Industrial Health 2013, **51**, 285–296

Original Article

On the Transition Thermal Discomfort to Heat Stress as a Function of the PMV Value

Francesca Romana d'AMBROSIO ALFANO[1], Boris Igor PALELLA[2]* and Giuseppe RICCIO[2]

[1] Dipartimento di Ingegneria Industriale, Università di Salerno, Italy
[2] Dipartimento di Energetica, Termofluidodinamica Applicata e Condizionamenti Ambientali, Università degli Studi di Napoli Federico II, Italy

Received September 26, 2012 and accepted January 9, 2013

Abstract: ISO 15265 Standard − Ergonomics of the thermal environment − Risk assessment strategy for the prevention of stress or discomfort in thermal working conditions − can be considered as a key document for helping responsible for the health protection and prevention of working situations. According to the SOBANE strategy, this standard provides a three-step protocol aimed to the prevention, elimination or reduction of risks affecting the workplaces. Although both methods and procedures suggested by ISO 15265 appear very clear, this standard could bring in confusion both beginners and not specialists in occupational health concerning Predicted Mean Vote (PMV) threshold values consistent with comfort − hot discomfort and the discomfort − hot stress transitions. In this work such matter has been extensively discussed showing a certain difficulty in the definition of an unambiguous PMV threshold value for each working situation in any microclimate.

Key words: Hot working environments, Physiological heat stress, Predicted heat strain model, PHS, Physical agents risk assessment

Introduction

The European Directive 89/391/EEC devoted to the introduction of measures to encourage improvements in the safety and health of workers at work[1] moved the interest of the occupational hygiene to the risk prevention rather the risk assessment, leading to an Industrial Health for all as stressed by Parsons[2]. This policy resulted in the formulation of a special strategy called SOBANE, developed by Malchaire at the beginning of 21st Century[3, 4] actually validated in 14 fields (social facilities, safety, machines and hand tools, electricity, fire and explosion, lighting, work on VDUs, noise, thermal environment, chemical agents, biological agents, musculoskeletal disorders, WBV, HAV). SOBANE strategy is developed in four phases: 1) screening; 2) Observation; 3) Analysis; 4). In the field of thermal environments, this strategy is the base of the International Standard ISO 15265[5] devoted to the evaluation of the risk for the prevention of constraints or discomfort under thermal working conditions. The Standard provides for a protocol of investigation characterized by a thorough analysis of the working conditions aimed to identify quick solutions for easy problems or special investigations in complex situations. Therefore the main goal is not the quantification of the risks but their prevention, elimination or reduction. In ISO 15265 the goal of the SOBANE phases are:

a) Observation. ISO 15265 Standard[5] requires only a preliminary collection of information about the work situation, in general, concerning the working conditions, the

---

*To whom correspondence should be addressed.
E-mail: palella@unina.it

climatic conditions and the heat or cold sources. The air temperature can be measured while the others variables responsible for the physiological response of the human body[6] to the microclimate (mean radiant temperature, air velocity, relative humidity, metabolic rate and clothing properties) have to be only estimated. Moreover it prescribes to take into account the workers' judgement attributed on mono- or bi-polar scales, where the zero score characterizes the optimal situation. The number of preventive and controlling actions to be implemented (e.g. a changing of the clothing, a shielding of the radiant surfaces and so on) is strictly related to the deviation with respect to zero (in principle the range of acceptability is in the range from −1 to +1 on a bi-polar scale). In any case, if the actions of control were not enough or their implementation did not lead to foreseeable results, a further step of analysis is needed.

b) Analysis. This phase is based on a three-steps investigation. The analysis on the sequence of activities carried out in the workplace and some thermal comfort facets is primarily required. In particular should be taken into account possible rises or falls of the air temperature, differences of the relative humidity indoor-outdoor, the solar direct radiation, hot and cold surfaces, draughts and, finally, the workload and the clothing characteristic especially if protective clothing is required. The second level deals with the assessment of the working situation and the calculation of the main indices. The third level requires the risk assessment based on the values of the indices previously calculated. Finally, after the identification of the preventive and the short-term controlling actions, the real situation has to be compared with the predicted one aiming to assess the residual risk and to define the protective and medical survey actions to be implemented. In this case the six variables responsible for the physiological response of the human body have to be estimated (in case of personal parameters by means of tables reported in Standards) only by common technicians.

c) Expertise. This further step is required if the analysis stage does not lead to the solution. In particular it is aimed to quantify, analyse and assess the risks trying to solve all those unsolved situations recognized in the previous steps. To this aim special skilled personnel and the use of sophisticated measurement techniques are required. The implementation of this step requires a preliminary selection of the situations to be deepened, the data collection under average and extreme conditions and the calculation of the indices. Moreover, it requires the definition of the preventive and controlling actions, the selection of the modifications to be implemented (e.g. microclimatic parameters, work organization and so on), the assessment of the residual risks and, eventually, the choice of the measures of personal protection and medical survey to be adopted.

Table 1. Classes of risk reported in ISO 15265 standard[5]

Class	Criteria
Immediate constraint	$D_{lim} < 30$ min
Constraint in the short term	$I_{clr} < IREQ_{min}$ $DLE < 120$ min
Constraint in the long term	$PMV < -2$ $IREQ_{min} \leq I_{clr} \leq IREQ_{neutral}$
Cold discomfort	$-2 \leq PMV < -0.5$
Comfort	$-0.5 \leq PMV \leq +0.5$
Warm discomfort	$+0.5 < PMV \leq +2$
Constraint in the long term*	$D_{lim} < 480$ min
Constraint in the short term*	$D_{lim} < 120$ min
Immediate constraint*	$D_{lim} < 30$ min

*in these situations the water loss for 8-h of continuous work and the predicted risk of increase of the internal temperature of the body according to ISO 7933 standard are required[7].

