Finite Element Modeling of Thermal Regulation in Extra Vehicular Activity

Rohit Biswas, Emma France, Mihir Paradkar, and Zach Woods

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Department of Biological and Environmental Engineering
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CONTENTS

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Astronauts perspire heavily during the strenuous exercise of Extravehicular Activity (EVA), and previous literature has expressed concern that this may negatively impact the ability of the LCVG to maintain thermal comfort. However, thorough testing of EVA suits on Earth is nearly impossible due to difficulty in replicating the harsh conditions of space. This project strived to alleviate the necessity of physical simulation with a computer-based model using the software package COMSOL.

The model was designed to simulate the fluid and heat transfer dynamics in EVA suits. In particular, we examined the suit's Liquid Cooling and Ventilation Garment (LCVG), an inner layer of fabric and coolant tubing that regulates astronaut body temperature. We modeled leakage of perspiration into this fabric layer, creating space- and time-dependent heat flow properties in the system. We used both a 2D simplified geometry and a realistic humanoid 3D geometry to balance physical accuracy requirements with available computational power.

We show that skin temperature in anatomical locations of heavy perspiration varies more than in drier locations. We also show that the skin surface temperature is maintained at a comfortable level by the LCVG even during swings in levels of external radiative heating. Finally, we show that a varying metabolic rate corresponds to variations in skin temperature with time.

Skin surface temperature and its control have implications for both astronaut comfort and LCVG efficiency. We have shown that it is possible to study the effects of various parameters on skin temperature using a simple finite element model. This enables safer and more comfortable suit design without the undue time, cost, and complexity of full physical testing. We have also shown that the effects of perspiration can be consequential, and are worth exploration in further research.

I. Introduction

A. Background

EVER since humanity has had the audacity to venture into space, we have required protection from its elements. Commonly known as a spacewalk, Extra-Vehicular Activity (EVA) is often required of astronauts both for exploration and for maintenance and repair of space vehicles. During any spaceflight mission, astronauts operating outside the regulated environment of the spacecraft require the use of a space suit. These activities range from basic scientific research to vital spacecraft repairs needed to continue missions and ensure astronaut safety. This suit must protect the astronaut from the many dangers associated with extraterrestrial travel including extreme temperatures, low pressure, high levels of radiation and abnormal gas composition. The first spacesuits used in 1965 were crude, but Russian cosmonaut Alexei Leonov proved their effectiveness as he became the first man to walk in space [1]. Space suits today have vastly improved life support systems with increased astronaut comfort and flexibility needed to perform extended EVAs. However, efforts to improve space suit performance are ongoing as we intend to travel farther to Mars and beyond.

B. Previous Work

With the help of NASA, researchers have utilized numerical simulation and modeling to optimize LCVG control systems needed to maintain a constant body temperature [2]. While these works have examined the regulation of body temperature under varying metabolic rates, they either neglect or make general assumptions about the effect of perspiration on skin temperature and thermal control systems. Another study used a Wissler model of thermoregulation to monitor skin temperature, metabolic rate, and environmental temperature during an arm-cranking exercise. However, these models were not geometry based and lacked consideration of perspiration [3]. The role of sweating in the thermoregulated space suits was examined for the first time as a function of external body temperature. Subjects were exposed to different levels of activity and temperatures. It was ultimately concluded that while it may be possible to decrease the amount of sweat produced with certain temperature conditions and clothing, this extra fluid will play a role in the thermal behavior of a spacesuit. However, these effects are not studied [4]. More recent models have begun to account for perspiration, but with simplifying assumptions. One explored a static perspiration model, but is invariant in time and does not capture any transient behaviors which arise due to sweat production [5].

