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Thermal Environment Assessment Reliability Using Temperature —Humidity Indices

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Abstract: A reliable assessment of the thermal environment should take into account the whole of the six parameters affecting the thermal sensation (air temperature, air velocity, humidity, mean radiant temperature, metabolic rate and thermo-physical properties of clothing). Anyway, the need of a quick evaluation based on few measurements and calculations has leaded to like best temperature-humidity indices instead of rational methods based on the heat balance on the human body. Among these, Canadian Humidex, preliminarily used only for weather forecasts, is becoming more and more widespread for a generalized assessment of both outdoor and indoor thermal environments. This custom arouses great controversies since using an index validated in outdoor conditions does not assure its indoor reliability. Moreover is it really possible to carry out the thermal environment assessment ignoring some of variables involved in the physiological response of the human body? Aiming to give a clear answer to these questions, this paper deals with a comparison between the assessment carried out according to the rational methods suggested by International Standards in force and the Humidex index. This combined analysis under hot stress situations (indoor and outdoor) has been preliminarily carried out; in a second phase the study deals with the indoor comfort prediction. Obtained results show that Humidex index very often leads to the underestimation of the workplace dangerousness and a poor reliability of comfort prediction when it is used in indoor situations.

Key words: Thermal environment assessment, Comfort indices, Stress indices

Introduction

The evaluation of the thermal sensation is often a crucial matter of indoor environments assessment since their quality affects the health safeguarding as well as the productivity of subjects[1]. Thermal sensation depends on the subject-environment heat transfer which is strictly related to subjective variables (metabolic rate and clothing thermo-physical properties) and four environmental variables (air temperature, mean radiant temperature, air velocity and relative humidity) according to the following energy balance equation:

$$M - W - E - E_{res} - C_{res} - C - R = S \qquad (1)$$

Equation (1) can be profitably used both in moderate environments, where the main designer goal is reaching thermal comfort conditions, and in severe environments where workers health protection to cold or hot stress is required. Nevertheless using equation (1) does not result in a friendly evaluation of the thermal environment; therefore, the only road to be turned into is making use of a right microclimatic index[2–5] usually based on:

- subjective evaluation of climatic conditions by means of investigations in situ;
- grouping the whole of six variables in a single index based on analytical or empirical investiga-

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tions;
- identification of the combinations of climatic parameters producing the same physiological effect.

These different approaches have leaded to the formulation of several indices (see Table 1) aimed to reach a balanced compromise among a reliable assessment, an easy calculation and a reduced number of measurements (i.e. some indices need only the air temperature and relative humidity values).

Table 1 clearly shows that in Nineties, due to a continuous enhancement of the basic know-how of thermal environment field, a large number of new indices for moderate and severe environments (based also on sophisticated thermoregulation models[31] as UTCI[30]) has been formulated. The presence of a so large number of new indices generates some confusion, especially if we take into account that:
- some indices (often validated only under outdoor conditions) after their issue appear almost ignored by the scientific community in spite of their interesting features;
- International Standard Organisation (ISO) has devoted to the thermal environment assessment field an impressing number of Standards (see Fig. 1). On this point of view, ISO Standard 1526532) requires for each environment category (moderate and extreme) the calculation of a special index dispelling any doubt on both evaluation and prevention strategy (see Table 2). In particular:
  a) moderate environments should be treated by means of PMV index (adopted by ASHRAE also in favour to ET* index[33]) according to ISO 7730 Standard[20];
  b) hot extreme environments should be roughly assessed through the WBGT index, purpose of ISO 7243 Standard[27]. For a more in-depth analysis the PHS (Predicted Heat Strain) approach, based on the equation (1) solved under transient conditions, is required, according to ISO 7933 standard[28];
  c) cold extreme environments have to be evaluated through the IREQ index, as suggested by ISO 11079 Standard[10].

Moreover, almost the whole of indices proposed by ISO, on the heat balance equation (1) is based on (apart from WBGT and indices involved in the local discomfort assessment of moderate environments).

In spite of the regulation clearness on both methods and investigation procedures supported by a wide numerical and experimental analyses and by the continuous enhancement of the human thermoregulation modelling, it is anyway necessary to underline that thermal environment assessment does not appear an easy matter. In fact, depending on the index which has to be calculated, more or less complicated algorithms requiring special software[35, 36] as well as the measure-

Table 1. Main comfort and stress indices proposed by thermal environment literature under chronological order

