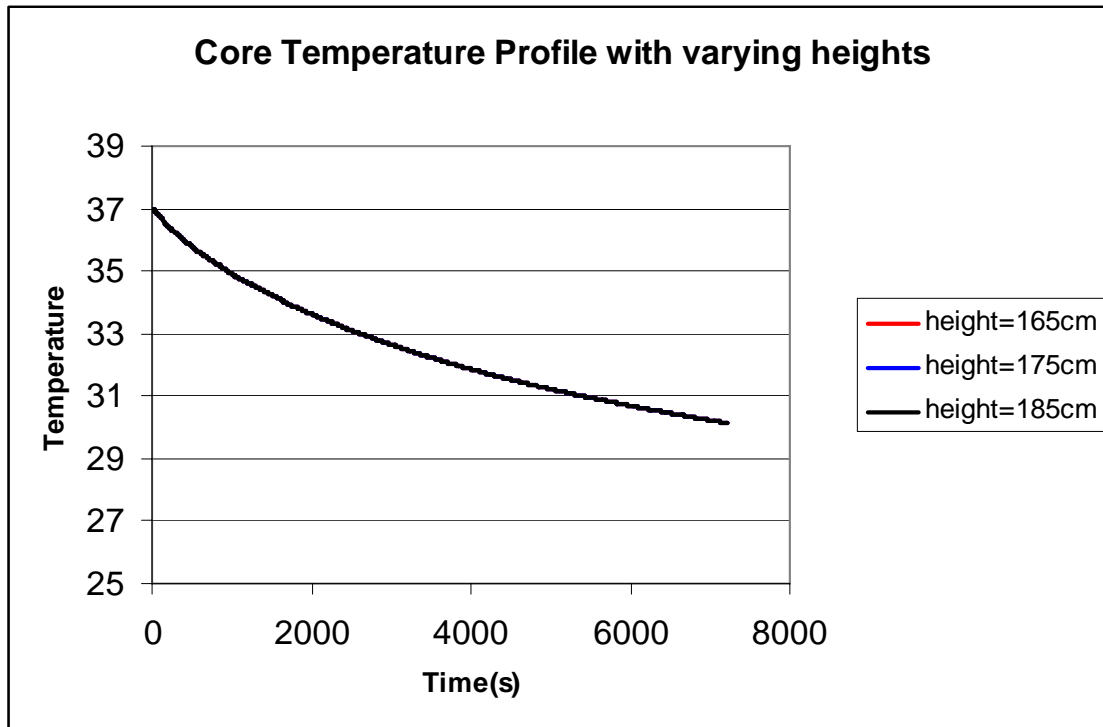
With Wetsuit

Figure 10. Plot of change in core temperature with varying body heights: 165cm, 175cm, 185cm in the case with wetsuit.
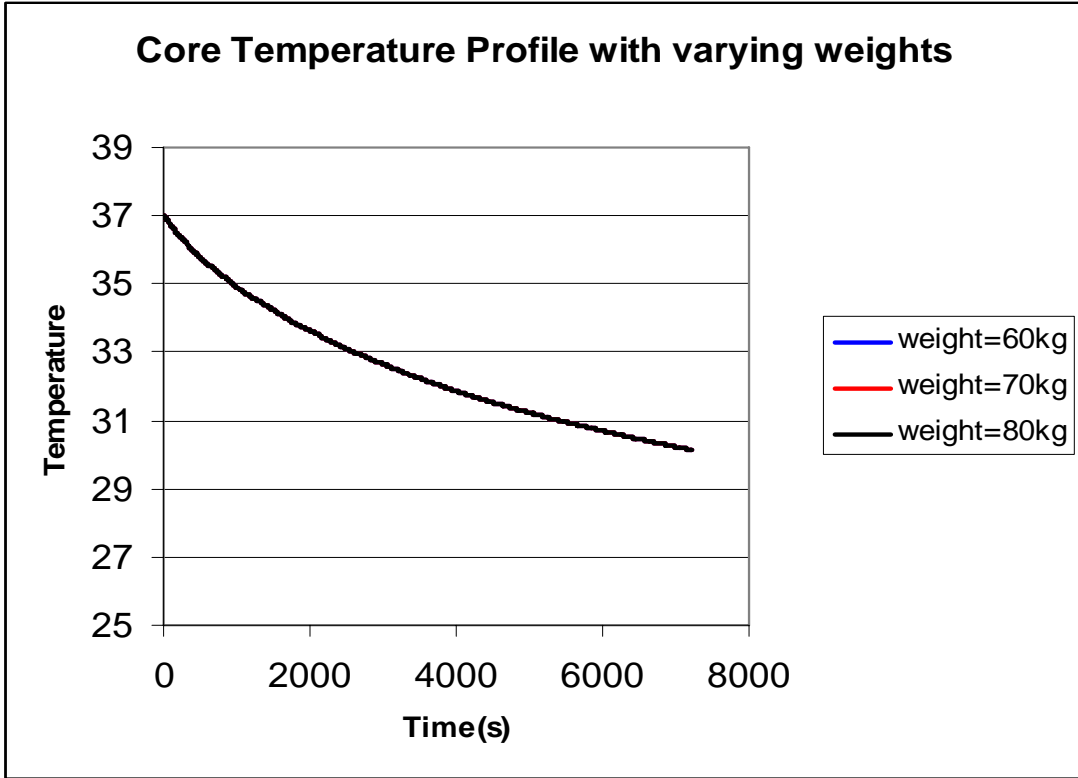
Figure 11. Plot of change in core temperature with varying body weights: 60kg, 70kg, 80kg in the case with wetsuit.