C. Problem Statement

Without physical or simulated models of time-varying thermal properties, perspiration and its effect on the comfortability and efficacy of the suit has not yet been thoroughly determined. In this study we attempted to use a computer simulation in order to simulate the changes in the cooling system's effectiveness that occur when heavy perspiration saturates the innermost fabric layer of the LCVG. The process involves two major transfers: 1) a mass transfer of perspiration from a skin boundary condition into the fabric of the suit and 2) a heat transfer involving the human's inherent bioheat, the cooling system of the EVA suit, and the external radiation. COMSOL is used not only to model these processes, but a parameter sweep shows what amount of perspiration can cause the cooling system's effectiveness to decrease. We will quantify the effectiveness by comparing post-EVA skin temperature to normal skin temperature.

D. Design Objectives

We developed our geometries with the aim of examining how differential fluid flow within the fabric layer of the EVA suit affects heat transfer to the skin. Our objectives were to:

1) Measure skin temperature in heavy perspiration regions after 4 hours of EVA and compare it to regions of lower perspiration to establish the impact of perspiration on the performance of the cooling system
2) Determine the skin temperature change when environmental temperature swings increase skin surface temperature through radiative heating
3) Compare changes in skin surface temperature to changes in metabolic rate to infer an effect of activity level on skin temperature.

We developed two separate models for heat and mass transfer analysis. The 3D model uses a representative human geometry and examines heat transfer exclusively (objectives 2 and 3). However, determining the effect of coupling heat and mass transfer (objective 1) using the 3D model required an excessive amount of computational power. We developed the simplified 2D model to ease computation.

E. Problem Schematic

Figure 1 presents the design of our 2D model used to examine mass and heat flux in the LCVG, including boundary conditions, geometric dimensions, and appropriate parameters. The model consists of a small patch of LCVG fabric with attached tubing.

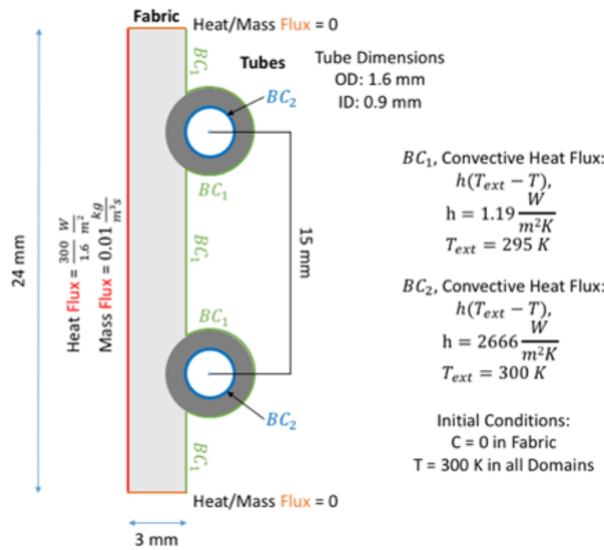


Figure 1. Problem Schematic
Above is a cross-sectional representation of our 2D system. Coolant is passed through tubing sewn to the fabric of the LCVG. The boundary conditions and initial conditions are shown for the respective heat and mass properties.

II. Methods and Results

A. Governing Equations

This system involves a coupled transient heat and mass transfer, with primarily conductive heat transfer and mass transfer of moisture through capillary diffusion. For the heat transfer problem, the governing equation is the transient heat equation shown in (1)

$$\rho c_p \frac{\partial T}{\partial t} = \nabla(k \nabla T) \tag{1}$$

where ρ represents material density, c_p represents material specific heat capacity, T represents temperature, and k is the thermal conductivity. This form of the standard heat equation neglects a heat generation term or convection terms, as convection is negligible in our system and metabolic heat generation and heat of blood perfusion were implemented in the boundary conditions.

In the mass transfer problem, we assumed no pressure-driven flow because the capillary and attractive forces involved with water in quantities produced by sweat glands (matric potential) far outweigh gravitational potential in microgravity. Sweat generation is also neglected in this equation and instead implemented as a boundary condition. A mass balance on a differential quantity gives the capillary diffusion governing equation (2)

$$\frac{\partial c}{\partial t} = \nabla(D \nabla c) \tag{2}$$

where c is the sweat concentration and D is the capillary diffusivity.