Cold Environments	Moderate Environments	Hot Environments
IS, Sharlau Index[6] (1950)	IS[6], Sharlau Index (1950)	P4SR[21], Predicted 4 h sweat rate (1947)
DI, Discomfort Index[7] (1959)	DI[7], Discomfort Index (1959)	IS[6], Sharlau Index (1950)
T_{eq}[8], Equivalent temperature Index (1984)	HD[14, 15], Humidex (1965, 1979)	HSI[22], Heat Stress Index (1955)
IREQ[9, 10], required insulation (1993, 2007)	ET*[16] (1971)	DI[7], Discomfort Index (1959)
WCI, wind chill index[9] (1993)	T_{eq}[8], Equivalent temperature Index (1984)	RHS[23], Relative Heat Strain (1964)
THI[11], temperature humidity index (1994)	SSI[17], New Summer Simmer Index (1987)	ITS[24], Index of thermal Stress (1976)
PT[12], Perceived Temperature (1997)	RSI[18], Relative Strain Index (1992)	HD[14, 15], Humidex (1965,1979)
PET[13], Physiological Equivalent Temperature (1999)	THI[11], temperature humidity index (1994)	HI[25], Heat index (1979)
T_{wc}[10], wind chill temperature (2007)	**PMV[2, 19, 20], predicted mean vote (1994, 2005)**	T_{eq}[8], Equivalent temperature Index (1984)
UTCI[30] (2009)	PT[12], Perceived Temperature (1997)	SSI[17], New Summer Simmer Index (1987)
	PET[13], Physiological Equivalent Temperature (1999)	**SW_{req}[26], Required sweat rate (1989)**
	UTCI[30] (2009)	RSI[18], Relative Strain Index (1992)
		WBGT[27], Wet bulb globe temperature (1989)
		THI[11], temperature humidity index (1994)
		PT[12], Perceived Temperature (1997)
		PET[13], Physiological Equivalent Temperature (1999)
		PHS[28], Predicted heat strain(*) (2004)
		STI[29] (2005)
		UTCI[30] (2009)

In bold letters international standardised indices. (*) In place of SW_{req} index.

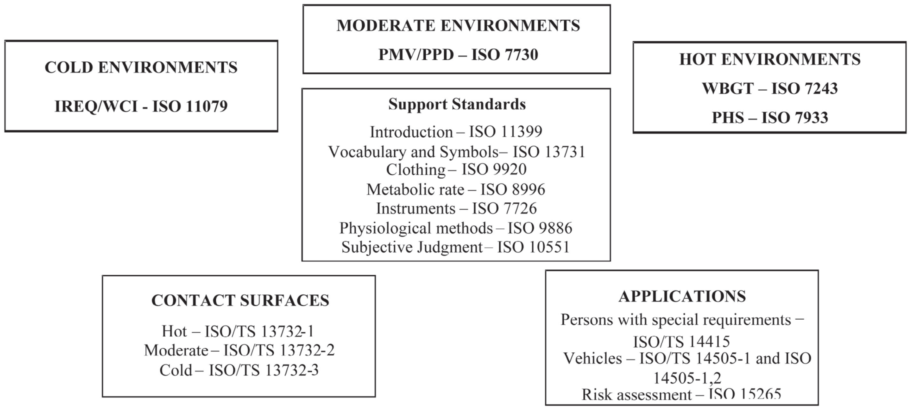

Fig. 1. Thermal Environment assessment according to International Standards actually under force.

Table 2. Criteria suggested by regulations in force for the risk assessment in thermal environments[30)]

Class	Criteria
Immediate constraint	$D_{lim} < 30$ min
Cold constraint in the short term	$I_{clr} < IREQ_{min}$ DLE < 120 min
Cold constraint in the long term	PMV < –2 $IREQ_{min} \le I_{clr} \le IREQ_{neutral}$
Cold discomfort	–2.0 ≤ PMV< –0.5
Comfort	–0.5 ≤ PMV ≤ +0.5
Warm discomfort	+0.5 < PMV ≤ +2.0
Hot constraint in the long term*	$D_{lim} < 480$ min
Constraint in the short term*	$D_{lim} < 120$ min
Hot immediate constraint*	$D_{lim} < 30$ min

(*) In these three cases, derive the following information according to ISO 7933:
- predicted mean water loss over the 8-h day;
- predicted risk of increase of the internal temperature of the body.

ment of physical parameters (subjective ones by means of tables can be evaluated) are required. These are the reasons of the rising success of temperature-humidity indices which allow the thermal condition through a "felt temperature". Among these, Humidex, born as a bio-meteorological index at first, is winning an increasing spreading both in Europe and in North-America on the strength of its easiest calculation; in fact, a more and more increasing number of climate stations, trying to help people on the summer thermal strain, supplies its on-line evaluation.

Humidex is a temperature-humidity index definitively introduced in 1979 by Masterton and Richardson[15)] for correlating outdoor thermal discomfort of mild Canada's areas to the two main meteorological parameters: the air temperature and the relative humidity. Its formulation is based on two hypotheses on the thermoregulatory system:

- the "neutral point" of the human body, defined as the temperature range in which, for a naked subject exposed to quiet air, the human body heat balance equation (1) in the absence of the accumulation term is satisfied, is from 27°C to 30°C;
- the human body is unable to get over the heat accumulation when its temperature exceeds a minimum value of 32°C in the presence of a relative humidity value greater than 75%.

According to these hypotheses, Humidex results an empirical index formulated under particular hypotheses and under particular climatic conditions (Mild Canada areas) and it is intrinsically unable to take into account the radiative heat flow, the metabolic rate, the air velocity and finally the clothing insulation as well as the heat balance equation (1).

HD calculation is based on a Thom's index modification[7)] and it is expressed through the merely empirical equation:

$$HD = t_a + \frac{5}{9} \cdot \left(p_{as} - 10\right) \quad (2)$$

where

$$p_{as} = 6{,}112 \cdot \left(10^{\frac{7{,}5 \cdot t_a}{237{,}7 + t_a}}\right) \cdot \frac{RH}{100} \quad (3)$$

Equation (2) results in an index which appears even more easy than WBGT (effective both indoors and outdoors and taking into account the radiative thermal flow), suggested by ACGIH[37)] and by ISO[27)] also for a first rough hot stress assessment. In Table 3, HD limit values are reported.

