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Application of a Sweating Manikin Controlled by a Human Physiological Model and Lessons Learned

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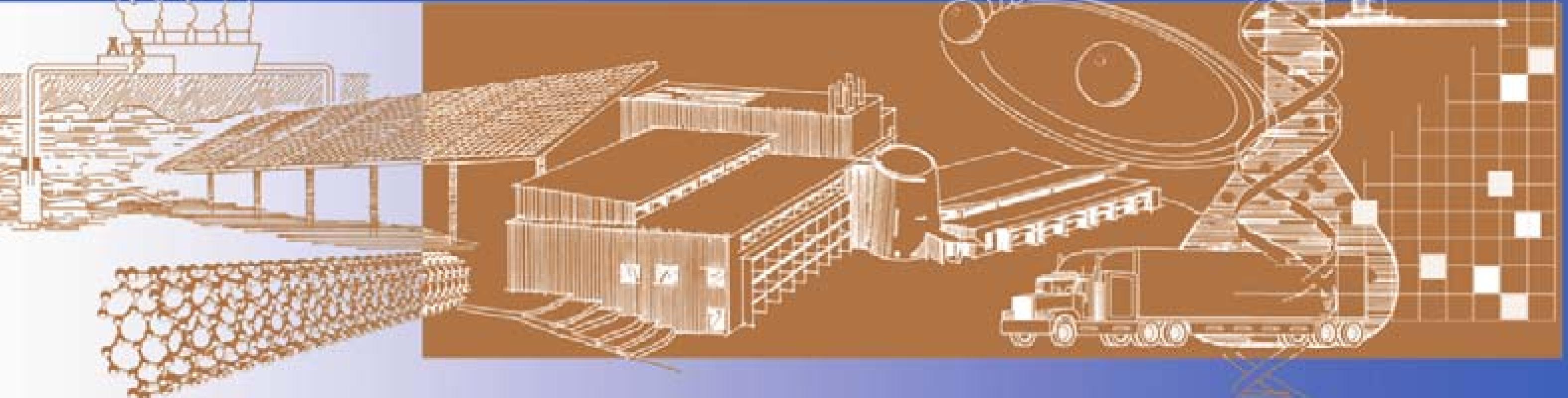

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Application of a Sweating Manikin Controlled by a Human Physiological Model and Lessons Learned

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Abstract

The National Renewable Energy Laboratory (NREL) has developed a suite of thermal comfort tools to help develop smaller and more efficient climate control systems in automobiles. The tools consist of a thermal comfort manikin, physiological model, and psychological model that are linked together to assess comfort in a transient non-homogeneous environment. The manikin and models have been validated against physiological data that are available in the literature and test subject data that were used to develop the psychological model. The manikin was used in NREL's Vehicle Climate Control Laboratory (VCCL) to assess the impact of an automotive ventilated seat on thermal comfort and fuel economy. In a test program with NASA, the manikin was used to evaluate liquid cooling garments (LCGs) worn underneath spacesuits.

1. Introduction

Our goal at NREL is to help the automotive industry reduce the fuel used for air conditioning (A/C). NREL is investigating techniques to reduce the peak soak temperature, which allows the A/C system size to be reduced. We are also looking at improved delivery systems and alternative methods to cool the passenger compartment, which will reduce the power requirements of a climate control system.

Since a key requirement is to maintain or enhance passenger comfort, we need to understand how advanced cooling techniques will affect human thermal comfort. NREL has developed a portfolio of thermal comfort tools, including an ADvanced
Automotive Manikin (ADAM), Human Thermal Physiological Model, and Human Thermal Comfort Empirical Model to assess comfort in automobile passenger compartments[1].

2. Thermal Comfort Tools

The integrated human thermal comfort system consists of the thermal manikin controlled by a finite element physiological model of the human body. The thermal manikin is a surface sensor that measures the rate of heat loss at 120 independently controlled zones. The skin heat transfer rates are sent to the physiological model, which computes the skin and internal temperature distribution and surface sweat rates. This information is then sent back to the manikin, which generates the prescribed skin temperatures, surface sweat rates and breathing rates. As the model steps forward in time, this loop provides a transient measurement tool. The psychological comfort model uses temperature data from the physiological model to predict the local and global thermal comfort as a function of local skin and core temperatures and their rates of change. Using this manikin as a sensor simplifies the complex clothing and environmental heat transfer into local heat loss measurements from the skin.

