ASSESSMENT OF ENVIRONMENTAL HEAT LOAD

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ABSTRACT

Merits and demerits of existing indices of heat stress like Effective Temperature, Corrected Effective Temperature and Predicted Four-Hour Sweat Rate, have been briefly discussed. None of them being applicable in the open sun, two indices, New Corrected Effective Temperature and the Modified Effective Temperature, have been developed respectively at the Defence Research Laboratory (Stores), Kanpur; and the Defence Science Laboratory, New Delhi, taking into account different colours of clothing and complexion of skin. The possibility of using dry and wet Kata cooling powers for rough but quick assessment of heat load has been explored.

Introduction

The practical importance of assessment of environmental heat load and definition of limiting conditions in relation to comfort and efficiency of working personnel, can be hardly overemphasized. We have not yet got a clear picture of what is meant by endurable limit in the objective sense, as ordinary observations are most likely to be influenced by the motivation factor. For operational purposes, much of the existing confusion and empiricism can be avoided if the entire range of hot environments is divided into two distinct zones in relation to clothing and activity, as follows:—

(1) Zone of thermal balance or prolonged tolerance.

(2) Zone of thermal unbalance.

The line separating the two zones may be termed as the "limit of thermal balance" which should be defined by the limiting environments in which soldiers can perform prolonged work without any irreparable damage to the system. This limit should, however, be distinguished from "comfort limit", for, unlike the latter, thermal balance is maintained at the highest equilibrium level of the physiological variables concerned with body heat regulation, *viz.*, pulse rate, body temperature, sweating rate, etc., involving maximal physiological stress, within the range of thermal equilibrium.

The 'zone of thermal unbalance' is clearly beyond the 'limit of thermal balance', and in this zone, it is extremely important to know, not only the severity of the heat stress, but also the 'tolerance time' or the period for which a soldier can be safely allowed to perform his specific task under the given stress.

The total heat load on the working personnel exposed to a given hot environment, should, therefore, be assessed on a suitable thermal scale which takes due account of the two zones defined above, and also enables us to work out the tolerance time in the zone of thermal unbalance.

Factors in heat load

The total heat load on the human body is the sum of the internal heat load, determined by the grade of activity, and the external heat load, determined by the environmental factors taking part in the various processes of heat exchange between the body and its surroundings, namely, conduction, convection, radiation and evaporation. These factors are, primarily, the air temperature, air velocity, relative humidity, and the mean black body temperature of the surrounding surfaces. Measurement of these with sufficient accuracy under indoor conditions, no longer presents any difficulty, and can be carried out with simple instruments, like the sling psychrometer (for air temperature and humidity), silvered Kata thermometer (for air velocity) and the black globe thermometer (for mean radiant temperature, m.r.t.). What still remains to be solved satisfactorily, is the problem of integrating the environmental factors into a composite index of heat stress as an adequate measure of the environmental heat load. The problem is further complicated by clothing, acting as a thermal barrier between the body and its surroundings and modifying all the processes of heat exchange. The variable mean skin temperature of the human body is another complicating factor. Assessment of solar heat load under outdoor conditions, presents yet another problem.

Indices of Heat Stress

It is not possible here to give a detailed account of the various attempts made from time to time to evolve a suitable index of heat stress, nor is it possible to present a critical assessment of the merits of the several indices developed so far. Some of the existing indices of comfort have been admirably reviewed by Yaglou[1]. Mention may be made here, of those indices in current use which have proved to be more or less satisfactory for many practical purposes.

Standard Operative Temperature

The Standard Operative Tempeature, (T_o) developed by Winslow, Herrington and Gagge[2], is a physical index combining air temperature, air velocity, mean radiant temperature and mean skin temperature. This index, though objective, fails in heat as it ignores humidity, the most important factor in evaporative heat regulation of the body.

