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An objective method for screening and selecting personal cooling systems based on cooling properties

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ABSTRACT

A method is proposed for evaluation and selection of a personal cooling system (PCS) incorporating PCS, subject, and equipment weights; PCS run time; user task time; PCS cooling power; and average metabolic rate. The cooling effectiveness method presented is derived from first principles and allows those who select PCSs for specific applications to compare systems based on their projected use. This can lower testing costs by screening for the most applicable system. Methods to predict cooling power of PCSs are presented and are compared to data taken through standard manikin testing. The cooling effectiveness ranking is presented and validated against human subject test data. The proposed method provides significant insight into the application of PCS on humans. However, the interaction a humans with a PCS is complex, especially considering the range of clothing ensembles, physiological issues, and end use scenarios, and requires additional analysis.

1. Introduction

Heat stress has long been recognized as a risk to personnel health and work performance, particularly in highly radiant or hot environments, and at high-activity levels. This is especially true in desert and jungle conditions, deep mines, firefighting situations, or other locations where high radiant loads, high air temperatures, high humidity, or a combination of these elements, can lead to heat stress incidents (Buller et al., 2008; Chou et al., 2008; Duncan et al., 1979). In high-temperature applications, where the ambient temperature is greater than body temperature, the physiological defense against heat stress is the evaporation of perspiration. Unfortunately, protective equipment and clothing limit the body's ability to evaporate perspiration and expel heat to the environment (Cadarette et al., 2001). This also contributes to the buildup of heat in the body, raising the body's core temperature, and eventually leading to heat stress.

In recent years, numerous new technologies in protective fabrics, clothing systems, and cooling systems have been designed to help mitigate the onset of heat stress. Consequently, acquisition specialists, trainers, equipment developers, and researchers are faced with many product choices in the marketplace. For example, more than 300 different personal cooling systems for use in hot environments are available on the market (McCullough et al., 2013). Technical information available from manufacturers of these products is often incomplete, confusing, or misleading, so it is difficult to decide which products are appropriate for a particular application.

Use of PCSs has been investigated for many years by the military, government agencies, private and public organizations, and universities (Barwood et al., 2009; McCullough and Eckels, 2009; McLellan et al., 1999). The analysis of PCSs for use in various industries is challenging due to the inherent variability in human physiology, range of expected work or activities, and variability in environmental conditions. A common method of screening PCSs is to use a thermal manikin to measure the cooling rate. In the standard, systems must meet a 50-W minimum, then systems are compared to one another based on their cooling power (ASTM, 2010b). The thermal manikin provides a cost-effective and timely alternative to testing each variation of PCSs on humans (Bogerd et al., 2010). Even with this economic advantage, 300 PCSs can't be screened for each end use scenario. Therefore, additional tools are needed.

In previous studies, criteria used to select PCSs were often not reported or quantified. These were sometimes confined to cooling ability in watts (Endrusick et al., 2007), ergonomic factors

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(Goodman et al., 2008), or some combination. Selection criteria could include many different categories, which are necessary, but generally deemed 'self-explanatory' and not reported in literature. Obviously, some criteria will vary between applications. In past studies performed by the authors, potential systems have been removed from consideration when they didn't pass certain metrics such as system weight, tethered operation only, PPE compatibility, flammability, and other safety concerns. The work by Laprise (2012) provides a very inclusive list of selection criteria intended as a standard for PCS solicitations from companies for "emergency responder operations." These can be very useful in narrowing systems based on safety and ergonomic factors, especially when paired with systematic selection methods such as those presented in Ullman (1992). More refinement can be added if this is coupled with the standards proposed by organizations such as ISO, NIOSH, OSHA, and NFPA. While this necessary step is important, a metric for evaluation of personal cooling system effectiveness is lacking.

Currently there is a strong dependence on thermal manikin testing, which can be very expensive when evaluating large numbers of systems. Thermal manikin testing has inherent limitations and does not always include issues such as weight, PCS runtime, and availability of supplies. This paper proposes a unique cooling effectiveness metric that incorporates task time, PCS runtime, weight, and work rate for stationary tasks. There is interest in a comparative cooling effectiveness measure. Work by Xu and Gonzalez (2011) developed a relative efficiency measure for air circulation systems to compare measured power from the manikin to a modeled value. The proposed measure of cooling effectiveness in this paper will be introduced and defined. This will be followed by validation and discussion of the method incorporating existing standards for measuring PCSs, using thermal manikins and previously reported human subject testing.