Although Humidex was at first formulated for weather forecasts, its use has been extent to the assessment of hot thermal stress in indoor and outdoor environments. As a matter of fact, Santee *et al.*[38, 39)] compared the rectal temperature predicted by a heat-balanced-based thermal model in order to find a statistically significant relation between the heat index values and the predicted

Table 3. Limit values and ranges of the Humidex index corresponding to rising thermal discomfort conditions[15)]

Humidex range	Thermal discomfort level
20°C ≤ HD ≤ 29°C	Comfort
30°C ≤ HD ≤ 39°C	Some discomfort
40°C ≤ HD ≤ 45°C	Great discomfort, avoid exertion
Above 45°C	Dangerous
Above 54°C	Heat stroke imminent

Table 4. Limit values and ranges of the Humidex index suggested by the Humidex Heat Stress response plan by Occupational Health Clinics for Ontario Workers[49)]

Humidex range	Response
25°C ≤ HD ≤ 29°C	supply water to workers on an "as needed" basis.
30°C ≤ HD ≤ 33°C	post Heat Stress Alert notice; encourage workers to drink extra water; start recording hourly temperature and relative humidity.
34°C ≤ HD ≤ 37°C	start recording hourly temperature and relative humidity 34–37°C post Heat Stress Warning notice; notify workers that they are drinking extra water; ensure workers are trained to recognize symptoms.
38°C ≤ HD ≤ 39°C	provide 15 min relief per hour; provide adequate cool (10–15°C) water; at least 1 cup (240 ml) of water every 20 min workers with symptoms should seek medical attention.
40°C ≤ HD ≤ 42°C	provide 30 min relief per hour in addition to the provisions listed previously.
43°C ≤ HD ≤ 44°C	if feasible provide 45 min relief per hour in addition to the provisions listed above. if a 75% relief period is not feasible then stop work until the Humidex is 42°C or less.
45°C over	stop work until the Humidex is 44°C or less.

rectal temperature, finding a good correlation between HD values and the predicted rectal temperature under hot stress conditions. On this point of view, several Italian reports on the unexpected death related to the heat waves of summers 2003 and 2004[40, 41)] correlate highest HD values with the danger of death. This custom has been very recently adopted by European Commission all the more because in a special document called "Pan European Assessment of weather driven natural risks" a HD limit value of 35°C for reducing excessive hot risks has been proposed[42)]. In the recent past the Occupational Health Clinics for Ontario Workers Inc. (OHCOW) created a "Humidex Based Heat Response Plan" (HBHRP) briefly summarized[43)] in Table 4, that translated the WBGT limit values into Humidex values and developed recommended responses for each Humidex range. This plan was developed as a tool to help workplaces as most find using the WBGT complicated and expensive. On the other hand the Canadian Centre for Occupational Health and Safety (CCOHS) states[44)]: « When the humidex rating is in the 40–45°C range, most people would it uncomfortable. However, many kinds of work must be restricted when the humidex is above 45°C ». Moreover Use and Occupancy of Buildings Directive of the Treasury Board of Canada[45)] makes use of Humidex as effective parameter for the thermal comfort in office accommodations considering as unsatisfactory a Humidex value, based on indoor microclimatic measurements, beyond 40°C.

Assuming that a strong strain level or even the risk of death under hot conditions in the presence of high temperature and humidity values (incipient heat stroke) is almost a trivial consequence, two questions take place:

- both thermal stress and comfort assessment can be carried out ignoring the physiological response of subject to the thermal environment?
- using a bioclimatic index in conditions different from those in which it has been formulated can lead to a reliable assessment of both outdoor and indoor thermal environment?

In order to answer to these questions this paper deals with a comparison between the thermal environment assessment carried out according to ISO standards and the Humidex index. Analyses through a special software designed according to International Standards of the field has been carried out[34)] trying to highlight the presence of any structural lacks due to a so simplified formulation[14, 15, 46)].

Methods

The comparative analysis of the same thermal environment assessment by means of HD and standardised indices/procedures above quoted, in two different ways has been carried out:

1. by means of an indirect evaluation (for both comfort and stress situations) aimed to evaluate the "limit situations" corresponding to an assigned value of the mean radiant temperature, the air velocity, the metabolic rate, the clothing insulation and, in case of PHS, the vapour permeability of clothing required for the assessment of the evaporative heat flow at the skin surface[28)].
2. by means of a direct evaluation (only for comfort situations) of the same thermal environment starting from a reasonable set of microclimatic and subjective parameters;

As a consequence, two special computer programs have been designed:

- the former, for each HD value, returns correspond-

Table 5. Dynamic clothing insulation values as a function of the metabolic rate used for thermal comfort[20] and hot stress[28] assessment

Metabolic rate M (met)	Static clothing insulation I_{cl} (clo)	Dynamic clothing insulation $I_{cl,dyn}$ (clo)	
		ISO 7730 ISO 9920	ISO 7933
1.4	0.60	0.57	0.60
1.8	0.60	0.55	0.57
2.8	0.60	-	0.52

v_a = 0.10 m/s.