The assessment of the class of risk in the analysis step is based on the calculation of the PMV index (and the application of PHS[7–11] and IREQ[12–14] models depending on the situation) which plays only a role of indicator in long term expositions as showed in Table 1. In particular, ISO 15265 requires for hot discomfort situations a PMV value in the range 0.5–2.0, thereby the transition value between discomfort and stress is just at PMV=2.0. Under hot severe conditions, when PMV exceeds 2, the implementation of PHS (Predicted Heat Strain) model is required[8–11]; by this way the maximum allowable exposition time, D_{lim}, should be calculated according to ISO 7933 Standard[7]. In this way, the class of risk seems very easy to assign, but two aspects appear not clear enough: i) ISO 15265 places the onset of discomfort at PMV = ± 0.5 in disagreement with ISO 7730 Standard[15] where the comfort-discomfort transition is settled at PMV = ± 0.7 (low end and high end of the comfort range of the class C); ii) working situations in the PMV range 0.5–2.0 have to be considered as only uncomfortable or in this range is it possible to reach the limit situation D_{lim} = 480 min with the consequent need to modulate the working turn? In other words PMV=2.0 has really to be considered as a threshold value of the hot stress for any microclimate and working activity?

These facets cannot be ignored by both practitioners and experts of Occupational Health since a wrong assignation of the class of risk of the environment could bring to an

Table 2. Ranges of validation for PMV index[15) and PHS model[7)

Parameter	PMV	PHS	Unit
Air temperature	10–30	10–50	°C
Mean radiant temperature	10–40	–	°C
Difference between mean radiant and air temperature	–	0–60	°C
Water vapour partial pressure	0–2,700	0–4,500	Pa
Air velocity	0–1.0	0–3.0	$m \cdot s^{-1}$
Metabolic rate	0.8–4.0	1.0–4.0	met
Clothing thermal insulation	0–2.0	0–1.0	clo

ineffective strategy of prevention and protection. Moreover this uncertainty could be further increased by the high sensitivity of PMV index and PHS model to the errors of measurement of personal and physical parameters, as showed in several papers16–20). As a matter of fact, a poor measurement accuracy on one or more parameters (in particular the mean radiant temperature) although within the accuracy requirements suggested by ISO 7726 Standard21), or unforeseeable numerical matters22), can lead in hot environments to a wrong assessment of maximum allowable exposure times which under certain conditions can be underestimated up to 5 h16).

Aiming to lead to a clear and unmistakable classification of the risk of working situations in the presence of heat strain, this paper will deal with the identification of the PMV threshold value for which the transition discomfort-hot stress can occur.

Methods

In order to evaluate, in case of long term exposition (D_{lim} = 480 min), the minimum PMV value at which the working activity should be interrupted, numerical analyses in three sequential steps have been carried out:

a) in the first phase both personal parameters (metabolic rate and clothing insulation) the mean radiant temperature and the air velocity values have been settled in the range of validity of both PMV and PHS model (Table 2). It is noteworthy to observe that ISO 7730 Standard15), devoted only to moderate indoor environments, suggests the use of PMV index only in the range from −2 to +2; anyway, since the goal of EN ISO 152655) is the protection of workers by the onset of such conditions recognized dangerous for workers we have taken into account PMV values up to +3 consistently with the original Fanger's approach23);

b) on the basis of abovementioned values, the air temperature and the humidity ratio values consistent with 8 h of continuous work according to PHS model have been calculated (these values, have been depicted on a psychometric chart to define in a graphical way the *limit curves* of the working situation under examination11, 16));

c) Finally, the PMV index has been calculated from the values obtained as in b).

As the mathematical function binding personal and microclimatic variables to the physiological response of the subject to the thermal environment according to the PHS model is not handy to treat8–11), a special package developed in Delphi language has been designed24). According to the case under investigation it is able to return:

- the final values of the rectal temperature and the water loss predicted by PHS model8) after eight hours of continuous work;
- limit curves for 8 h of working duration in terms of temperature-humidity pairs;
- PMV value as a function of the air temperature and the humidity on a limit curve.

The calculation of the PMV index has been carried out by taking into account the correction of the intrinsic clothing insulation values related to the effect of body movements25–28).

Numerical calculations have been carried out in the ranges of personal and physical parameters consistent with the validation of both PMV index and PHS (Table 2) and here reported in Table 3. In particular, concerning the metabolic rate, the average reference values for low (1.7 met, class 1), moderate (2.8 met, class 2) and high (4.0 met, class 3) activities proposed by the ISO 8996 Standard29) have been studied. Due to the obvious narrow range of application of PMV index (Table 1) with respect to PHS model, under environmental situations characterised by temperature-humidity values over the application range of PMV (or such as PMV value is greater than 3), Fanger's index can only to be considered as indicator of extreme conditions. Other personal or behavioural parameters required by PHS model have been finally reported in Table 3; in particular as PHS model has been validated for clothing provided with a vapour permeability similar to those exhibited by cotton fabrics8, 10, 30), a reference value of

Table 3. Physical and personal variables values investigated and non-measurable parameters values required by PHS model[7]

Parameter	Values
Measurable	
Air temperature	15–50 °C
Mean radiant temperature	20–60 °C
Difference between mean radiant temperature and air temperature	5÷10 °C
Air velocity	0.10, 0.50, 1.0 m·s^{-1}
Water vapour partial pressure	0–4,500 Pa
Metabolic rates	1.7, 2.8, 4.0 met
Clothing thermal insulation	0.20–1.0 clo
Non-measurable	
Weight	75 kg
Height	1.70 m
Posture	Standing
Static moisture permeability index	0.38
Acclimatization status	Yes/Not
Freely drinking possibility	Yes

