Comparing a Finite Element Analysis Model to Various Existing Mathematical Models to Describe Heat Transfer Within Recent Post-mortem Human Bodies

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Abstract

Points of a dead body cool at different rates. This phenomenon was described in Scientific Literature ([1], [2], [3]) and helped conceptualize the specific process of cooling to create an ANSYS simulation to quantify how fast a body cools in different thermal environments. In 12-hour cooling periods with varying environment temperatures (10C, 20C, 30C) and convective heat transfer coefficients ($6\mathrm{W/m^2C}$ and $10\mathrm{W/m^2C}$), It was found that a higher air temperature linearly increased the average temperature of the post-mortem body after a 12 hour period, and lower convective coefficients resulted in a higher average body temperature after the 12 hour period.

Introduction

The problem

The primary question asked "Quantitatively, how fast does a body cools in different thermal environments"? and to compare our predictions with literature expectations from other researchers [1,2].

Background Literature

To gain a better understanding of the concepts at hand it was important to understand the scope of existing literature and documentation made to quantify the rate at which a dead body cools.

Brown and Marshall's article [1] explains that the sigmoid shape of the cooling curve of the human corpse is derived from an interpretation of Newton's Law of Cooling. Newton's Law of Cooling is a concept that has been used to estimate time of death given the current temperature of the body. Brown notes that Newton's Law of Cooling is only valid under certain circumstances and that often times there are too many variables that affect the time for any semblance of an accurate estimate.

Newton's Law of Cooling states that "The rate of loss of heat from a surface of a solid body to the surrounding fluid is directly proportional to the difference in temperature between the surface and the fluid". Newton's Law of Cooling can be represented by the equation (I):

$$q = hA(T_s - T_f) \tag{I}$$

Where q is the heat transfer rate from the surface of the body, h is the heat transfer coefficient from surface to fluid, A is the surface area, T_s is the surface temperature of the body and T_f is the bulk temperature of the fluid which can be a liquid or a gas, moving or stationary.

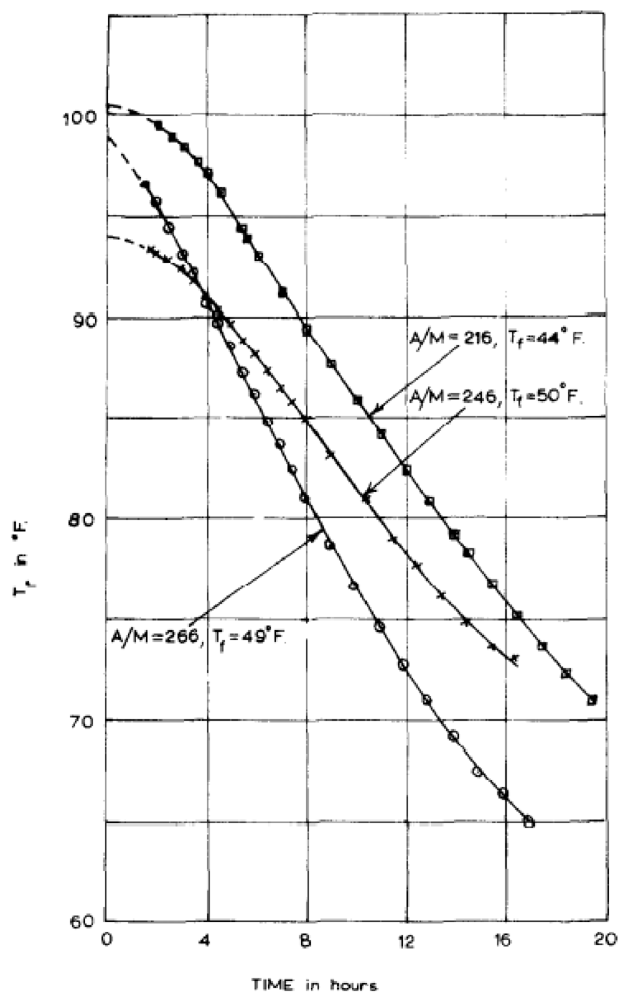
The varying heat resistivities within a dead body as it cools does not make Newton's Law of Cooling appropriate for this application. Temperature of the skin will be different than say the rectal temperature, at varying points in time as the body cools. The heat transfer coefficient is not constant through out the body and the resulting rate of heat transfer of energy from the body into the surrounding environment is not constant either.

The actual trend of the body is a slow cooling rate during early post-mortem period. This is most likely because of the thermal conductivity and thermal capacity of the human body. As surface heat is lost, heat is transferred to the surface from the internal organs of the body by conduction. However, convection is the means of heat transfer that removes heat from the layers of the skin.

Such behaviors of heat transferring through the body by layer results in a temperature gradient, where temperatures are still relatively high in the center of the body and dissipate to cooler temperatures as the point of reference becomes closer to the outer surface of the body, and generally cooler points around parts of the body that carry less mass—i.e. hands, legs, arms, etc.

Brown says that such gradients can allow the body's central core to lose little heat for 3-5 hours after death. Various equations termed "cooling formulas" were then listed to describe the heat gradient of a cooling body.

When graphed:



Graph 1: Sigmoid shape of cooling curve of various mathematical models of dead bodies [1]

Graph 1 shows various curves depicting bodies of varying compositions (fat, thin, average), with rectal temperature on the left, and time after death on the right. A sigmoid shape can be described where temperature is slow to decrease after about 1 hour before becoming a negatively trending curve.

In the ANSYS simulation we can expect to see a similar sigmoid curve for respective analysis.

Hennsge's article [2] gives a report on the development of a time of death nomogram, coined "The Nomogram Method". This method is based on a single measurement of the rectal temperature obtained immediately at a scene of a crime. This method also includes documentation for practical application of the method and data for the accuracy of estimated death time, again resulting in a sigmoid shape. The article does give a discussion on "Special Problems" that limit accuracy of the model.

Problems include any variation of the ambient temperature affecting the rate at which the body cools, and with temperatures above 23 degrees C.

Knight's article from 1988 [3] describes various concepts and techniques to estimate time since death. The article debates the accuracy of using initial temperature as a viable means to estimate time since death.