Table 6. Metabolic rate values suggested by ISO 8996 as a function of the subject activity[46]

Class	Average metabolic rate with range in brackets, (met)	Examples
0 Resting	1.1 (0.95 ÷ 1.2)	Resting, sitting at ease.
1 Low metabolic rate	1.7 (1.2 ÷ 2.2)	Light manual work (writing, typing, drawing, sewing, book-keeping); hand and arm work (small bench tools, inspection, assembly or sorting of light materials); arm and leg work (driving vehicle in normal conditions, operating foot switch or pedal). Standing drilling (small parts); milling machine (small parts); coil winding; small armature winding; machining with low power tools; casual walking (speed up to 2.5 km/h).
2 Moderate metabolic rate	2.8 (2.2 ÷ 3.4)	Sustained hand and arm work (hammering in nails, filing); arm and legwork (off-road operation of lorries, tractors or construction equipment); arm and trunk work (work with pneumatic hammer, tractor assembly, plastering, intermittent handling of moderately heavy material, weeding, hoeing, picking fruits or vegetables, pushing or pulling lightweight carts or wheelbarrows, walking at a speed of 2.5 km/h to 5.5 km/h, forging).
3 High metabolic rate	4.0 (3.4 ÷ 4.5)	Intense arm and trunk work; carrying heavy material; shovelling; sledgehammer work; sawing; planning or chiselling hard wood; hand mowing; digging; walking at a speed of 5.5 km/h to 7.0 km/h. Pushing or pulling heavily loaded hand carts or wheelbarrows; chipping castings, concrete block laying.
4 Very high metabolic rate	5.0 (> 4.5)	Very intense activity at fast to maximum pace; working with an axe; intense shovelling or digging; climbing stairs, ramp or ladder; walking quickly with small steps; running; walking at a speed grater than 7.0 km/h.

ing (t_a, RH) couples;

- the latter, upgraded in accordance to the regulations in force[34], allows the calculation of (t_a, RH) couples corresponding to:

a. a required value of PMV according to ISO 7730;
b. a required vale of WBGT according to ISO 7243;
c. the overall amount of sweat and the final rectal temperature evaluated in accordance with PHS method inspiring ISO 7933 and for eight-hours of continuous work[a]. In order to make easy the interpretation of the assessment, temperature-humidity limit values on special psychrometric charts have been reported, allowing the definition of safe working areas[47].

[a]ISO 7933 Standard requires the comparison between the limit values of produced sweat and the rectal temperature and those predicted by PHS model.

Numerical evaluations have been carried out settling, when necessary, some variable. In particular:

- since HD index has been validated under of mild Canada's summer situations static clothing insulation value at 0.60 clo has been chosen[47]. Moreover, according to ISO 9920 and ISO 7730, both movements and pumping effect on the clothing insulation have been take into account resulting in dynamic clothing insulation values reported in Table 5;
- metabolic rate values have been chosen in the range corresponding to a light activity according to ISO 8996[48] as reported in Table 6;
- in not uniform environments the mean radiant temperature value at most greater than 10°C with respect to the air temperature has been chosen;
- quiet air, freely drinking acclimatised subjects

have been finally assumed in the hot environments assessment.

We need to highlight that this compared assessment in a range of subjective and physical parameters resulting in a Humidex value in the range from 20°C to 55°C has been carried out. As a consequence the assessment of comfort situations dealt with microclimatic situation with PMV values in the range [–0.50 ÷ 0.50], typical of class (B) environments[20].

Results and Discussion

Hot environments

The Humidex reliability reported for the assessment of hot environments[38, 39] as well as severe hot climatic conditions[41, 42] has been checked by comparing limit curves compatible with eight hours of continuous work obtained according to WBGT index and PHS model. Such analyses for two metabolic rate values typical of a light activity (M=1.4 and 1.8 met) and only one typical value of moderate activity (M=2.8 met) have been carried out (see Table 5).

Curves depicted in Fig. 2A clearly demonstrate that, in uniform environments (t_a=t_r) and for light metabolic rates (M=1.4 met), HD index generally exhibits a restrictive behaviour with respect to both WBGT and PHS. Moreover, concerning ISO[27] and ACGIH[37] layouts, $WBGT_{lim}$=29°C exhibits a dual behaviour in the 40 ≤ HD ≤ 45 area:

- below t_a=36°C, WBGT limit curve is above HD=40 limit curve: HD index appears more restrictive than WBGT;
- over t_a=36°C, WBGT limit curve is below HD=40 limit curve: WBGT appears more restrictive than HD.

On the contrary, if the evaluation of the working situation is carried out by means of PHS method, actually the thorough method for stress assessment in hot environments, up to t_a=40°C a less restrictive than HD evaluation is revealed; as a matter of fact $D_{lim,PHS}$ limit curve is always over HD=45 limit one. On the contrary hand, over 40°C, PHS assessment becomes more restrictive than HD so that PHS limit curve falls in the 40 ≤ HD ≤ 45 area: as a consequence a microclimatic situation judged as certainly dangerous by PHS method, is ambiguously interpreted by Humidex as only greatly uncomfortable. It is noteworthy highlighting that, according to our previous results[35] in this range the different slope of the limit curve is related to the different protection criterion[28, 47]. As a matter of fact, at higher temperature (and low humidity) the subject exposure should be interrupted due to the overcoming of the maximum water loss (5 ÷ 7.5% of the subject weight

