Evaluation of physiological comfort index for workers wearing protective clothing in nuclear or other harsh environments

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Abstract

The assessment of thermal stress and the translation of the stress in terms of physiological strain is complex. There are many indexes evaluating thermal stress but most of them don't take into account physiological variables such as core temperature, heat rate and sweat rate. The need to wear protective clothing in harsh environments, such as for example those affected by nuclear, chemical or biological contamination, may lead to intolerable heat strain, as the clothing limits the workers' ability to lose heat to the environment. A survey on physiological comfort indices showed that PSI (Physiological Strain Index) is the most appreciated one, as individual reactions to it are only based on core temperature and heart rate. Moreover, PSI index can assess in real time both physiological response to heat and heat strain among any combination of climate, clothing and work rate. This index does not consider sweat rate, because of its intrinsic difficulty in performing an on-line measurement: nevertheless this term should be taken into account, especially in the case of short and repeated operations. This work proposes the use of two physiological comfort indices: the first one concerns long-lasting operations and the second concerns short and repeated operations. In order to calculate the value of coefficients in the new physiological comfort index, it is necessary to carry out a measurement campaign on a sufficiently wide statistical population. These measurements should lead to a quantitative evaluation of the importance of the term taking into account the presence of cooling systems in personal protective clothing.
Keywords: physiological comfort index, personal protective equipment, heat stress, heat strain.

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1 Introduction

The use of personal protective equipment (PPE), when required by hazardous activities, is often opposed by workers because of its lack of comfort, both thermal and physiological. The need to wear protective clothing may lead to intolerable heat strain, as clothing will have a detrimental effect on the workers ability to lose heat to the environment. Even though PPE offer the required protection, in some conditions they may increase the risk of heat strain, that could be a threat to worker's life. When heat stress may cause a risk, this can be assessed directly, by means of physiological measurements, but in many situations it is not practical. Different methods for estimating potential heat stress have been developed and many indices exist, but none of them is widely accepted.

2 Personal protective equipment in nuclear decontamination activities

While in nuclear power plants it is possible to use robots, in nuclear fuel cycle facilities, because of their geometry, this possibility not always occurs. In this case the use of a ventilated-pressurized protective clothing is required to ensure workers against the hazard of radioactive contamination [1].

The clothing is made of impermeable material that protects the whole body (head, hands and feet) and it is equipped with a ventilation system to supply breathable air and to ensure required overpressure. Studies and interventions, performed during the deactivation and decontamination of Hot Cells in ENEA Casaccia Research Centre, showed performance improvements in the protective equipment usage if a direct skin ventilation and an emergency extracting system (ENEA patent, see fig. 1) are used too. Emergency extracting system offers many advantages like: easy employability in limited spaces, simplicity and reliability, ease of removal of the operator to be succoured toward the exit.

Figure 1: ENEA extracting system.

Direct skin ventilation in ventilated-pressurized protective clothing guarantees a better thermal regulation especially when operations should be performed in hot environments. This system directly ensures cooling of the wearer's skin. The studies, supported by occupational physicians, proved that for the same ventilation rate and the same physical work rate, the acceptability duration may be improved by 50% by means of the body refreshing due to direct skin ventilation, in comparison with the traditional clothing in which the ventilation is fed into the suit, that is only over the underwear [2]. Workers audit carried out in ENEA confirmed the benefit of the ventilated-pressurized clothing especially as regards the increasing in comfort. The acceptability duration is defined as the time at which the wearer, performing a heavy work, has accomplished some physiological limits:

- skin temperature increase $\leq 3°C$
- increase of heart rate $\leq 30\%$
- rectal temperature increase $\leq 2°C$
- body mass loss ≤ 2 kg.