Effective Temperature

The "Effective Temperature Scale" (E.T.) developed by Houghten, Yaglou and Miller,[3,4,5] is the most popular and widely used index of comfort, which, though based on subjective feeling of warmth, still remains the best index of warmth, particularly in heat. This index combines dry and wet bulb temperature together with air velocity, and is applicable to persons engaged in light activity. Two different scales of E.T. are in use, the 'Basic scale' for persons stripped to the waist, wearing trousers, socks and shoes, and the 'Normal Scale' for persons in normal winter clothing. A separate chart is provided for each scale. When the mean radiant temperature of the surrounding surfaces differs significantly from the dry bulb temperature, Bedford[6] has proposed an arbitrary correction for radiation, incorporated in the Corrective Effective Temperature Scale (C.E.T.). In this, the black globe temperature is taken as the air temperature corrected for radiation, and the same E.T. charts can be used. But one important point overlooked by many and not mentioned by Bedford[6] has been stated by Yaglou[1] to be that, the globe reading must be used with the given dew point in computing the C.E.T., for otherwise while correcting for radiation a new error will be introduced by changing the vapour pressure of the atmosphere. This means that a corresponding radiation correction must be applied to the prevailing wet bulb reading in order to maintain a constant specific humidity (not relative).

None of the above indices takes into account the effect of clothing or activity, nor is applicable in the sun under outdoor conditions. In the E.T. or C.E.T. scale, it is, however, possible to incorporate the grade of activity, in the manner suggested by Smith [7], by the addition of a simple supplementary nomogram.

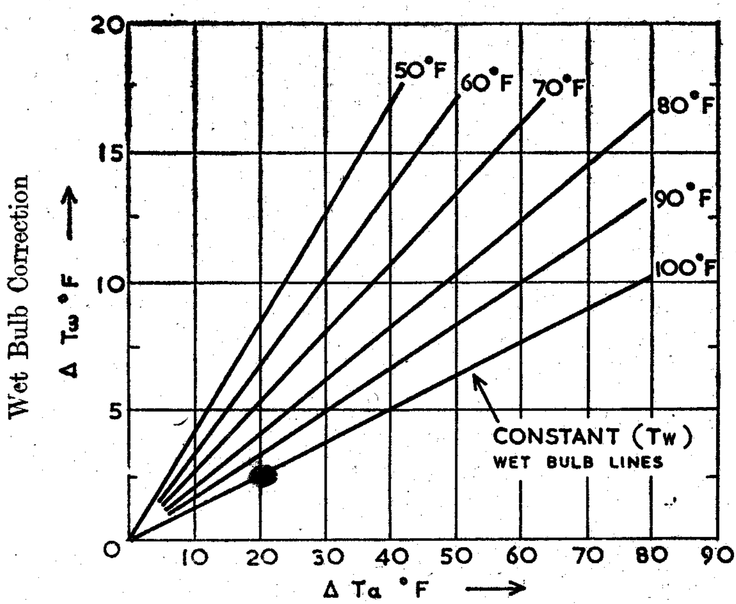
Predicted Four-Hour Sweat Rate

The 'Predicted Four-Hour Sweat Rate' or the P4SR index of heat stress, recently developed by McArdle et al [8], though based on observed sweating rates of a large number of individuals exposed to various environmental conditions, may be regarded as an objective index which includes, in a very rough and empirical manner, the effect of clothing and activity as well. Even then its superiority over the C.E.T. scale has not yet been firmly established[7]. Our studies [9] have shown that sweating rate alone cannot be taken as an adequate measure of comfort. In the P4SR scale a radiation correction is applied to the wet bulb reading, given by $\triangle$ Tw=0·4 (Tg—Ta), Ta, Tw and Tg being the dry bulb, wet bulb and the black globe readings respectively. From theoretical considerations it can be easily shown that the correction factor 0·4 is disproportionately high, and should actually vary from about 0·34 to 0·13 as Tw changes from 60°F to 100°F. Our results [10] show that at a given wet bulb temperature, $\triangle$Tw, the radiation correction to wet-bulb varies directly as $\triangle$Ta, the radiation correction to dry bulb, the constant of proportionality decreasing with increasing Tw. The results are graphically shown in Fig. 1. The P4SR index also is not applicable under outdoor conditions in the sun.