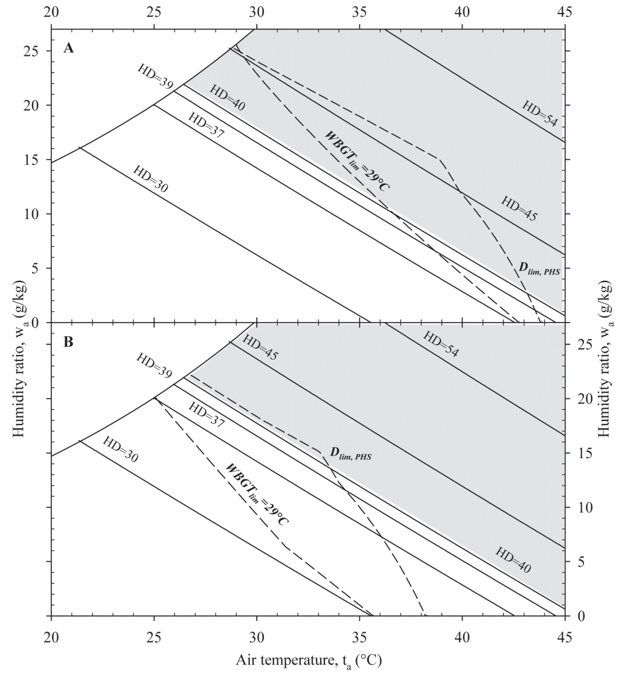

Fig. 2. Hot stress assessment carried out by means of HD (continuous lines) and methods provided by the regulations in force (dashed lines).

Metabolic rate M=1.4 met – Not acclimatised subject freely drinking – Static clothing insulation I_{cl} = 0.60 clo – Quiet air. t_r=t_a (A), t_r = t_a+10°C (B). Filled areas refer to such microclimatic conditions judged from discomfortable to dangerous by HD (see Table 3).

depending on the acclimatisation and according to ISO 7933), whereas at lower temperature (and high humidity) the ineffectiveness of thermoregulation by perspiration avoids the body cooling with the consequent overcoming of maximum allowable value of the rectal temperature (38°C) due to the highest heat accumulation.

These results appear just a little bit surprising especially taking into account Humidex Based Heat Response Plan[45, 50]. As a matter of fact the HD=37 limit curve depicted in Fig. 2A, corresponding to the maximum index value consistent to a continuous working situation (see Table 4) is always below $WBGT_{lim}$=29°C limit curve; therefore the whole microclimatic situations between $WBGT_{lim}$=29°C and HD=37 (or HD=39) curves would be assessed as dangerous on the base of HD approach.

The singular behaviour of HD index with respect to WBGT and PHS methods highlighted in uniform environments, has been also verified in environments characterised by $t_a \neq t_r$ (i.e. in sheet metal factories, hot forming, engine rooms, mines or in the presence of radiation or outdoor situations). According to data reported in Fig. 2B, in each microclimatic condition the $WBGT_{lim}$=29°C curve is always below both HD=37

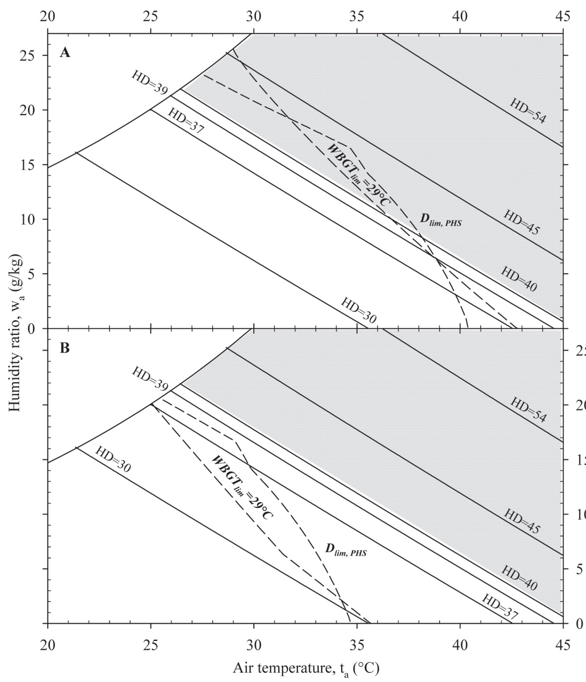

Fig. 3. Discomfort and hot stress assessment carried out by means of HD (continuous lines) and methods provided by the regulations in force (dashed lines).

Metabolic rate M=1.8 met – Not acclimatised subject freely drinking – Static clothing insulation I_{cl} = 0.60 clo – Quiet air. t_r=t_a (A), t_r = t_a+10°C (B). Filled areas refer to such microclimatic conditions judged from discomfortable to dangerous by HD (see Table 3).

