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Developing a Software to Predict Thermal Comfort of Humans at Work

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Abstract

The goal of this research work is to develop a user-friendly software that is capable of estimating the thermal comfort of a human working in the open air. Several numerical approaches were considered in the literature. The computational time and the complexity of those computational methods make it usable by professionals only. The developed computer software under this work can be used by low ranking field managers, who may not be computer experts, operating in the field where the workers are performing their duties. An important parameter crucial for the calculation of the energy transfer around the human is the mean radiant temperature, MRT. A method has been developed here to evaluate the MRT. It is suitable for indoor as well as outdoor applications. Weather and solar data are expected to be available for the outdoor applications. It can either be actively measured at the actual site under consideration, or calculated from the available data documented for numerous sites around the world.

Keywords: thermal comfort; human comfort

1. Introduction

The goal of this research work is to develop a user-friendly software that is capable of estimating the thermal comfort of a human working in the open air. Several approaches were considered in the literature. They vary from very sophisticated codes that use well-known commercially available CFD codes (ANSYS[1] , FLUENT[2], PHEONIX[3]) that segment the human body into large number of segments each represent a independent source/sink of heat. The computational time and the complexity of the codes make it usable by professionals only. The goal of this work is to develop computer software that can be used by low ranking field managers, who may not be computer experts, operating in the field where the workers are performing their duties.

The approach followed here is similar to that recommended by ISO standard 7933[4] second edition 2004-8-15 entitled "Ergonomics of the thermal environment — Analytical determination and interpretation of heat stress using calculation of the predicted heat strain." An important parameter crucial for the calculation of the energy transfer around the human is the mean radiant temperature, MRT. The methods recommended by ASHRAE or ISO Standards to determine the MRT are not suitable for the applications under consideration. The reason is that this method is designed to calculate thermal comfort indices in black enclosures where there is no direct solar radiation; the case under consideration.

A method (called thereafter as "Modified ASHRAE method") has been developed here to evaluate the MRT. It is suitable for indoor as well as outdoor applications. Weather and solar data are expected to be available for the outdoor applications. It can either be actively measured at the actual site under consideration, or calculated from the available data documented for numerous sites around the world.

The clothing insulation properties of the subject under consideration must be supplied as input data. Thermal insulation properties for normal clothing are available from literature ([5-9]).

The computer program developed under this work is capable of handling the following scenarios:

a. Operator defines all environmental conditions in the vicinity of the subject:

This scenario is applied when the operator wishes to know how a human, wearing specified clothes and doing specified work, feels thermally if subjected to any practical, field type conditions. Air temperature, air velocity, humidity, solar radiation, space dimensions, geographical data, and radiative properties must be well defined within the vicinity of the worker.

b. Operator defines the subject's geographical location; country and city name:

The program reads weather and geographical information on over a thousand cities worldwide from data available on the web (data has been compiled and linked to the program.) The compiled data includes all of the above-mentioned parameters. This scenario is applied only for outdoor operating conditions. Certainty the computed

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results depend largely on the accuracy of the available weather data.

c. Operator defines the subject's geographical location through latitude and longitude:

Empirical correlations are used to estimate the solar radiation ([10-11]). The mean radiant temperature is then calculated. Compilation of those correlations is provided through this work. The correlations cover Jordan, however it can be extended to cover most regions of the world. Information on these correlations' uncertainty is not available yet. A subroutine has been written to accommodate this scenario. Extending the correlations to cover most regions of the world in the third scenario is a future extension for this research work.

2. Factors Effecting Thermal Comfort

Aims of comfort research are to find the factors for an individual or group that make them feel comfortable. Six major variables determine how warm or cold (i.e., how comfortable) a person feels[12]. Four of them classified as environmental; Air temperature, Air speed, Humidity, and Mean radiant temperature, and two are classified as personal; Activity, and Clothing insulation. Other factors that could be of importance in some cases are the individual differences, and recent thermal history.

3. Thermal Comfort Models

3.1. ASHRAE STANDARD 55 – 2004[13]

In this standard, thermal comfort is defined as the condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation. The standard presents a method for predicting the thermal sensation and the degree of discomfort (thermal dissatisfaction) of healthy people exposed to moderate thermal environments. It also specifies acceptable environmental conditions for comfort of adults at atmospheric pressures equivalent to altitudes up to 3000 m. It applies to indoor environments where the aim is to attain thermal comfort or indoor environments where moderate deviations from comfort occur.

The standard determines an index that **p**redicts the **m**ean **v**alue of the votes (**PMV**) of a large group of people on a 7-point thermal sensation scale;

	3	Hot
	2	Slightly Warm
	1	Warm
PMV =	0	Neural
	-1	Slightly Cool
	-2	Cool
	-3	Cold

and the PPD (predicted percentage of dissatisfied). The PMV/PPD model takes into account the main factors related to the steady-state thermal balance of the body;

- Environmental parameters:
  - Air temperature,
  - Mean radiant temperature,
  - Air velocity (< 0.2 m/s).
  - Partial water vapor pressure (< 1.910 kPa).
- Activity level, affecting metabolic rate (1.0 met < metabolic rate < 2.0).
- Clothing level, affecting thermal resistance (<1.5 clo).