Wet Bulb Globe Temperature Index

Recently we have come to know that a simple index has been developed in the U.S.A., with a linear combination of wet-bulb and Black Globe readings, known as the 'Wet-bulb globe temperature' index or the WBGT index, which is supposed to be applicable in the sun as well, for a particular colour of clothing. Detailed information on this index is lacking, and as such we are not in a position to comment on its merits, except that it is definitely a simple one.

However, one or two remarks may be made in passing. This index is not likely to be applicable to different shades of clothing in the sun or to different grades of activity. Secondly, a constant weightage given to the wet bulb reading does not appear to be justified because the relative importance of the wet bulb reading should be greater with increasing warmth of the environment.



Dry Bulb Correction

Fig. 1—*Correction to Wet-bulb, required to maintain constancy of specific humidity, in relation to Dry-bulb correction for radiation and Wet-bulb reading.*

As such the effect of humidity is not correctly expressed in this index. Thirdly, the air movement is not measured, and is supposed to be taken care of by the reading of the wet bulb thermometer itself, which is exposed to the prevailing wind and not used as a psychrometer. Whether this is adequate or not has yet to be seen. It appears, however, that this index, if suitably amended, offers great promise.

Solar Heat Load

From the foregoing, it will be seen that the indices of heat stress which are more or less reliable under indoor conditions even in the presence of hot surfaces or additional sources of radiation, cannot serve the purpose under outdoor conditions in the sun. The black globe thermometer, while quite satisfactory under indoor conditions, fails to assess the radiant heat load in the sun. This is because, indoor radiation is only long infra-red while solar radiation is essentially made up of visible and short infra-red radiations. While all colours of clothing and all complexions of skin are nearly black (i.e. having high emissivity) with respect to long infra-red, they have widely different emissivities for visible and short infra-red radiations. Hence black-globe reading in the sun cannot be regarded as the air temperature corrected for radiation.

New Corrected Effective Temperature

Mani and Mehra[11] rejected the use of the Black Globe for assessment of solar heat load, and used Blum's [12] equations for computing the same, using figures for reflectance of direct solar radiation by clothing or skin (as the case may be). Solar heat load, so computed was converted into equivalent increment to dry-bulb reading according to Burton's [13] formula, which is therefore the radiation correction to air temperature. They applied a corresponding correction to the wet-bulb reading, with the help of a psychrometric chart, and used the standard Effective Temperature chart (Normal or Basic, as the case may be) with the corrected dry and wet bulb readings. The Effective Temperature so computed, was called by them the 'New Corrected Effective Temperature' or the N.C.E.T. This method of computing solar heat load on man is more or less justified on theoretical grounds, and takes into account the posture of the mass as well. But the practical difficulties in using this scale are too many, for the factors required for its computation are, latitude and altitude of the place, the time and day of the year, the optical characteristics of the terrain, the posture, the colour of clothing or complexion of skin, and above all, the degree of dustiness or cloudiness of the atmosphere, which is a highly variable and uncertain quantity. More-over, this method ignores the long infra-red radiation exchange between the man and the sky and the heated ground and sorrounding objects. As such, the effective emissivity for total solar radiation (including long infra-red) should be much higher than the value used by Mani and Mehra[11].

Modified Effective Temperature

All these difficulties can be avoided if the use of black globe is retained, provided its reading is corrected for the particular colour of clothing, or complexion of skin, as the case may be. In this laboratory, we have been using this method for assessment of solar heat load with satisfactory results for most practical purposes. From our observations[14], we have found that the absorptivity of black globe, black cloth, olive-green, khaki, and white cloth for total solar radiation are about 0·89, 0·89, 0·70, 0·64 and 0·45 respectively while for visible and short infra-red radiations, the values are about 0·86, 0·86, 0·57, 0·53 and 0·30 respectively. The values for total solar radiation are, however, likely to vary slightly with optical characteristics of the terrain and surrounding objects. From a knowledge of the absorptivity for total solar radiation and the dry bulb and black globe reading, we worked out the radiation correction to be applied to the air temperature. To avoid computational work we have devised a simple nomogram shown in Fig. 2. The corresponding wet-bulb correction can be read from Fig. 1. The standard E.T. chart (Basic or Normal) can be used for the above corrected air temperature and wet bulb readings together with the prevailing air velocity. The Effective temperature so obtained is a measure of environmental warmth including solar heat load, and has been called by us the Modified Effective Temperature [15] (M.E.T.). It is applicable to subjects in the erect posture, with or without clothing. We have not yet incorporated the grade of activity in this scale, but it can be done in the manner suggested by Smith[7].