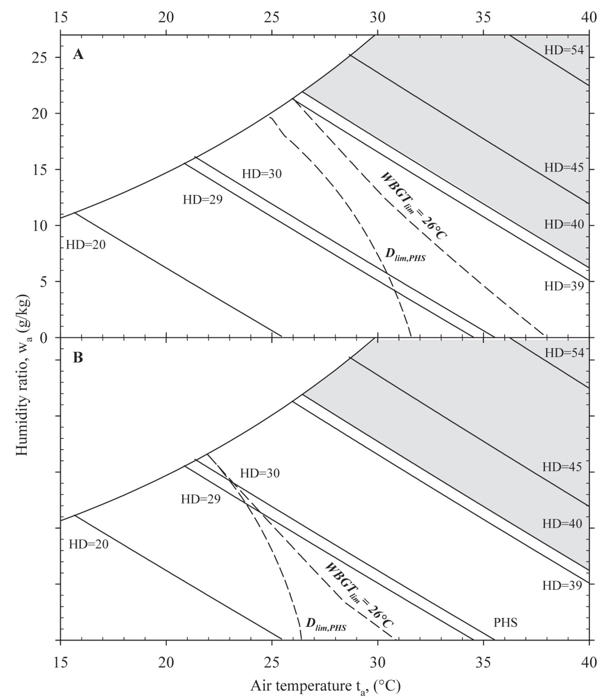

Fig. 4. Discomfort and hot stress assessment carried out by means of HD (continuous lines) and methods provided by the regulations in force (dashed lines).

Metabolic rate M=2.8 met – Not acclimatised subject freely drinking – Static clothing insulation I_{cl} = 0.60 clo – Quiet air. t_r=t_a (A), t_r = t_a+10°C (B). Filled areas refer to such microclimatic conditions judged from discomfortable to dangerous by HD (see Table 3).

and HD=39 curves. Therefore, even in the presence of so low metabolic rate (M=1.4 met), Humidex index results in an evaluation even less restrictive than WBGT, which, according to ISO 7243, appears an useful index only for a rough assessment. As a consequence, a dangerous microclimatic condition is misinterpreted by HD as only uncomfortable.

A similar behaviour occurs also when the environment assessment is carried out by means of PHS rational method: in fact at above 34°C, PHS 8-h limit curve falls in the 30 ≤ HD ≤ 39 area. This means that microclimatic conditions over 34°C and at low humidity are considered only as slightly uncomfortable (or not so dangerous on the base of above quoted HBHRP) whereas on the base of PHS approach, are inconsistent with 8 h of continuous work due to the overcoming of the maximum allowable dehydration.

Data reported in Fig. 3A show that a light increase of the metabolic rate (from 1.4 to 1.8 met), consistent with a light activity yet, results in the shifting downward of 8-h limit curve provided by PHS (WBGT limit value is always 29°C for M=1.8 met). This occurrence on one hand makes WBGT more strict than PHS in the temperature range 32 ÷ 38°C, and on the other one returns a very ambiguous assessment of the working situation through HD, especially under not-uniform situations (Fig. 3B) where both WBGT and PHS limit curves fall down in microclimatic conditions assessed by Humidex as only slightly uncomfortable.

Figure 4 finally reports the hot stress assessment results in typical conditions for a medium metabolic activity (M=2.8 met), t_a=t_r (Fig. 4A) and $t_a \neq t_r$ (Fig. 4B). These graphic data further demonstrate the full disagreement between assessment criteria suggested by the existing regulations and Humidex index. In these particular conditions it is possible find microclimatic conditions evaluated comfortable by HD whereas they could be practically lethal if assessed by means of both WBGT and PHS.

Moderate indoor environments

In order to compare the assessment of a moderate indoor environment by means of PMV and HD index, in Table 7 both PMV and HD values for an uniform environment (t_a=t_r), under typical summer clothing[49)] situations and for two light activity metabolic rates[46)] are reported.

Table 7 data analysis seem to lead to contrasting

Table 7. Comparison between the assessment of thermal comfort carried out by means of Humidex index (HD) and regulations in force (PMV) as a function of the air temperature t_a. Relative humidity RH = 50%; $t_a = t_r$; v_a = 0.10 m/s; static clothing insulation I_{cl} = 0.60 clo

$t_a = t_r$ (°C)	PMV		HD
	M=1.4 met	M=1.8 met	
19.0	–1.30	–0.72	19.5
19.5	–1.17	–0.61	**20.2**
20.0	–1.04	**–0.50**	**20.9**
20.5	–0.91	**–0.38**	**21.6**
21.0	–0.78	**–0.27**	**22.3**
21.5	–0.64	**–0.16**	**23.1**
22.0	–0.51	**–0.04**	**23.8**
22.5	**–0.38**	**0.07**	**24.5**
23.0	**–0.25**	**0.18**	**25.2**
23.5	**–0.11**	**0.30**	**26.0**
24.0	**0.02**	**0.41**	**26.7**
24.5	**0.15**	0.53	**27.5**
25.0	**0.29**	0.65	**28.2**
25.5	**0.42**	0.76	**29.0**
26.0	0.56	0.88	29.8

In bold letters comfort index values required by each index (20 ≤ HD ≤ 29 and –0.50 ≤ PMV≤ +0.50) have been reported.

