J5B.4 AN UPDATE ON THE DEVELOPMENT OF A UNIVERSAL THERMAL CLIMATE INDEX

Gerd Jendritzky*, Abdel Maarouf**, Dusan Fiala***, Henning Staiger*
*Deutscher Wetterdienst, Freiburg, Germany
**Environment Canada, Toronto, Canada
***De Montfort University, Leicester, U.K.

1. INTRODUCTION

One of the fundamental issues in human biometeorology is the assessment of the atmospheric environment in a thermophysiologically meaningful and useful way. Due to the fact that air temperature is not the only relevant variable, more than 100 simple thermal indices - most of them two-parameter indices - have been developed in the last 150 years to describe the complex conditions of heat exchange between the human body and its thermal environment. Well-known and still popular examples are the heat index and the windchill index. For excellent reviews, see Fanger (1970), Landsberg (1972), Givoni (1976), and Driscoll (1992). However, due to the simple formulation of these indices an essential requirement was never fulfilled, that is for each index value there must always be a unique thermophysiological effect, regardless of the combination of the input meteorological values.

Complete heat budget models take all mechanisms of heat exchange into account, and can be considered as state-of-the-art. Input variables include air temperature, water vapour pressure, wind velocity, mean radiant temperature including solar radiation, in addition to metabolic rate and clothing insulation. Such models possess the essential attributes to be utilized operationally in most biometeorological applications in all climates, regions, seasons, and scales. This is certainly true for MEMI (Höppe, 1984,1999), and the Outdoor Apparent Temperature (Steadman, 1984, 1994). However, it would not be the case for the simple Indoor AT, which is the basis of the US Heat Index, often used in outdoor applications neglecting the addition "Indoor". Other good indices include the Standard Predictive Index of Human Response approach (Gagge et al., 1986), and Out_SET* (Pickup and de Dear, 2000; de Dear and Pickup, 2000) which is based on Gagge's work. Blazejczyk (1994) presented the man-environment heat exchange model MENEX, and the extensive work by Horikoshi et al. (1995, 1997) resulted in a Thermal Environmental Index. With Gagge`s et al. (1986) improvement in the description of latent heat fluxes by the introduction of PMV*, Fanger's (1970) approach can also be considered among the advanced heat budget models. This approach is generally the basis for the operational thermal assessment procedure Klima-Michel-model (Jendritzky et al., 1979; Jendritzky et al., 1990) of the Deutscher Wetterdienst with the outcome "perceived temperature, PT" (Staiger et al., 1997) that considers a certain degree of adaptation by various clothing.

Based on current scientific progress, and with increased international travel and easy access to information, there is a need for global harmonization of the development and dissemination of various weather and climatic indices. Considering the recent successful experience with the worldwide introduction of a universal UV-index under the umbrella of WHO and WMO, the idea came up to review what has been achieved in the past 30 years in thermophysiological modeling. Consequently, ISB has established Commission 6 to integrate new knowledge and concerns into a Universal Thermal Climate Index, UTCI, for assessments of the outdoor thermal environment.

2. Basic features of UTCI

The Universal Thermal Climate Index must meet the following requirements:

1) thermophysiologically significant in the whole range of heat exchange
2) valid in all climates, seasons, and scales
3) useful for key applications in human biometeorology such as:
   - daily forecasts:
     - public weather service
     - warnings of the danger of thermal extremes (windchill, heat load)
     - advice (clothing, outdoor activities)

* *Corresponding author address*:
Gerd Jendritzky, Deutscher Wetterdienst,
Unit Human Biometeorology, Freiburg, Germany,
+49761-2820254; e-mail: gerd.jendritzky@dwd.de

● climatology:

- bioclimatological assessments
- urban design and engineering of outdoor spaces
- consultancy for residence
- outdoor recreation and climatotherapy
- bioclimate maps in all scales from micro to global
- epidemiological studies
- climate impact research

The degree of sophistication of the complete UTCI model should focus on the aims listed in the above three main conditions in order to generate reliable results. Nevertheless certain standardizations - which also mean simplifications - are necessary. For example, it seems appropriate to concentrate on steady-state conditions in order to achieve practically useful results. Personal characteristics of individuals such as age, gender, specific activities (i.e. unusual) and clothing can also be neglected.