The capillary diffusivity D is given by equation (3), and is dependent on temperature.

$$D_{cap}(T) = D(T) = \frac{K}{\frac{\partial c_p^*}{\partial h}} \tag{3}$$

κ represents the hydraulic conductivity of the fabric and $\frac{\partial C}{\partial h}$ is the differential water capacity of the fabric. This temperature dependence couples the mass transfer equation to the heat transfer equation. Heat of blood perfusion was calculated using the blood perfusion term of the Pennes bioheat equation.

B. Boundary Conditions

In our simplified two-dimensional schematic, there are five boundaries. At the top and bottom boundaries (from the point of view of the schematic, Figure 1), there is no heat or mass flux, so those were represented as insulating. On the left boundary with the skin, there is a constant heat flux determined by metabolic heat generation and blood perfusion, and there is flux of perspiration out of the body into the fabric. On the right boundary, towards the exterior of the suit, there is also a constant heat flux dependent on whether or not the astronaut is in sunlight. The fabric boundary on the right is insulating to water, and so the tubing is considered to have a hydraulic conductivity of zero and no boundary conditions are needed. On the inside of the tubing, at the boundary with coolant, we model a convective condition with a constant heat transfer coefficient.

The 3D schematic involves more complex boundary conditions. Boundary conditions at the model surface represent the interface between the LCVG and the outer portion of the suit. At this boundary we implemented a constant heat flux with temperature 295K and a heat transfer coefficient of 1.19 W/m ^{2}-K.

C. Initial Conditions

At the start of the simulation, we assumed the LCVG system is at room temperature (25°C) due to holding conditions in the International Space Station. The skin temperature was modeled at 33°C. Furthermore, since activity and thus sweating has not yet begun, there is no moisture in the system. These conditions apply to both the two and three dimensional models.

D. Parameters

The LCVG was assumed to be composed of Nylon fabric and PVC tubing. Thermal properties of Nylon are available in the default COMSOL library. As a rough initial estimation, Nylon was assumed to have the mass transport properties (porosity, permeability) of cotton and the sweat diffusivity was modeled as the diffusivity of pure water. The thermal conductivity and heat capacity of Nylon are dependent on the volume fraction of sweat (ϕ_{sweat}) and volume fraction of nylon (ϕ_{nylon}) at the node. In COMSOL this is implemented as shown in equations 4 and 5:

$$k_{sweatynylon} = (k_{nylon}\phi_{nylon}) + (1-\phi_{nylon})(k_{sweat}\phi_{sweat} + k_{air}(1-\phi_{sweat})) \tag{4}$$

and

$$c_{p_{sweatynylon}} = (c_{p_{nylon}}\phi_{nylon}) + (1-\phi_{nylon})(c_{p_{sweat}}\phi_{sweat} + c_{p_{air}}(1-\phi_{sweat})) \tag{5}$$

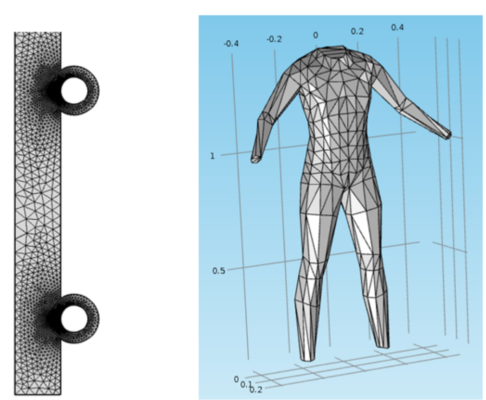
E. Mesh Design and Geometries

For the 2D calculations, we chose an unstructured tetrahedral mesh which allowed us to examine heat and mass transport most finely near the interface between the tubing and fabric (Figure 2a). The mesh was chosen to show enough of the system such that differential sweat sourcing could be implemented. The 3D model was generated from an ultra low-polygon base mesh and exported to a Stereolithography (STL) file from the free and open-source program MakeHuman, and then the hands, feet, and head regions were removed in MeshLab, after which any remaining holes in the mesh were filled.