Evaporation Rate as an Index of Comfort

For some time past, we have been trying to evolve some simple method for a rough but quick evaluation of environmental warmth in tropical heat. In such environments, evaporation of sweat being practically the only avenue of body heat dissipation, the evaporation rate of water near the body temperature should roughly yield the cooling power of the environment, which in turn could be used as an inverse measure of heat stress. Results of work in the past, with the body-temperature Kata thermometer, introduced by Hill [16], are not very hopeful. Neither dry-Kata cooling power nor wet-Kata cooling power

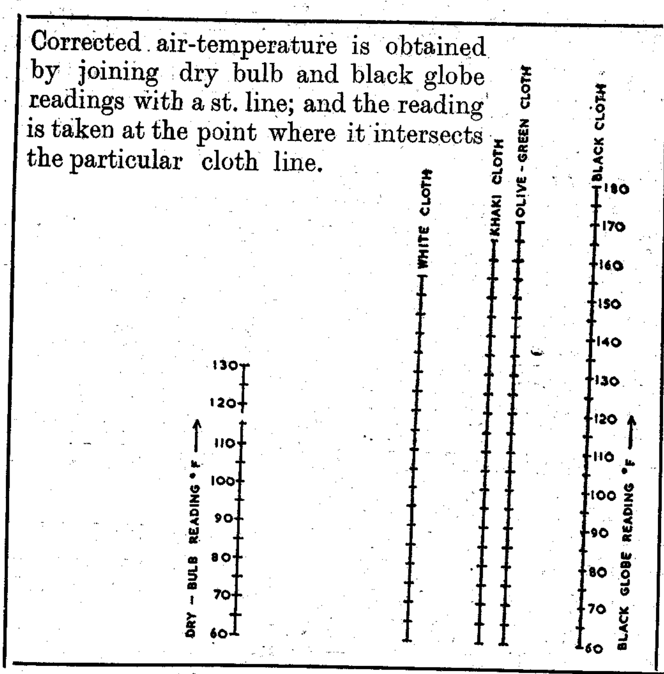


Fig. 2—*Nomogram to find air-temperature corrected for radiation, from dry-bulb and Black-Globe readings.*

gave reasonably good correlation with physiological reactions, while Effective Temperature was found to be much more satisfactory than either of them [17,18]. The principal objection against the use of Kata thermometer for assessment of comfort has been that it is much more sensitive than the human body to changes in air movement. This objection, in our opinion, is not entirely valid. Studies[19] undertaken in this Laboratory, have yielded almost similar convection-radiation formulæ for the body-temperature dry-Kata thermometer (unsilvered, range 95°—100°F), and the nude human body under indoor conditions, the cooling power measured per unit area of surface being, throughout the practical range of air velocities, about 40% higher for the Kata. So far, we have been able to establish that the main difference between the dry-Kata and dry, nude human body, is in a cold environment, where the skin temperature falls with lowering of environmental temperature, thereby modifying the heat exchange process.

In heat, on the other hand, there is very little change in skin temperature within the zone of evaporative regulation, and the "body temperature Wet Kata Thermometer" behaves very nearly in the same way as the human body all covered with sweat, as is the case in extreme dry heat or in humid heat. But under less severe conditions, the human body is somewhat intermediate between a dry-Kata and a wet-Kata thermometer. Cooler the environment, the nearer the human body approaches a dry-Kata thermometer. This appears to explain why dry-Kata cooling power or wet-Kata cooling power singly failed as a measure of comfort. It is likely that a suitable combination of the two will provide the answer. There is, however, another objection against the use of wet-Kata thermometer, that the use of the wet cover changes the effective surface area for radiation, convection and evaporation, as also the emissivity of the surface. The change in emissivity should not be appreciable, except in the sun, and even then it seems possible to provide a cover minimising such changes. As regards the increase in surface area, it should be constant for a given cover, and was found in our studies, to be about 10 % of the area of the glass bulb. It, therefore, seems possible to take this factor into account while developing an index of heat stress. Although our preliminary observations have yielded encouraging results, it is still too premature to arrive at any definite conclusions.

