Model of Human/Liquid Cooling Garment Interaction for Space Suit Automatic Thermal Control

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Background

Human activities during space missions that occur outside the confines of a capsule that maintains a near-earth atmospheric state require that a space suit be worn. These activities are dubbed "extravehicular," or EVA. The space suit provides a local and mobile safe micro-environment that protects the astronaut during EVA from a host of insulting stresses that would be injurious or lethal. Included among these stresses are UV irradiation, high-velocity particles, very low pressure, gas chemistry different from earth, and extreme temperature. As a consequence, it is necessary to isolate, at least partially, the astronaut from space in many energy domains, including mechanical, optical, chemical, and thermal. Space suits are designed with highly effective thermal insulation to satisfy this objective.

The thermal insulative properties of the space suit cause a physiological problem for astronauts during EVAs owing to the diminished ability to transfer metabolic waste heat to the environment. Therefore, a separate cooling garment is worn beneath the space suit with the capability of providing refrigeration to the mass contained within the suit. Refrigeration is achieved by circulating a steady stream of cooling water through tubing sewn into a full-body garment (liquid-cooled garment, LCG) worn by the astronaut. The cooling water enters and leaves the garment via a manifold at the waist and is distributed over four quadrants, two symmetrically for both the upper and lower body, but excluding the head. The capacity of refrigeration is modulated by regulating the inlet temperature of water while it flows through the LCG at a constant rate. The water is chilled and pumped by hardware carried on the space suit external backpack, through which the water is circulated. To the present time, the cooling water inlet temperature is set manually via a dial positioned on the outer surface of the space suit. No active heating is incorporated into the loop, so that the primary source of heating to the water is parasitic heat transfer from the body of the astronaut. A too frequent occurrence during EVAs is that an astronaut becomes occupied with a project that produces a high level of metabolic heat generation and requires a low cooling water inlet temperature to maintain thermal comfort. At the completion of the task, the metabolic rate is reduced substantially, but the astronaut may not remember to set the controller to a higher inlet water temperature. As a result, the astronaut becomes severely over-cooled before the control dial is reset, with a concomitant compromise in the ability to function. Although this state is normally transient until the cooling water temperature is raised sufficiently by heat transfer from the body, often stimulated by vigorous shivering, in extreme cases it can be necessary to terminate the EVA. The basic manual control scheme for LCG inlet water temperature has been used since the days of the Apollo missions, and there is clearly an opportunity to improve system performance by implementing an automatic temperature control process.

Past investigations have evaluated the potential for applying automatic control for regulating the inlet water temperature to an LCG and the feasibility of distributed cooling to different areas of the LCG [1]. However, for multiple reasons, an automated controller has yet to be implemented. A primary consideration in the design of a practical automatic control system for an LCG is identification of the feedback signals, which can be incorporated safely and effectively into the control loop. The present study is focused on evaluating the efficacy of various physiological state measurements for controlling cooling inlet water temperature to maintain a constant condition of human thermal comfort during transient metabolic profiles representative of those encountered during EVA.
Introduction to the Research

The Wissler thermoregulation model [2,3] for humans was applied to the design of an automatic control system to regulate inlet water temperature for an LCG worn under a space suit. The LCG automatic control system uses two types of feedback signal that provide information about the thermal state of the subject. One type relates to the rate of energy expenditure and one to the energy storage in the body. The first type of signal is based on the overall metabolic rate, which is measured via the concentration of carbon dioxide in expired respiratory gases. The CO2 generation rate may change rather quickly (on the order of a minute) in response to alterations in the level of physical activity. Thus, it can provide information useful for indicating the need for initiating a change in the temperature of cooling water supplied to the LCG. The second type of feedback signal is based on an average of the subject’s body temperature (which is estimated from the ear canal temperature and mean skin temperature). This signal responds much more slowly than metabolic rate to changes in environmental conditions and work loads, and it provides information useful for maintaining the stored energy of the body near the value that ensures a condition of thermal comfort.