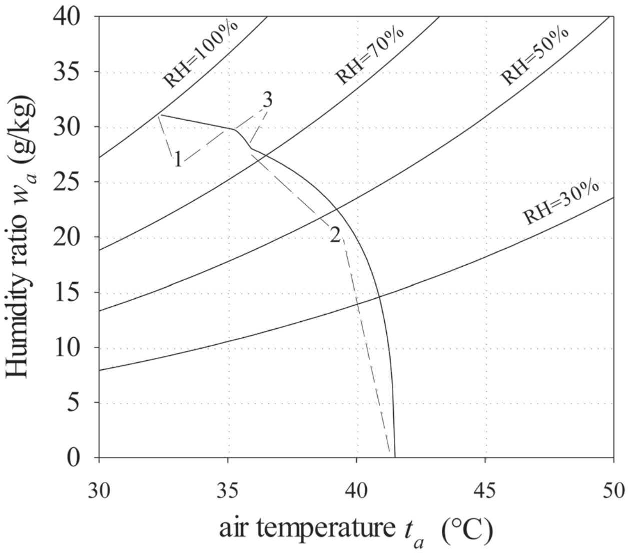

Fig. 1. Microclimatic conditions expressed in terms of temperature−humidity pairs consistent with 8 hours of continuous exposition predicted by PHS model.

M = 1.7 met, I_{cl} = 0.2 clo, v_a = 0.1 m/s, acclimatized subject.

0.38 has been adopted for the static moisture permeability index i_{mst}.

Results and Discussion

In order to make easier both the reading and the interpretation of the results here discussed, a typical limit curve of 8-h of continuous work in Fig. 1 has been depicted. According to previous results[11, 16, 17], such a kind of curve usually exhibits two discontinuities in the slope related to a different kind of physiological strain induced by heat in the human body:

- Area 1. In the low temperature − high humidity area of the psychometric chart, the physiological response of the human body to the heat is mainly related to the attainment of the maximum value of 38.0°C admitted for the rectal temperature[31]. Under these microclimatic conditions, sweating is unable to get over the heat accumulation from the body. In particular, the poor driving force available for the evaporation of sweat favours the increasing of the skin wettedness − with the consequent sweat trickling − leading to a supplementary dumping of the evaporation due to a high skin wettedness and/or a poor sweating efficiency[8, 9, 32, 33]. As a consequence even slightly changes of the air humidity result in strong variation of the air temperature values consistent with a 8 h-work shift;
- Area 2. In the high temperature − low humidity zone, the thermoregulatory system tries to remove the heat accumulated by the body by means of a high sweating rate. Under these conditions the rectal temperature predicted by PHS model is always below 38.0°C, but the stress induced by the hot microclimates is leading the body to the incipient dehydration (according to protection criteria on which ISO 7933 Standard is based on, the maximum admitted water loss is from 5% to 7.5% in weight of the whole body mass depending by the acclimatation status of the subject). In this area the high slope exhibited by the limit curve is the consequence of

the poor sensitivity of PHS model to the relative humidity due to the high sweating rate and efficiency favoured by the low *RH* values.

- Area 3. This is a transition zone where body heat removal is simultaneously related to the reaching of the maximum heat accumulation and the maximum water loss.

Discomfort-stress transition under uniform conditions (t_a=t_r)

The discomfort-stress transition under uniform conditions as a function of the value of the PMV index has been highlightened by means of the special plots showed in the Figs. 2 and 3 where the effects of the metabolic rate, the clothing insulation and the air velocity have been taken into account. Before starting the discussion, a preliminary introduction for help the reading of the figures is anyway necessary. From a general perspective, to describe the changing of the PMV index on a 8-h limit curve consistent with PHS model, a special 3-D plot should be necessary with a consequent poor readability and a hard interpretation of obtained results. To avoid a so complex representation, two stack-plots have been used: in the upper box for the desired metabolic rate and the specific clothing insulation values, the nominal microclimatic conditions consistent with 8 h of continuous work are have been depicted; following the arrow, the corresponding PMV value can be read on the plot below.

According to the curves depicted in Fig. 2, the increase of the air temperature on a 8-h limit curve consistent with PHS model, generally results in the increase of the PMV index with a sensitivity softened by the increase of both metabolic rate and clothing insulation. In particular, as the slope of the 8-h limit curves increases with both M and I_{cl} up to become quite vertical, the consequent variation of the PMV is softened, obviously due to its well-known poor sensitivity to the humidity[23)]. Due to the promoting effect of the air velocity on the heat transfer by convection and evaporation, the 8-h limit curves shift towards higher values of the air temperature (Fig. 2 on the bottom): as a consequence the PMV value increases in all investigated situations and systematically exceeds the threshold value of PMV=2 suggested by ISO 15265 Standard for v_a=1.0 $m{\cdot}s^{-1}$.

On the basis of the results summarized in Table 4, it is possible to recognize that the minimum value of the PMV index $PMV_{8h,min}$ at which the working condition should be interrupted seems to be strongly affected by the clothing insulation, the metabolic rate and the air velocity values. The general trend appears decreasing with the increasing of both the metabolic rate and the clothing insulation values. In particular, under almost still air conditions (v_a=0.1 $m{\cdot}s^{-1}$), $PMV_{8h,min}$ varies from 2.32 to 1.65 when the I_{cl} value increases from 0.2 to 1.0 clo, whereas a variation of the metabolic rate from 1.7 to 4.0 met results in a reduction of $PMV_{8h,min}$ from 1.65 to 1.03 at I_{cl}=1.0 clo.

Anyway, the main patency highlightened by our simulations is that it seems quite impossible to find an unique minimum PMV value for which the work shift has to be stopped due to the overcoming of the maximum rectal temperature or water loss predicted by PHS. In fact, at low air velocity the discomfort-stress transition occurs for M=1.7 met in the range 1.5–2.3 whereas at M=4.0 met this phenomenon appears anticipated in the range 1.0–1.5 as a function of the clothing insulation value. From this perspective it is very important to highlight that so low values of PMV occur for I_{cl} values typical for work clothing ensembles (always over 0.6–0.8 clo, according to ISO 9920 Standard[28)]).