Conclusions

Much of the existing confusion and empiricism can be avoided if the entire range of hot environments is divided into a 'zone of thermal balance' and a 'zone of thermal unbalance' in relation to clothing and activity with special emphasis on 'tolerance time' in the latter zone.

Measurement of the various factors in the total heat load does not present so much difficulty as their integration into a single, comprehensive index of heat stress.

'Corrected Effective Temperature' Scale, though subjective, still remains the best index of comfort under indoor conditions provided proper radiation correction is applied to wet bulb readings. It can be further improved upon by incorporating clothing and activity in a suitable manner.

The Predicted Four Hour Sweat Rate, an objective index, makes a rough allowance for clothing and activity but too large a correction to wet bulb temperature for radiation. Moreover, results of our study indicate that sweating rate alone cannot be taken as an adequate measure of comfort.

None of the indices in current use can be applied to outdoor conditions, in the sun, for which two indices have been developed in this country, the 'New Corrected Effective Temperature' at the Defence Research Laboratory (Sotres), Kanpur and the 'Modified Effective Temperature' at the Defence Science Laboratory, New Delhi. While the former is mainly of theoretical interest, the latter is a practical index of total solar heat load.

Recently a very simple index known as the 'Wet-bulb-Globe Temperature' has been developed in the U.S.A., which is applicable even in the sun for a particular colour of clothing, but does not include the grade of activity. The major defect seems to be the constant weightage given to wet bulb reading. If suitably amended, this index offers great promise. However, detailed information on this is lacking.

In tropical heat, rate of evaporation of water at near the body temperature may form a basis for evolving a simple method for a rough but quick assessment of environmental warmth. Our observations with dry and wet body temperature Kata-thermometer show promising results. A suitable combination of the two is likely to yield a reliable index of heat stress.

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References

1. Yaglou, C.P., "Physiology of Heat Regulation", edited by L. H. Newburgh, W.B. Saunders Company (1949).
2. Gagge, A.P., "Temperature : Its Measurement and Control in Science and Industry", American Institute of Physics, New York, Reinhold Publishing Co. (1941).
3. Houghten, F.C., and Yaglou, C. P., Trans. Amer. Soc. Heat. and Ventil Engrs., **29**, 163 (1923).
4. Houghten, F.C., and Yaglou, C.P., Ibid. **30**, 193 (1924).
5. Yaglou, C.P., and Miller, W.E., Ibid, **31**, 89 (1925).
6. Bedford, T., "Medical Research Council, War Memorandum No. 17, H.M.S. Office, London (1946).
7. Smith, F.E., "Medical Research Council, Memorandum No. 29, H.M.S. Office, London (1955).
8. Mc Ardle, B., Dunham, W., Holling, H.E., Ladell, W.S.S., Scott, J.W. Thomson, M.L. and Weiner, J.S., Medical Research Council, Report No. 47/391 (1947).
9. Mookerjee, G.C. and Majumdar, N.C., Def. Sc. Jour. **4**, 183 (1954).
10. Majumdar, N.C., unpublished report.
11. Mani, K.V. and Mehra, N.C., J. Sci. Industr. Res., **16C**, 61 (1957).
12. Blum, H.F., J. Clin. Invest. **24**, 712 (1945).
13. Burton, A.C., Assessment of Thermal Demands of the Environment, paper presented by Canada at the 4th Commonwealth Conference on Clothing and General Stores (1953).
14. Sharma, R. N., and Majumdar, N.C., unpublished data.
15. Majumdar, N.C., and Sharma, R.N., unpublished report.
16. Hill, L., Griffith, O.W., and Flack, M., Phil. Trans. Roy. Soc. (B) **207**, 183 (1916).
17. Yaglou, C.P., J. Industr. Hyg., **9**, 297 (1927).
18. Vernon, H.M. and Warner, C.G., J. Hyg., **32**, 431 (1932).
19. Majumdar, N.C. and Sharma, R. N., unpublished data.