With different measuring sites, under varying environmental conditions, a separate paper summarized by this article stated issues with accuracy with higher environmental temperatures and extended measurements post-mortem.

The Why

Technology and computer software in 2021 allows students to recreate complex environments where recent post-mortem bodies may be found.

Conditions such as air temperature, metabolism (body heating), effect of clothing, and skin all influence the rate of cooling of a dead body and can be taken into account to create a simulation more realistic than the extent of the above studies ([1], [2], [3]).

Varying environmental changes can be simulated via time steps at which temperature of the environment can be changed. Other conditions can also be changed, like how the body interacts with the environment and if there are elements like wind involved.

This team is contributing efforts to build a basic simulation that consists of 6 different trials of varying convective coefficients. If the results of the simulation align well with previously mentioned research, this paper can serve as a proof of concept to encourage further exploration for quantifying cooling of a post-mortem body via finite element analysis.

Modeling

Computer Simulation-ANSYS

A finite element analysis tool, ANSYS, was used to virtually simulate and determine the temperature of a freshly deceased body after a period of time. A CAD model of a human body was provided by our course instructor, Professor John Abraham.

The CAD file was uploaded into ANSYS where boundary conditions were applied to simulate properties of a freshly deceased body and the surrounding environment. Once the respective boundary conditions were plugged into ANSYS, "steady-state" simulations were run before inputting resulting values to create an "unsteady transient" simulations.

The steady state simulation was performed to find the initial temperature of the body at time of death. Once this initial temperature was found, the unsteady transient simulation was calculated.

Steady and unsteady simulations had 1 “domain” and 2 “boundary conditions”. The “domain” was the entire body. “Boundary conditions” assumed convection where heat could transfer everywhere except the head and wrist. Finally, the “boundary condition” to describe metabolism was again the entire body.

A closer analysis on the boundary conditions and phenomena's will be discussed in the following section.

Boundary conditions

Steady State Boundary Conditions:

Steady state analysis was performed in order to find the initial temperature in which the body died at.

Convective boundary: To incorporate the effect of clothing into the scenario, a convective coefficient was factored in. Prior to death, the effective convective coefficient was set at 1.2 W/m^2/C. In addition, the temperature of air surrounding the body at the time prior to death was 20C.

Metabolism boundary: To incorporate the effect of heat generation within the body, a metabolism value was set at 27.5 Watts.

Unsteady State (transient) Boundary Conditions:

Unsteady state was done in order to compare the dead body’s temperature throughout a 12-hour period at a variety of varying temperature and clothing options.

Convective boundary: After death, in all 6 cases the convective heat transfer was set at either 6 W/m^2/C r 10 W/m^2/C. The temperature in all 6 cases was manually set at 37.1C. This temperature was given by Dr. Abraham, but from our own steady state simulation we had gotten the value 310.195K (37.045C) seen below in Figure 1.

Metabolism boundary: After death, in all 6 cases the metabolism was value was set to 0 Watts. This value makes sense since after death, the body is no longer producing energy.

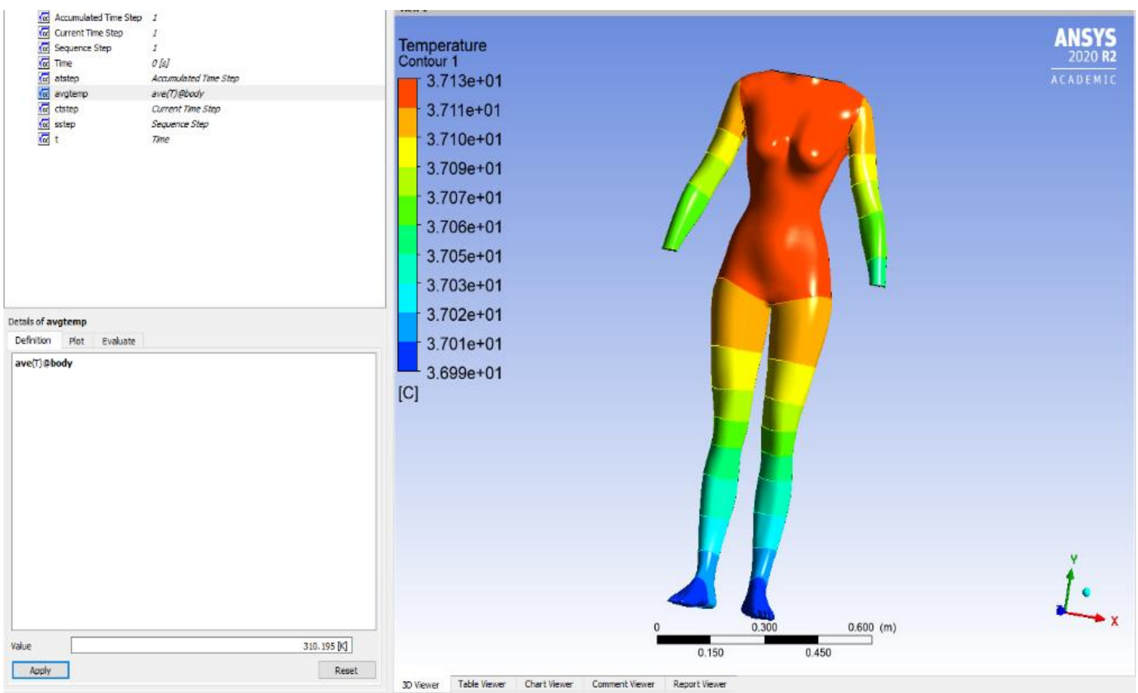


Figure 1: Ansys screenshot of Steady State simulation. The average temperature value was found to be 310.195K.

For this steady state simulation, the average temperature value was found to be 310.195K, with decreasing temperature ranges as the point of reference moves from the torso of the body out towards the arms, legs and feet.

Before plugging this temperature value into an unsteady simulation, it was necessary to define the properties of the body itself to simulate variables of tissue and clothes for different convective coefficients.

In both cases, a new material was created, set and labeled “flesh”. The properties used in ANSYS to create the material included Specific Heat and Density shown in Table 1.