When fully developed, UTCI will be:

- based on the most advanced multi-node thermophysiological models using key results from systematic simulations (see section 4 below),
- capable of predicting whole body thermal effects (hypothermia and hyperthermia; heat and cold discomfort), and local effects (facial, hands and feet cooling and frostbite),
- linked to an expert system (e.g. look-up tables, parameterization by regression).

UTCI will be a temperature scale index, (i.e. the air temperature of a defined reference environment providing the same heat exchange condition).

3. INPUT DATA

3.1 Atmospheric Environment

The atmospheric variables determining the complex heat exchange conditions are air temperature, wind velocity, water vapour pressure, and short-wave (solar) radiation and the long-wave (infrared) radiant fluxes emitted by the surroundings including the sky. Difficulties in obtaining the required meteorological input data are often underestimated, particularly with respect to wind and radiation. Data availability and observational practices in various geographical regions need to be addressed in consultation with WMO standards and guidelines.

According to WMO wind should be measured at 10 m height, but we need the wind velocity at a height representative of the human being, which has been defined as 1.1 m. So measured or computed wind data must be adjusted to that height. The additional wind speed induced by the movement of the person requires the calculation of a "relative" wind velocity. We assume that the observed "meteorological" wind blows at 90 degrees of the direction of a walking person.

Dealing with radiant fluxes is even more complex. The human heat budget is very sensitive to radiation, especially when wind velocity is low. Representative data are more often than not unavailable. They must usually be parameterized and then be related to the special geometry of an upright standing person. Calculation of solar radiation even for a plain area (no limits to horizon) is quite complex. Sun elevation, turbidity, cloudiness, altitude and - for the reflected portion - albedo are input variables. Direct and diffuse fluxes must be distinguished due to the deviation of an upright standing person from a horizontal receptor area. The infrared radiation of the ground depends on surface (not air!) temperature (rarely measured) and emissivity, that of the sky on air temperature, water vapour pressure and also clouds (VDI, 1994). Numerical forecast models currently operational by various national weather services should facilitate direct access to the necessary radiant fluxes. In more complex environments such as street canyons modeling of radiant fluxes becomes even more difficult (see e.g. Matzarakis et al., 2000). The UTCI Commission agreed to relate the radiant fluxes to the human being by a mean radiant temperature, an approach described comprehensively by Fanger (1970).

3.2 Personal Factors

Of great importance are the non-meteorological variables: metabolic rate MET and thermal resistance of clothing. When MET is derived from tables based on given activity levels, an error in the order of ± 20% can be assumed due to the influence of training, shoes, soil and other individual effects. This results in heat flux changes of the same order. Comparable problems occur with clothing. The thermal resistance of a business suit, for example, is given as 1 clo = 0.155 Km^2/W. However, it is not possible to determine accurately the actual clo-value of clothing, especially when humidity transfer and other uncertainties are involved. All these uncertainties suggest that it may be reasonable to avoid too sophisticated formulations with details that only make minor contribution in heat budget models.

The UTCI Commission has defined a representative activity to be that of a person walking with a speed of 4 km/h. This provides a metabolic rate of 2.3 MET (135 W/m²). Clothing will be considered as an intrinsic clo-value in the range of Icl = 0.4 - 2.6 clo. This should cover the kinds of clothing worn by people who are adapted to their local climate. With respect to the need to address specific characteristics of clothing, such as significant ventilation between body surface and inner surface of clothing or the extreme heat resistance of traditional Inuit clothing, these issues will be considered in a later stage.