2.1 ADvanced Automotive Manikin

The manikin is approximately 175 cm tall and was sized to comply with the 50th percentile western person. He weighs approximately 61 kg; heavy enough to compress an automotive seat and give a realistic contact area. The manikin's skeleton is composed of laminated carbon fibre, which supports its structure, houses all internal components and provides mounting locations for surface zones[2].

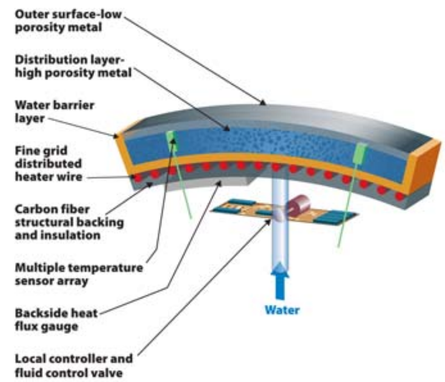

Figure 1 Manikin Segment

The manikin's fundamental components are the 126 individual surface segments, each with a typical surface area of 120 cm^2. Each segment (Figure 1) is a stand-alone device with integrated heating, temperature sensing, sweat distribution and dispensing, a heat flux gauge, and a local controller to manage the closed-loop operation of the zone. The high-thermal conductivity of the all-metal sweating surface yields increased thermal uniformity and response speed. A high-porosity layer within the surface provides lateral sweat distribution while the lower porosity exterior promotes uniform sweat across the surface. Distributed resistance wire provides uniform heating across the zone surface. Six segments are controlled in pairs, and result in 120 separately controlled zones. A single zone controller, including flow control, is mounted directly on the back of each segment. The skin temperature of each zone is determined by an array of thermistors (typically four) on each zone. A heat flux gauge, integrated onto the internal surface of each zone, measures heat transfer between the surface zones and the internal body cavity.

ADAM was built by Measurement Technology Northwest in Seattle, Washington. The characteristics that make ADAM a unique thermal manikin are:

- High spatial resolution (120 zones)
- Self-contained
- Uniform sweating and heating over the entire area of the manikin
- Finite element physiological model control.

2.2 Human Thermal Physiological Model

The NREL Human Thermal Physiological Model is a three-dimensional transient finite element model of the human body. The model simulates the human internal thermal physiological systems, such as muscle and blood, and thermoregulatory responses. The model was developed with the commercially available finite element software ANSYS. This software computes heat flow by conduction, convection and mass transport of the blood. The arms and legs consist of bone, muscle, fat and skin. There are additional lung and abdominal tissues in the torso and brain tissues in the head.

Blood flow is modelled with a network of supply and return pipe elements within each body zone. The diameter of the pipes decreases from the centre of each zone outward, toward the skin and extremities. The thermoregulatory system controls physiological responses, such as vasoconstriction/dilation, sweating, shivering, and metabolic changes.

2.3 Human Thermal Comfort Empirical Model

The University of California, Berkeley performed 109 human subject tests in its Controlled Environmental Chamber under a range of steady-state and transient thermal conditions to explore the relationship between local thermal conditions and perception of local and overall thermal comfort. Core and local skin temperature data and subjective data were used to develop a predictive model of thermal sensation and perception[3,4].

Zhang concluded that overall comfort is not an additive function of all local perceptions, but instead is "complaint" driven. This means that the most uncomfortable body parts drive the overall thermal comfort perception. We encountered difficulties using this approach. Using the data available, we found a straight average to be a better predictor of subjective responses. This topic may warrent further investigation.

3. Validation Tests

3.1 Steady-State Conditions

NREL ran a series of tests to compare ADAM's skin temperatures with steady-state subject data from Werner and Reents[5]. We placed ADAM nude and horizontal in our Manikin Environmental Chamber. The chamber was maintained at a uniform temperature with negligible airflow. We ran ADAM with physiological model control. Although the actual metabolic rates of the subjects are unknown, the suggested 45 W/m^2 for a reclining human from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Fundamentals Handbook[6] was applied to the human in the model.

We compared the resulting core and skin temperatures with the Werner and Reents data in Fig. 2 for an air temperature of 23.2°C. The manikin/model tended to predict warmer skin temperatures than those measured, with a maximum deviation of 4.2°C. The overall trends were encouraging: the core temperature agreed within 0.6°C, and skin temperatures decreased in regions further from the torso.