Table 1 – Properties of living and non-living tissue

Property	**Living**	**Non-living**
Thermal Conductivity (W/m/C)	10	0.5
Specific Heat (J/kg/C)	3600	3600
Density (kg/m^3)	1000	1000

As was previously stated, in the unsteady simulation, metabolism was set to zero and the initial temperature was manually set at 37.1C. The program thereafter was run 6 times at varying cases for convective coefficients and air temperatures over a 12-hour simulation time length with 4 timesteps.

This particular time step number was chosen in order to provide temperature ranges at different periods of time over 12 hours in order to compare the resulting information to relevant literature.

A definition of the properties for each of the 6 simulations are shown in Table 2 below.

Table 2 – Property table for unsteady cases

Case	Air Temperature (C)	Convective Coefficient (W/m^2C)
1	10	6
2	10	10
3	20	6
4	20	10
5	30	6
6	30	10

Unique Phenomena

We are taking this real-world problem and making many assumptions in ANSYS resulting in unique phenomena. Assuming values of thermal conductivity from Table 1 is not “exact” per say because they are not measured from a real-life scenario. The meshing of the model can also result in how heat transfers throughout the body. Collection of heat at unwanted points of the mesh may result in unique phenomena that would not be seen in real life.

Governing Phenomena

The governing phenomena in this simulation focused on the reproducibility of the steady state simulation. Without an accurate initial temperature there would be issues arising in the unsteady state simulation, so an initial temperature of 37.1 degrees C was assumed.

Accuracy of Simulation

The mesh for both unsteady and steady state cases can be visualized in Figure 2 below. The value used in this simulation was a 7.0×10^{-2} m with capture curvature enabled.

Choosing a finely refined mesh is usually ideal, but issues arise when too many elements slow down computation. This model simplified computation by removing complex geometries of the head, hands, and curvature that would exist on a more defined model. A mesh that further simplifies these smoothed-out contours has it's limitation in terms of accurately depicting real-life anatomy and heat transfer as a result.

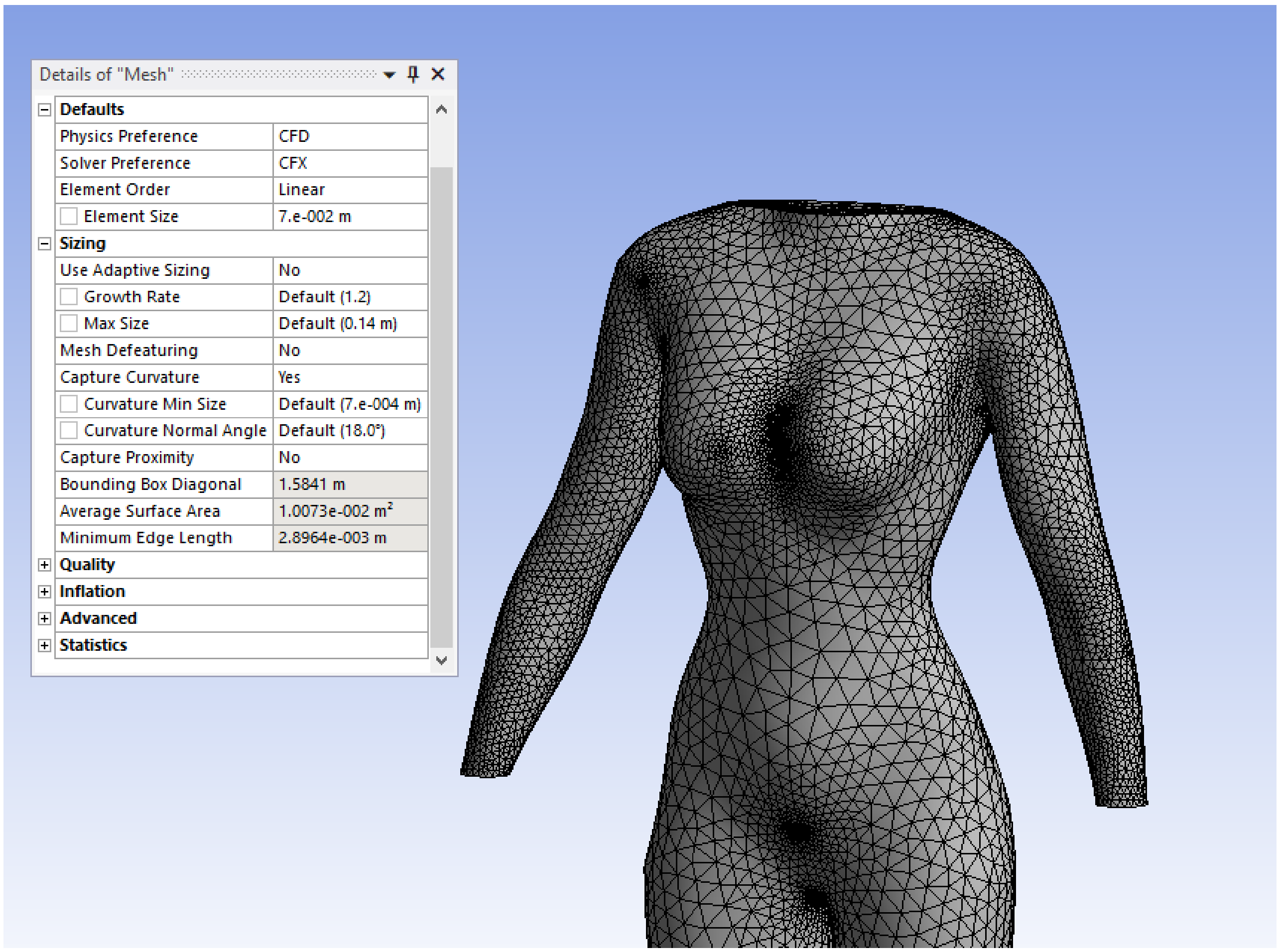


Figure 2: Meshing of the 3D Model

In addition to having a more defined model and refined mesh, the number of time steps for the unsteady simulations could have been increased for higher accuracy. More time steps would smooth out resulting graphs that compare heat transfer to time step and improved averages for heat of the body after 12 hours for each simulation.

