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<td>Citation</td>
<td>Energy and Buildings 37(3), p.287-294</td>
</tr>
<tr>
<td>Issue Date</td>
<td>2011-07</td>
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<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/10935/3237">http://hdl.handle.net/10935/3237</a></td>
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New index indicating the universal and separate effects on human comfort under outdoor and non-uniform thermal conditions

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Abstract

The purpose of this study is to propose new thermal index for outdoor and non-uniform environments with heat conduction, such as when a person sits on a bench at a park. This paper describes mathematically the theory of how solar radiation and heat conduction, as well as air temperature, humidity, air velocity and longwave radiation, are incorporated into the new index and how these thermal factors that may not be uniform are treated. Another important feature is that separate indices are generated for each factor while the new index is derived. It is expected that the new index will help us to understand how much each factor affects the human thermal comfort in outdoor and non-uniform environments with heat conduction.

Keywords

Human heat balance; Solar radiation; Heat conduction; Body segment; Universal effect; Separate effect

1. Introduction

Widely known indices such as PMV by Fanger [1] and SET* by Gagge et al. [2], based on human heat balance, consider air temperature, longwave radiation, humidity, air velocity, metabolic rate, and garment insulation. The two indices evaluate only the universal effect of these environmental factors on human thermal comfort. In contrast, HOTV proposed by Horikoshi et al. [3] and ETV proposed by Horikoshi et al. [4], which also consider the same six environmental factors, indicate not only the universal effect but also the separate effects of air movement, longwave radiation, and humidity as effective temperature differences independent of air temperature. These separations indicate how much each environmental factor affects the universal effect; therefore, it is helpful to understand which factors should be improved to make us feel thermally comfortable. Since then, new indices indicating both universal and separate effects, e.g., ETVO [5], ETF [6], and ETFe [7], have been proposed. ETVO is applicable to the outdoors with solar radiation, not to non-uniform conditions or situations involving sitting or lying on something with heat conduction. ETF is applicable to situations involving heat conduction, but not to non-uniform conditions or the
outdoors. ETFe is applicable to the outdoors and to situations involving heat conduction, but not to non-uniform conditions. Thus, there is as yet no index that can evaluate non-uniform thermal environments that include both solar radiation and heat conduction, such as when a person sits on a bench at a park. Such an index is the target of this study. That is, this paper describes mathematically the theory of a new thermal index that can take into account both solar radiation and heat conduction, can indicate the universal and separate effects simultaneously, and can be applied to non-uniform as well as uniform thermal environments.

The new index is derived to expand the index ETV on the basis of the heat balance equation between the human body and the thermal environment. First, the solar radiation is incorporated into ETV, and then the heat conduction is incorporated, and finally an adjustment to non-uniform environments is made.

2. Consideration of solar radiation

The index that incorporates solar radiation into ETV corresponds exactly to ETVO (Outdoor ETV) proposed by the present authors (Nagano and Horikoshi [5]). This section details the theory of how the ETVO is derived, although the acronym ETVS, which means “ETV including Shortwave radiation,” is used instead.

The convective heat loss from the human body to the surrounding environment \( C \) [W/m\(^2\)] can be expressed as follows:

\[
C = h_c F_{cl} f_{cl} (t_{sk} - t_a) = h_c F_{cle} (t_{sk} - t_a)
\]

(1)

where \( h_c \) [W/(m\(^2\)K)], \( F_{cl} \) [n.d.], \( f_{cl} \) [n.d.], \( t_{sk} \) [\(^\circ\)C], \( t_a \) [\(^\circ\)C], and \( F_{cle} \) (= \( F_{cl} f_{cl} \)) [n.d.] are the convective heat transfer coefficient, thermal efficiency factor of clothing, clothing area factor, mean skin temperature, air temperature, and effective clothing thermal efficiency, respectively.