Since the human body has a complex, nonlinear thermoregulatory mechanism, it is necessary to consider carefully the interaction of the body and the LCG when designing an automatic control scheme. While it is important to understand the thermal behavior of the human body under various work loads and environmental conditions, it is virtually impossible to test physically all scenarios that could be encountered by an astronaut wearing an LCG. Therefore, a mathematical model must be incorporated into the design process to simulate and predict performance in the broadest spectrum of operating states. The Wissler model provides a general and versatile platform on which to simulate human thermal behavior for many combinations of environmental conditions, metabolic loads, and clothing ensembles [2,3].

Initial simulations were performed for experimental data obtained from NASA Johnson Space Center (JSC) for two different trials conducted in the 1980s and 1990s. In those experiments, the subjects wore a complete space suit ensemble, which included the liquid cooling garment and a pressurized outer garment. The pressurized outer garment included the circulation of ventilation gas through the suit. The Wissler model was originally developed to allow simulation with either a liquid-cooled or an air-cooled vest, but not for both acting on the body at the same time. Therefore, changes in the model code were required so that both a liquid-cooled vest (the LCG) and an air-cooled vest (the pressurized suit vent flow) could be evaluated simultaneously.

The Wissler human thermoregulation model was refined to incorporate simulations of simultaneous interaction of the body with serial layers of an LCG and space suit vent gas flow over its outer surface. Data correlation with the two separate sets of JSC experimental data have shown that the model can predict a subject’s core body and average skin temperatures for a variety of work rates and LCG inlet temperatures and for extended durations of testing (a total of 90 minutes for one trial set and six hours for the other). Details of the model modification and correlation with JSC experimental data are presented in [4].

The present paper reports the results of modeling and experiments for which an automatic control scheme for LCG inlet cooling water was evaluated. A series of experimental trials was conducted to measure automated inlet water temperature control for a unique liquid cooling garment and outer garment combination that had not previously been evaluated. Results from the study indicate that the modified Wissler model is an effective tool for predicting the human thermal state while wearing an LCG and space suit ensemble and that it can be used for further design and evaluation of LCG automatic control schemes.

Methods

Experiments. A series of experimental trials were conducted on nine subjects dressed in the LCG and an outer insulating suit with the water inlet temperature to the LCG controlled automatically by an algorithm developed based on analysis of human thermoregulatory behavior by the Wissler model. The goal of the experiments was to evaluate the ability of the automatic control algorithm to maintain a subject’s thermal comfort and thermal neutrality during a one and one-half hour transient exercise regime on an arm cranking ergometer and in differing thermal environmental conditions. The experimental protocols were representative of metabolic profiles and external heat loads encountered during extravehicular activity.

Physiological parameters measured during the tests included metabolic energy expenditure, core body temperature, and skin temperature. Body core temperature was monitored via a thermocouple inserted into the ear canal. A custom silicone ear mold was made for each of the test subjects, and a thermocouple was mounted permanently in each ear mold so that the bead junction protruded slightly toward the inner ear. With the mold inserted during a trial, the probe was positioned approximately 1 cm into the ear canal, with the outer portion of the cavity fully filled by the mold. Temperature measurements were indicative of the air temperature within the ear canal cavity. Mean skin temperature was found as a weighted average of measurements at three locations: the right thigh, right biceps, and right mid-back.

Tests were conducted in an environmental chamber at three temperatures: 26.7°C, designated as WARM; 18.3°C, COOL; and 10°C, COLD. Nine test subjects participated in the study, including six males and three females varying in age from 22 to 55 years. Subjects wore a nylon hooded warm-up suit over the liquid cooling garment to minimize environmental evaporation and convection. Long silk underwear was worn between the LCG and the skin. All work was performed using an arm-cranking ergometer at various work rates. The 90 minute metabolic profile was designed to incorporate a variety of exercise intensities and resting periods typical of those encountered during extravehicular activity of an astronaut. The profile included numerous step changes in activity level, a long duration steady-state period of work, and multiple short duration large magnitude changes in work rate. The standard exercise regimen that was used for all of the trials is shown in Fig. 1.