Equation for PMV: The heat balance equation can be written as follows;

$$(M\text{-}W) = 3.96\times10^{-8} f_{cl} [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} h_c (t_{cl}-t_a) + 3.05 [5.73 - 0.007 (M\text{-}W) - p_a] + 0.42 [(M\text{-}W) - 58.1] + 0.0173 M (5.87 - p_a) + 0.0014 M (34 - t_a) + L \quad (1)$$

Where:

$$t_{cl} = 35.7 - 0.0275(M\text{-}W) - I_{cl} \{(M\text{-}W) - 3.05 [5.73 - 0.007 (M\text{-}W) - p_a] - 0.42 [(M\text{-}W) - 58.1] - 0.0173 M (5.87 - p_a) - 0.0014 M (34 - t_a)\} \quad (2)$$

and L equals the imbalance between heat generated and heat dissipated. The values of hc and fcl can be estimated from tables and equations given in the Engineering Data and Measurements section, Table 6, Chapter 8 ASHREA Fundamental Vol., 2001.

$$h_c = \begin{cases} 2.38(t_{cl}-t_a)^{0.25} & \text{for } 2.38(t_{cl}-t_a)^{0.25} > 1.21\sqrt{v_a} \\ 12.1\sqrt{v_a} & \text{for } 2.38(t_{cl}-t_a)^{0.25} < 1.21\sqrt{v_a} \end{cases}$$

$$f_{cl} = \begin{cases} 1.00+2.0\, I_{cl} & I_{cl} < 0.5 clo \\ 1.05+0.1\, I_{cl} & I_{cl} > 0.5 clo \end{cases} \quad (3)$$

The PMV empirical equation is expressed as follows;

$$PMV = [0.303\, e^{(-0.036M)} + 0.028]\, L \quad (4)$$

Where L is the imbalance between net heat generated within the body and the actual heat transferred to the environment;

$$L = (M\text{-}W) - \{3.96\times10^{-8} f_{cl} [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} h_c (t_{cl}-t_a) + 3.05 [5.73 - 0.007 (M\text{-}W) - p_a] + 0.42 [(M\text{-}W) - 58.1] + 0.0173 M (5.87 - p_a) + 0.0014 M (34 - t_a)\} \quad (5)$$

Substituting for (M-W) in the tcl equation to get

$$t_{cl} = 35.7 - 0.0275(M\text{-}W) - I_{cl} \{39.6\times10^{-9} f_{cl} [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} h_c (t_{cl}-t_a)\} \quad (6)$$

tcl should be found by iterative methods.

PMV	is the Predicted Mean Vote.
M	is the metabolic rate, in W/m^2 of body surface area.
W	is the external work, in W/m^2, equal to zero for most activities.
I_{cl}	is the thermal resistance of clothing, in (m K / W.)
f_{cl}	is the ratio of a person's surface area while clothed, to the surface area while nude.
v_a	the average wind velocity
t_a	is the air temperature, in ^oC.
t_r	is the mean radiant temperature, in ^oC.
p_a	is the partial water vapor pressure, in Pa.
h_c	is the convective heat transfer coefficient, in W/m^2K.
t_{cl}	is the surface temperature of clothing, in ^oC.

PMV is derived for steady state conditions but can be applied during minor fluctuations of one or more variables (time-weighted averages during previous 1- hour period should be used). It is calculated for conditions when the human body is in thermal equilibrium. PMV index should only be used for PMV between -2 and 2 and it is recommended for use only for the following range of conditions

M = 58 to 116 W/m^2 (1.0 to 2 met)
I_{cl} = 0 to 0.310 m^2k/W (0 to 2 clo)
t_a = 10 to 30 ^oC; tr = 10 to 40 ^oC
v_a = 0 to 0.2 m/s (or less if draughts are important)
p_a = 0 to 1910 Pa. (also relative humidity should be between 30 and 60%)

3.2. Predicted percentage dissatisfied:

PPD is a measure of the number of people likely to feel uncomfortably warm or cool in a given environment, i.e., the number of people voting -3, -2, +2 or +3 within the PMV scale.

$$PPD = 100 - 95.0\ exp\ [-(0.03353\ PMV^4 + 0.2179\ PMV^2)] \quad (7)$$

The PPD index predicts the number of thermally dissatisfied people within a large group. The rest of the group would vote -1, 0 or +1 on the PMV scale. The minimum PPD is 5%.

3.3. The MEMI model[14-15]:

The predicted mean vote, PMV, model explained earlier is a steady-state theoretical model that is widely recognized and used worldwide. It can only applies to humans exposed for a long period to constant conditions at a constant metabolic rate. The major limitation of the PMV model is the explicit constraint of skin temperature and evaporative heat loss to values for comfort and "neutral" sensation at a given activity level. The PMV model has a physical and also thermophysiological background and considers all relevant meteorological parameters. However it can only be used to determine a comfort index. It cannot be used to quantify real values of heat fluxes or body temperatures for a given environment. The MEMI (Munich Energy Balance Model for Individuals) takes care of this issue by introducing an assumption that the sensible heat lost from the skin is equal to the heat carried by the blood flow from the core to the skin. MEMI uses the following heat balance equation:

$$H + C + R + E_D + E_{sr} + E_{lr} + E_{sw} + E_f = S \quad (8)$$

H	=	Heat production;
C	=	Covective heat flux;
R	=	Radiative heat flux
ED	=	Water vapor diffusion
Esr	=	Sensible heat loss by respiration
Elr	=	Latent heat lost by respiration
Esw	=	Heat lost by sweat evaporation
Ef	=	Heat added or lost from food or drink
S	=	Net heat stored in the core.

The output of this method is: S, the net heat stored in the body, tc, the core temperature and tsk, the skin temperature. The details of this method can be found in [14-15].

3.4. The 2- Node model (ET- DISC)*

The 2-Node theoretical Model also uses a heat balance method to predict thermal comfort, but the model is transient with time rather than being steady state like PMV. ET* stands for New Effective Temperature where "effective temperature" is an temperature index that accounts for radiative and latent heat transfers. ET* can be calculated using the '2-Node' model. The 2-node model determines the heat flow between the environment, skin and core body areas on a minute-by-minute basis. Starting from an initial condition at time=0, the model iterates until equilibrium has been reached (60 minutes is a typical time). The final mean skin temperature and skin wettedness are then associated with an effective temperature. DISC predicts thermal discomfort using skin temperature and skin wettedness. Details of this method can be found in [16].