ETVS refers to a velocity of 0.1 m/s (a convective heat transfer coefficient of 3.0 W/(m\(^2\)K) [8]) and a clothing insulation of 0 clo as a standard environment. Assuming that the convective heat loss in this standard environment corresponds to the heat loss \( C \) given by Eq. (1) while \( t_a \) equals a hypothetical air temperature \( t_v \) [\(^\circ\)C], the loss \( C \) can be expressed as follows:

\[
C = h_c F_{cle} (t_{sk} - t_a) = h_{co} F_{cleo} (t_{sk} - t_v)
\]

(2)

where \( h_{co} \) [W/(m\(^2\)K)] and \( F_{cleo} \) [n.d.] are the convective heat transfer coefficient in the standard environment (= 3.0 W/(m\(^2\)K)) and the effective clothing thermal efficiency in the standard environment, respectively.

Horikoshi et al. [3] defined the temperature \( t_v \) in this equation as the wind velocity temperature, which indicated the air temperature including the cooling effect of air movement. The temperature \( t_v \) is expressed from Eq. (2) as:
\[ t_v = t_a + \frac{TVF}{h_{co} F_{cleo}} \]  

\[ TVF = (h_{co} F_{cleo} - h_c F_{cle})(t_{sk} - t_a) = h_{co} F_{cleo} (t_v - t_a) \]  

TVF \([\text{W/m}^2]\) is a measure of the cooling power of the actual air velocity and is defined as the net convective heat energy exchanged on the body surface. This quantity is referred to as the thermal velocity field by Horikoshi et al. \([3]\).

The net heat loss by means of longwave radiation from the human body \(R_L\) \([\text{W/m}^2]\) can be expressed as follows:

\[ R_L = h_r F_{cle} (t_{sk} - t_r) \]  

where \(h_r\) \([\text{W/(m}^2\text{K})]\) and \(t_r\) \(\text{[}^\circ\text{C}]\) are the radiant heat transfer coefficient and mean radiant temperature, respectively. The coefficient \(h_r\) can be expressed as follows:

\[ h_r = \varepsilon \sigma f_{rd} (T_{cl}^4 - T_r^4) / (T_{cl} - T_r) \]  

where \(\varepsilon\) \(\text{[n.d.]}\), \(\sigma\) \([\text{W/(m}^2\text{K}^4]\), \(f_{rd}\) \(\text{[n.d.]}\), \(T_{cl}\) \([\text{K}]\), and \(T_r\) \([\text{K}]\) are the average emissivity of the clothed body, Stefan-Boltzmann constant, effective radiation area factor, mean temperature of the outer surface of the clothed body in Kelvin and mean radiant temperature in Kelvin, respectively.

Winslow et al. \([9]\) developed an operative temperature \(OT\) \(\text{[}^\circ\text{C}]\), and Gagge et al. \([10]\) derived an effective radiant field \(ERF\) \([\text{W/m}^2]\) from the definition of the operative temperature to separate the effect of thermal radiation. The ERF is defined as the net radiant heat flux exchanged between the human body surface and the surrounding surfaces at temperatures other than the air temperature \(t_r \neq t_a\). It is noted that this ERF consists of the longwave component of radiation; therefore, \(ERF\) \([\text{W/m}^2]\) as an effective longwave radiant field is used in the following equations:

\[ C + R_L = h_c F_{cle} (t_{sk} - t_a) + h_r F_{cle} (t_{sk} - t_r) = h' (t_{sk} - OT) \]  

\[ OT = \frac{F_{cle} (h_c t_a + h_r t_r)}{h'} = t_a + \frac{ERFL}{h'} \]  

\[ ERFL = h_r F_{cle} (t_r - t_a) \]  

\[ h' = (h_c + h_r) F_{cle} = h F_{cle} \]  

The heat loss by convection and longwave radiation, \(C + R_L\) as given in Eq. (7), can be rewritten using Eq. (2) and Eq. (5) as follows:

\[ C + R_L = h_{co} F_{cleo} (t_{sk} - t_v) + h_r F_{cleo} (t_{sk} - t_r) = h_v (t_{sk} - OTV) \]  

\[ OTV = h_{co} F_{cleo} t_v + h_r F_{cleo} t_r \]  

\[ h_v = h_{co} F_{cleo} + h_r F_{cleo} \]  

OTV is the modified operative temperature and can be written in the following equation using TVF and \(ERF\).
Horikoshi et al. [3] that adds to the solar effect, saturated water vapor pressure at
humidity without altering the total heat loss from
Fobelets and Gagge [11]
i actual clothing effect
and water vapor pressure at

Thus, OTV can be expressed as the summation of air temperature and the effects of air movement and longwave radiation.