Control Algorithm. Control of the comfort inlet water temperature, \( T_{in} \), was governed by two thermal control signals, \( K \Delta M \) and \( DT_{int} \). The control signal, \( K \Delta M \), is merely a constant, \( K \), multiplied by the difference between the metabolic rate at time, \( t \), and the resting metabolic rate, \( M = [M_{rest} - M(t)] \). Any change in metabolic rate elicited a proportional change in the LCG inlet temperature, \( T_{in} \). The proportionality constant, \( K \), was...
empirically adjusted to a value of 0.05°C/W to provide an effective level of influence of metabolic rate on the cooling water inlet temperature. Since metabolic rate measurement has a relatively short time constant (~0.5 minute), the KAM signal for a measured change in metabolism following a step change in work rate served to initiate the control response for a change in activity level.

The $DT_{err}$ signal is derived on the assumption that, for thermally comfortable conditions to be maintained during metabolic activity, the mean body temperature must remain constant. The same assumptions were evaluated by [5] with the mean body temperature defined as a function of skin and core body temperatures, $T_{body} = a T_{core} + (1 - a) T_{skin}$. The $DT_{err}$ signal is comprised of a proportionality constant, $D$, multiplied by $T_{err}$, the difference between the measured skin temperature and a calculated comfort temperature, $T_{comf} = T_{skin} - T_{conf}$. The comfort temperature is the sum of the change in body core temperature, $\Delta T_{core}$ (as measured in the ear canal), modified by a scaling factor, and the average skin temperature measured at a resting metabolic state, $T_{skin,conf} = a/(1 - a) T_{err} + T_{skin,rest}$. The constant $a$ specifies the relative weighting of core temperature and skin temperature in setting the control input signal. Based on extensive pretrial testing, a value of $a=0.9$ was identified empirically as providing a reasonable control response. The value of $D$ was also determined during preliminary experiments to be $3.0 C_{2.7}/C_{2.8}$. The input signal to set the change in temperature of cooling water at the inlet to the LCG, $\Delta T_{in}$, was calculated by an expression that incorporated a time constant, $\tau$, to modulate the rate of implementing the change:

$$\Delta T_{in} = (K\Delta M + DT_{err})(1 - e^{-t/\tau})$$

(1)

The time constant, $\tau$, was set to match the physical time response of heat loss in the human thermal control system to changes in internal energy production. Initial determination of the control constants, $K$, $D$, $a$, and $\tau$ was accomplished during an extensive series of preliminary experiments, all of which were conducted at 25°C, in which LCG control performance was evaluated for a broad range of transient metabolic profiles. The experiments also were simulated with the Wissler model to test the behavior of the control system. In particular, the sensitivity of changes in water inlet temperature to perturbations in each of the four control constants was evaluated.

An empirical relationship was developed as a function of metabolic rate and environmental temperature to describe the difference between the experimentally measured core mouth temperature and the core temperature calculated by the model. The experimental data were simulated with the varying LCG inlet water temperature specified in an input file (rather than calculated by the thermal control algorithm) at each of the three environmental temperatures studied, 26.7°C, 18.3°C, and 10°C. Based on data from the numerical simulation and experimental trials, the difference between the numerical rectal temperature and the experimental ear canal temperature ($T_{rect,meas} - T_{ear}$) was found for each of the three environmental temperatures. This difference was plotted as a function of metabolic rate, and a regression analysis was applied to determine a linear equation describing the relationship between the core temperature difference and the metabolic rate:

$$T_{rect,meas} - T_{ear} = a M - b$$

(2)

$$a = -0.000004 T_{env} + 0.0011$$

(3)

$$b = -0.0544 T_{env} + 0.0011$$

(4)

Equation (2) was applied to calculate the ear canal temperature in the model as a function of environmental temperature, metabolic rate and computed core (rectal) temperature.