Mesh convergence, shown for the 2D model in the appendix, was not conducted for the 3D mesh because of limited computing power, as our solution took nearly a half-hour to compute with default element size settings.

Table 1. Model parameter values.
Parameters were taken from various literature sources and from COMSOL's internal properties database.

Parameter	Value	Source
Sweat Flow Rate skin surface	25mL/m^2-hr	[6]
Metabolic Heat Generation	187.5 W/m^2	[7]
PVC Properties		
Thermal Conductivity	0.19 W/m-K	[8]
Heat Capacity	900 J/kg-K	[9]
Density	1100 kg/m^3	[10]
Sweat Properties		
Heat Capacity water approximation	4178 J/kg-K	[11]
Density water approximation	1000 kg/m^3	[11]
Nylon Properties		
Thermal Conductivity	0.26W/m-K	COMSOL
Heat Capacity	1700 J/kg-K	COMSOL
Density	1150 kg/m^3	COMSOL
Blood Properties		
Heat Capacity	3617 J/kg-K	[11]
Density	1050 kg/m^3	[11]
Perfusion Rate	0.0036 s^{-1}	[11], [12]
Skin Tissue Properties		
Density	1109 kg/m^3	[11]



a b

Figure 2. Meshes
Figure 2a is a simple 2D geometry representing a cross-section of a portion of the LCVG with visible tubing. Figure 2b shows the human model in 3D after import from MakeHuman and cropping of the hands, feet, and head, since the LCVG does not cover these areas.

For the 3D model, the human and LCVG system were represented as a single solid with the mesh shown in figure 2b. The boundary between the LCVG fabric and the skin is represented as a wall distance established in the Eikonal equation. The wall distance, which is effectively the fabric thickness, was set to 1 cm. This is much thicker than the actual nylon due to meshing constraints. However, based on comparison to the 2D model, which includes a reasonable 2 mm thickness, we believe the approximation to be adequate. A time-variant metabolic heat source term is set at the skin-LCVG interface according to the metabolic profile in figure 9. We model the coolant tubes in the 3D model as strips on the surface of the LCVG defined by a rectangle wave function that has a constant heat transfer coefficient.

F. 2D Simulations: Heat and Mass Transfer

Initial simulations showed variations in temperature based on proximity to the cooling tubes (Figure 3 and diffusion of sweat for a perspiring region from y=50 mm to y=100mm. These initial simulations were run for the uncoupled condition, in which the material properties of the nylon liner (C_p and k) determining temperature were taken as constants, independent of sweat concentration. To couple the heat and mass transfer systems, we made heat capacity C_p and thermal conductivity k of nylon dependent on sweat concentration as shown in Table 1. Sweat concentration has a small effect on the heat capacity and thermal conductivities of the material, as shown in the appendix. When the heat and mass transfer problems were coupled, the small differences in material properties created a minor variation in skin temperature in the perspiring region. The final skin temperature profiles for the coupled and uncoupled cases are shown in Figure 3.

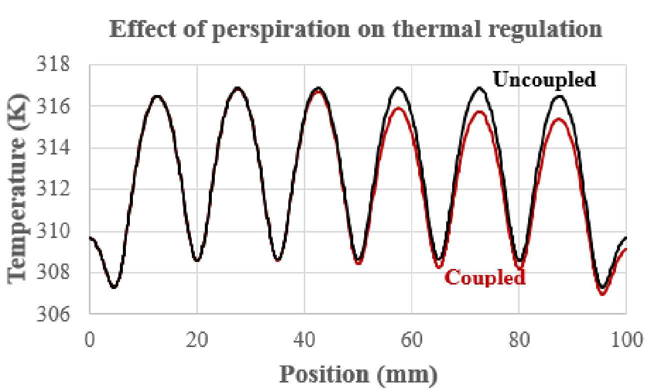
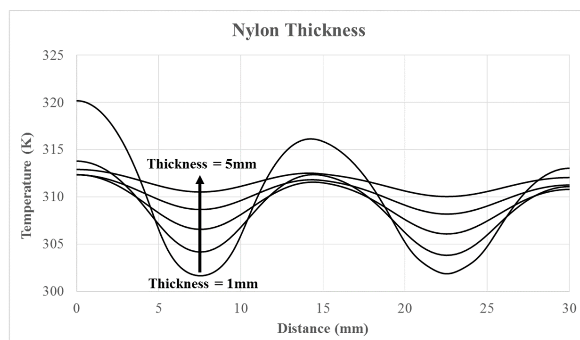