The sensible heat loss outdoors can be expressed by subtracting the net heat gain due to shortwave radiation to the body, \( R_S \) [W/m\(^2\)], from the heat loss given in Eq. (11):

\[
C + R_L - R_S = h_v (t_{sk} - OTV) - R_S = h_v (t_{sk} - OTVS)
\]

OTVS = OTV + \( \frac{R_S}{h_v} = t_a + \frac{TVF}{h_v} + \frac{ERFL}{h_v} + \frac{ERFS}{h_v} \) (16)

ERFS = \( R_S \) (17)

The modified operative temperature OTVS [°C] can be expressed as the summation of air temperature and the effects of air movement, longwave radiation, and shortwave radiation. ERFS [W/m\(^2\)] signifies the separate effect of shortwave radiation, and is defined as the net solar energy exchanged on the body surface. This quantity is referred to as the effective shortwave radiant field by Nagano and Horikoshi [5].

The evaporative heat loss from the skin surface \( E \) [W/m\(^2\)] can be expressed as follows:

\[
E = w h_e F_{pcl} f_{cl} (p_{sk,s} - p_a) = w h'_e (p_{sk,s} - p_a)
\]

where \( w \) [n.d.], \( p_{sk,s} \) [kPa], and \( p_a \) [kPa] are skin wettedness, saturated water vapor pressure at \( t_{sk} \), and water vapor pressure at \( t_a \), respectively. The evaporative heat transfer coefficient including the actual clothing effect \( h'_e \) [W/(m\(^2\)kPa)] can be expressed using the total vapor permeation efficiency \( i_m \) [kPa/K] and Lewis ratio LR [K/kPa] as follows:

\[
h'_e = h_e F_{pcl} f_{cl} = h_e F_{pcl} f_{cl} LR = h'i_m LR
\]

Adding the evaporative heat loss given in Eq. (18) to Eq. (15) yields the following:

\[
C + R_L - R_S + E = h_v (t_{sk} - OTVS) + w h'_e (p_{sk,s} - p_a)
\]

Fobelets and Gagge [11] expressed ET* to shift the balance between the operative temperature and humidity without altering the total heat loss from the skin. In the same manner, the balance between OTVS and humidity is shifted as follows:

\[
C + R_L - R_S + E = h_v [(t_{sk} + \frac{wh'_e}{h_v} p_{sk,s}) - (OTVS + \frac{wh'_e}{h_v} p_a)]
\]

\[
= h_v [(t_{sk} + \frac{wh'_e}{h_v} p_{sk,s}) - (HOTVS + \frac{wh'_e}{h_v} p_{HOTVS,s})]
\]

\[
= h_v [(t_{sk} + \frac{wh'_e}{h_v} p_{sk,s}) - (ETVS + 0.5 \frac{wh'_e}{h_v} p_{ETVS,s})]
\]

where HOTVS [°C], \( p_{HOTVS,s} \) [kPa], and \( p_{ETVS,s} \) [kPa] are a modification of HOTV proposed by Horikoshi et al. [3] that adds to the solar effect, saturated water vapor pressure at HOTVS, and
saturated water vapor pressure at ETVs, respectively. ETV is defined as the hypothetical air
pressure of the isothermal environment at 50% relative humidity, a velocity of 0.1 m/s (a
convective heat transfer coefficient of 3.0 W/(m²K)) and a clothing insulation of 0 clo, in which a
human body would have the same heat exchange at the skin surface as in the actual outdoor
environment.

\[
ETVS = OTVS + \frac{wh_v}{h_v} (p_a - 0.5p_{ETVS,s})
\]

(22)

\[
EHF_{ETVS} = wh_v (p_a - 0.5p_{ETVS,s})
\]

(23)

EHF [W/m²] indicates the separate effect of humidity, with reference to 50% relative humidity, and
is defined as the humid energy exchanged on the body surface. This quantity is referred to as the
effective humid field by Horikoshi et al. [4]. It is noted that this EHF refers to 50% relative
humidity at ETVS, and so “ETVS” is included as a subscript in the equations. ETVS is expressed as
the summation of the air temperature plus the effective temperature differences caused by TVF,
ERFL, ERFS, and EHF. These quantities represent the effective fields in relation to air movement,
longwave radiation, shortwave radiation, and humidity, respectively. In other words, this index is a
modification of ETV proposed by Horikoshi et al. [4] that adds to the solar effect, and like ETV it
can describe both the combined effect of environmental variables and their separate effects. This is
the definition of the original ETVS, i.e., ETVO.