**Model Inputs.** The Wissler model requires that a number of physiological and environmental data values be supplied in order to simulate thermoregulatory behavior for specific conditions. Mean values of all experimental subject metabolic rates were used as inputs to the model simulations. Initial values of LCG inlet temperature, ear canal temperature, and mean skin temperature were averaged for the resting state data for the nine test subjects in each of the three environmental conditions. The metabolic rate profiles were also averaged over the nine subjects to define a representative value for the simulations. These values are presented in Table 1. The environmental temperature was fixed independently for each of the experimental trials.

The mechanical work efficiency of the arms and legs was specified as 15 percent, a value determined from experimental data based on comparison of the measured metabolic rate at a particular

**Table 1** Resting state inputs to Wissler model simulations taken from mean of experimental data: $n = 9$

<table>
<thead>
<tr>
<th></th>
<th>WARM</th>
<th></th>
<th>COOL</th>
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<tbody>
<tr>
<td>$M_{rest}$ (W)</td>
<td>93.9 ± 19.5</td>
<td>98.2 ± 18.3</td>
<td>92.7 ± 18.9</td>
</tr>
<tr>
<td>$\Delta T_{core}$ (°C)</td>
<td>23.8 ± 2.6</td>
<td>26.8 ± 3.0</td>
<td>29.9 ± 2.1</td>
</tr>
<tr>
<td>$\Delta T_{ear}$ (°C)</td>
<td>37.0 ± 0.4</td>
<td>36.7 ± 0.3</td>
<td>36.2 ± 0.6</td>
</tr>
<tr>
<td>$\Delta T_{skin,rest}$ (°C)</td>
<td>31.4 ± 1.0</td>
<td>31.8 ± 1.2</td>
<td>21.9 ± 0.7</td>
</tr>
<tr>
<td>$T_{body,rest}$ (°C)</td>
<td>36.4 ± 0.4</td>
<td>36.2 ± 0.2</td>
<td>35.9 ± 0.6</td>
</tr>
<tr>
<td>$T_{env}$ (°C)</td>
<td>26.7</td>
<td>18.3</td>
<td>10.0</td>
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lar work rate on the arm-cranking ergometer. The distribution of work production within the body for arm-cranking exercise was set at 65 percent for the arms, 15 percent for the legs and 20 percent for the body torso.

Results

Figure 2 presents a comparison of the measured (averaged over all nine test subjects) and modeled transient physiologic and cooling water temperatures during the entire experimental protocols for all three environmental conditions studied. The model was implemented for the standard metabolic profile, appropriate environmental temperature, and resting state values of $T_{\text{in}}$, $T_{\text{out}}$, and $T_{\text{skin}}$. With the exception of the initial 10 minutes of the COLD test, the numerical LCG inlet temperature followed the transient behavior of the mean value of the experimental data, staying well within the bounds of the standard deviation.

The modified numerical core temperature (ear canal temperature) and the mean skin temperature outputs of the model also were within the experimental standard deviation of the data except for the COOL environment tests. In the COOL simulation, the numerical mean skin temperature data was at least one degree higher than the experimental mean through most of the protocol and twice crossed the bounds of the standard deviation.

The numerical calculation of stored body energy as a function of the change in mean body temperature also compared well with the experimental results. The close match indicates that the numerical model simulated the experimental control function well, since the control algorithm is designed to maintain a constant mean body temperature.

The numerical data was matched less well with experimental results for the change in water temperature across the LCG. Although the general profiles were the same, the calculated magnitude of $\Delta T_{\text{lcg}}$ was about 0.5°C higher than measured, which, in the COLD case, was more than 100 percent of the total $\Delta T_{\text{lcg}}$. This deviation may be due to the physical locations at which the inlet and outlet water temperatures were measured. In the experimental setup, the physical proximity of the in-flowing and out-flowing LCG water tubes could facilitate countercurrent heat exchange proximal to the location at which temperature readings were obtained, causing the measured value of the change in water temperature across the LCG to be less than it actually was. Also, the numerical $\Delta T_{\text{lcg}}$ value does not account for the time required for water to pass through the LCG. The fact that $\Delta T_{\text{lcg}}$ is being calculated from simultaneous measurements of inlet and outlet water temperatures could explain the peaks in the numerical $\Delta T_{\text{lcg}}$ associated with large transients in LCG inlet temperature.