Modeling Errors

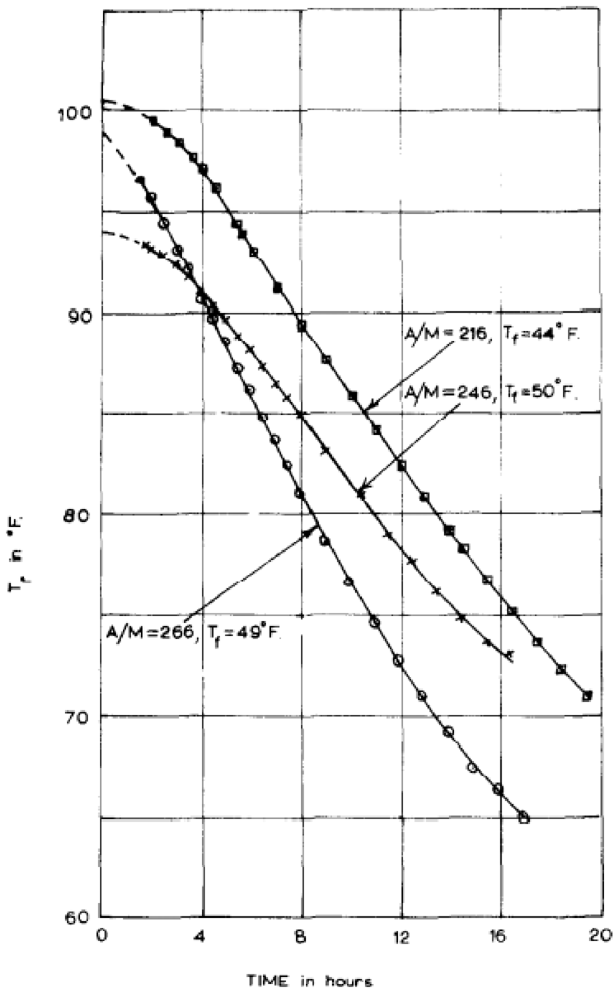
The model used in the simulation is static and unmoving. In real-life, a dead body might be bent and moved over time--not perfectly positioned for 12 hours as this simulation depicts. An additional modeling error is the use of a single value for the entire body's convective coefficient. The convective coefficient was meant to represent clothing, which is great, but a dead body is not dressed in a single piece of clothing with an identical convective coefficient throughout the entire body.

Ideally, convective coefficients would have accounted for irregular layers of clothing throughout the body, and anatomical variations such as, body hair, layers of muscle tissue, bones, oils, and other fluids that exist within the body.

These simplifications limit the realism of the simulation, but the proof of concept to simulate the trend of temperature of a post-mortem body still stands.

Results and Discussion

The first point of discussion centers around a comparison between aforementioned studies and ANSYS results. Graph 2 [1] is reshown below and then compared to various time step graphs.



Graph 2: A reiteration of Graph 1 that details the sigmoid shape of cooling curve of various mathematical models of dead bodies [1]

Parameters of the following time step curves that measure temperature of the body vs. time don't exactly match parameters of Graph 2, so it is difficult to make accurate comparison in that sense. What is important to note is the shape of the trendline for each case and how it compares to Graph 2.

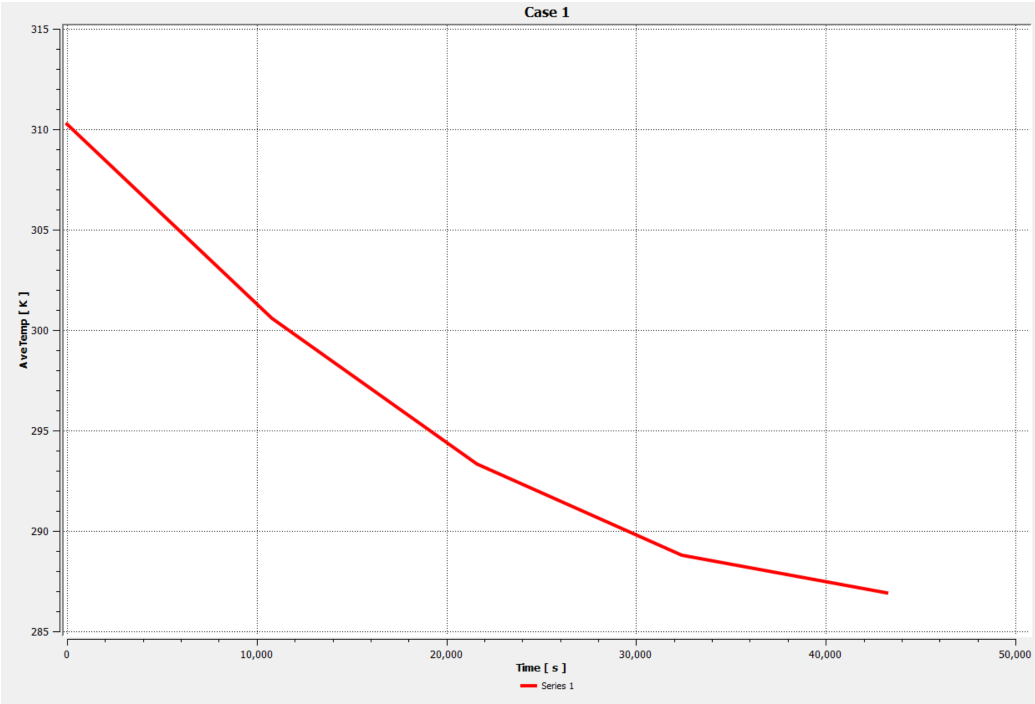


Figure 3: Case 1 parameters are such that $T_{initial}$ is 37.1 C, T_{air} is 10 C and convective coefficient is 6 W/m^2-C.