4. MULTI-NODE MODELS

Mathematical modeling of the human thermal system goes back 70 years. In the past four decades more detailed, multi-node models of human thermoregulation have been developed, e.g. Stolwijk 1971, Konz et al. 1977, Wissler 1985, Fiala et al. 1999 and 2001, Huizenga et al. 2001, and Tanabe et al. 2002. These models simulate phenomena of the human heat transfer inside the body and at its surface taking into account the anatomical, thermal and physiological properties of the human body. Environmental heat losses from body parts are modeled considering the inhomogeneous distribution of temperature and thermoregulatory responses over the body surface. Besides overall thermophysiological variables, multi-segmental models are thus capable of predicting 'local' characteristics such as skin temperatures of individual body parts. Validation studies have shown that recent multi-node models reproduce the human dynamic thermal behaviour over a wide range of thermal circumstances (Fiala et al. 2001, Huizenga et al. 2001).

From the mathematical point of view, the human organism can be separated into two interacting systems of thermoregulation: the controlling active system and the controlled passive system. The passive system of the IESD-Fiala model (Fiala et al. 1999), which has been used in this study, is a multi-segmental, multi-layered representation of the human body with spatial subdivisions. Each tissue node was assigned appropriate thermophysical and thermophysiological properties. The overall data replicates an average person with respect to body weight (73.5 kg), body fat content (14%wt), and Dubois-area (1.86 m²). The physiological data aggregates to a basal whole body heat output of 87.1W and basal cardiac output of 4.9 L min^{-1}, which are appropriate for a reclining adult in a thermo-neutral environment of 30°C. In these conditions, where no thermoregulation occurs, the model predicts a basal skin blood flow of 0.4 L min^{-1}; basal skin wettedness of 6%; a mean skin temperature of 34.4°C; and body core temperatures of 37.0°C in the head core (hypothalamus) and 36.9°C in the abdomen core (rectum), Fiala et al. (1999).

The active system predicts the thermoregulatory reactions of the central nervous system, i.e. suppression (vasoconstriction) and elevation (vasodilatation) of the cutaneous blood flow, shivering thermogenesis, and sweat moisture excretion. The active system of the IESD-Fiala model (Fiala et al. 2001) was developed by means of regression analysis using measured responses obtained from air exposures to cold stress, cold, moderate, warm and hot stress conditions, and exercise intensities between 0.8-10 MET. Verification and validation work using independent experiments revealed good agreement with measured data for regulatory responses, mean and local skin temperatures, and internal temperatures for the whole spectrum of boundary conditions considered.

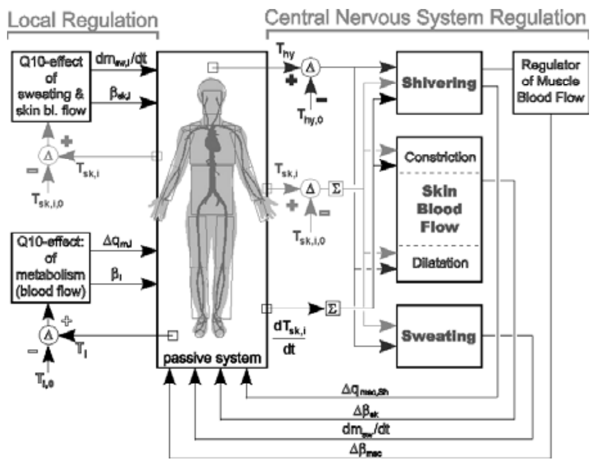

Figure 1: Schematic diagram of the active system model (Fiala et al. 2001).

5. SIMULATION PROCEDURE

The simulation series were conducted by 'exposing' the physiological model to combinations of the prevailing atmospheric environment conditions. A file matrix with various combinations of air temperature, mean radiant temperature, relative humidity, and (relative) wind speed was created and was used as input data into the model. Thereby, the ambient air temperature was varied between -40°C≤T_a≤45°C in successive steps of ΔT_a=5K. The relative humidity ranged between 5%≤rh≤95% in steps of 15%. The considered air velocities were v_a = 1.1, 2.2, 4.4, 8.8 and 17.6 m/s. The effect of short- and long-wave radiation was dealt with by using mean radiant temperatures, T_r, which deviated from the air temperature within -10K≤(T_a-T_r)≤+40K in steps of 10K.