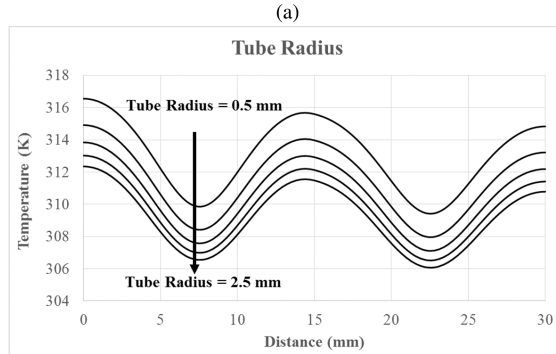
Figure 3. Final skin temperatures with and without coupling
Skin temperature is shown above as a function of position. In the coupled case, sweating was implemented between y=50mm and y=100mm. Peak temperatures are seen to decrease in the coupled case in the region of perspiration.

Capillary action can also be seen in this plot: At final time, sweat concentration has increased outside the initial region of perspiration (50mm to 100mm) as identified by the temperature change between y=40mm and y=50mm.

1) Sensitivity Analysis: By performing sensitivity analysis, we are able to determine how changes in suit design affect skin temperature. Figure 4 shows the sensitivity analysis results in our 2D model by plotting the skin temperature after four hours as a function of distance (y-coordinate). We have varied the thickness of the nylon, coolant tube radius, coolant temperature, distance between coolant tubes and tube wall thickness. From Figure 4a, we are able to see that in general, increasing the thickness of the nylon layer overall increases the skin temperature. Also, increasing nylon thickness reduces variability between skin under coolant tubes and those with just nylon. Finally, increasing nylon thickness decreases the effect of sweat on temperature, again leading to a more uniform skin temperature profile. Figure 4b shows that by increasing the radius of the coolant tubes, the temperature of the skin decreases. However, variability in temperature introduced by sweat is unaffected, which can be seen in the difference between the left and right minimum points below the tubes. Figure 4c shows that increasing coolant temperature linearly increases skin temperature. Figure 4d shows the skin temperature as a function of the normalized distance. By normalizing the distance to the distance between tubes, we can see that reducing this separation both minimizes the total skin temperature and variability. Finally, Figure 4e indicates that increasing the thickness of the tubes also increases skin temperature. Overall, this analysis shows the effect of each parameter on the skin temperature and its variability in space.



(a)