3.5. PD model[16]

PD or "predicted percent dissatisfied due to unwanted local cooling (draft)," is a empirical model. It is a fit to data of persons expressing thermal discomfort due to drafts. The inputs to PD are air temperature, air velocity, and turbulence intensity.The **PD** equation is:

$$PD = 3.413\ (34 - T_a)\ (v - 0.05)^{0.622} + 0.369\ v\ T_u\ (34 - T_a)(v - 0.05)^{0.622} \quad (8)$$

$\mathbf{T_u}$ is the turbulence intensity expressed as a percent. **0** represents laminar flow and **100** means that the standard deviation of the air velocity over a certain period is of the same order of magnitude as the mean air velocity. **v** is the air velocity (m/s) and $\mathbf{T_a}$ is the air temperature in ^oC.

The **PD** equation arises from two studies in which 100 people were exposed to various combinations of air temperature, air velocity, and turbulence intensity. For each combination of conditions, the people were asked if they felt a draft. **PD** represents the percent of subjects who voted that they felt a draft for the selected conditions.

3.6. PS model [16]

PS is a fit to data of comfortable persons choosing air velocity levels. The PS equation predicts the air velocity that will be chosen by a person exposed to a certain air temperature when the person has control of the air velocity source. The PS equation is

$$PS = 1.13\ (T_{op})^{0.5} - 0.24\ T_{op} + 2.7\ (v)^{0.5} - 0.99\ v \quad (9)$$

$\mathbf{T_{op}}$ is operative temperature (in degrees Celsius) and **v** is the air velocity in m/s. The **PS** equation arises from a study in which **50** people were asked to adjust an air velocity source as they pleased when exposed to a specific air temperature. **PS** represents the cumulative percent of people choosing a particular air velocity at the specific temperatures tested in this experiment.

3.7. TS model [16]

The TS model is a fit to data of thermal sensation as a linear function of air temperature and partial vapor pressure. TS is an equation that predicts thermal sensation vote using a linear function of air temperature Ta, and partial vapor pressure p, in kPa. The TS equation is:

$$TS = 0.245T_a + 0.248p - 6.475 \quad (10)$$

4. Input Data

4.1. Surface Area of Body

Du Bois area [17]: The surface area of skin of an "average" adult is 1.8 m^2. The total heat production of an "average" person at rest per hour is 58.2 x 1.8 = 104.76 = 105 watts.

The Du Bois area normally varies between 1.3 m^2 and 2.2 m^2 and in any setting the heat produced by sedentary adults will vary between about 75.66 watts for 1.3 m^2 and 128 watts for 2.2 m^2.

4.2. Activity Level in Mets

The level of activity of the person must be determined to calculate his thermal comfort level. ASHRAE standards 55-2004 list various activities with the metabolic rate expected from a healthy body. Table 1 is an extract from AHRAE standards 55.

Table 1: Metabolic Rates for Typical Tasks.*

Activity	Metabolic rate in mets
Reclining	0.8
Seated, quietly	**1.0**
Sedentary activity (office, dwelling, lab, school)	1.2
Standing, relaxed	1.2
Light activity, standing (shopping, lab, light industry)	1.6
Medium activity, standing (shop assistant, domestic work, machine work)	2.0
High activity (heavy machine work, garage work)	3.0

*See ASHREA for more data

4.3. Clothing:

Detailed data on the clothing of the person under consideration must be available. ASHRAE standards 55-2004 list clothing insulation data for typical ensembles as well as specific garments. Insulation values for special ensembles made of combination of garments can be calculated by adding insulation values of the individual garments. Below is useful data for clothing insulation;

- Clothing insulation is measured in clo units (Icl)
- 1 clo = 0.155 m^2 °C/ W
- Lowest clo value is 0 (naked body)
- Highest practical clo value = 4 clo (Eskimo clothing, fur pants, coat, hood, gloves etc.)
- Summer clothing ~ 0.6 clo
- Winter clothing ~ 1 clo
- Icl ~ 0.15 x weight of clothes in lbs.
- 10 lbs of clothing ~ 1.5 clo
- 1 clo maintains sedentary man (1 met) indefinitely comfortable at 21°C, 50% RH, 0.01 m/sec air speed.
- Wind speed affects clothing insulation
- Porosity - water vapor transfer through clothing affects its insulation value
- Permeation efficiency factor (Fpcl) ranges from 0 = completely impermeable fabric 1 = absence of clothing
- Thickness - effects insulation value
- Tog - European unit of thermal insulation 1 tog = 0.645 clo
- Tested insulation values for 7 chairs ranged between 0.1 – 0.3 clo for chairs with solid seats and backs.

4.4. Thermal Conditions:

Atmospheric influences on the thermal sensations of a person depend on four thermal environmental variables listed below.

- Air temperature (t_a): is the average temperature of the air surrounding the body. The average is with respect to location and time.
- Mean radiant temperature (MRT): is the average temperature of the surfaces in a space. Mean radiant temperature may be higher or lower than the air temperature in a space. Mean Radiant Temperature (t_r) is the uniform temperature of the surface of an imaginary black enclosure where the radiant exchange of heat between this enclosure and a man would be equal to the radiant exchanges in the actual environment.
- Air speed v_a: Is the average speed of the air to which the body is exposed. The average is with respect to location and time.
- Humidity: Humidity refers the mass of water vapor present in a unit volume of air (moisture content). It may be expressed in terms of several thermodynamic variables, including vapor pressure, dew point temperature, humidity ratio, and relative humidity.

4.5. Solar and Site Geographical Data:

Site data including altitude, elevation, absorptivity or albedo, slope azimuth, solar azimuth, slope angle, zenith angle, declination angle, hour angle, date and time of the day are all necessary to calculate the ground temperature needed for calculating the mean radiant temperature [18-23].