3. Modification of the coefficient

As thus far described, the effect of the air velocity is separated as the term TVF/hv. However,
ERFL/hv, ERFS/hv, and EHF/hv are not entirely independent of the velocity, since the coefficient hv,
as shown in Eq. (13), includes Fc, which is a function of the air velocity. Therefore, this paper
modifies ETVS, on the basis of the heat balance between the human body and the thermal
environment. Assuming that net heat loss by means of longwave radiation from the human body in
the standard environment corresponds to the heat loss RL of Eq. (5) while tr equals a hypothetical
radiant temperature trv [°C], the loss RL can be expressed as follows:

\[
R_L = h_r F_c (t_{sk} - t_r) = h_{ro} F_{clo} (t_{sk} - t_{rv})
\]

(24)

where \( h_{ro} [W/(m^2K)] \) is the radiant heat transfer coefficient in the standard environment. In this
paper, since hr can be simply expressed as 4.7ε in ordinary indoor environments [12], hro is taken to
be a constant of 4.5 W/(m²K), corresponding to 4.7ε at \( \varepsilon = 0.95 \). The hypothetical radiant
temperature trv is expressed from Eq. (24) as:
\[ t_{rv} = t_r + \frac{TVFr}{h_c F_{cleo}} \]  

\[ TVFr = (h_c F_{cleo} - h_c F_{cleo}) (t_{sk} - t_r) = h_v F_{cleo} (t_{rv} - t_r) \]  

The temperature \( t_{rv} \) indicates the radiant temperature including the effect caused by the difference between the actual and the standard environments. TVFr [W/m\(^2\)] is defined as the net heat energy exchanged by means of longwave radiation when the actual velocity and clothing do not correspond to the standard environment. This paper refers tentatively to this quantity as the radiation-related TVF, because TVFr in relation to the loss \( R_L \) and the hypothetical radiant temperature \( t_{rv} \) is analogous to TVF in relation to the loss \( C \) and the wind velocity temperature \( t_v \).

Replacing the radiant heat loss of Eq. (11) by that of Eq. (24), the heat loss by convection and longwave radiation \( C + R_L \) can be expressed as follows:

\[ C + R_L = h_c F_{cleo} (t_{sk} - t_r) + h_v F_{cleo} (t_{sk} - t_{rv}) = h_v (t_{sk} - OTV) \]  

\[ OTV = h_c F_{cleo} t_v + h_v F_{cleo} t_{rv} \]  

\[ h_v = (h_c + h_v) F_{cleo} \]  

\[ ERFL = h_v F_{cleo} (t_r - t_a) \]  

These are the redefinitions of OTV, \( h_v \), and ERFL. The coefficient \( h_v \) in Eq. (29) is a constant of 7.5 W/(m\(^2\)K) regardless of the air velocity, since \( F_{cleo} = 1 \). ERFL of Eq. (30) indicates the net radiant heat flux exchanged when \( t_r \) is not equal to \( t_a \), regardless of the clothing insulation and the air velocity in the actual environment.

In the same manner, assuming that evaporative heat loss in the standard environment corresponds to the heat loss \( E \) of Eq. (18), while \( p_a \) is equal to a hypothetical vapor pressure \( p_v \) [kPa], the loss \( E \) can be expressed as follows:

\[ E = w h'_e (p_{sk,s} - p_a) = w h_{eo} (p_{sk,s} - p_v) \]  

where \( h_{eo} \) [W/(m\(^2\)kPa)] is the evaporative heat transfer coefficient in the standard environment and is equal to 3.0 LR W/(m\(^2\)kPa) according to Eq. (19). The hypothetical vapor pressure \( p_v \) is expressed from Eq. (31) as:

\[ p_v = p_a + \frac{TVFe}{w h_{eo}} \]

\[ TVFe = (w h_{eo} - w h'_e) (p_{sk,s} - p_a) = w h_{eo} (p_v - p_a) \]  

The temperature \( p_v \) indicates the vapor pressure including the effect caused by the difference between the actual and the standard environments. TVFe [W/m\(^2\)] is defined as the net heat energy exchanged by means of evaporation when the actual velocity and clothing do not correspond to the standard environment. This paper refers tentatively to this quantity as the evaporation-related TVF, because TVFe in relation to the loss \( E \) and the hypothetical vapor pressure \( p_v \) is analogous to TVF.
in relation to the loss \( C \) and the wind velocity temperature \( t_v \).