The simulations were performed as individual two-hour-exposures to steady environmental and personal conditions assuming subjects walking at 1.1m/s (i.e. ~135 W/m² or 2.3 MET) and wearing various garments. Clothing was modeled by applying individual items to the appropriate body parts of the multi-segmental model. Six ensembles were specified to account for different 'seasonal outfits'. The overall clothing resistance resulted in insulation values of I_{cl} = 0.4, 0.6, 0.9, 1.3, 1.8, and 2.6 clo. Simulations using the light summer ensemble of I_{cl} = 0.4 clo were run for a range of air temperature between +20°C≤T_a≤+45°C. The bandwidth of air temperatures for other dresses was: I_{cl}=0.6clo: +15°C≤T_a≤+35°C, I_{cl} =0.9clo: +5°C≤T_a≤+25°C, I_{cl}=1.3clo: -5°C≤T_a≤ +15°C, I_{cl}=1.8clo: -15°C≤T_a≤+5°C, and I_{cl}=2.6 clo: -40°C≤T_a≤-10°C. Within a given range of T_a all combinations of T_r, v_a, and rh were simulated using a constant I_{cl}.

A total of 6930 combinations of environmental and personal conditions emerged for which overall and local thermophysiological variables after two hours of exposure were predicted. The predictions included the mean skin temperature, Tsk,m; the (head) core temperature, Thy (hypothalamus); the total evaporative heat loss from the skin, Esk; skin wettedness; and local skin temperatures, Tsk, of bare body parts such as of hands and face. In addition to the 2 hour results, in severe cold, also the time after which any local skin temperature fell below 0°C was indicated. All simulation results will be made available as spreadsheets in numerical and graphical form for further analysis.

Acknowledgement
The views of the authors do not necessarily represent the views of all ISB Commision 6 (UTCI) core group members.

6. REFERENCES

Blazejczyk, K. (1994): New climatological-and-physiological model of the human heat balance outdoor (MENEX) and its applications in bioclimatological studies in different scales. *Zeszyty IgiPZ PAN*, **28**, 27-58.

Driscoll, D.M. (1992): Thermal Comfort Indexes. Current Uses and Abuses. *Nat. Weather Digest,* **17**, (4), 33-38.

De Dear, R., Pickup, J. (2000): An Outdoor Thermal Environment Index (OUT_SET*) - Part II - Applications. In, de Dear, R., Kalma, J., Oke, T., Auliciems, A. (eds.), Biometeorology and Urban Climatology at the Turn of the Millenium. *Selected Papers from the Conference ICB-ICUC'99 (Sydney, 8-12 Nov. 1999). WMO, Geneva, WCASP*-**50**, 258-290.

Fanger, P.O. (1970): Thermal Comfort, Analysis and Application in Environment Engineering. Danish Technical Press, Copenhagen.

Fiala D., Lomas K.J., and Stohrer M. (1999): A computer model of human thermoregulation for a wide range of environmental conditions: The passive system. *Journal of Applied Physiology*, **87** (5), 1957-1972.

Fiala D., Lomas K.J., and Stohrer M. (2001): Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. *Int. J. Biometeorol.*, **45**, 143-159.

Givoni, B. (1976): Man, Climate and Architecture. Appl. Sci. Publishers, London, 483.

Gagge, A.P., Fobelets, A.P., Berglund, P.E. (1986): A standard predictive index of human response to the thermal environment. *ASHRAE Trans.,* **92**, 709-731.

Höppe, P. (1984): Die Energiebilanz des Menschen. *Wiss. Mitt. Meteorol. Inst. Uni München,* **49**.

Höppe, P. (1999): The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment. *Int. J. Biometeorol.*, **43**, 71-75.