5. Calculation of Mean Radiant Temperature

5.1. ASHRAE Standard for Calculation of MRT (t_r):

The classical method to calculate t_r uses the values of the surrounding surface (i.e. wall, window, sofa) temperatures (ASHRAE, 2001). Each temperature is weighted according to its position relative to the person. The method assumes the surface materials have a high enough emittance, ε, to be considered radiatively black or ideal. This assumption is reasonably valid for most enclosures, but its effect should be considered when analyzing the results. If the surfaces of the analyzed enclosure do not have a high emittance, then the results are not reliable. This assumption imposes a critical limitation on this method. In addition, this method does not take into account low-E glass or other types of advanced glazing systems. The published emissivity of low-E glass is less than 0.1 in the infrared wavelength range. Since the glass is opaque in that range, the rest of the radiant energy is reflected back into the room. The classical t_r method does not have the capability to handle this situation. Another case where the ASHRAE method would fail is solar radiation, which is short-wavelength radiation, shining through a window. This method fails to consider any window transmission and only considers the wall surface temperatures as boundary conditions.

Each of the surfaces is considered to be isothermal or has a uniform temperature, t_i. If this assumption is not valid for a single large surface, the surface is sub-divided until the assumption is valid. The view factors, F_{p-i} between the point P to be analyzed and all the surfaces i are calculated by some method. The t_r is then calculated as (ASHRAE, 2001).

$$t_r^4 = t_1^4 F_{p-1} + t_2^4 F_{p-1} p\text{-}2 + t_i^4 F_{p-i} + \ldots + t_n^4 F_{p-n} \quad (11)$$

The temperatures for the calculation are in Kelvin and the view factors are dimensionless. For rectangular surfaces, ASHRAE (2001) provide view factor charts for the human body. View factors for standard geometric shapes can be found in a standard heat transfer text such as Incropera and DeWitt (1990) [24] or Siegel and Howell (1981) [25].

5.2. Radiant Intensity Method [26-27]:

The second method uses the fundamental t_r definition to calculate t_r in terms of the radiant intensity balance at a particular point in the room. This definition states that t_r is the uniform surface temperature of an imaginary black enclosure in which the radiation from the occupant equals the radiant heat transfer in the actual non-uniform enclosure. In a room where all the surfaces and the air are at the same temperature, the mean t_r and the air temperature are equal. As the difference between the surface temperatures and the air temperature increases, the difference between the t_r and the air temperature increases. This approach determines the radiant intensity field within the room and then uses that intensity field to calculate the actual radiant heat transfer from the occupant. The two primary advantages of this method are that: (1) determination of the view factors is unnecessary; and (2) the intensity field includes the effect of wall surface properties and any other intensity boundary condition, such as solar insolation.

The basic formulation begins with writing the definition of the t_r in terms of mathematical quantities;

$$Q_{p,b}(t_r) = Q_{p,act} \quad (12)$$

In this equation, the term Qp,b represents the radiant heat transfer from the occupant in a room with radiatively black walls and a uniform surface temperature. According to this definition, this term is determined by

$$Q_{p,b} = A_{eff}\,\sigma\, t_r^4 \quad (13)$$

The effective area is calculated by (ASHRAE, 1996)

$$A_{eff} = f_{eff} A_D \quad (14)$$

The effective radiation area of a person, f_{eff} equals 0.73 for a standing person (ASHRAE, 1996) and the DuBois area, A_D is estimated from a person's height and mass. For an average person, A_D equals 1.821 m^2.
The term on the right side of Equation (6.2) represents the actual radiation heat transfer experienced by an occupant. This term is directly related to the intensity field by

$$Q_{p,act} = \int I_\lambda(\Omega)\, A_p(\Omega)\; d\Omega \quad (15)$$

This equation is an integral over all the directions represented by the solid angle Ω [28]. The intensity and projected area in the direction Ω are represented by $I_\lambda(\Omega)$ and $A_p(\Omega)$, respectively.

Figure 2 shows a sample two-dimensional intensity distribution for a point. At this point in the development, some method must be employed to determine the intensity field. The development is discussed next.

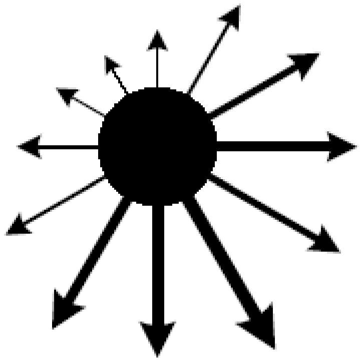

Figure 1: Sample two-dimensional radiant intensity field.

The net radiation at a particular point in the room as represented by the intensity arrows in Figure 1 is calculated using an approximation of the continuous form around the point [Equation (15) above]. This approximation was first employed in the early 1960's as a technique to determine neutron transport. Since then, the approximation has been extensively validated and used in radiation heat transfer studies. The approximation is given by

$$\dot{Q}_p = I^j A^j w^j \quad (16)$$

where, the variable I^j is the intensity coming from a given discrete direction j, w^j is the quadrature weighting function for that direction, and A_p^j is the projected area in the given direction. The projected area from direction j is provided in the *HVAC Systems and Equipment Handbook* (ASHRAE, 1996). The general equation for the projected area is

$$A_p^j = f_p^j f_{eff} A_D \quad (17)$$

where f_p^j is the projected area factor in direction j. Factor charts for sitting and standing people are given by Fanger (1967) [28] and ASHRAE (1996).

Combining Equations (12) through (17) results in the final form of a very generalized method for determining t_r.

$$t_r \cong \left[\frac{\sum I^j A_p{}^j w^j}{f_{eff} A_D \sigma}\right]^{0.25} \quad (18)$$

This equation provides a more generalized approach to calculate t_r than using the surrounding surface temperatures given in the classical method. This approach, using the localized radiant intensity field, was extensively validated lately since it accurately incorporates the various emissivities and non-uniform surface temperatures of the surrounding environment. When enough information about I^j is available, Equation 18 can be executed and an approximate value of t_r is calculated.