The acclimatation status of the worker does not affect the limit value of PMV especially at mean and high metabolic rates. Only at low metabolic rate and under quite still air condition (v_a=0.1 $m{\cdot}s^{-1}$) the PMV limit value for a non-acclimatized subject was about 2 decimals lower than that exhibited by acclimatized.

Finally, it is very important to highlight that, especially at low metabolic rate (M=1.7 met), the limit curves obtained according to PHS model fall in a range microclimatic conditions inconsistent with PMV[15, 23)] (e.g. t_a>30°C and/or p_a>2,700 Pa corresponding to a humidity ratio greater than 17 g/kg). Such occurrence has not to be interpreted as a weakness of the discussion since the goal of this work is not using PMV as a primary index for the hot stress assessment, forcing its application in a range of both microclimatic and personal parameters, rather using PMV only as indicator of the transition discomfort-stress.

Discomfort-stress transition under non-uniform conditions (t_r>t_a)

The discomfort-stress transition in terms of PMV has been also investigated under non-uniform environments for different values of the difference between the mean radiant temperature and the air temperature (up to 10°C). These values have to be considered very likely in the presence of direct solar load[34)] as in building construction activities[35, 36)], in mines[37)], in the presence of hot surfaces or high-temperature ovens[38)] and in industrial sheds during the summer.

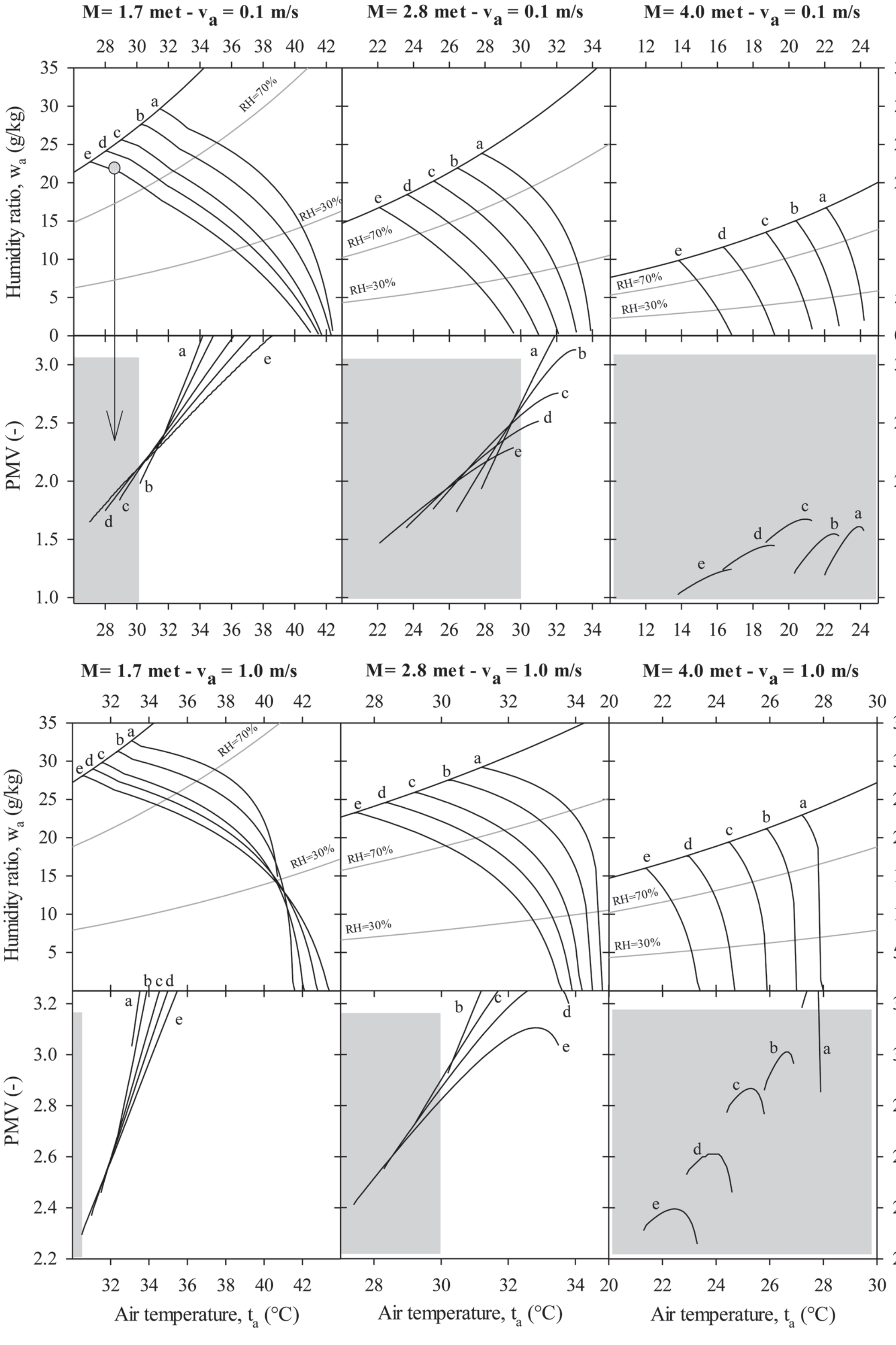

Fig. 2. Changing of the PMV index for microclimatic conditions consistent with 8 hours of work shift (acclimatized subjects) as a function of the metabolic rate, the air velocity and the clothing insulation. On each psychrometric chart the air temperature-humidity values consistent with 8 h of continuous work predicted by PHS.