Horikoshi, T., Tsuchikawa, T., Kurazumi, Y., Matsubara, N. (1995): Mathematical expression of combined and seperate effect of air temperature, humidity, air velocity and

thermal radiation on thermal comfort. *Archives of Complex Environmental Studies*, **7**, **(3-4)**, 9-12.
Horikoshi, T., Einishi, M., Tsuchikawa, T., Imai, H. (1997): Geographical distribution and annual fluctuation of thermal environmental indices in Japan. Development of a new thermal environmental index for outdoors and its application. *Journal of the Human-Environment System*, **1 (1)**, 87-92.
Huizenga C., Zhang H., and Arens E. (2001): A model of human physiology and comfort for assesssing complex thermal environments. *Building and Environment* **36**, 691-699.
Jendritzky, G., Sönning, W., Swantes, H.J. (1979): Ein objektives Bewertungsverfahren zur Beschreibung des thermischen Milieus in der Stadt- und Landschaftsplanung ("Klima-Michel-Modell"). *Beiträge d. Akad. f. Raumforschung und Landesplanung,* **28**, Hannover.
Jendritzky, G., Menz, G., Schirmer, H., Schmidt-Kessen, W. (1990): Methodik zur raumbezogenen Bewertung der thermischen Komponente im Bioklima des Menschen (Fortgeschriebenes Klima--Michel-Modell). *Beiträge d. Akad. f. Raumforschung und Landesplanung,* **114**, Hannover.
Konz S., Hwang C., Dhiman B., Duncan J., and Masud A. (1977): An experimental validation of mathematical simulation of human thermoregulation. *Comput Biol Med*, **7**, 71-82.
Landsberg, H.E. (1972): The Assessment of Human Bioclimate, a Limited Review of Physical Parameters. World Meteorological Organization, *Technical Note No. 123, WMO-No. 331*, Geneva
Matzarakis, A., Rutz, F., Mayer, H. (2000): Estimation and calculation of the mean radiant temperature within urban structures. In, de Dear R., Kalma J., Oke T., Auliciems A. (eds.), Biometeorology and Urban Climatology at the Turn of the Millenium. *Selected Papers from the Conference ICB-ICUC'99 (Sydney, 8-12 Nov. 1999). WMO, Geneva, WCASP-***50**, 273-278.
Pickup, J., de Dear, R. (2000): An Outdoor Thermal Comfort Index (OUT_SET*) - Part I - The Model and its Assumptions. In, de Dear, R., Kalma, J., Oke, T., Auliciems, A. (eds.), Biometeorology and Urban Climatology at the Turn of the Millenium. *Selected Papers from the Conference ICB-ICUC'99 (Sydney, 8-12 Nov. 1999). WMO, Geneva, WCASP-***50**, 279-283.
Staiger, H., Bucher, K., Jendritzky, G. (1997): Gefühlte Temperatur. Die physiologisch gerechte Bewertung von Wärmebelastung und Kältestress beim Aufenthalt im Freien in der Maßzahl Grad Celsius. *Annalen der Meteorologie,* **33**, 100-107.
Steadman, R.G. (1984): A Universal Scale of Apparent Temperature. *J. Climate and Appl. Meteor.*, **23**, 1674-1687.
Steadman, R.G. (1994): Norms of apparent temperature in Australia. *Aust. Met. Mag.*, **43**, 1-16.
Stolwijk, J.A.J. (1971): A mathematical model of physiological temperature regulation in man. *NASA contractor report, NASA CR-1855*, Washington DC.
Tanabe S.I., Kobayashi K., Nakano J., Ozeki Y., Konishi M. (2002) Evaluation of thermal comfort using combined multi-node thermoregulation (65MN) and radiation models and computaional fluid dynamics (CFD). *Energy and Buildings*, **34**, 637-646.
VDI (1994): Guideline VDI 3789, Part 2, Environmental Meteorology. Interactions between Atmosphere and Surfaces. Calculation of Short-wave and Long-wave Radiation. *VDI-Handbuch Reinhaltung der Luft*, Bd. 1.
Wissler E.H. (1985): Mathematical simulation of human thermal behaviour using whole body models. In: Shitzer A. and Eberhart R.C. (ed) Heat transfer in medicine and biology - analysis and applications, Plenum Press, New York and London, 325-373.