2. Methods

2.1. Cooling effectiveness

The primary purpose of the PCS is to protect the end user from heat stress by providing cooling to the body. As a result, it is tempting to select a PCS based only on its cooling rate. However, literature suggests that selecting a suitable system is more complicated than just the cooling rate. House et al. (2013) found that the melting temperature of phase-change material PCS affects the cooling experienced by the body. Another factor is weight of the PCS. Some users, such as the U.S. Army, prefer to use cooling effectiveness as a variable consisting of the cooling, measured in watts, divided by PCS weight, to help account for the impact of the PCS weight on the soldier. However, duration of the cooling effect is as important as the cooling rate in longer work times, when the system is not tethered to a continuous or large power or cooling source. After systems are no longer providing cooling, they can become extra weight for the user to carry; thus, adding to the physiological strain on the user. Therefore, it was recognized that time — including both task time and length of cooling time for a PCS — needed to be incorporated into the analysis.

Developing a measure of the cooling effectiveness incorporating these parameters allows systems to be ranked in order of their expected contribution to mitigating heat stress in end users. The numerical score is based on the cooling rate, duration of cooling effect, task time, and system weight. Basic energy balances are used to derive the metrics. The energy balance approach used by House et al. (2013) and Barwood et al. (2009) to estimate the cooling rate from human subject data, except with the inclusion of time and weight parameters, is used here. For demonstration purposes of thermal modeling, the physical aspects of the average-sized man were set to be 81.6 kg (180 lbs) and 1.8 m tall, with 1.8 m^2 of surface area, as given by ASHRAE (ASHRAE, 2013).

2.2. Energy balance

Heat storage occurs when the body is unable to dissipate the energy generated. This can be examined using an energy balance. In this analysis, a first-order energy balance is used. This simple approach was also used in research done for the Air Force (Pandolf et al., 1995) and in the research of House et al. (2013) and many other sources. The heat storage (*St*) equation for a user without a PCS is shown here:

$$St = \sum_{i=1} Wt_{,i} * Cp_{b,i} * \Delta Tb_{,i} = (Mr - Wr - Ht) * \Delta t \quad (1)$$

where, *St* is heat storage by the body (kJ), $Wt_{,i}$ is body segment mass (kg), $Cp_{b,i}$ is body segment specific heat (kJ/kg*°C), $\Delta Tb_{,i}$ is the change in body segment temperature (°C), *Mr* is metabolic rate (W), *Wr* is work rate performed on the environment (W), *Ht* is natural heat transfer to/from the body (W), and Δt is task time (sec). The work rate performed on the environment (*Wr*) is the physical effect of extra metabolic energy such as moving the body by walking, biking, climbing, etc. Possible methods to determine metabolic rate (*Mr*) and heat loss to the environment (*Ht*) will be discussed in the following sections. The storage term summation term highlights the effects of different specific heats, temperatures and masses of different body segments and layer. In this simplistic analysis, $i = 1$, yielding $St = Wt^* Cp_b{}^* \Delta Tb$, where all values are the average body values. This is discussed more in depth in Section 2.5.

Including the PCS in the energy balance analysis somewhat complicates the heat storage equation, because the difference in PCS cooling duration and the task time (i.e. work time) must be reflected in the equation. It was decided this would be approximated as a path-independent heat gain over a task time with a constant work rate and cooling rate similar to Equation (1). Weight of the personal cooling system was accounted for by using the weight-adjusted metabolic rate, (Mr_{PCS}), which will be discussed in a following section. If the cooling duration was greater than the examined task time, the cooling duration was set to the task time. The body heat storage equation with a PCS becomes—

$$St = (Mr_{PCS} - Wr - Ht_{PCS}) * \Delta t_1 - Cl * \Delta t_2 \quad (2)$$

where $\Delta t_2 \leq \Delta t_1$, and *St* is heat storage by the body (kJ), Mr_{PCS} is weight-adjusted metabolic rate (W), *Wr* is work rate performed on the environment (W), Ht_{PCS} is natural heat transfer to/from the body with the PCS (W), Δt_1 is task time (sec), Δt_2 is cooling duration (sec), and *Cl* is cooling rate (W).

Equation (2) highlights both and potential positive and negative effects from the PCS. For longer work times and short cooling durations, the increased metabolic work due to weight of the system will likely exceed the cooling benefit of the PCS. The cooling rate and metabolic rates used in Equation (2) are averages over the associated times. A time-dependent version of this equation can be produced if additional information is known about the cooling rate versus time.

2.3. Metabolic rate

To determine heat storage, metabolic work levels need to be estimated based on the tasks being performed by the wearer. Tables of metabolic rates for different activities can be found in the literature (Ainsworth et al., 2011; American College of Sports Medicine, 2010; Parsons, 2006) if the task metabolic rate is not