$t_r = t_a$; static clothing insulation value: 0.20 clo (a), 0.40 clo (b), 0.60 clo (c), 0.80 clo (d), 1.0 clo (e). The gray area highlights conditions out of the validation range of the PMV index[23] (Table 2).

Table 4. Minimum PMV values $PMV_{8h,lim}$ consistent with 480 min of exposure times according to PHS model for acclimatized (A) and non-acclimatized (NA) subjects as a function of the metabolic rate, the static clothing insulation and the air velocity under uniform conditions (t_r=t_a)

I_{cl} (clo)		M=1.7 met		M=2.8 met		M=4.0 met	
		A	NA	A	NA	A	NA
v_a = 0.1 m·s^{-1}	0.2	*2.32*	*2.07*	*1.93*	*1.93*	1.19	1.19
	0.4	*1.98*	*1.77*	1.74	1.74	1.20	1.20
	0.6	*1.84*	*1.65*	1.76	1.78	1.47	1.47
	0.8	*1.74*	*1.53*	1.6	1.64	1.24	1.24
	1.0	*1.65*	*1.46*	1.47	1.47	1.03	1.03
v_a = 0.5 m·s^{-1}	0.2	*2.66*	*2.61*	*2.68*	*2.68*	2.20	2.20
	0.4	*2.35*	*2.19*	*2.47*	*2.37*	2.03	2.03
	0.6	*2.22*	*2.04*	*2.29*	2.29	2.13	2.13
	0.8	*2.12*	*1.93*	*2.11*	2.11	1.87	1.87
	1.0	*2.01*	*1.82*	*1.97*	1.97	1.66	1.66
v_a = 1.0 m·s^{-1}	0.2	*>3*					
	0.4	*2.65*	*2.61*	*2.93*	*2.93*	2.86	2.86
	0.6	*2.46*	*2.36*	2.72	2.72	2.77	2.77
	0.8	*2.37*	*2.25*	2.55	2.55	2.53	2.53
	1.0	*2.29*	*2.32*	2.41	2.41	2.31	2.31

In italics have been reported PMV values obtained under conditions over the ranges of validation showed in Table 2.

The main results are showed in Fig. 3 and summarized in Table 5. On the basis of the $PMV_{8h,\ lim}$ values reported in Table 5 it is almost trivial to recognize that in the presence of high air velocity values the long-term criterion proposed by ISO 15265$^{5)}$ Standard is always satisfied since in all the investigated conditions $PMV_{8h,min}$ is always greater than 2 for 8 h of work shift predicted by PHS. On the contrary, a very different behaviour has been found at low air velocity values where the clothing insulation, the metabolic rate, and, the value of the difference t_r-t_a play a crucial role.

In particular, under almost still air conditions (v_a=0.1 m·s^{-1}) and low metabolic rate, the range of $PMV_{8h,min}$ value slightly moves to higher values with the increasing of the difference t_r-t_a (from 1.65–2.32 under uniform conditions to 1.88–2.80 at t_r-t_a=10°C for acclimatized subjects). For moderate metabolic rate values, $PMV_{8h,min}$ does not change significantly being always in the range of about 1.5–2.0, whereas at high metabolic rate a certain shift of the $PMV_{8h,min}$ range to lower values, has been found (from 1.03–1.47 under uniform conditions to 0.88–1.26 at a value of the difference t_r-t_a=10°C for acclimatized subjects).

The PMV transition values up to now discussed have to be considered as absolutely precautionary since they have been calculated on the PHS limit curve in the area 1 (Fig. 1) simultaneously characterized by very high relative humidity values. To provide a picture as wide as possible of the situation under less precautionary and more realistic conditions with respect to those exposed till to now, in Table 6 have been summarized the PMV values calculated on the PHS limit curves for a settled relative humidity value of 50% $PMV_{8h,50}$ for the two investigated values of the difference t_r-t_a. Obtained results clearly prove that the PMV threshold value of the discomfort-stress transition is substantially related to the metabolic rate and the air velocity with a mild of effect of the difference t_r-t_a. In fact, at low metabolic rate most of investigated conditions reveal a PMV often exceeding 3. For moderate metabolic rate only at low air velocity and high t_r-t_a values the protection criteria at the base of the PHS model are exceeded for PMV values lower than 2 (for I_{cl} = 1.0 clo at PMV=1.52 for an non-acclimatized subject). Finally at high metabolic rate (4.0 met) the discomfort-stress transition can occur also at PMV values near to 1 under quite still air conditions.

Conclusions

The main goal of this paper devoted to the risk assessment of hot environments has been the identification of a PMV limit value for which the transition discomfort stress