Figure 3 shows the comparison for an air temperature of 30°C. The core temperature was within 0.1°C, and the maximum skin temperature deviation was 2.1°C at the hands. The manikin and model under-predict skin temperatures at higher ambient air temperatures. The core temperature matched exactly, but the maximum under-prediction was 2.5°C at the hands.

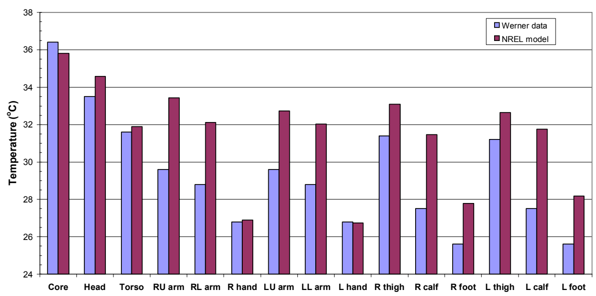

Figure 2 ADAM/Human Comparison, T_{air}=23.2°C

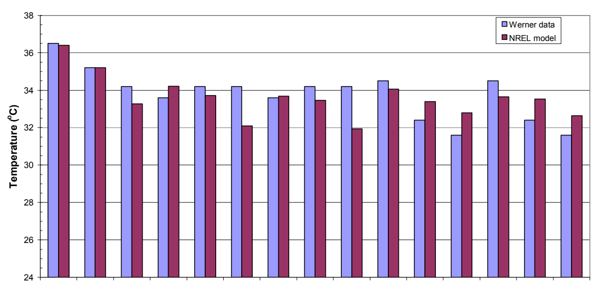

Figure 3 ADAM/Human Comparison, T_{air}=30°C

Initial results indicate the manikin with physiological model control yields human-like skin temperature distribution. Compared to data from Werner, the skin temperatures were within approximately +4.2/-2.5ºC for a wide range of ambient air temperatures. The core temperatures agreed to within 0.6ºC. Details on the testing and analysis are available in Rugh and Bharathan[7].

3.2 Transient Conditions

During our automotive testing, we noted the predicted core temperature responded quickly when ADAM was moved into a hot passenger compartment environment. Xu and Werner[8] and Haslan and Parsons[9] show a 0.004-0.007 ºC/min change in core temperature during temperature step-up experiments. Similar transient step change tests were performed at NREL. ADAM and the subject each were dressed in cotton pants, short sleeve shirt, undergarment and socks. The subject core temperature was monitored with a wireless pill that was injested ~4 hours prior to the test. The Manikin Environmental Chamber was conditioned to 38ºC and 50% relative humidity. ADAM and the subject were seated and conditioned in a 21ºC office environment for ~ 3 hr. Then both were moved to the Manikin Environmental Chamber for 2 hr. Figure 4 shows the core temperature of the two NREL subjects was similar to the Xu and Werner data, while ADAM's core temperature overshot. We are looking into the reasons, including the model circulation system and the lag between commanded sweat and actual evaporation.

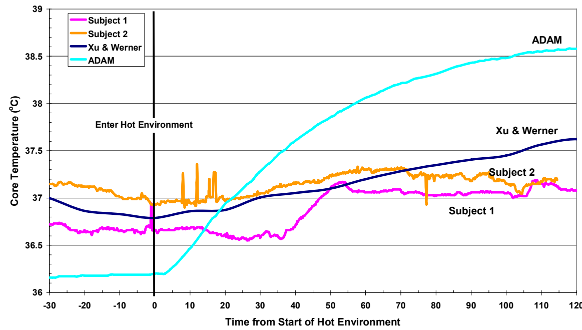

Figure 4 T_{core} during Step-up Temperature Test

4. Ventilated Seat Application

Improving the delivery methods for conditioned air in an automobile is an effective way to increase thermal comfort with little energy cost. This reduces A/C needs and thus fuel use. Automotive seats are well suited for effective delivery of conditioned air due to their large contact area with, and close proximity to, the occupants. Normally a seat acts as a thermal insulator, increasing skin temperatures and reducing evaporative cooling of sweat. Ventilating a seat has low energy costs and eliminates this insulating effect while increasing evaporative cooling. W.E.T. Automotive Systems manufactures a ventilated seat that pulls air through the seat cushion and back. We assessed one of these seats using ADAM.