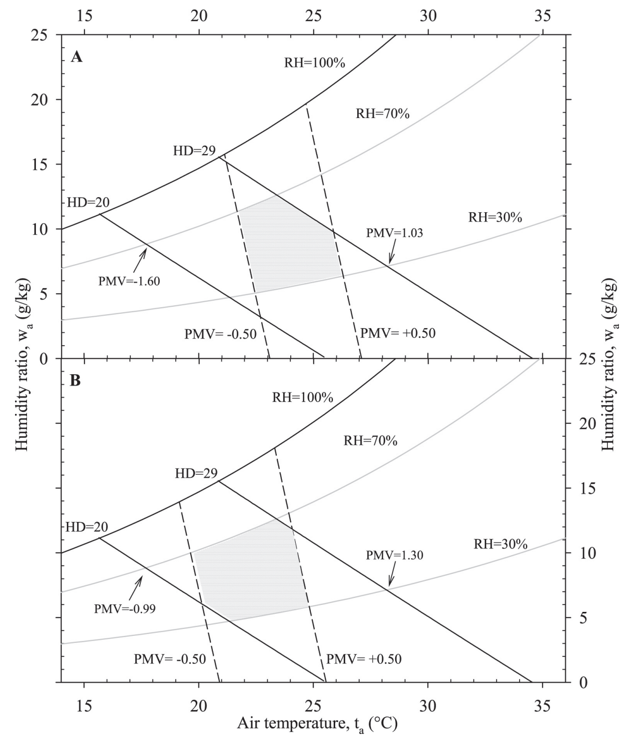

Fig. 5. Thermal comfort assessment carried out by means of HD (continuous lines) and PMV (dashed lines) indices, respectively.
I_{cl} = 0.60 clo. Metabolic rate M=1.4 met (A) or M=1.8 met (B) – Air velocity v_a = 0.10 m/s, t_a=t_r. Filled areas refer to microclimatic conditions for which there is agreement between the assessment carried out through two indices.

results:

- PMV and HD appear in good agreement only in a narrow range of temperatures: 22.5 ÷ 25.5°C for M=1.4 met and 20.0 ÷ 24.0°C for M=1.8 met; moreover, if comfort temperature range predicted by HD is 6.0°C, PMV shows a reduced comfort temperature range: 3.0°C (4.0°C) at 1.4 met (1.8 met);
- the agreement in the thermal comfort assessment is obtained at higher temperature values (at 1.4 met) while at lower temperature, PMV appears more restrictive than HD;
- an improved agreement at lower temperature is possible only by increasing the metabolic activity, but this occurrence results in the shifting of the maximum comfort temperature to lower values (from 25.5°C at 1.4 met to 24.0°C at 1.8 met).

These results clearly demonstrate the inability of HD index in a reliable assessment of comfort situations at lower temperatures, probably due to its formulation under mild hot climatic outdoor conditions[15].

A more in-depth comparative analysis of the same environment, also taking into account the combined effect of the air temperature, the mean radiant temperature and the humidity, has been carried out. Results on special psychrometric charts, provided with upper and lower comfort curves in accordance with PMV and HD, in Figs. 5 and 6 are reported. Before showing these results we like to highlight that under typical indoor environment situations, the comparative analysis in the humidity ratio range 30 ÷ 70% has been discussed. The reasons of this choice are easy: below humidity level of 30% mucous membranes start to dry up with the consequent reduction of the body defences towards germs and bacteria; on the other hand over 70% become to be important the allergenic factors and the superficial condensate formation responsible for moulds making worse the indoor air quality[51].

As clearly shown in Fig. 5A, corresponding to typical summer office conditions (M=1.4 met, I_{cl}=0.60 clo), Humidex index appears unable in a reliable assessment of thermal comfort in every microclimatic condition. As a matter of fact, the comparison between comfort curves required for the B-class by ISO 7730 (PMV= ± 0.50) and those required by Humidex (HD=20 and HD=29) results in a perfect agreement only in filled areas.

On the contrary, outside filled areas, that is in more "cool-humid" and in "warm-dry" conditions, microclimates judged as comfortable by HD, appear absolutely uncomfortable on the base of the PMV index. Moreover, Fig. 5A curves highlight a dual behaviour:

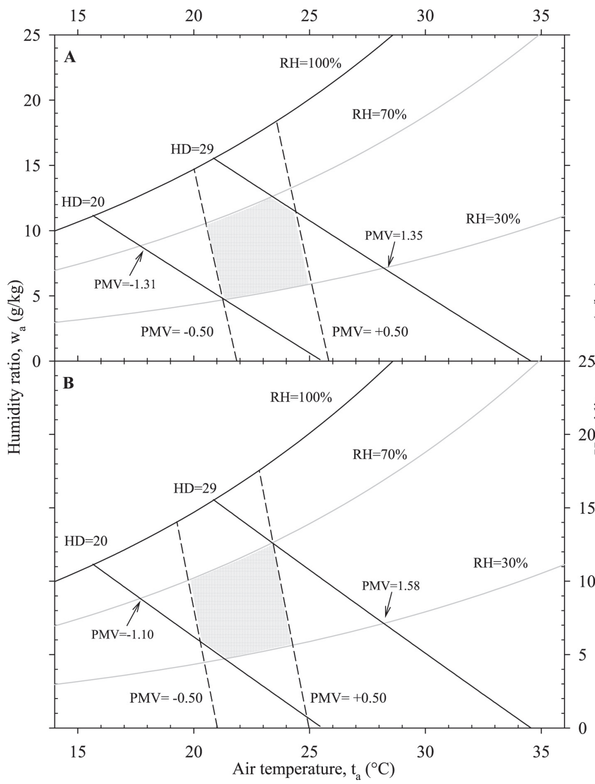

Fig. 6. Thermal comfort assessment carried out by means of HD (continuous lines) and PMV (dashed lines) indices, respectively. Metabolic rate M=1.4 met – Static clothing insulation I_{cl} = 0.60 clo – Air velocity v_a = 0.10 m/s. $t_r = t_a + 3.0°C$ (A), $t_r = t_a + 5.0°C$ (B). Filled areas refer to microclimatic conditions for which there is agreement between the assessment carried out through two indices.