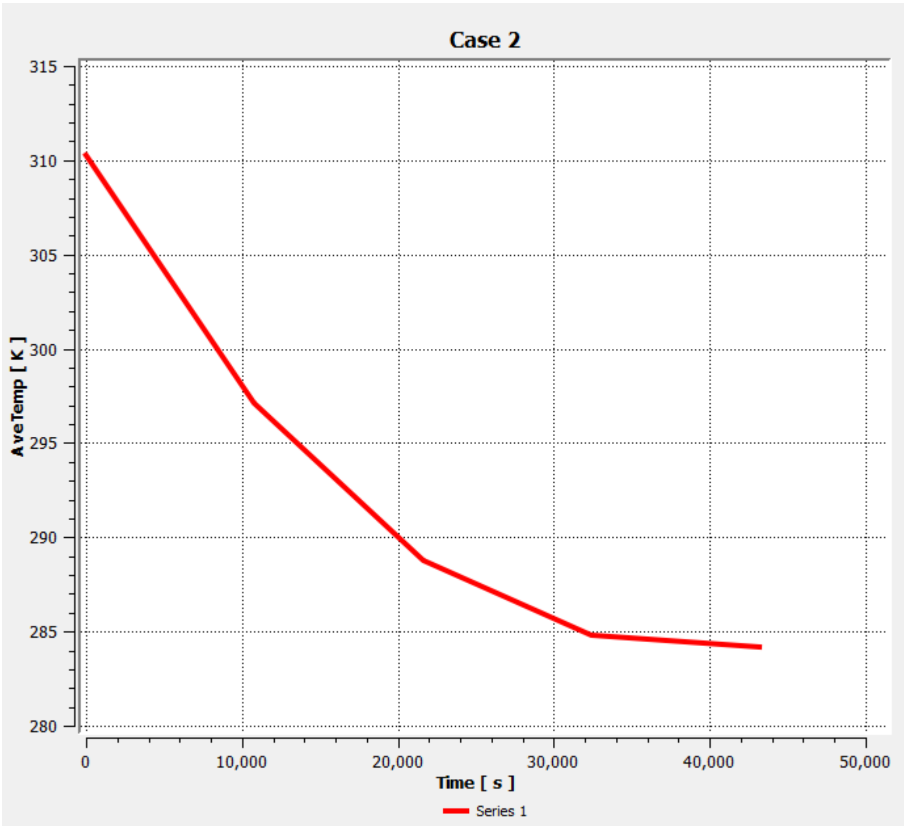


Figure 4: Case 2 parameters are such that $T_{initial}$ is 37.1 C, T_{air} is 10 C and convective coefficient is 10 W/m^2-C.

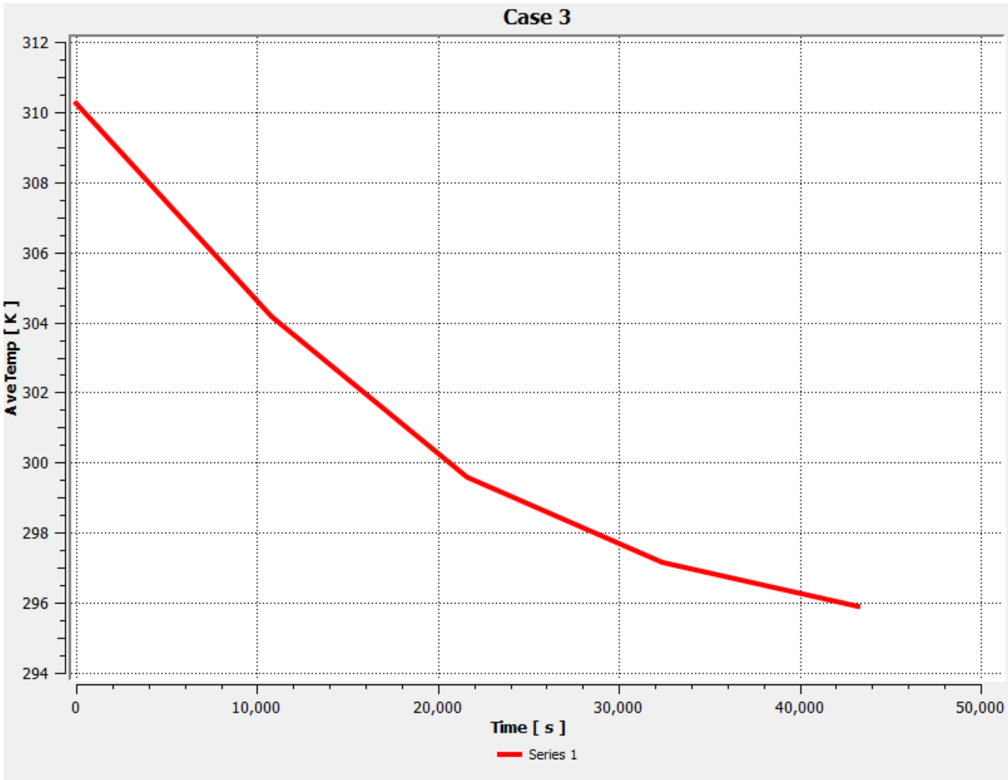


Figure 5: Case 3 parameters are such that $T_{initial}$ is 37.1 C, T_{air} is 20 C and convective coefficient is 6 W/m^2-C.