Data collected in ENEA Casaccia Research Centre, over more than 500 interventions, showed that the ventilated-pressurized protective clothing may be successfully used both in hazardous operations developed in nuclear and chemical industry, and in environment with low air contamination levels, due to the following advantages:

- the conspicuous reduction of the wastes volume (with broad advantages for the environment);
- the remarkable decrease of the contamination risk for personnel;
- the operator safety, due to the resistance and reliability of materials and systems.

The usage of a protective clothing places workers at risk because it prevents the loss of heat by convection, radiation and evaporation from the body. When the body temperature rises above about 40°C the mechanisms that usually control body temperature at around 37°C stop working, with potential lethal consequences [3]. If the body cannot lose heat, then even small amounts of heat, generated by doing a physical task, will cause heat strain in less than 30 minutes. Frequently the signs of heat illness, such as nausea, irritability, sluggishness, pallor, lack of sweating, are misunderstood with fatal consequences.

3 Thermal comfort indices

Heat stress is a combination of factors, such as air temperature, air movement, humidity, radiant heat and accomplished work that influence the body heat balance; the physiological responses to heat stress is the heat strain.

Thermal comfort is defined in the ISO 7730 [4] as "that condition of mind that expresses satisfaction with the thermal environment". As a matter of fact thermal comfort is very difficult to define because it is necessary to take into account a range of environmental and personal factors when deciding what will make people feel comfortable.

The assessment of this psychological state may be quantified by means of indices taking into account environmental factors such as:

- air temperature;
- radiant temperature;
- air velocity;
- humidity;

and personal factors such as:

- metabolic heat;
- clothing insulation.

Among the available indices, one of the most widely used index is the PMV (Predicted Mean Vote) and the PPD (Predicted Percentage of Dissatisfied) index. This index predicts the thermal comfort of people working in a given environment. PPD is the predicted percent of dissatisfied people at each PMV. As PMV changes away from zero in either the positive or negative direction, PPD increases.

The ISO 7243 [5] provides a simple method and uses the Wet Bulb Globe Temperature (WBGT) index to assess hot environments. This index is obtained from three parameters: black globe temperature (T_g) which reflects the solar radiation, wet bulb temperature (T_w) and dry bulb temperature (T_a). This index is calculated as follows:

$$WBGT = 0.7T_w + 0.2T_g + 0.1T_a \quad (1)$$

The WBGT index was found to be limited in evaluating heat stress, due to the inconvenience of measuring T_g. Besides the correlation of this index to physiological responses was only partially tested.

Other indices exist, such as for example HSI (Heat Stress Index) and ESI (Environmental Stress Index) index, proposed by Moran et al [6], but none of them takes into account physiological parameters.

While indices of heat stress have become widely used in occupational settings, attempts at developing indices of heat strain have been less successful. The increased needs for workers to wear heavy, impermeable clothing while working in hot environments, has the potential to increase heat related injuries.

The high number of heat stress indices developed over the years, the lack of broad acceptance of any single index reinforce the problems of managing heat stress, especially in occupational setting. The problem of clothing, and personal protective equipment in particular, is another item, in addition to the above mentioned ones. Most indices are used to predict whether continuous work is possible or some sort of work/rest cycle is required under particular conditions.

4 Physiological comfort indices

In order to monitor heat strain, physiological variables must be taken into account. Physiological comfort indices try to quantify thermal environment comfort with regard to the physiological reactions to heat exposure. Many attempts have been carried out in order to combine environmental parameters with the physiological ones to develop a single index [7]. Currently there are many indices but none of them is widely accepted. The main reason lies in the greatest complexity and plurality of interactions among the main factors to take into account when defining the index.