The net heat gain from shortwave radiation \( R_S \) [W/m\(^2\)] can be expressed using the net direct solar radiation to the body \( R_{dir} \) [W/m\(^2\)], the net diffuse solar radiation to the body \( R_{dif} \) [W/m\(^2\)], and the net reflected solar radiation to the body \( R_{ref} \) [W/m\(^2\)]:

\[
R_S = R_{dir} + R_{dif} + R_{ref} \quad (34)
\]

\[
R_{dir} = a_h f_p f_{cl} I_{dn} \quad (35)
\]

\[
R_{dif} = a_h q_{sky-h} f_{rd} f_{cl} I_{dif} \quad (36)
\]

\[
R_{ref} = \alpha a_h q_{ground-h} f_{rd} f_{cl} I_{th} \quad (37)
\]

where \( a_h \) [n.d.], \( f_p \) [n.d.], \( I_{dn} \) [W/m\(^2\)], \( q_{sky-h} \) [n.d.], \( I_{dif} \) [W/m\(^2\)], \( \alpha \) [n.d.], \( q_{ground-h} \) [n.d.], and \( I_{th} \) [W/m\(^2\)] are the solar absorptivity of the clothed body, projected area factor, normal direct solar radiation, angle factor between the human body and sky surface, diffuse solar radiation on horizontal surfaces, albedo, angle factor between the human body and ground surface, and global solar radiation, respectively.

Subtracting the net heat gain \( R_S \) from Eq. (27) and adding the evaporative heat loss of Eq. (31) yield the following:

\[
C + R_L - R_S + E = h_v (t_{sk} - OTVS) + wh_{eo} (p_{sk, s} - p_v)
\]

\[
= h_v [(t_{sk} + \frac{wh_{eo}}{h_v} p_{sk, s}) - (OTVS + \frac{wh_{eo}}{h_v} p_v)]
\]

\[
= h_v [(t_{sk} + \frac{wh_{eo}}{h_v} p_{sk, s}) - (HOTVS + \frac{wh_{eo}}{h_v} p_{HOTVS, s})]
\]

\[
= h_v [(t_{sk} + \frac{wh_{eo}}{h_v} p_{sk, s}) - (ETVS + 0.5 \frac{wh_{eo}}{h_v} p_{ETVS, s})]
\]

\[
OTVS = t_o + \frac{TVF}{h_v} + \frac{ERFL}{h_v} + \frac{TVFr}{h_v} + \frac{ERS}{h_v} \quad (39)
\]

\[
HOTVS = OTVS + \frac{wh_{eo}}{h_v} (p_v - p_{HOTVS, s}) \quad (40)
\]

\[
ETVS = OTVS + \frac{wh_{eo}}{h_v} (p_v - 0.5 p_{ETVS, s}) \quad (41)
\]

\[
SEHF_{ETVS} = wh_{eo} (p_a - 0.5 p_{ETVS, s}) \quad (42)
\]

These are the redefinitions of OTVS, HOTVS, ETVS, and SEHF. EHF in Eq. (42) indicates the separate effect of humidity, regardless of the clothing insulation and the air velocity in the actual environment.

The modified ETVS in Eq. (41) was compared to the original in Eq. (22) through calculated
results. Table 1 shows the data used for the calculation, which were based on observations in Nara city in Japan during a summer day, but in which the air velocity was replaced with 0.1~5.0 m/s. Figure 1 and Figure 2 show the results of the original and modified ETVS, respectively, along with the results of the modified SET* proposed by Horikoshi et al. [17] (almost the same as OUT_SET* proposed by Pickup and de Dear [18]) and UTCI proposed by International Society of Biometeorology [19], which both adopt the mean radiant temperature integrating the shortwave and longwave components as follows:

\[
t_r = \left[ \frac{1}{\sigma} \sum (L_i + \frac{a_b D_i}{e}) q_{i-h} + \frac{a_b f_p I_{dn}}{e \sigma} \right]^{0.25} - 273.15
\]  

(43)

where \( L_i \) [W/m²], \( D_i \) [W/m²], and \( q_{i-h} \) [n.d.] are the longwave radiation from the surrounding i, diffuse shortwave radiation from the surrounding i, and the angle factor between the human body and the surrounding i, respectively.