5.3. Modified ASHRAE method:

To calculate t_r, the relevant properties and dimensions of the radiating surfaces and the sky view factor as well as the posture of the human body (e.g. seated or standing) must be known. The entire surroundings of the human body are divided into n thermal surfaces with the temperatures t_i (i = 1, n) and emission coefficients ε_i, to which the solid angle proportions ("angle factors") F_i are to be allocated as weighting factors. Long-wave radiation [$E_i = \varepsilon_i * \sigma * t_{Si}^4$, with σ the Stefan-Boltzmann constant (=5.67 * 10^{-8} W/m^{2}K^4) and t_{Si} the temperature of the ith surface,] diffuse short-wave radiation D_i are emitted from each of the n surfaces of the surroundings. This results in a value for t_r (K) as:

$$t_r = \left[\frac{1}{\sigma} \sum_{i=1}^{n} \left(E_i + a_k \frac{D_i}{\varepsilon_p} \right) F_i \right]^{0.25} \qquad (19)$$

ε_p is the emission coefficient of the human body (standard value 0.97.) D_i is the total of diffuse solar radiation and diffusely reflected global radiation. a_k is the absorption coefficient of the irradiated body surface for short-wave radiation (standard value 0.7.) The mean radiant temperature, t_r is replaced by t_r^*, if there is also direct solar radiation:

$$t_r^* = \left[t_r^4 + f_p a_k \frac{I}{\sigma \varepsilon_p} \right]^{0.25} \qquad (20)$$

I is the radiation intensity of the sun on a surface perpendicular to the incident radiation direction. The surface projection factor f_p is a function of the incident radiation direction and the body posture. For practical application in human-biometeorology, it is generally sufficient to determine f_p for a rotationally symmetric person standing up or walking. f_p ranges from 0.308 for 0° of the angle of the solar altitude and 0.082 for 90°.

Therefore;

$$t_r^* = \left[\left(\frac{1}{\sigma} \sum_{i=1}^{n} \left(E_i + 0.722 D_i \right) F \right) + 0.722 f_p \frac{I}{\sigma} \right]^{0.25} \qquad (21)$$

The problems associated with determining the angle factors F_i are discussed in detail in ASHRAE Fundamentals 2001. In the case of large flat surfaces without any restrictions of the horizon, the problem of determining F_i is reduced to an upper and a lower hemisphere with angle factors of 0.5 for both situations.

For cases where the object is in the outdoor conditions, solar irradiation can be calculated if solar data is available for outdoor conditions for that location. Solar data is available on the web or can be purchased and stored for faster recall. Note that the equation for calculating mean radiant temperature would then be;

$$t_r^* = \left[\frac{\sigma \varepsilon_g F_g t_g^4}{\sigma} + \frac{0.722 * F_{uh} D_{uh}}{\sigma} + 0.722 f_p \frac{I}{\sigma} \right]^{0.25} \qquad (22)$$

Where the subscript uh and g stand for upper hemisphere and ground respectively, $F_g = F_{uh} = 0.5$.

Therefore;

$$t_r^* = 100 \left[0.45 * 10^{-8} t_g^4 + 0.06 D + 0.127 f_p I \right]^{0.25} \qquad (23)$$

Where the first term between square brackets accounts for the long wave radiation from the ground, the second term accounts for the short wave diffuse radiation from the sky on a horizontal surface, and the third term accounts for the short wave direct beam radiation on a surface normal to the beam direction. The diffuse irradiation intensity D is different than (D_i,) and I is the beam solar radiation in that outdoor location, $\varepsilon_g \cong 0.9$ is the emissivity of the ground and t_g is the temperature of the ground. The ground temperature is calculated using the procedure described in [29].

6. Conclusion and Recommendations

A computer code is developed to estimate the thermal comfort indices PMV/PPD for a human carrying some well-defined activity and wearing well-defined clothes and exposed to well-defined environmental conditions. A method recommended by ASHRAE and modified by the author is used to calculate the comfort indices and in the construction of the computer code. The method is simple and it is based on a steady state analysis. The modification included the effect of solar direct and diffused radiation and the radiation reflected and emitted from the ground surrounding the worker on the mean radiant temperature. It also included the effect on the mean radiant temperature of any radiating surfaces close to the subject. More data is needed regarding environmental conditions and insulation properties of special operations clothing.

Future work may include transient conditions whereby the code should deal with the worker intervention in a harsh environmental condition gradually. That is to say, a worker can be connected to a computer by remote device that sends information about the conditions in his immediate vicinity. The computer code will then calculates the expected comfort indices and warn the worker ahead of time before reaching the critical limit of comfort.

7. Acknowledgment

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Appendices

A. The Computer Code:

The computer program handles the following scenarios:

- The operator defines all environmental conditions. This scenario is applied when the operator wishes to know how a human, wearing specific clothes and doing specific work, feels thermally if subjected to any practical, field type conditions. Air temperature, air velocity, humidity, solar radiation, and space dimensions and radiative properties must be well defined. This scenario applies for both indoor and outdoor conditions.
- The location is determined through country and city name. The program reads weather and geographical

information from data incorporated within the code. Data includes all of the above-mentioned parameters. This scenario is applied only for outdoor operating conditions. Accuracy of computed results depends largely on the uncertainty of the weather data available.

- The location is determined through elevation, longitude and latitude. Empirical correlation to estimate the solar radiation is used. The mean radiant temperature is then calculated. A subroutine is written to accommodate such needs, however the available correlations cover the city of Amman, Jordan. This of course can be extended to cover other regions of the world as needed.