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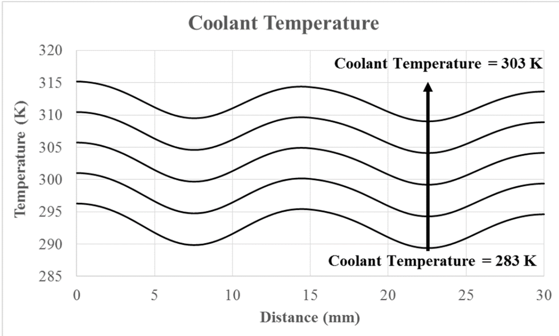
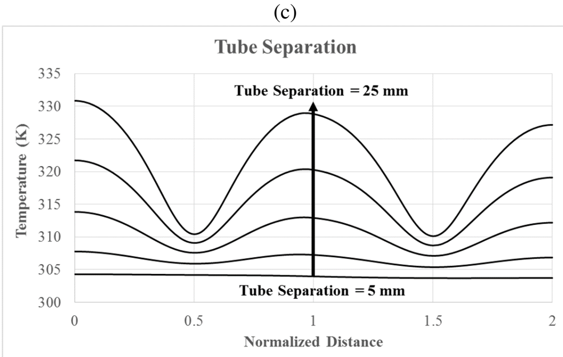
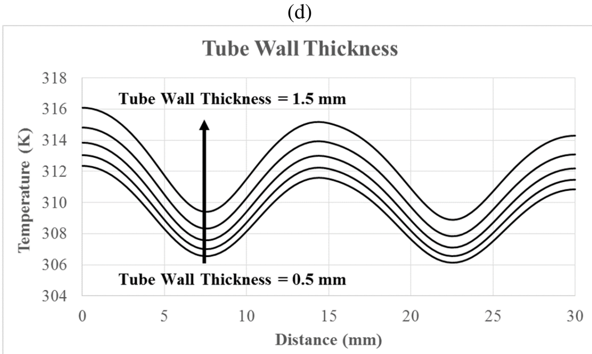


(c)



(d)



(e)

Figure 4. Sensitivity Analysis
Shown above are various suit design parameters and their effects on skin temperature after 4 hours as a function of distance. **a.** Nylon thicknesses (model value 2mm) **b.** Tube radii (model value 1.8 mm) **c.** Coolant temperatures (model value 300K) **d.** Tube separation values (model value 15 mm) **e.** Tube wall thicknesses (model value 0.9 mm)

Nylon thicknesses were tested from 1mm to 5mm in intervals of 1mm, with an original model value of 2mm. Tube radii were tested from 0.5mm to 2.5mm in intervals of 0.5mm with an original model value of 1.8mm. Coolant temperatures were tested from 283 K to 303 K in intervals of 5 K, with an original model value of 300K. Tube separation values were tested from 5mm to 25mm in intervals of 5 mm, with an original model value of 15mm. Tube wall thicknesses were tested from 0.5mm to 1.5mm in intervals of 0.25mm, with an original model value of 0.9mm.

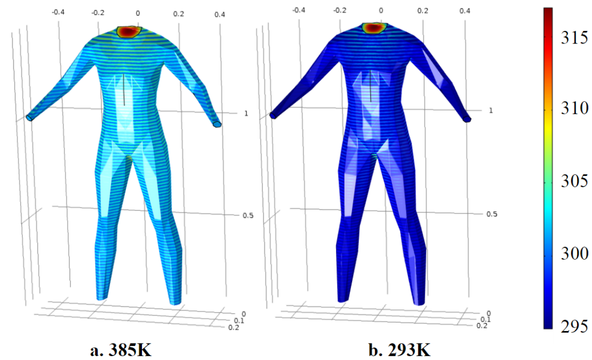


Figure 5. Heat transfer under T_{ext} = 385K
Solar radiation can create increased external suit temperatures up to 385K, causing increases in skin temperature of about 5K.

G. 3D Simulation: Heat Transfer Only

We conducted similar calculations on the 3D mesh using boolean step functions to model body heat flux, blood perfusion and heat conduction. However, the same volumetric calculations for human heat generation do not translate into formulae for moisture flux, because sweat is produced at the skin layer only and does not leak out of the body otherwise. Therefore, we restricted our analysis in 3D to heat transfer only. The metabolic profile was based on that of Wissler et. al. and is shown in Figure 7. This metabolic profile is typical of a 6-hour EVA mission. We also show in Figure 5 that there is a change in skin temperature between a no solar radiation case (No heat loss or addition, T=293K) and the maximum solar radiation case (T=385K)[1].