Overall, the simulation results display the power and accuracy of the Wissler model in predicting the thermal behavior of the LCG automatic control algorithm in varying environmental conditions. The model can be used with confidence to predict the system behavior for protocols not verified experimentally and for process design.

Predictive Capabilities of the Wissler Model

Since experimental trials are costly and time consuming, it is desirable to use a model to evaluate the performance behavior of the LCG system for untested operating conditions. Three such applications of the Wissler model will be discussed.
Evaluation of the $\alpha$ Constant. As discussed earlier, the performance of the LCG thermal control algorithm is dependent on the constant $\alpha$, which determines the ratio of the change in skin and core temperatures to best achieve mean body temperature constant. Values of $\alpha$ between 0.67 and 0.90 have been specified in other studies [8,9]. $\alpha$ is likely dependent on a combination of environmental, physical, and physiological parameters. The value of $\alpha$ used in the calculation of $T_{\text{body}}$ for this research was determined empirically and was held constant for all the tests. Although a single value of $\alpha=0.9$ was used in simulations of the entire set of standard protocols tested, it is possible that more effective control could be achieved with $\alpha$ variable over the different thermal and metabolic conditions encountered during the experiments. Therefore, a simulation was conducted to evaluate the effect of changing $\alpha$ on control algorithm performance. Simulations were run in both the WARM and COLD environmental temperatures with $\alpha=0.67$ and all other parameters identical to the prior trials. The results are presented in Fig. 3.

With a smaller value of $\alpha$, increases in ear canal temperature in conjunction with alterations in metabolic rate result in small changes in comfort skin temperature. The result is a decreased magnitude of LCG cooling for a given increase in ear canal temperature. In general, during the WARM experimental tests, subjective comfort levels were slightly warmer. Using a value of $\alpha=0.67$, the controlled LCG inlet water temperature is expected to be higher than with $\alpha=0.90$ (based on the numerical results) resulting in warmer comfort levels for the subjects. Therefore, for a WARM environment $\alpha=0.90$ yields a better controller performance than $\alpha=0.67$.

In the COLD environment, a reduced value of $\alpha$ made the LCG inlet temperature much more responsive to changes in metabolic rate since the control signal was biased more strongly to skin temperature. Accordingly, in the COLD chamber experiments the subjects were, on the average, cool during the first twenty minutes of the work profile.

In general, the mean skin temperature responds rapidly and in proportion to changes in LCG inlet water temperature owing to the close thermal coupling between the LCG and the skin. Thus,
the value chosen for $\alpha$ has a major influence on the skin temperature and only a minor influence on ear canal temperature. The change in mean body temperature, $\Delta T_{\text{body}}$, was much more biased toward negative values for a lower $\alpha$, indicating a loss of stored body energy in both the WARM and COLD environments.

The simulation shows the reducing $\alpha$ results in compromised performance of the thermal controller for the range of conditions studied. A stronger bias of calculated body temperature toward the skin value is undesirable, particularly for colder environments.

Effect of Vent Flow on System Performance. Since an automatic controller for LCG inlet water temperature will ultimately be used in a space suit that has integral vent gas circulation, it is desirable to know how vent flow heat exchange will affect the controller performance. Simulations with the Wissler model were run for vent gas flow added to the environmental heat exchange. The flow of vent gas between the LCG and the space suit was specified at a rate of 0.22 kg/min and an inlet temperature of 15.6°C. Simulations were run for the WARM and COLD environments, with the results presented in Fig. 4.

The most significant effect of vent flow is seen in the WARM environment, wherein the water inlet temperature must be incremented by as much as 2.5°C to compensate for the added heat loss to gas flowing on the outside of the LCG. Increases in the required water inlet temperature may indicate that the vent gas enhances cooling of the skin surface, thereby reducing the effect of the control signal $\Delta T_{\text{err}}$.