The work done by many Jordanian researchers provides a useful resource of modeling of the solar energy data in Jordan. The empirical correlations reported by A. Al-Salaymeh [11] are considered here to feed the necessary information to the computer code. The global solar radiation G(kW.hr/m^2day) for Amman, Jordan is expressed using the following 4^{th} order polynomial correlation

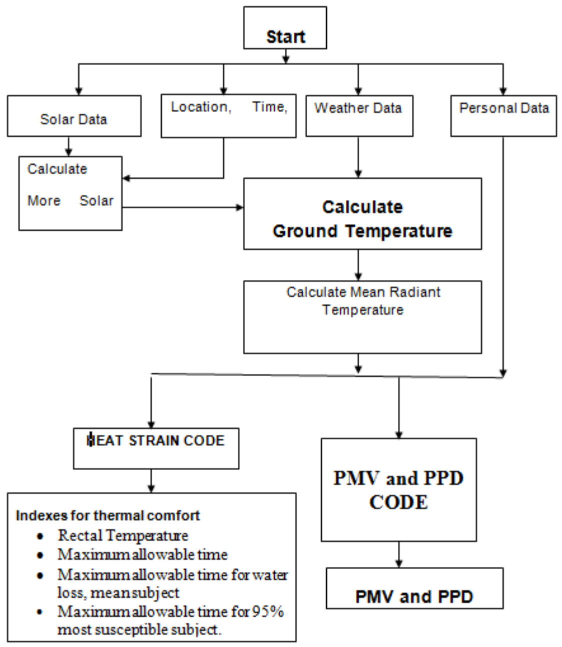
$$G = 2706.8 - 15.5\,x + 0.84\,x^2 - 0.000431x^3 + 5.9*10\text{-}6\,x^4 \qquad (24)$$

Where x is the day number in the year.

This correlation is used because its regression coefficient is high (=0.96) which means excellent fit for the measured data of the global solar radiation of Amman-Jordan.

B. The Code Flowchart

The flow chart explaining the code calculation steps is shown below. The boxes shown on the flow chart are detailed in Appendix c. The code is written in Visual Basic and is very much user friendly. Examples on code execution results are also shown in Appendix D.



Flow chart showing the general procedure in estimating the thermal comfort indexes.

C. Data boxex

Location, time, and date BOX

- Country (optional)
- **City (optional)**
- Latitude: Φ = -90° → +90°
- Longitude L = -180→+180
- Altitude; z = - 400m→5000m
- Date; m-d-y
- Time: 24 hr base
- Slope angle φ = 0→ 90°
- Slope azimuth angle Ω_{sl} = 0→360

Weather Data BOX

Air temperature t_a = -15→ 55°C
Air pressure P_a = 99 kPa→102 kPa
Vapor pressure P_v= 0.1 kPa →15.68 kPa
Humidity ratio H_u = 30%→100%
Wind velocity v = 0 → 0.3
Bowen ratio δ = 0.1→ 12
Thermal conductivity of substrate k= 0.25→ 2.7
Ground surface emissivity ε_g = 0.8→ 0.9

Solar Data BOX

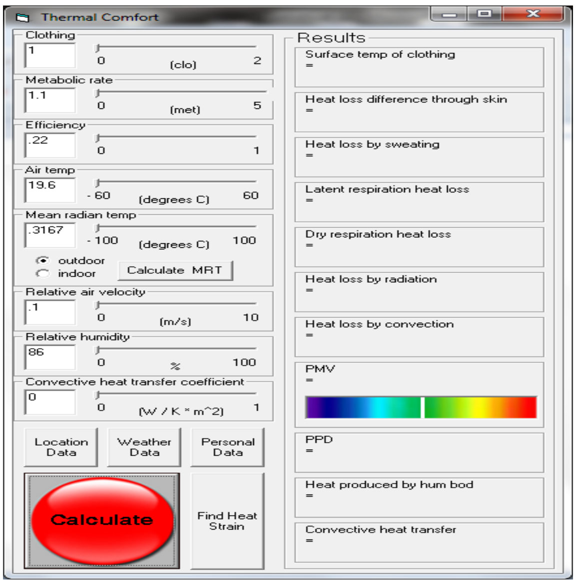
INPUT:
Solar radiation at top of atmosphere I_{et} = 1370 W/m^2
Stefan Boltzmann constant, σ=5.67 * 10^{-8} W/m^2/K^2
Solar radiation at horizontal surfaces, I_o = 200 → 1000 W/m^2