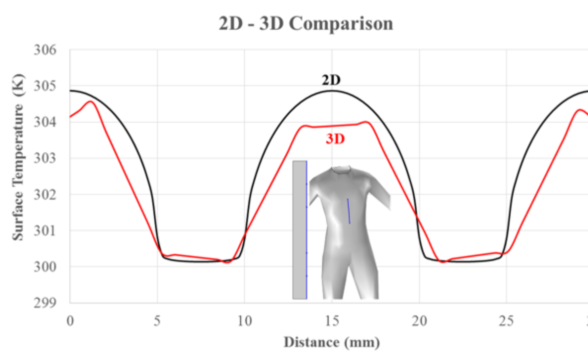
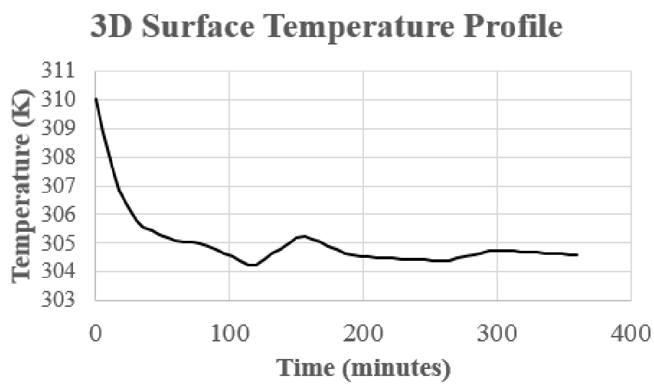


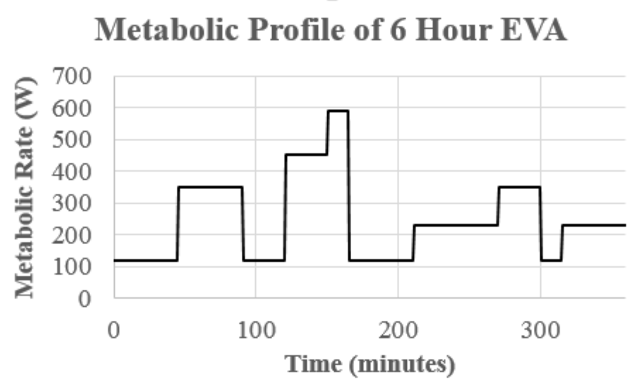
Figure 6. Validation by comparison of 2D and 3D models
Surface temperature profile comparing 2D (black) and 3D (red) models. Inlay shows locations of cut lines for data extraction in blue.

H. Model Validation

1) 2D and 3D Validation: We constructed a simple 2D model to validate our results against the 3D heat transfer model. This is necessary since the 3D model does not actually include tube geometries or sweat. To simplify our 2D model for validation, we changed the material properties of the fabric to be 100% nylon, the same as in the 3D model. Also, we removed tube geometries and instead applied the convective heat flux boundary directly to the fabric as lines of 5mm at intervals of 15mm to represent cooling tubes. Since it is difficult to extract temperature results from the 3D model underneath the surface of the fabric, we chose to compare the temperature profiles of the two models at the surface of the fabric. This can be seen in Figure 6. This result shows good agreement between the two models. The error in the 3D model results can be explained by the significantly decreased mesh resolution, and linear interpolation between exported data points.



(a)



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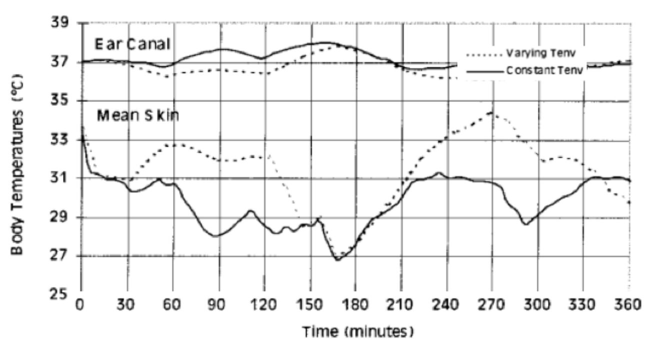

(c)

Figure. 7. Validation with Wissler Model
The above plots show similar minimum and maximum temperatures between the current (left) and Wissler (right) models. Our model also shows increases in skin temperature during higher rates of metabolic activity.