In Figure 1, \( \text{ERFS} / h_v \) becomes larger as the velocity increases, despite constant solar radiation. In contrast, in Figure 2, \( \text{ERFS} / h_v \) is constant regardless of the velocity.

### 4. Consideration of heat conduction

The previous section treated the skin surface as if it were not in contact with anything solid. From this point on, the skin surface is divided into contact and non-contact areas. Using the ratio of the non-contact area to the whole skin surface \( f_n \) [n.d.], the heat loss of Eq. (38) can be modified as follows:

\[
C + R_L - R_S + E = h_v f_n (t_{sk} - \text{OTVS}) + wh_{eo} f_n (p_{sk,s} - p_v)
\]

= \( h_v f_n \left[ (t_{sk} + \frac{wh_{eo} f_n}{h_v f_n} p_{sk,s}) - (\text{OTVS} + \frac{wh_{eo} f_n}{h_v f_n} p_v) \right] \)

= \( h_v f_n \left[ (t_{sk} + \frac{wh_{eo} f_n}{h_v f_n} p_{sk,s}) - (\text{ETVS} + 0.5 \frac{wh_{eo} f_n}{h_v f_n} p_{ETVS,s}) \right] \)  

(44)

\[
\text{OTVS} = t_a + \frac{\text{TVF}}{h_v f_n} + \frac{\text{ERFL}}{h_v f_n} + \frac{\text{TVFr}}{h_v f_n} + \frac{\text{ERFS}}{h_v f_n}
\]  

(45)

\[
\text{ETVS} = \text{OTVS} + \frac{wh_{eo} f_n}{h_v f_n} (p_v - 0.5 p_{ETVS,s})
\]  

(46)

\[
\text{TVF} = h_{co} F_{cleo} f_n (t_v - t_a)
\]  

(47)

\[
\text{ERFL} = h_{ro} F_{cleo} f_n (t_r - t_a)
\]  

(48)

\[
\text{TVFr} = h_{ro} F_{cleo} f_n (t_{rv} - t_r)
\]  

(49)

\[
\text{ERFS} = R_S f_n
\]  

(50)
SEHF<sub>ETVS</sub> = \( wh_{eo} f_n (p_a - 0.5 p_{ETVS}, s) \) \hspace{1cm} (51)

TVFe = \( wh_{eo} f_n (p_v - p_a) \) \hspace{1cm} (52)

TVF, ERFL, TVFr, ERFS, SEHF, and TVFe are redefined here by multiplying them by \( f_n \). In contrast, OTVS of Eq. (45) corresponds to that of Eq. (39), and ETVS of Eq. (46) corresponds to that of Eq. (41).

The heat loss by means of conduction from the human body \( Cd \) [W/m<sup>2</sup>] can be expressed as follows:

\[
Cd = \frac{\lambda}{l} F_{cd} f_d (t_{skd} - t_b)
\] \hspace{1cm} (53)

where \( \lambda \) [W/(mK)], \( l \) [m], \( F_{cd} \) [n.d.], \( f_d \) [n.d.], \( t_{skd} \) [°C], and \( t_b \) [°C], are the heat conductivity of the contact material, thickness of the contact material, thermal efficiency factor of clothing with respect to heat conduction, ratio of the contact area to the whole skin surface, mean skin temperature at the contact area, and rear surface temperature of the contact material, respectively.