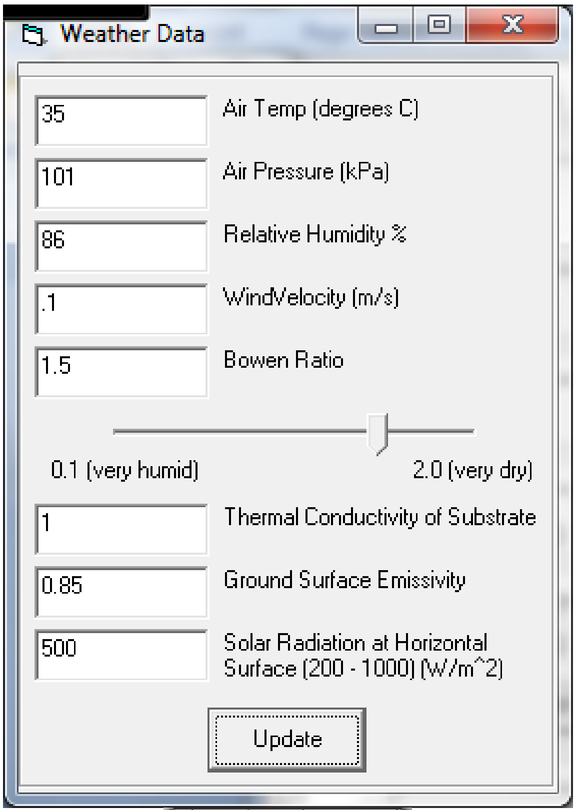
Subject Personal Data Box

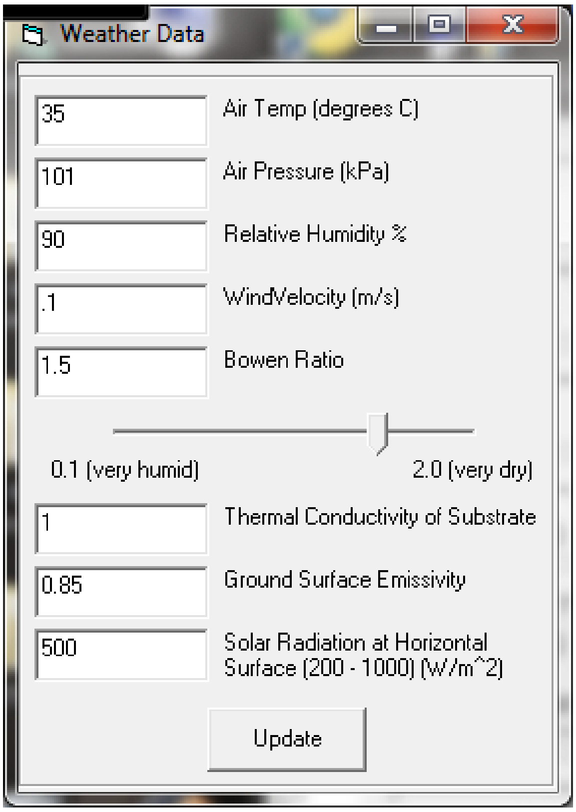
Height, Weight

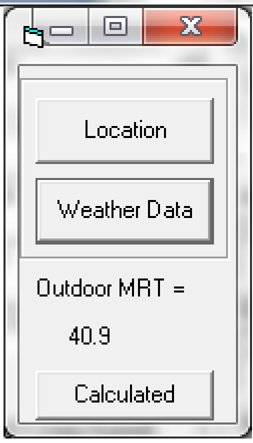
Kind of clothing he is wearing
% of his body surface not covered
Type of activity and metabolic rate
Motion velocity
Posture

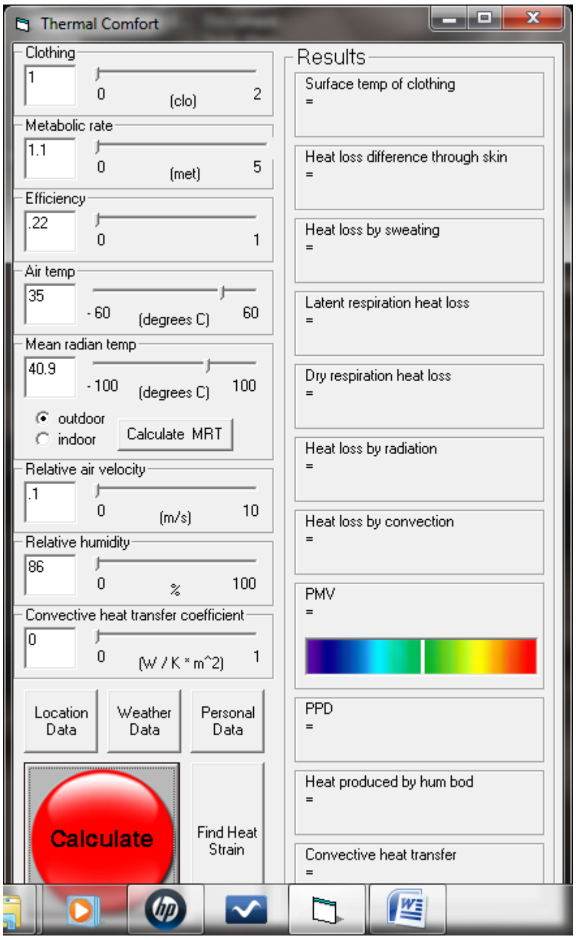
D. Results from actual Runs of the code.