The VCCL at NREL was developed to simulate the soak and cool-down of a vehicle passenger compartment[10]. The passenger compartment from a compact car, A to C pillar, was heat soaked using a 963 W/m^2 ± 23% full spectrum solar simulator for 3.5 hours. During this time, the average room environment was controlled at 31.6°C ± 0.4°C and 30% ± 5% RH. ADAM and the subjects were conditioned in an office environment. The subject entered the heat soaked room, stood for 30 seconds, and then did step exercises for one minute to simulate walking to the car. The subject entered the heat soaked car and took a pre-cool-down thermal comfort and sensation vote. The A/C system was started 45 seconds after the subject entered the vehicle, at which time the first cool-down vote was taken. Thermal comfort and sensation votes followed every two minutes for the duration of the test.

Figure 5 shows that an operating ventilated seat increased the heat loss from ADAM's back and bottom by ~ 60 W/m^2 (25-35 minutes into the cool-down) compared to no ventilation (baseline). The seat contact temperature was reduced by ~ 4.7ºC resulting in an overall thermal sensation improvement of 0.28 (on a +4 to –4 scale) shown in Fig. 6. We determined that if the A/C system capacity was reduced by 7% and the ventilated seat was used, the same thermal sensation and comfort as the baseline seat would result. Using NREL's A/C fuel use model[11], an estimated 522 million gal/year or 7.5% reduction in U.S. A/C fuel use could be achieved.

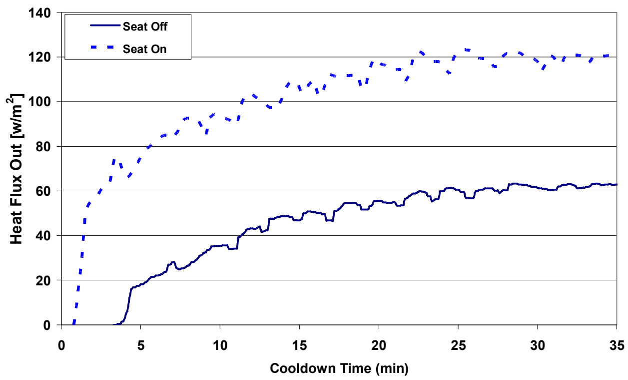

Figure 5 Heat Loss from ADAM's Back and Bottom

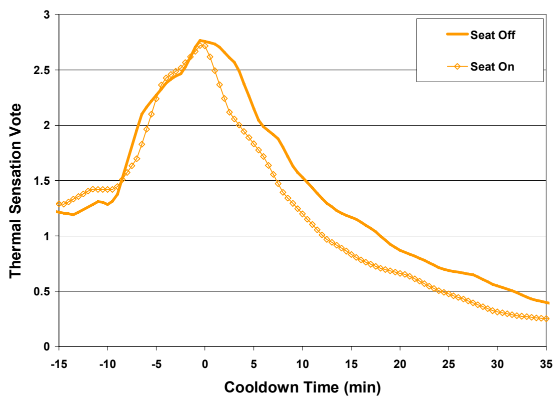

Figure 6 ADAM Thermal Sensation

5. Liquid Cooling Garment Application

NASA currently uses LCGs under spacesuits to remove heat from the human body during a spacewalk. Thermally conditioned liquid is circulated through small tubes distributed around the suit. We used ADAM to assess a Shuttle LCG (Fig. 7) as well as an Orlan LCG, a Russian-designed cooling garment[12]. NASA uses a comfort curve to determine the inlet flow temperature as a function of metabolic rate for the Shuttle LCG. We tested three points on the curve and two points off the curve. The test is determined to reach steady state when the core temperature stabilizes.

The room temperature was set at 27ºC, which yielded a spatially averaged air temperature of 26.6ºC around ADAM. The room humidity was maintained at 25%.

Figure 7 Shuttle LCG

A flow rate of 1.81 l/min was used in all tests. It took 3-4 hours to reach steady state for M=275 W and 7 hours for M=350 W. At the higher metabolic rates and inlet temperatures, the core temperature initially overshoots due to a lag in sweat evaporative cooling, which subsequently causes excessive sweating. This sweat (deionised water) flows into the segments, evaporates, and causes a resulting undershoot in core temperature.

Figure 8 shows the core temperature for the Orlan LCG was an average of 0.06ºC lower than the Shuttle LCG for all tests. Since the sweat rate is a function of core temperature in the model, the Orlan LCG also has lower sweat rates. The heat transfer to the LCG fluid in Fig. 9 was on average 15 W greater with the Orlan suit indicating the improved heat transfer compared to the Shuttle LCG.

