AUTOMATIC CONTROL OF LIQUID COOLING GARMENTS: WHAT IS THE IDEAL CONTROL MODE?

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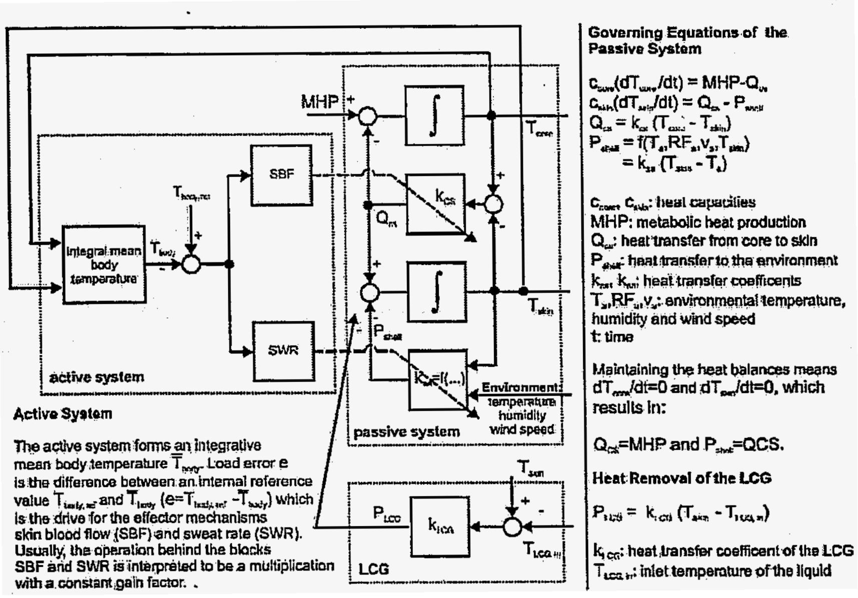
INTRODUCTION

Liquid cooling garments (LCG) are well established to maintain the thermal balance during work in extreme environmental conditions, but no gold standard exists concerning the strategies of an automatic cooling control.

METHODS (System Analysis of the Human Thermal System)

Figure 1 displays the simplified schematic of the human thermal system, which can be subdivided into the passive (controlled) and the active (controlling) system. These two are linked via the afferent signals (body temperatures) and the efferent ones (skin blood flow [SBF] and sweat rate [SWR]). The passive system itself is represented by two compartments, core/muscle and skin, with heat balances being the basis for the flow chart. There **MHP** is the metabolic heat production, Q_{CS} is the heat transfer between core and skin and P_{shell} is the entire heat **loss** to the environment at the skin surface (convection, radiation, sweating).

It seems that all the physiological variables that are linked to the thermal state may serve as input for an artificial controller. These variables may be clas-



Governing Equations of the Passive System

$C_{core}(dT_{core}/dt) = MHP - Q_{cs}$
$C_{skin}(dT_{skin}/dt) = Q_{cs} - P_{shell}$
$Q_{cs} = k_{cs}\,(T_{core} - T_{skin})$
$P_{shell} = f(T_a, RF_a, v_a, T_{skin})$
$= k_{se}\,(T_{skin} - T_a)$

C_{core}, C_{skin}: heat capacities
MHP: metabolic heat production
Q_{cs}: heat transfer from core to skin
P_{shell}: heat transfer to the environment
k_{cs}, k_{se}: heat transfer coefficents
T_a, RF_a, v_a: environmental temperature, humidity and wind speed
t: time

Maintaining the heat balances means $dT_{core}/dt=0$ and $dT_{skin}/dt=0$, which results in:

Q_{cs}=MHP and P_{shell}=QCS.