A simple, easily calculated physiological strain index for use in hot environments, that provides a rapid and accurate assessment of the heat strain, could reduce the risk of heat exposure. Moran et al. [8] developed a Physiological heat Strain Index (PSI) based upon the summation, with equal weight factors, of individual strains for core temperature (T_c) and heart rate (f_c) as follows:

$$PSI = 5\frac{\left(T_{cf} - T_{c0}\right)}{39.5 - T_{c0}} + 5\frac{\left(f_{cf} - f_{c0}\right)}{180 - f_{c0}} \tag{2}$$

where T_{cf} and f_{cf} are simultaneous measurements taken at any time during the exposure and T_{c0} and f_{c0} are the initial measurements. The index represent the combined strains of the termoregulatory and cardiovascular systems. Each strain system was scaled between 0 and 5. The PSI index places the heat strain on a scale of 0 through 10. It can be applied at any time, including rest or recovery periods, whenever T_c and f_c are measured.

5 Proposal for the definition of a new physiological comfort index

A survey on physiological comfort indices has been carried out. It showed that PSI (Physiological Strain Index) is the most appreciate one. It offers advantages such as the following ones:

- it gives on line values, for a real time evaluation of physiological response to heat. It can be calculated while the subject is exposed to heat stress and it is not necessary to wait till the end of the exposure to analyze the heat strain; moreover it allows to take action quickly, before physiological parameters reach dangerous values for the operator's health;
- it can also be calculate in rest situations, when the values of core temperature and heart rate are recorded;
- it is able to evaluate heat strain under different combinations of work rate, environmental conditions and clothing.

The PSI index does not contain sweat rate intentionally, because of its inherent on-line measurement difficulty even if, as everybody knows, it is a parameter that should be taken into account in order to have a whole evaluation.
For these reasons it is possible to alter the Moran et al. definition of PSI index in order to introduce some improvements:

- in PSI index, core temperature and heart rate have equal weights; it could be possible to modify the weight of the two parameters if experimental proofs justify a different influence of the above mentioned parameters to physiological comfort;
- PSI index has been obtained for healthy young men; for this reason 3°C and 120 beats/min were the maximal rise for core temperature and heart rate respectively from normothermia to hyperthermia during exposure to heat stress. It is generally known that heat stress tolerability for middle-aged men and women is less than for those younger; to apply PSI to women and different age groups, corrective coefficients, taking into account the age and the sex of individuals, should be brought in;
- insert a term linked to sweat rate;
- put in a corrective term, reducing the index value when there is an appropriate skin ventilation system in the personal protective equipment, worn by the operator.

The term referred to sweat rate is easily measurable, in case of short-lasting and repeated operations, by means of the difference between the weight of the subject before and after the operation. This term, especially when short-lasting and repeated operations should be performed in harsh environment, should be taken into account.

Two indices are proposed, to employ depending on the intervention length, for operators wearing personal protective equipment:

1) index for long-lasting operations;
2) index for short-lasting operations.

On first approximation an intervention is considered long-lasting when its length is greater than 40 minutes.

In case of long-lasting operations the authors propose an index very similar to PSI including, as far as concerns the physiological parameters, only the two terms: core temperature and heart rate.

As regards the core temperature measurement, it is manifest that a system based upon the on-line measurement of the rectal temperature is rather awkward for operators performing long-lasting operations and still are up for numerous and also hard movements. Therefore it is proposed, in case of long-lasting operations, the use of an alternative core temperature measurement method, based on the aural temperature. The walls of the auditory meatus, immediately adjacent to the tympanum, are vascularized by the external carotid artery and their temperature is affected both by the arterial blood temperature at the heart and by the cutaneous blood flow around the ear and adjacent parts of the head. A temperature gradient is thus observed between the tympanum and the external orifice of the auditory meatus. Insulating the ear adequately from the external climate may reduce this gradient [9]. Literature data highlight that this method shows greater errors than the one based on rectal temperature measurement; nevertheless these errors, which are affected by the external climate, in the case of operators wearing ventilated full suit, are undoubtedly smaller in comparison with the case of operators wearing standard clothing and working outdoor.