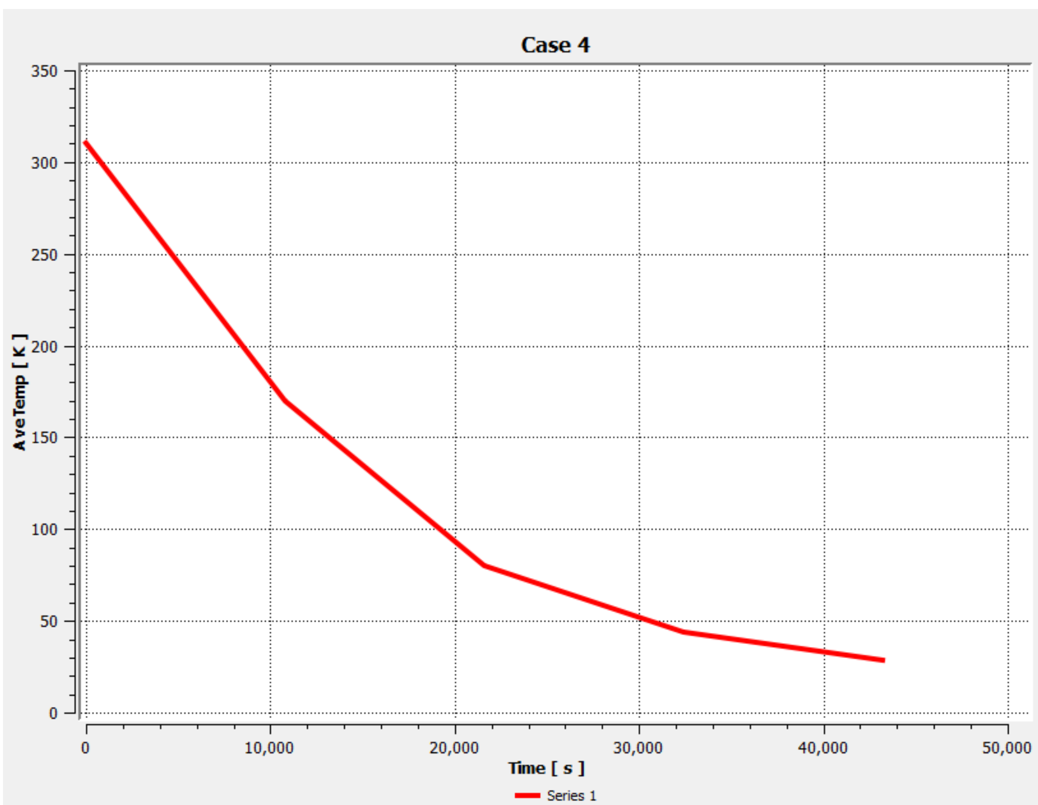


Figure 6: Case 4 parameters are such that $T_{initial}$ is 37.1 C, T_{air} is 20 C and convective coefficient is 10 W/m^2-C.

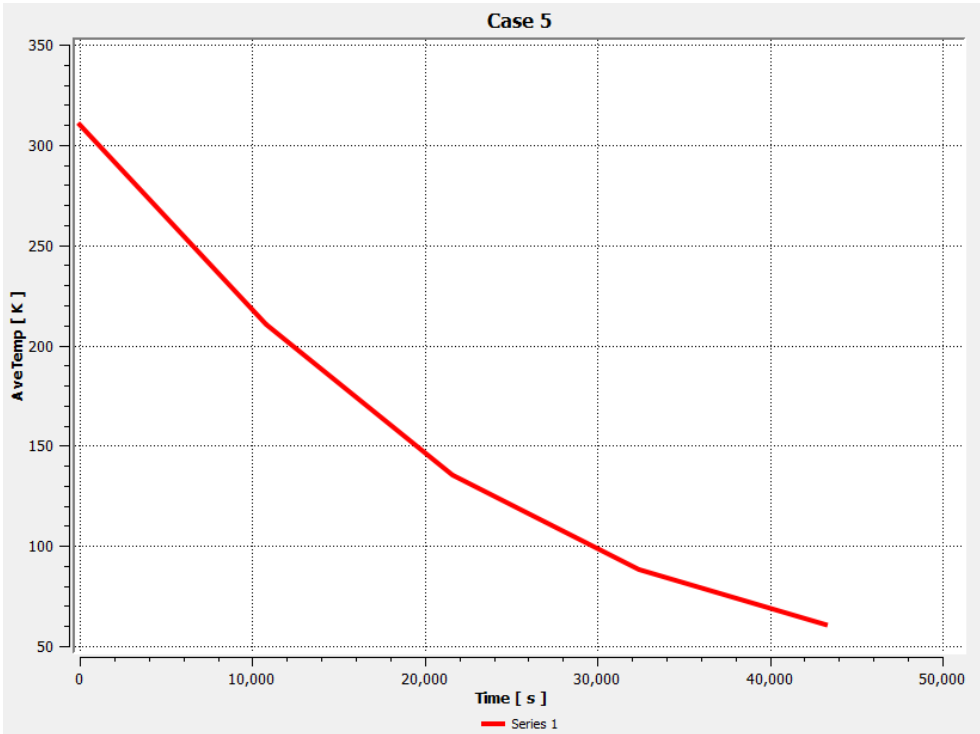


Figure 7: Case 5 parameters are such that $T_{initial}$ is 37.1 C, T_{air} is 30 C and convective coefficient is 6 W/m^2-C.

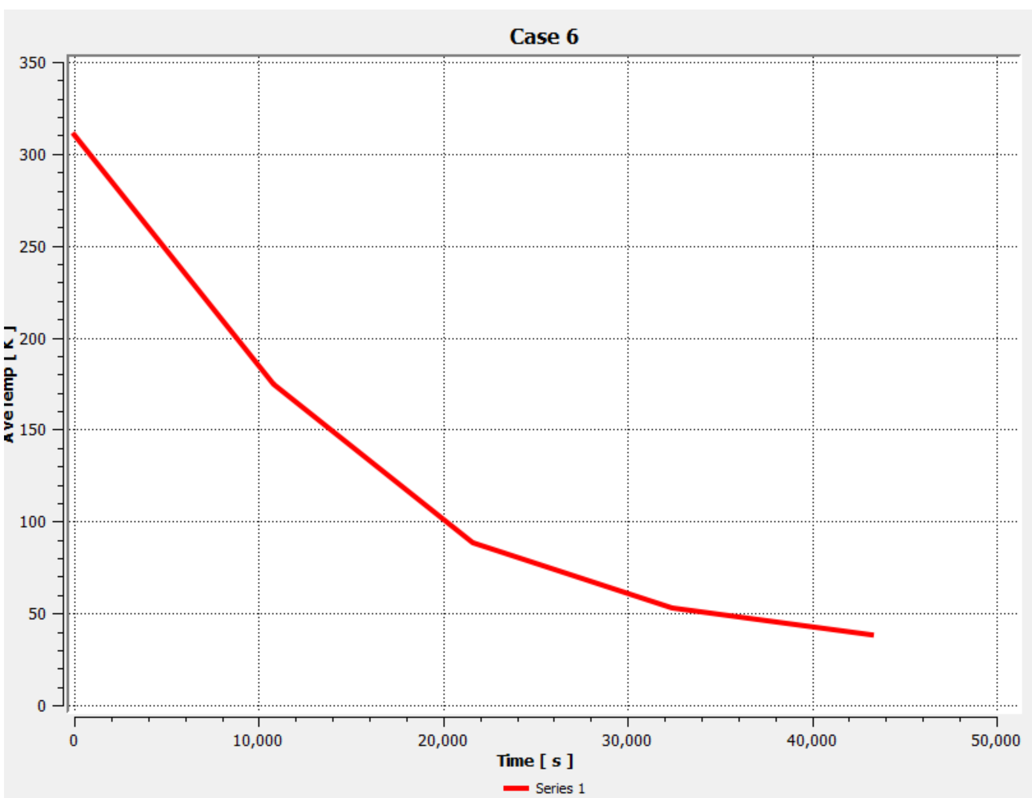


Figure 8: Case 6 parameters are such that $T_{initial}$ is 37.1 C, T_{air} is 30 C and convective coefficient is 10 W/m^2-C.