Heat Removal of the LCG

$P_{LCG} = k_{LCG}\,(T_{skin} - T_{LCG,in})$

k_{LCG}: heat transfer coefficent of the LCG
$T_{LCG,in}$: inlet temperature of the liquid

Active System

The active system forms an integrative mean body temperature $\overline{T}_{body}$. Load error e is the difference between an internal reference value $T_{body,ref}$ and $\overline{T}_{body}$ ($e=T_{body,ref} - \overline{T}_{body}$) which is the drive for the effector mechanisms skin blood flow (SBF) and sweat rate (SWR). Usually, the operation behind the blocks SBF and SWR is interpreted to be a multiplication with a constant gain factor.

Figure **1.** Schematic of the human thermal system sified according to their occurrence in the natural control loop of the human thermal system: Class I—variables reflecting the activity of the effector mechanisms SWR and SBF; Class 2—variables reflecting the sensory input of the active system (= output of the passive system), which are the body temperatures and perhaps the perceived subjective thermal comfort and Class 3—variables that are an estimate of the disturbance (exercise) acting on the thermal system such as metabolic rate and heart rate. Unfortunately, the response of all these parameters to exercise and ambient conditions depends greatly on the individual, and that must be considered when designing a control-loop for a LCG. But things are much more challenging, because the application of an LCG inherently interferes with the thermal system: P_{shell} the heat loss at the body shell may be described by a heat transfer coefficient k_{SA} (shell to ambient), which is a nonlinear function of skin temperature (T_{sk}), SWR and the environmental conditions. The active system influences the heat transfer of the passive system via two effector mechanisms: SBF adjusts k_{CS}, the heat transfer coefficient between core and shell, and the heat loss at the body surface is influenced by the postulated k_{SA}, which in turn depends on the SWR. Applying an LCG, the evaporation of sweat is blocked and with this the heat transfer coefficient k_{SA}, which originally can be tuned by the active system, is replaced by the almost constant k_{LCG}. Therefore, an LCG must be considered as a complete new effector, with other mechanisms, either inlet temperature or flow rate of the coolant, to adjust heat removal. (Concerning air-cooling garments, the situation is different. There, the natural effector mechanism still works and the task of a controller can be reduced to provide enough effector capacity.)

RESULTS

Class l a (SWR). Any adjustment of SWR by the active system is aimed to maintain the heat balance at the body surface ($P_{shell} = Q_{CS}$). On this basis, one can derive the cooling level from SWR. We tested a controller by which chest-SWR was clamped to a moderate value of 55 $g \cdot h^{-1} \cdot m^{-2}$, a value that was in agreement with the findings of others (1). The measurements of temperatures, metabolic, heart and sweat rates (capsules) in our experiments are described in detail in a previous study (2). An ILC-Dover LCG with a constant flow rate (1.8 $L \cdot min^{-1}$) was used. Exercise was performed on a cycle-ergometer with constant environmental conditions (35°C, 45% humidity). Our results can be summarized by a linear regression, by which the controller-induced lowering of T_{sk} is linked to the individual rectal temperature rise (T_{re}) during exercise (75W):

$$(T_{sk}-T_{sk,rest}) = 1.08 - 3.67 T_{re},$$

$r = 0.89$; $P < 0.05$; $n = 5$: steady state conditions

T_{re}, an estimate for the central drive of sweating, differed among the subjects 0.15 to 0.95°C. Now, to guarantee a constant SWR (60 ± 9 $g \cdot h^{-1} \cdot m^{-2}$), T_{WI} and T_{sk} were adjusted accordingly. At first glance this result may satisfy, but the subjects complained of cold discomfort, and this may have indicated vasoconstriction, leading to an impeded internal heat transfer and therefore, to higher T_{re}.

So we concluded 'that, depending on the chosen set point of SWR, there may be the risk of a controller wind up.