The most pronounced effect of the vent gas flow on mean body temperature is also seen in the WARM environment. The lower mean body temperature in the case with the vent flow supports the hypothesis that the vent gas provides extra cooling to the skin surface, being more significant in the WARM environment for which there is less heat exchange through the suit to the environment. The addition of vent flow showed little effect on controller performance in the COLD external environment. The simulation results show that in general the presence of vent gas flow external to the LCG should not significantly affect performance of the LCG automatic thermal controller.

Transient Environmental Conditions. Calibration of the control algorithm constants requires the determination of steady-state resting conditions based on the initial thermal state of the subject in the specific test environment for each trial. The robustness of this calibration is important since the environmental conditions in space are dynamic, and heat loss through the space suit can vary with orbit altitude, position of the space walking astronaut relative to the sun, and proximity of the astronaut to radiation surfaces on the space shuttle. This analysis was conducted to determine if the resting states defined for one set of initial conditions would be valid throughout an EVA for which there might be substantial environmental changes.

A pair of six-hour simulations was conducted for the metabolic exercise profile shown in Fig. 5. The model was run with a constant environmental temperature of 26.7°C to provide a performance reference for a second simulation that incorporated changes in environmental temperature between 26.7°C and 10.0°C in a cyclic manner, also shown in Fig. 5. The inlet water temperature setting was calculated with the WARM environment calibration values for LCG inlet, ear canal, and skin.

Comparison of the two simulations shows that a changing environment can have a large effect on the controller setting for the inlet water temperature. With the constant warm environment, much lower inlet temperatures are computed. As the environment cycles to lower temperatures, the controller compensates accordingly with less cooling provided from the LCG. A provision was programmed into the Wissler model to set the lowest temperature available to the LCG at 8°C since the EMU LCG cooling system has a similar lower limit in cooling capacity.
The dependence of ear canal temperature on environmental conditions is obvious from the data and anticipated. Large downward deviations in ear canal temperature resulted in the controller decreasing in inlet water temperature so as to raise the skin temperature to maintain a constant mean body temperature. The body energy storage increased above the proposed comfort level limit of 68.4 kJ [10] at between two and three hours into the metabolic profile. The inlet water temperature at that time had reached its lower limit of 8°C, and no additional cooling of the subject was possible. For varying environmental temperature, the body energy storage also surpassed the lower comfort limit of –68.4 kJ.

The resting comfort inlet temperature for WARM conditions found experimentally was 6°C lower than for the COLD conditions, showing the effect of the environmental state on calibration of the control system. If the resting comfort value is biased low, the controller will set water inlet temperatures that are too low for comfort. Given the dependence of ear canal temperature on environmental state, decreases in environmental temperature will cause decreases in ear canal temperature and concomitant increases in inlet water. However, the ear canal temperature dependency on environmental temperature may help compensate for differences in resting inlet water temperatures.

This modeling analysis indicates that further evaluation of the control system calibration based on measurement in the resting state are necessary to account for the effect of changing environmental conditions.

Summary and Conclusions

The Wissler human thermoregulation model was modified to incorporate the combined effects of a liquid cooled garment and external vent gas flow. The model was applied to aid the design and development of an LCG automatic thermal controller. The control algorithm logic was programmed into the Wissler model to calculate LCG inlet temperature at each new time step based on inputs for the environmental conditions, metabolic and work rates, and physiological state. Since the model could be used to simulate both the automatic control function and human thermal response during experimental protocols, it was used to evaluate the LCG control system calibration constants and overall performance. Simulations of actual experimental data showed good prediction capabilities under a wide variety of environmental conditions and exercise intensities. The model was further used to evaluate performance of the thermal control algorithm using alternate control parameters and unique system and environmental scenarios. It was shown in the numerical simulations that the behavior of the control algorithm is affected by the extreme and dynamic thermal conditions as encountered in space. The dependence on environmental conditions therefore requires further analysis.

Further utilization of the model could include predicting human thermal response to a variety of exercise protocols and environmental conditions that would obviate lengthily and costly experimental testing. The model could also be used as a design tool in optimizing the performance of the LCG, and it could be integrated into a model of the entire EMU system for complete thermal analysis of an astronaut’s micro-environment.

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