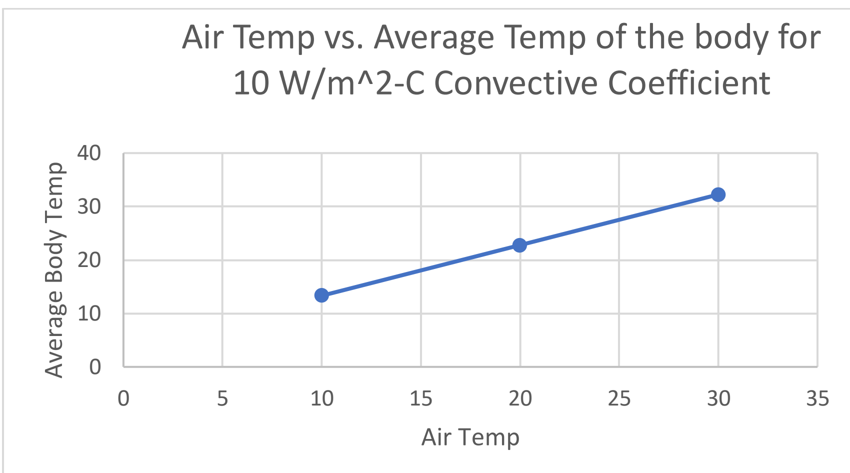
As shown from figures 3-8, experimental temperature change over time trends downward, from a high $T_{initial}$ of 37.1 to near ambient temperatures after the 12 hour period. The initial curve from figures 3-8 match the literature referenced trend of temperature dropping over time (Graph 2), though this particular essay being compared [1] had time only going to 8 hours, and not 12 like with the experimental ANSYS simulation.

The next point of discussion compares the average temperatures of each body after 12 hour periods and argues that within the simulation, ambient air temperature has a greater effect on body temperature after a 12 hour period than convective coefficient does.

Table 4: Average temperature of the Body in Degrees C for Cases 1-6

Case	Air Temperature (C)	Convective Coefficient (W/m^2C)	Average Temperature of the Body (Degrees C)
1	10	6	18.12
2	10	10	13.34
3	20	6	26.39
4	20	10	22.74
5	30	6	34.22
6	30	10	32.28

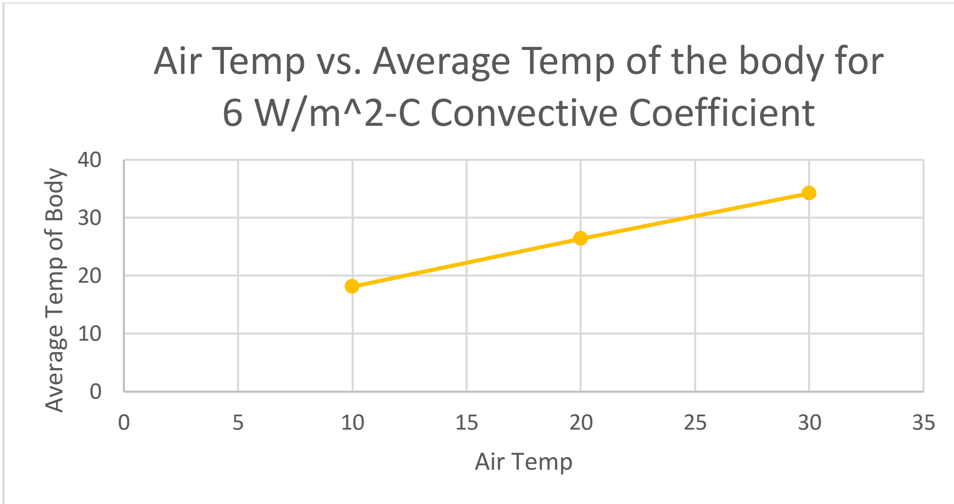
By utilizing data from Table 4, cases were grouped by convective coefficients. Graphs 3 and 4 plot Average Temperature of the Body versus Air Temperature when the convective coefficient is 10 and 6 W/m^2-C.



Graph 3: Air temperature versus the average temperature of the body when the body has a convective coefficient of 10 W/m^2-C.

The upward trend of the curve in Graph 1 and intersection of the points at the trendline show that for a convective coefficient of 10 W/m^2-C, the average body temp increases as well. Physically, this means that as the temperature of the environment increases, the body is likely to match that temperature after 12 hours.

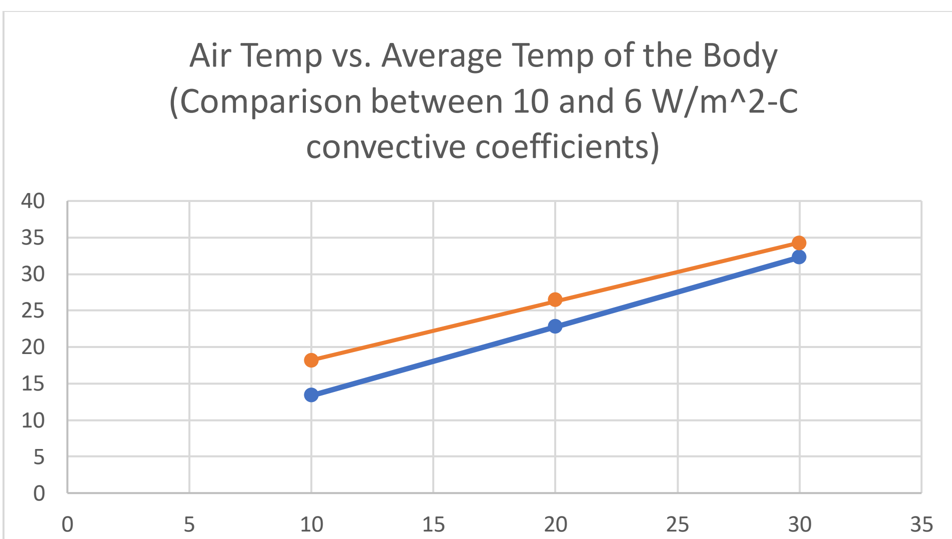
Similar trends can be found for when the convective coefficient of the simulation is 6 W/m^2-C in Graph 4.