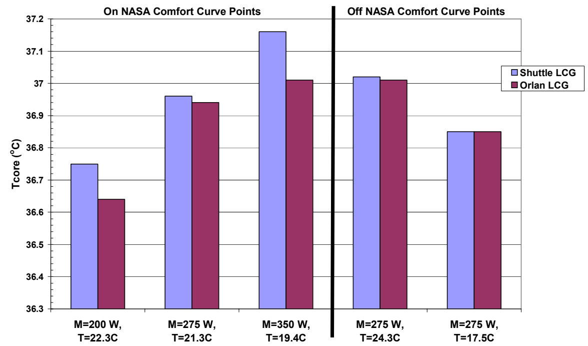

Figure 8 Core Temperatures

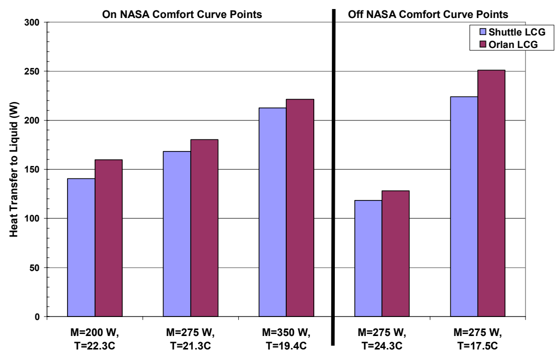

Figure 9: Heat Transfer to LCG Fluid

The skin temperature results are not as consistent. While the Orlan LCG resulted in a lower average skin temperature in two cases, a higher average skin temperature resulted during the lowest fluid inlet temperature cases. This is because the Orlan LCG does not have cooling tubes in the calf region. The Shuttle LCG has tubes and subsequently lower calf temperatures. This also lowers the foot temperatures due to cooler blood flow and results in a lower overall average skin temperature. The dashed lower curves in Figure 10 present the average skin temperature for three inlet temperature cases at M=275 W. At Tinlet=17.5ºC, the Orlan LCG has a higher average skin temperature. Taking the calves and feet out of the average (solid lines), the Orlan LCG has significantly lower skin temperatures for the M=275 W cases, as well as for the M=350 W and M=200 W cases.

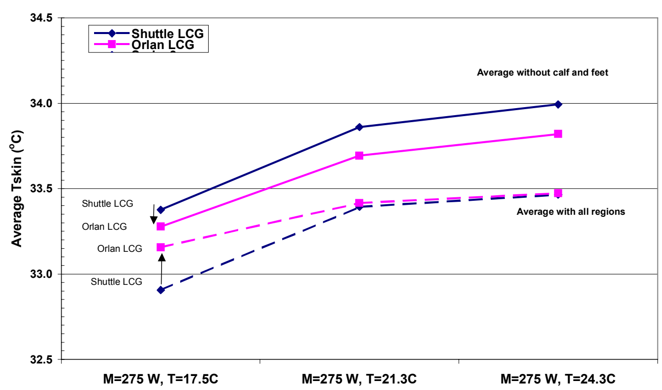

Figure 10 Skin Temperatures

6. Conclusions

Results of validation testing of NREL's thermal comfort tools indicate the manikin with physiological model control yields human-like skin temperature distribution. Comparison with subject data shows the predicted skin temperature distribution of the manikin and model is similar to that of the human subject except for the hand and foot. The manikin and subject data were used in NREL's VCCL to assess the impact of an automotive ventilated seat on thermal comfort and fuel economy. Results show an improvement in thermal comfort with the ventilated seat. This yields a potential 7% reduction in A/C compressor power and 7.5 % reduction in vehicle fuel use. ADAM was successfully used to assess the thermal performance of Shuttle and Orlan LCGs. Comparing results with the same manikin and room conditions, the Orlan LCG had slightly better heat transfer, which resulted in lower core and skin temperatures.

During these previously discussed test programmes, a number of challenges with the manikin and physiological model were encountered. At high metabolic rates or high temperature/humidity environments, it took a long time for the system to reach steady state due to an oscillation in the predicted core temperature. This may be caused by a lag in evaporative cooling compared to the commanded sweat rate or an artifact of the model responding too quickly to changes in skin heat loss. A few segments failed due to broken heaters and controllers, but the large number of segments allowed testing to continue using data from adjacent segments. We reviewed the psychological results (sensation and comfort) and determined an average of local comforts was a better method to calculate the overall comfort than the original correlation.

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