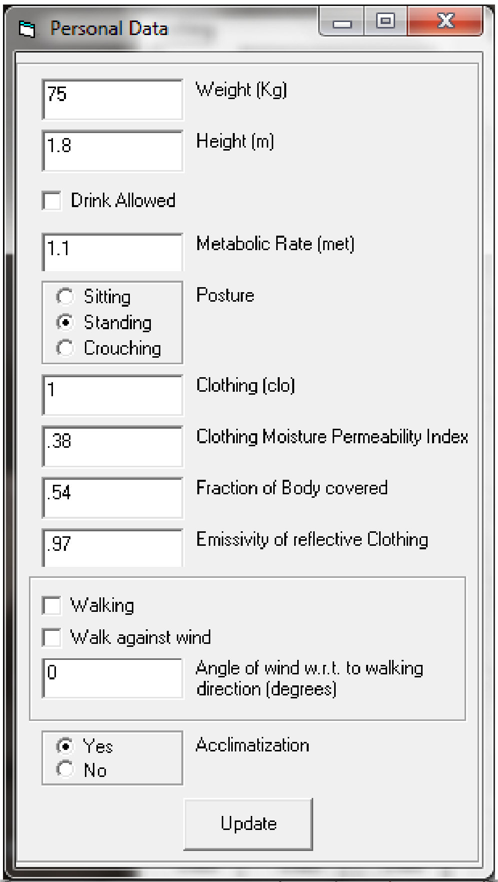


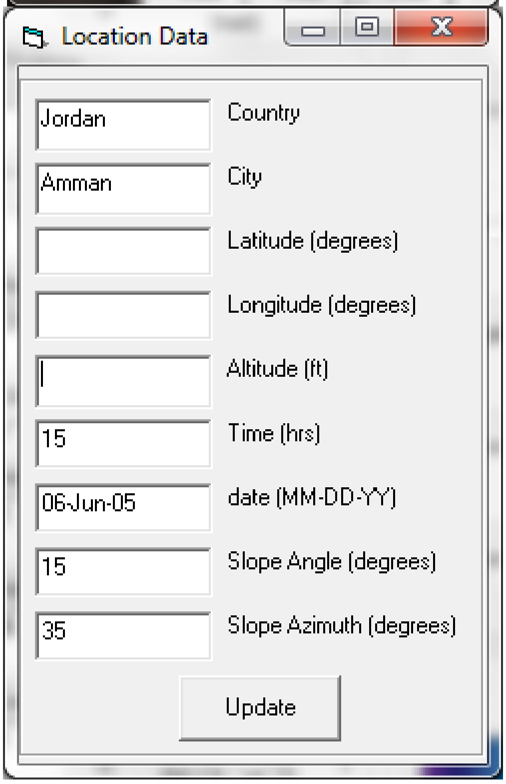

Weather Data
35
Air Temp (degrees C)
101
Air Pressure (kPa)
86
Relative Humidity %
.1
WindVelocity (m/s)
1.5
Bowen Ratio
0.1 (very humid)
2.0 (very dry)
1
Thermal Conductivity of Substrate
0.85
Ground Surface Emissivity
500
Solar Radiation at Horizontal Surface (200 - 1000) (W/m^2)
Update

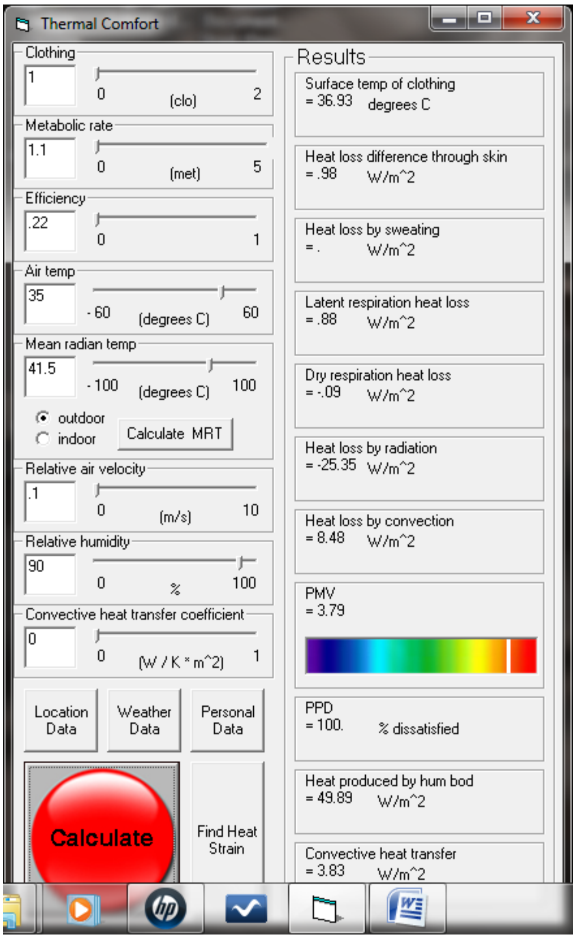

Weather Data
35
Air Temp (degrees C)
101
Air Pressure (kPa)
90
Relative Humidity %
.1
WindVelocity (m/s)
1.5
Bowen Ratio
0.1 (very humid)
2.0 (very dry)
1
Thermal Conductivity of Substrate
0.85
Ground Surface Emissivity
500
Solar Radiation at Horizontal Surface (200 - 1000) (W/m^2)
Update


Location
Weather Data
Outdoor MRT =
40.9
Calculated


Thermal Comfort
Clothing
1
0
(clo)
2
Metabolic rate
1.1
0
(met)
5
Efficiency
.22
0
1
Air temp
35
- 60
(degrees C)
60
Mean radian temp
40.9
- 100
(degrees C)
100
outdoor
indoor
Calculate MRT
Relative air velocity
.1
0
(m/s)
10
Relative humidity
86
0
%
100
Convective heat transfer coefficient
0
0
(W / K * m^2)
1
Location Data
Weather Data
Personal Data
Calculate
Find Heat Strain
Results
Surface temp of clothing =
Heat loss difference through skin =
Heat loss by sweating =
Latent respiration heat loss =
Dry respiration heat loss =
Heat loss by radiation =
Heat loss by convection =
PMV =
PPD =
Heat produced by hum bod =
Convective heat transfer =


Personal Data
75
Weight (Kg)
1.8
Height (m)
Drink Allowed
1.1
Metabolic Rate (met)
Sitting
Standing
Crouching
Posture
1
Clothing (clo)
.38
Clothing Moisture Permeability Index
.54
Fraction of Body covered
.97
Emissivity of reflective Clothing
Walking
Walk against wind
0
Angle of wind w.r.t. to walking direction (degrees)
Yes
No
Acclimatization
Update


Location Data
Jordan
Country
Amman
City
Latitude (degrees)
Longitude (degrees)
Altitude (ft)
15
Time (hrs)
06-Jun-05
date (MM-DD-YY)
15
Slope Angle (degrees)
35
Slope Azimuth (degrees)
Update


Thermal Comfort
Clothing
1
0 (clo) 2
Metabolic rate
1.1
0 (met) 5
Efficiency
.22
0 1
Air temp
35
-60 (degrees C) 60
Mean radian temp
41.5
-100 (degrees C) 100
outdoor
indoor
Calculate MRT
Relative air velocity
.1
0 (m/s) 10
Relative humidity
90
0 % 100
Convective heat transfer coefficient
0
0 (W / K * m^2) 1
Location Data
Weather Data
Personal Data
Calculate
Find Heat Strain
Results
Surface temp of clothing
= 36.93 degrees C
Heat loss difference through skin
= .98 W/m^2
Heat loss by sweating
= . W/m^2
Latent respiration heat loss
= .88 W/m^2
Dry respiration heat loss
= -.09 W/m^2
Heat loss by radiation
= -25.35 W/m^2
Heat loss by convection
= 8.48 W/m^2
PMV
= 3.79
PPD
= 100. % dissatisfied
Heat produced by hum bod
= 49.89 W/m^2
Convective heat transfer
= 3.83 W/m^2