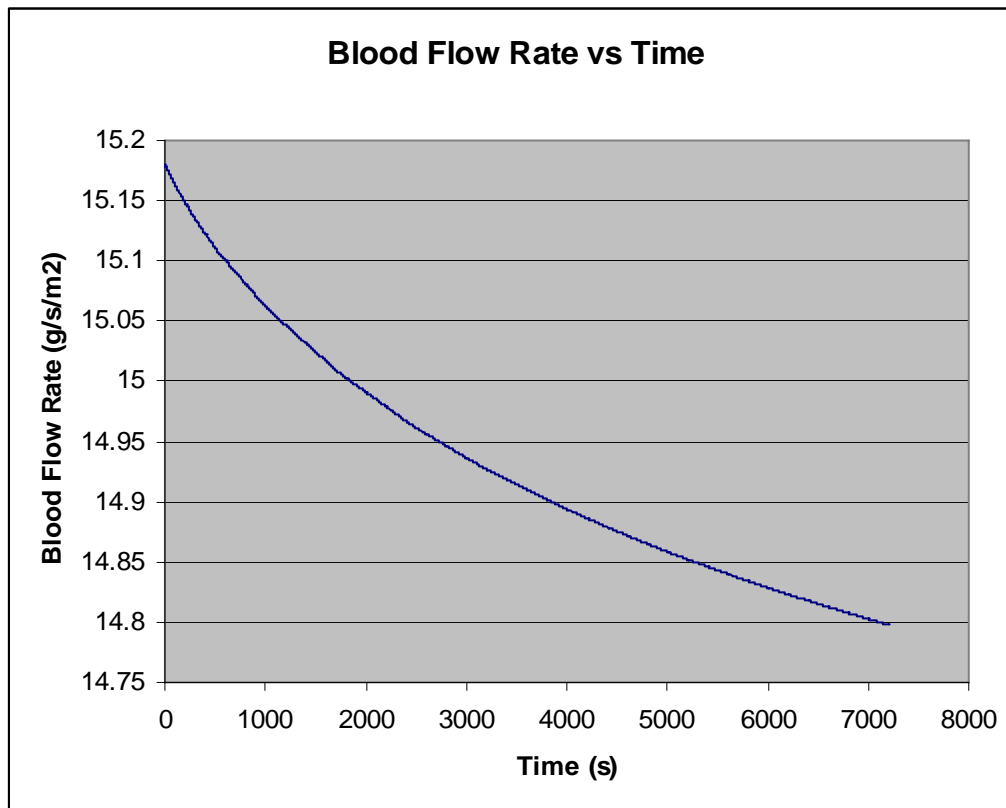
Blood Flow Rate

Figure 12. Change in blood flow rate with increase in time. The blood flow rate decreases as time increases. Blood is cooled down as the temperatures of core body and tissue layers decrease.

Appendix C

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