It is suggested to carry out preliminarily a comparative study on the operators which will be involved in the operational campaign, between the rectal temperature and the aural temperature, in order to establish the correlation between them. Just after that it could be possible to make use of the following formula containing the rectal temperature as a measure for core temperature. This formula includes a third term taking into account a possible presence of cooling equipment in the personal protective equipment under consideration (for example direct skin ventilation):

$$PCI = a\frac{\left(T_{Ct} - T_{C0}\right)}{39.5 - T_{C0}} + b\frac{\left(HR_t - HR_0\right)}{180 - HR_0} - rC \tag{3}$$

where:
PCI is the physiological comfort index;
a is a coefficient;
T_{Ct} is the core temperature during the intervention;
T_{C0} is the core temperature at the beginning;
b is a coefficient;
HR_t is the heart rate at the end of the intervention;
HR_0 is the heart rate at the beginning;
r is a coefficient;
C is the term taking into account the presence of cooling equipment in the personal protective equipment.

For short-lasting and repeated operations two terms should be added compared to PSI index:

- the first one pertains to sweat rate;
- the second one takes into account the presence of a cooling system in the personal protective equipment.

The numerator of the term concerning the sweat rate contains the sweat rate, obtained from the difference between the worker body mass before and after the operation, adjusted for water intake and urine output. The denominator contains the numeric value 1.25 is referred to the limit for sweat rate, as indicated by ISO 7933 [10] for acclimatized subjects (1.25 l/h):

$$PCI = a\frac{\left(T_{Ct} - T_{C0}\right)}{39.5 - T_{C0}} + b\frac{\left(HR_t - HR_0\right)}{180 - HR_0} + c\frac{M}{1.25 * t} - rC \qquad (4)$$

where:
PCI is the physiological comfort index;
a is a coefficient;
T_{Ct} is the core temperature during the intervention;
T_{C0} is the core temperature at the beginning;
b is a coefficient;
HR_t is the heart rate at the end of the intervention;
HR_0 is the heart rate at the beginning;
c is a coefficient;
M is the sweat rate, equal to the difference between the worker body mass before and after the operation;
t is the duration of the operation;
r is a coefficient;
C is the term taking into account the presence of a cooling equipment in the personal protective equipment.

In order to calculate the numeric value of a, b, c coefficients pertaining to the three physiological parameters (core temperature, heart rate and sweat rate), an ad hoc measurement campaign will be necessary on an enough wide statistical population, because of variability of individual physiological reactions.

In the case of workers wearing personal protective equipment the thermal load is most of all of metabolic type, rather than environmental. Workers wearing ventilated-pressurized protective clothing experienced the presence of sweating inside the suit at the end of the operation. The sweating quantity surely has to be correlated to physiological strain. The quantification of the negative corrective term, linked to the cooling system, if it exists in the protective equipment, should be experimentally obtained, evaluating the trend of the three physiological parameters in the presence and in the absence of the system itself.

6 Conclusions

The WBGT index is essentially a first stage assessment method: it can be used to evaluate the heat stress only on first approximation. Furthermore WBGT index is limited in evaluating heat stress due to the inconvenience of measuring T_g (the black globe temperature) and it is not well-suited in measuring the body reactions to heat, particularly when workers wear impermeable personal protective equipment [11]. The ESI index does not consider any physiological parameter revealing body reactions.

The PSI index takes into account physiological parameters such as core temperature and heart rate, but it does not consider the body mass loss. This index has been validated on young and healthy men, performing work outdoor and wearing different kind of clothing.

This work proposes to make use of two new indices, to apply depending on the heat exposure duration and trying to overcome limits of PSI index. Both new indices contain a term reckoning with the possible presence of cooling systems inside the protective equipment, capable of improving operators' physiological comfort. It could be convenient to carry out experimental surveys aiming, first of all, at a quantitative assessment of this contribution. These surveys should also lead up to the determination of a, b, c and r coefficients when workers wear protective equipment in harsh environments. Only by means of these experimental surveys it could be possible to attain a correct definition of a physiological comfort index: it is an important item because it allows to determine the maximum employment time for the protective equipment as well as the duration of work-rest cycles.

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