A concept is reported (1) where the whole-body evaporative heat loss **was** controlled. There, the special condition, an astronaut with an LCG worn under the outer visible pressure suit, allowed the measurement of the total amount of evaporated sweat. The proportional-type controller used a constant gain factor and its set point was the individual resting value of evaporation. One result of the experiments was an impressive diagram with relationships between MHP, SWR, T_{sk} and comfort. But the authors reported problems concerning the absorption of sweat by the LCG, which resulted in delayed reactions of the control loop

Class 1b (SBF): Another control strategy was the maintenance of the peripheral heat balance. This can be achieved explicitly by clamping T_{sk} to a fixed value (set point) by means of an LCG with an integral-type controller. We tested this concept successfully (3). Exercise-induced changes of MHP, which led to a higher SBF and, therefore, a higher Q_{CS}, were counteracted by the artifical controller with adjustments of the LCG's heat removal rate. Except for some transient deviations, T_{sk} was nearly constant throughout the experiments. Unfortunately, sweating was still initiated by the active system, so that it is not enough to clamp T_{sk} to one distinct set point but must be lowered during increasing exercise, enabling the body to get rid of the heat mainly by conduction into the LCG. Several ways are possible to adjust T_{sk}. We used the close correlation of heart rate to MHP, to adapt the set point of T_{sk} (3). During the experimental validation, a reduction of sweating and an enhancement of the subjective comfort level was attained.

Another concept **(4)** to achieve a lowering of T_{sk} is based on transient imbalances at the **skin** level. There, the new inlet temperature of the LCG ($T_{WI,set}$) was derived from the actual temperature gradient of the cooling liquid between inlet and outlet (T_{WI}, T_{WO}) and the value of T_{sk}:

$$T_{WI,set} = 35°C-6(T_{WO}-T_{WI})-1.1(T_{sk}-33.8°C)$$

The parameters **in** that equation had been tuned so that at rest T_{WI},set, T_{sk}, T_{WI} and T_{WO} are constant. When work begins, T_{sk} and therefore T_{WO} increases. This causes the controller to lower $T_{WI,set}$. The lowering of T_{WI} lowers T_{sk} and increases the difference (T_{WO}-T_{WI}) further until the system seeks to stabilize. Stabilization arises **from** the onset of vasoconstriction, which forces T_{sk} to be too low and a reduction of the difference T_{WO}-T_{WI}. Both effects cause the controller to allow T_{WI},set to rise. This controller was tested even in experimental **runs** lasting 24 h (calorimetric studies). A similar strategy is reported (5), but T_{sk} was not incorporated; instead, a complex combination of the integral and derivative of T_{WI} with respect to time was used. A disadvantage of both approaches is their positive feedback nature. T_{WI} is mainly derived from the difference T_{WI}-T_{WO} or the heat removal rate. This particular part of the control algorithm performs a positive feedback path, meaning that an increase of the heat removal rate will lower cooling temperature which again will increase the heat removal rate **and** so on. For the "metabolic part" of the total heat removal rate, stabilization **arises** due to vasoconstriction. However, for the "environmental part," no stabilization mechanism exists and, indeed, it was remarked *(5)* that an increasing heat exchange between the LCG and the environment may lead to problems.

Class **2** (Core Temperature). In another aproach we used the inherent rise of T_{re} during exercise to initiate a lowering of T_{sk} with the intention to keep **mean** body temperature (T_{body}) constant (2). The experiments confirmed that except for some transient fluctuations, Tbody could be clamped to the pre-exercise level. However, some problems, explainable by the individual time course of T_{re} became obvious: **A** minor problem was the delayed reaction of T_{re} to exercise, but the major problem had been its naturally existing variations due to individual differences of the fitness/heat acclimatization. When cooling depended on T_{re}, the reaction **was** delayed and heat removal differed considerably among the subjects.

Class **3** (Metabolic Rate). Metabolic rate is a good estimate of the endogenous disturbance acting on the passive system. The increase of this parameter above its resting value was used (2,4) to lower inlet temperature of **an** LCG proportionally. Because this concept is an open-loop control, it operates in an absolutely stable fashion. However, during a fever, there exists a situation under which this control mode may fail.

CONCLUSION

We prefer control concepts based on Class 1b (SBF), because there the body's efforts to maintain the thermal balance are supported in a very direct sense. Using any other variable, one should always be aware **of** the individual responses **and,** additionally, the interference of the LCG with the thermal system (e.g., the direct blocking of evaporating sweat).

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