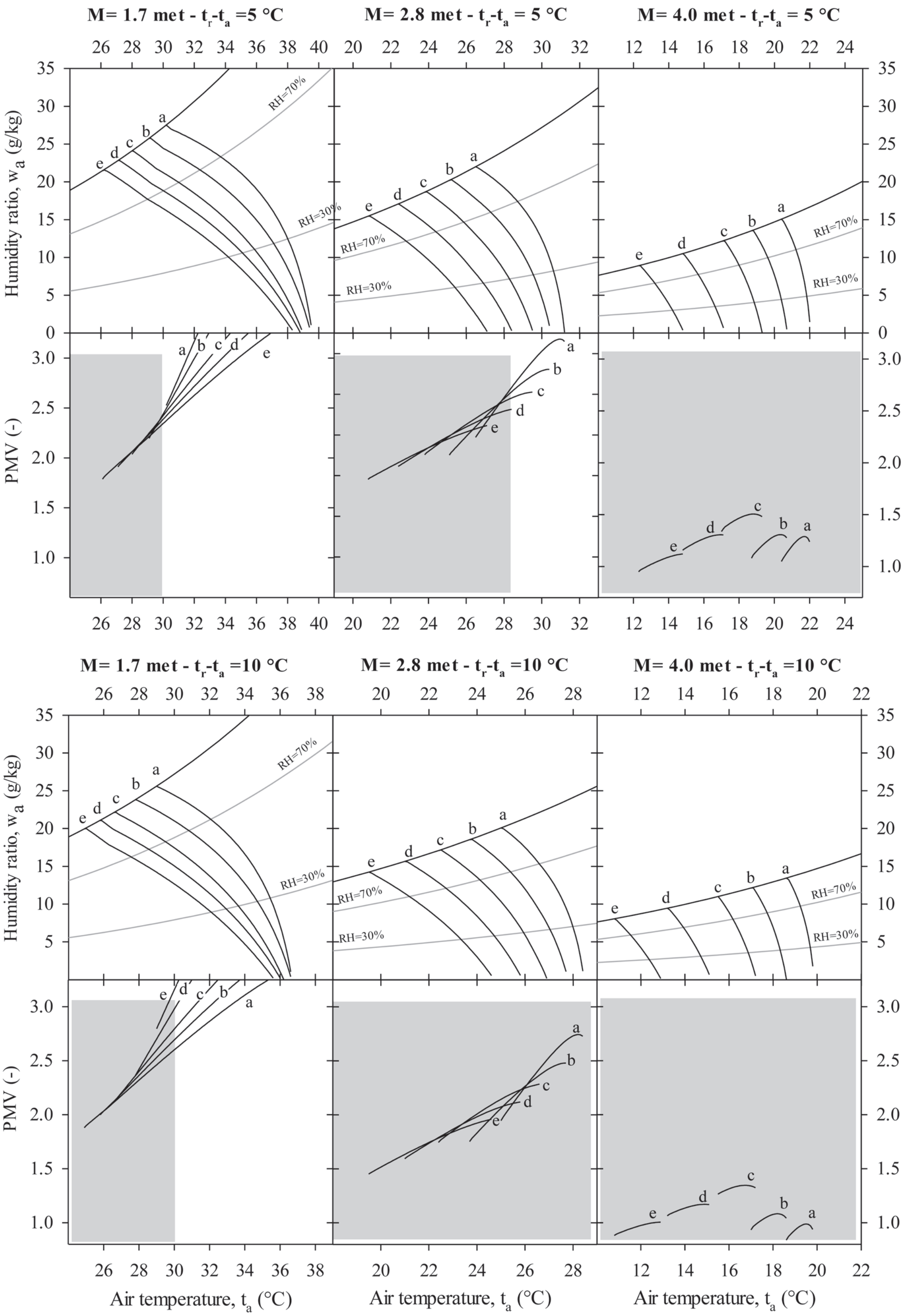

Fig. 3. Changing of the PMV index for microclimatic conditions consistent with 8 hours of work shift (acclimatized subjects) as a function of the metabolic rate, the air velocity and the clothing insulation. On each psychrometric chart the air temperature-humidity values consistent with 8 h of continuous work predicted by PHS.

Air velocity $v_a = 0.1\ \text{m}\cdot\text{s}^{-1}$; static clothing insulation value: 0.20 clo (a), 0.40 clo (b), 0.60 clo (c), 0.80 clo (d), 1.0 clo (e). The gray area highlights conditions out of the validation range of the PMV index[23)] (Table 2).

Table 5. Minimum PMV values $PMV_{8h,lim}$ consistent with 480 min of exposure times according to PHS model for acclimatized (A) and non-acclimatized (NA) subjects as a function of the metabolic rate, the static clothing insulation and the air velocity at $t_r = t_a + 5.0°C$ and $t_r = t_a + 10°C$

I_{cl} (clo)		M=1.7 met		M=2.8 met		M=4.0 met	
		A	NA	A	NA	A	NA
$t_r = t_a$ +5 °C							
$v_a = 0.1\ m{\cdot}s^{-1}$	0.2	*2.53*	*2.49*	*1.97*	*1.97*	1.05	1.05
	0.4	*2.2*	*2.06*	1.75	1.75	1.08	1.08
	0.6	*2.04*	*1.82*	1.76	1.76	1.34	1.34
	0.8	*1.91*	*1.68*	1.61	1.61	1.16	1.16
	1	*1.79*	*1.56*	1.46	1.46	0.95	0.95
$v_a = 1.0\ m{\cdot}s^{-1}$	0.2	*>3*					
	0.4	*2.89*	*3.03*	*2.93*	*>3*	2.76	2.76
	0.6	*2.62*	*2.62*	2.8	2.8	2.68	2.68
	0.8	*2.5*	*2.47*	2.61	2.62	2.45	2.45
	1	*2.41*	*2.36*	2.46	2.47	2.26	2.26
$t_r = t_a$ +10 °C							
$v_a = 0.1\ m{\cdot}s^{-1}$	0.2	*2.8*	*2.93*	*1.95*	*1.95*	0.84	0.84
	0.4	*2.37*	*2.33*	1.75	1.75	0.93	0.93
	0.6	*2.12*	*2.01*	1.75	1.75	1.26	1.26
	0.8	*2*	*1.83*	1.59	1.59	1.06	1.06
	1	*1.88*	*1.69*	1.45	1.45	0.88	0.88
$v_a = 1.0\ m{\cdot}s^{-1}$	0.2	*>3*				2.29	2.29
	0.4	*2.71*	*2.89*	*2.7*	*2.7*	2.21	2.21
	0.6	*2.45*	*2.49*	2.54	2.54	2.3	2.3
	0.8	*2.36*	*2.36*	2.41	2.41	2.14	2.14
	1	*2.25*	*2.25*	2.28	2.28	1.98	1.98

In italics have been reported PMV values obtained under conditions over the ranges of validation showed in Table 2.

should be identified in an unmistakable way by means of the PHS approach. Obtained results stressed the crucial role played by the metabolic rate of the working situation; particularly, for low metabolic rate, PMV transition value can take place at a PMV value of 1.5–1.9 depending on the clothing insulation, the mean radiant temperature and the humidity. For higher metabolic rates (up to 4 met) such stress threshold dramatically decreases up to PMV=1.0–1.4 depending the air velocity and the radiant asymmetry with a negligible effect of the relative humidity. On the contrary hand, the effect of the clothing insulation on the PMV transition value appeared significant only in the presence of high metabolic rates. Concerning microclimatic parameters, the effect of the air velocity obviously resulted in a very strong promotion of the PMV transition value to highest values often more than 3 (due to an enhancement of both convective and evaporative thermal flows which favour the heat removal by the body). Finally, as the mean radiant temperature is concerned, obtained results highlight − especially at low I_{cl} values and high metabolic rate − the different sensitivity to PHS and PMV model to the heat transfer by radiation which can result in a PMV threshold value very far to the value required by ISO 15265 Standard.