Graph 4: Air temperature versus the average temperature of the body when the body has a convective coefficient of 10 W/m^2-C.

Similarly, the upward trend of the curve in Graph 2 and intersection of the points at the trendline show that for a convective coefficient of 6 W/m^2-C, the average body temp increases as well. Physically, this means that as the temperature of the environment increases, the body is likely to match that temperature after 12 hours.

To compare the difference of heat loss between convective coefficients, Graphs 3 and 4 were overlayed. The small difference in body temperatures between 6 and 10 W/m^2-C at each environmental temperature supports the claim that ambient air temperature has a greater effect on body temperature than convective coefficient does.



Graph 5: Air temperature versus the average temperature of the body when the body has a convective coefficient of 10 W/m^2-C (blue line) and 6 W/m^2-C (orange line)

From graph 5, it is apparent that the blue trend line sits lower than the orange trend line. This means that on average, the temperatures of the body with a higher convective coefficient are closer to the given environments. From this data, it is possible to infer that bodies with higher convective coefficients do not hold onto heat as well as bodies with lower convective coefficients.

In general, objects with respectively lower convective coefficients are more insulating than objects of higher convective coefficients. Within the scope of a post mortem body, a lower convective coefficient body will hold onto heat better than a body with a higher convective coefficient. Relevant literature points to the variability of temperatures at different areas of a post mortem body. A range of temperatures is expected, though the literature did not go so far as to describe what temperatures might be found where and how the shape of certain body parts might affect where the body might hold on to more heat.

With ANSYS, we are able to view the temperature gradient of the body within each scenario and visually see how heat leaves a post-mortem body within different environments. The following image represents the body at progressive time steps, where the current state of heat distribution is captured in 3 hour time increments. With each time steps, notice how the color changes from green to turquoise, then to light blue, and then finally dark blue, as the body cools over 12 hours.

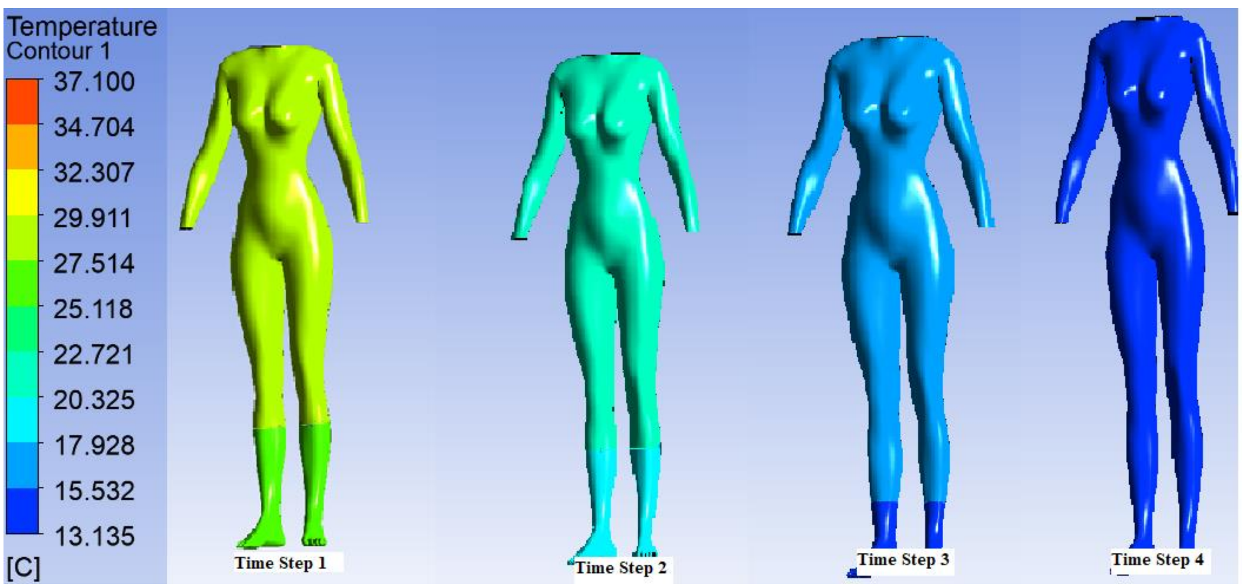


Figure 9: ANSYS images for each of the 4 time steps as heat distribution changes within the body for Case 1.

Qualitatively, we can use the contrast maps to better understand how heat leaves the body over a period of time. It's important to note that in all figures, body parts of larger mass like torso still hold lots of heat compared to the upper thighs, which still hold more heat that even smaller body parts like the arms and feet. Assumptions made with the removal of the head and hands reduced the complexity of the simulation, but temperature gradients as mentioned in literature are still being recreated.

Concluding Remarks

The goal of our project was to quantify how fast a death body cools in varying thermal environments (temperature and heat transfer coefficient) and compare our results with literature expectations from other researchers ([1], [2], [3]].

Key results showed that both convective coefficient and air temperature in the case of a dead body cooling play an important role in figuring out the time of death. The literature does not exactly match our results exactly given the constraints of inexperience in ANSYS. ANSYS is a powerful tool, with experience we can expect to consider the various complexities of the human anatomy and create a more reliable model of temperature of a recent post-mortem body.

References:

[1] Henssge, C., Death time estimation in case work. I. The rectal temperature time of death nomogram, Forensic Science International, Vol. 38, pp. 209, 236, 1968.

[2] Brown, A., and Marshall, T.K., Body temperature as a means of estimating the time of death, Forensic Science, Vol. 4, pp. 125-133, 1974.

[3] Knight, B., The evolution of methods for estimating the time of death from body temperature, Forensic Science International, Vol. 36, pp. 47-55, 1988.