2) Validation Against Previous Models: In current EVA suit models, cooling systems keep skin surface temperature between 10 and 45°C [1]. Each experimental condition fits this range, however, this is a broad constraint. Better validation can be found with comparison to the Wissler model, which shows skin temperature closely following metabolic rate and ranging from 27 to 33°C [3]. Our model similarly follows the metabolic profile, and after a transient cooling period ranges from 31 to 33°C. Figure 7 shows a comparison of the two models alongside the metabolic profile.

III. Conclusion

Our model demonstrates that perspiration from an astronaut can have an effect on their skin temperature, and therefore, their comfort and safety in an extraterrestrial environment. We saw changes in material properties based on sweat saturation, leading to a noticeable effect on skin temperature as per design objective one. We performed sensitivity analysis on a number of the variables which may change between suit designs. Our model appears to be as sensitive to these parameters, which included the nylon layer's thickness and sizing of the cooling tubes, as it was to perspiration. This indicates that although the perspiration does affect the ability of the LCVG to cool the astronaut, other suit design parameters may be just as or more important. We looked at the effects of external radiation on skin temperature, which ended up being more significant than the effects of perspiration. Lastly we showed that skin temperature roughly follows metabolic activity when the coolant temperature is not under any external control as it was in the Wissler paper. Through validation We have also demonstrated that a simpler, computationally easier 2 dimensional model can adequately substitute for the complex human geometry, enabling future research to dive deeper into these effects. We hope that this model will enable less time- and resource-consuming investigation into the design of more functional space suits for increasingly common space travel.

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APPENDIX

MESH CONVERGENCE

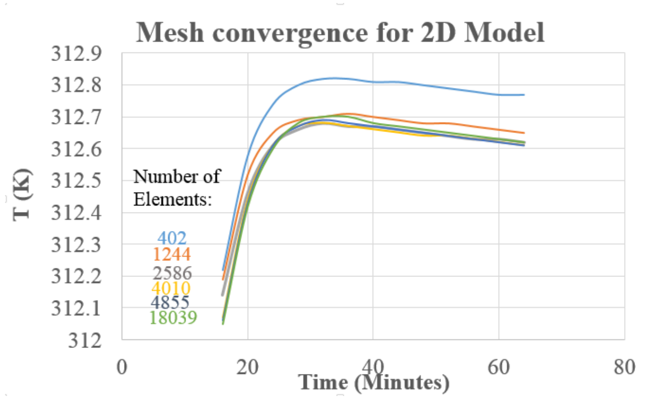

Figure 8. Mesh Convergence

Mesh convergence is shown above for a line average of surface skin temperature over time. The highest variation appeared in the region between 16 and 62 minutes, shown here. Mesh convergence is apparent for a mesh with at least 4000 elements. Accordingly, maximum element size was established to be 2 mm.

DEPENDENCE OF MATERIAL PROPERTIES ON SWEATING

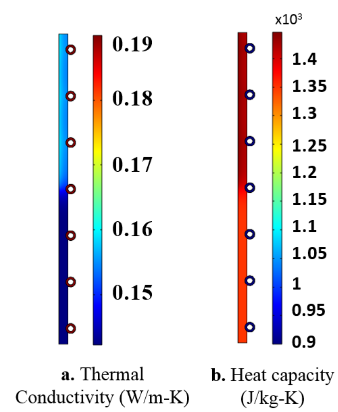

Figure 9. Dependence of Material Properties on Perspiration

Shown here are the spatial variations in material properties of nylon when sweating was introduced along the top left third of the domain. Thermal conductivity K (a) and Heat capacity C_p (b) rise as a function of the sweat concentration. Spatial variability can be seen in the regions of high perspiration.