First of all, it would be necessary a new definition of both lower and upper limits of thermal discomfort required by ISO 15265 Standard. Precisely, the lower limit should be increased up to PMV=0.7 in order to harmonize it with ISO 7730 Standard which requires, for the worst discomfort class (C), a PMV value such as $0.5 \leq PMV \leq 0.7$. Moreover, based on the numerical assessment here reported, upper limit should be decreased in a precautionary way at least to PMV=1.5 especially at high differences between the values of the mean radiant temperature and the air temperature (working outdoor or in the presence of hot surfaces and high-temperature ovens), low clothing

Table 6. PMV values at RH = 50% $PMV_{8h,50}$ consistent with 480 min of exposure times according to PHS model for acclimatized (A) and non-acclimatized (NA) subjects as a function of the metabolic rate, the static clothing insulation and the air velocity at $t_r = t_a + 5.0°C$ and $t_r = t_a + 10°C$

I_{cl} (clo)			M=1.7 met		M=2.8 met		M=4.0 met	
			A	NA	A	NA	A	NA
$t_r = t_a$								
	$v_a = 0.1\ m{\cdot}s^{-1}$	0.2	*>3*		*>3*		1.58	1.58
		0.4			*2.76*	*2.75*	1.50	1.50
		0.6	*3.00*	*3.00*	2.42	2.42	1.69	1.69
		0.8	*2.73*	*2.73*	2.16	2.16	1.40	1.40
		1.0	*2.49*	*2.49*	1.93	1.93	1.18	1.18
	$v_a = 1.0\ m{\cdot}s^{-1}$	0.2	*>3*				3.00	3.00
		0.4					2.96	2.96
		0.6					2.82	2.82
		0.8					2.61	2.61
		1.0					2.38	2.38
$t_r = t_a$ +5.0 °C								
	$v_a = 0.1\ m{\cdot}s^{-1}$	0.2	*>3*		2.98	3.00	1.29	1.29
		0.4			2.55	2.55	1.30	1.30
		0.6			2.29	2.29	1.49	1.49
		0.8	*2.78*	*2.85*	2.06	2.06	1.27	1.27
		1.0	*2.54*	*2.49*	1.86	1.86	1.08	1.08
	$v_a = 1.0\ m{\cdot}s^{-1}$	0.2	*>3*		*>3*		2.85	2.85
		0.4					2.7	2.7
		0.6			*>3*		2.67	2.67
		0.8					2.47	2.47
		1.0			2.96	2.96	2.28	2.28
$t_r = t_a$ +10 °C								
	$v_a = 0.1\ m{\cdot}s^{-1}$	0.2	*>3*		*2.63*	*2.03*	0.99	0.99
		0.4			2.32	1.86	1.08	1.08
		0.6			2.16	1.82	1.34	1.34
		0.8	*2.80*	*2.8*	1.97	1.67	1.16	1.16
		1.0	*2.56*	*2.56*	1.78	1.52	0.97	0.97
	$v_a = 1.0\ m{\cdot}s^{-1}$	0.2	*>3*		*>3*		2.10	2.10
		0.4					2.20	2.20
		0.6			2.93	2.93	2.26	2.26
		0.8			2.79	2.79	2.09	2.09
		1.0			2.66	2.66	1.96	1.96

In italics have been reported PMV values obtained under conditions over the ranges of validation showed in Table 2.

insulation and high relative humidity values. In the future we will aim to extend this kind of investigations to the transition discomfort-cold stress.

Acknowledgement

We owe a special thanks to Mr. Raffaele Iovine (BSBE) for his valuable cooperation.

References

1) Council of the European Community (1989) Council Directive 89/391/EEC of 12 June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31989L0391:EN:HTML. Accessed September 25, 2012.

2) Parsons KC (2008) Industrial health for all: appropriate

physical environments, inclusive design, and standards that are truly international. Ind Health **46**, 195–7.