below 22.5°C and for RH ≥ 30% HD provides a less prescriptive assessment whereas, over 23.5°C and for RH ≥ 50%, the opposite occurrence has been revealed. This phenomenon is not surprising if we take into account that, unlike PMV, Humidex index exhibits a high sensitivity with respect to relative humidity[15, 51]. Anyway, inconsistencies in comfort assessment outside typical PMV comfort areas, require a more in-depth assessment of the work situation in order to avoid the onset of stress microclimatic conditions (i.e. |PMV|> 1,0) which by means of special cold or heat stress indices have to be investigated[32].

As far as a little increase of the metabolic rate effect is concerned, data reported in Fig. 5B more clearly show an improved agreement with PMV at lower temperature, while at higher temperature a significant discrepancy has been observed. This occurrence appears just a little surprising since only a slight increasing of the metabolic rate in the light activity range[48] results in a different evaluation of the same thermal environment. On the other hand a metabolic rate value of 1.8 met is typical of several indoor situations, as laboratory assistants, teachers and secretaries, respectively[48].

In order to highlight the different contributions of radiative and convective "subject-environment" heat transfer phenomena on the thermal environment assessment, two radiant temperature values have been investigated: $t_r = t_a+3.0°C$ and $t_r = t_a+5.0°C$ very likely situations in the presence of windows. Iso-PMV curves shown in Fig. 6 deal with the effect of the difference between the air temperature and the mean radiant temperature ($t_a \neq t_r$). The width of filled areas depicted in Fig. 5 clearly highlight that the increase of ($t_r - t_a$) difference results in a progressive worsening of the agreement between PMV and HD revealed in uniform environments (see Fig. 5). Such occurrence is the trivial consequence of the HD formulation: Humidex index takes into account only two (relative humidity and air temperature) out of four environmental parameters affecting the equation (1) ignoring both air velocity and mean radiant temperature as well as subjective parameters.

Conclusions

The comparative assessment of the thermal environment carried out in accordance with the International Standard in force and Humidex has shown a substantial disagreement between the two approaches both for the hot stress (indoor and outdoor) and comfort (indoor) assessment. Particularly, concerning the assessment of hot extreme environments, obtained results have highlighted that the simplified HD formulation results in an ambiguous assessment of the working situation, or, what is worse, in underestimating the workplace dangerousness especially for light metabolic rates and in dry conditions. Concerning moderate environments, Humidex provides a good estimation of thermal comfort only in a narrow range of thermohygrometric conditions (i.e. higher temperature and summer conditions or lower temperature and winter conditions) and at lowest metabolic activity since it is unable to take into account the clothing insulation effect, the metabolic activity changes and the presence of temperature non-uniformities.

Therefore bioclimatic indices like Humidex, although very easy to be interpreted, can be used only by media to give more useful information about kind of clothing to choose before going out, particularly the clothing most likely to provide thermal comfort or avoid a excessive hot sensation. In other situations (thermal comfort in buildings or thermal stress induced by the combination between the microclimate and the particular work activity) their use should be strongly restricted, since they loudly fail when used out of their narrow validation range as well as they do not take into account the physiological response of the subject to the thermal environment. On this point of view rational methods suggested by ISO Standards (PHS, PMV) offer a more reliable assessment although a special software is always required. In a further paper the compared analyses here discussed will deal with more promising indices as UTCI, based on a rational approach and validated in a widest range of microclimatic conditions.

Symbols

C	W/m^2	Convective heat flow
C_{res}	W/m^2	Respiratory convective heat flow
DI	°C	Thom Index
E	W/m^2	Evaporative heat flow at the skin
E_{res}	W/m^2	Respiratory evaporative heat flow
ET*	°C	New effective temperature
$D_{lim,PHS}$	min	Duration limited exposure according to PHS approach
HD	°C	Humidex index
I_{cl}	m^{2}K/W, clo	Clothing insulation
$I_{cl,dyn}$	m^{2}K/W, clo	Dynamic clothing insulation
IREQ	m^{2}K/W, clo	Required clothing insulation
M	W/m^2, met	Metabolic rate
PHS	-	Predicted Heat Strain
p_{as}	hPa	Saturated water vapour pressure
PMV	-	Predicted Mean Vote
R	W/m^2	Radiative heat flow
RH	%	Relative humidity
S	W/m^2	Body heat storage rate
t_a	°C	Air temperature
t_o	°C	Operative temperature
t_r	°C	Mean radiant temperature
t_{re}	°C	Rectal temperature
t_w	°C	Wet bulb temperature
v_a	m/s	Air velocity
W	W/m^2	Effective mechanical power
w_a	g/kg	Humidity ratio
WBGT	°C	Wet-bulb globe temperature
$WBGT_{lim}$	°C	Limit wet-bulb globe temperature

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