3) Malchaire J, Gebhardt HJ, Piette A (1999) Strategy for evaluation and prevention of risk due to work in thermal environment. Ann Occup Hyg **43**, 367–76.
4) Malchaire J, Piette A (2006) The SOBANE Strategy for the Management of Risk, as applied to whole body or Hand-Arm vibration. Ann Occup Hyg **50**, 411–6.
5) ISO 15265 (2004) Ergonomics of thermal environments − Strategy of evaluation of the risk for the prevention of constraints or discomfort under thermal working conditions. International Organisation for Standardization, Geneva.
6) Parsons K (2003) Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort and Performance, 2nd Ed., Taylor & Francis, London.
7) ISO 7933 (2004) Ergonomics of the thermal environment − Analytical determination and interpretation of heat stress using calculation of the predicted heat strain. International Organization for Standardization, Geneva.
8) Malchaire J, Piette A, Kampmann B, Menhert P, Gebhardt HJ, Havenith G, den Hartog E, Holmer I, Parsons K, Alfano G, Griefahn B (2001) Development and validation of the predicted heat strain model. Ann Occup Hyg **45**, 123–35.
9) Malchaire J, Kampmann B, Mehnert P, Gebhardt H, Piette A, Havenith G, Holmér I, Parsons K, Alfano G, Griefahn B (2002) Assessment of the risk of heat disorders encountered during work in hot conditions. Int Arch Occup Environ Health **75**, 153–62.
10) Malchaire JBM (2006) Occupational heat stress assessment by the predicted heat strain model. Ind Health **44**, 380–7.
11) d'Ambrosio FR, Palella BI, Riccio G, Alfano G (2004) Criteria for assessment of hot environments: WBGT index and PHS (predicted heat strain). Med Lav **95**, 255–74.
12) Holmér I (1984) Required clothing insulation (IREQ) as an analytical index of the cold stress. ASHRAE TRANS **90**, 1116–28.
13) Holmér I (2009) Evaluation of cold workplaces: an overview of standards for assessment of cold stress. Ind Health **47**, 228–34.
14) d'Ambrosio Alfano FR, Palella BI, Riccio G (2013) Notes on the Implementation of the IREQ-model for the assessment of extreme cold environments. Ergonomics **56**, 707–24.
15) ISO 7730 (2005) Ergonomics of the thermal environment − Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. International Organization for Standardization, Geneva.
16) d'Ambrosio Alfano FR, Palella BI, Riccio G (2007) The role of measurement accuracy on the heat stress assessment according to ISO 7933: 2004. WIT Trans Biomed Health **11**, 115–24.
17) d'Ambrosio Alfano FR, Palella BI, Riccio G (2011) The Role of Measurement Accuracy on the Thermal Environment Assessment by means of PMV Index. Build Environ **46**, 1361–9.
18) Dell'Isola M, Frattolillo A, Palella BI, Riccio G (2012) Measurement uncertainties influence on the thermal environment assessment. Int J Thermophys **33**, 1616–32.
19) Havenith G, Holmér I, Parsons K (2002) Personals factors in thermal comfort assessment: clothing properties and metabolic heat production. Energy Build **34**, 581–91.
20) Cordeiro Sousa Oliveira AR (2008) Avaliação da Incerteza na Determinação dos Índices de Conforto Térmico PMV e PPD. MSC degree thesis, Coimbra University, Portugal (in Portuguese).
21) ISO 7726 (1998) Ergonomics of the thermal environment − Instruments for measuring physical quantities. International Organization for Standardization, Geneva.
22) d'Ambrosio Alfano FR, Palella BI, Riccio G (2012) On the problems related to natural wet bulb temperature indirect evaluation for the assessment of hot thermal environments by means of WBGT. Ann Occup Hyg **56**, 1063–79.
23) Fanger PO (1970) Thermal Comfort. McGraw-Hill, New York.
24) d'Ambrosio Alfano FR, Palella BI, Riccio G (2005) TEE (Thermal Environment Assessment): a friendly tool for thermal environment evaluation. In: Proceedings of 11th International Conferences on Environmental Ergonomics, May 22–26, 503–6, Ystad, Sweden.
25) Parsons KC, Havenith G, Holmér I, Nilsson H, Malchaire JB (1999) The effects of wind and human movement on the heat and vapour transfer properties of clothing. Ann Occup Hyg **43**, 347–52.
26) Holmér I, Nilsson H, Havenith G, Parsons K (1999) Clothing convective heat exchange —proposal for improved in Standars and models. Ann Occup Hyg **43**, 329–37.
27) Havenith G, Nilsson H (2004) Correction of clothing insulation for movement and wind effects, a meta-analysis. Eur J Appl Physiol **92**, 636–40.
28) ISO 9920 (2007) Ergonomics of the thermal environment —Estimation of thermal insulation and water vapour resistance of a clothing ensemble. International Organization for Standardization, Geneva.
29) ISO 8996 (2004) Ergonomics of the thermal environment —Determination of metabolic rate. International Organization for Standardization, Geneva.
30) Wang F, Kuklane K, Gao C, Holmér H (2011) Can the PHS model (ISO7933) predict reasonable thermophysiological responses while wearing protective clothing in hot environments? Physiol Meas **32**, 239–49.
31) WHO (1969) Health factors involved in working under conditions of heat stress. Technical report 412. WHO Scientific Group on Health Factors Involved in Working under Conditions of Heat Stress, Geneva.
32) Candas V, Libert JP, Vogt JJ (1979) Human skin wettedness and evaporative efficiency of sweating. J Appl Physiol **46**, 522–8.

33) Candas V, Libert JP, Vogt JJ (1979) Influence of air velocity and heat acclimation on human skin wettedness and sweating efficiency. J Appl Physiol **47**, 1194–200.

34) Gaspar AR, Quintela DA (2009) Physical modelling of globe and natural wet bulb temperatures to predict WBGT heat stress index in outdoor environments. Int J Biometeorol **53**, 221–30.

35) Maiti R (2008) Workload assessment in building construction related activities in India. Appl Ergon **39**, 754–65.

36) Pérez-Alonso J, Callejón-Ferre AJ, Carreño-Ortega A, Sánchez-Hermosilla J (2011) Approach to the evaluation of the thermal work environment in the greenhouse-construction industry of SE Spain. Build Environ **46**, 1725–34.

37) Brake DJ (2001) Calculation of the natural (unventilated) wet bulb temperature, psychrometric dry bulb temperature and wet bulb globe temperature from standard psychrometric measurements. J Mine Vent Soc S Afr **54**, 108–12.

38) d'Ambrosio Alfano FR, Palella BI, Riccio G (2010) Risultati di una Indagine sulle Condizioni di Stress Termico all'Interno di Cristallerie. In: Proceedings of 65° Congresso Nazionale ATI, September 13–17, 503–6, Domus De Maria (CA), Italy. On CD ROM: ISBN 8890411635 (in Italy).