Replacing \( t_{skd} \) by \( t_{sk} \) and \( t_b \) by the contact surface temperature of the material \( t_d \) [°C] in the same manner as Kurazumi et al. [6, 7] yields the following:

\[
Cd = h_d F_{cd} f_d (t_{sk} - t_d)
\] \hspace{1cm} (54)

\[
h_d = \frac{\lambda (t_{skd} - t_b)}{l (t_{sk} - t_d)}
\] \hspace{1cm} (55)

This paper defines a material whose heat conductance is 7.5 W/(m<sup>2</sup>K) as one of conditions in the standard environment, since most common houses in Japan have wooden flooring with a thickness of 0.02 m, and a heat conductivity of typical wood is around 0.15W/(mK). It means these materials have this thermal characteristic, and benches in a park and chairs or stools in a dining or living room that are made of these materials are normally found in our daily life.

Assuming that the heat loss by conduction in this standard environment corresponds to the heat loss \( Cd \) of Eq. (47) while \( t_d \) equals a hypothetical surface temperature of the standard contact material \( t_{do} \) [°C], the loss \( Cd \) can be expressed as follows:

\[
Cd = h_{do} f_d (t_{sk} - t_{do})
\] \hspace{1cm} (56)

where \( h_{do} \) [W/(m<sup>2</sup>K)] is the heat conductance of the standard material ( = 7.5 W/(m<sup>2</sup>K)). Although Kurazumi et al. [6, 7] derived ETF and ETFe using the heat loss in Eq. (53), the present paper adopts Eq. (56). The total sensible heat loss including heat conduction of Eq. (56) can be expressed as follows:

\[
C + R_L - R_S + Cd = h_v f_n (t_{sk} - OTVS) + h_{do} f_d (t_{sk} - t_{do}) = h_v (t_{sk} - OTVSC)
\] \hspace{1cm} (57)

\[
OTVSC = \frac{h_v f_n OTVS + h_{do} f_d t_{do}}{h_v}
\]
Kurazumi et al. [6] derived an effective conduction field (ECF) [W/m²] that indicates the separate effect of heat conduction with reference to the actual contact material. This ECF is defined as the conductive energy exchanged on the body surface. SECF [W/m²], from Eq. (60), also indicates the separate effect of heat conduction, but refers to the standard environment, not to the actual material. This paper refers to this quantity as the standard effective conduction field (SECF).

Adding the evaporative heat loss to Eq. (31) yields the following:

\[ C + R_L - R_S + C_d + E = h_u (t_{sk} - \text{OTVSC}) + wh_{co} f_n (p_{sk, s} - p_v) \]

\[ = h_u [(t_{sk} + \frac{wh_{co} f_n}{h_u} p_{sk, s}) - (\text{OTVSC} + \frac{wh_{co} f_n}{h_u} p_v)] \]

\[ = h_u [(t_{sk} + \frac{wh_{co} f_n}{h_u} p_{sk, s}) - (\text{ETVSC} + 0.5 \frac{wh_{co} f_n}{h_u} p_{ETVSC, s})] \]

\[ \text{ETVSC} = \text{OTVSC} + \frac{wh_{co} f_n}{h_u} (p_v - 0.5 p_{ETVSC, s}) \]

\[ = t_o + \frac{TVF}{h_u} + \frac{ERFL}{h_u} + \frac{TVFr}{h_u} + \frac{ERFS}{h_u} + \frac{SEHF_{ETVSC}}{h_u} + \frac{TVFe}{h_u} + \frac{SECF}{h_u} \]  

\[ \text{SEHF}_{ETVSC} = wh_{co} f_n (p_a - 0.5 p_{ETVSC, s}) \]  

The coefficient \( h_u \) in Eq. (59) is a constant, 7.5 W/(m²K), regardless of the contact and non-contact area ratios, since \( h_v = h_{do} = 7.5 \) W/(m²K) and \( f_s + f_d = 1 \). Therefore, all effective fields in Eq. (62) are divided by 7.5, just as those in Eq. (41). ERFS/\( h_u \) in Eq. (62) is also independent of the actual air velocity, just like ERFS/\( h_u \) in Eq. (41) as shown in Fig. 2. The only difference between ETVSC of Eq. (62) and ETVS of Eq. (41) is the presence of the term \( \text{SECF}/h_u \). That is, ETVSC can take both the solar radiation and heat conduction into consideration, and can describe the universal effect of environmental factors and the separate effects of each factor simultaneously in the same unit of °C. ETFe proposed by Kurazumi et al. [7] can also consider solar radiation and heat conduction, but has the same disadvantage as the original ETVS of Eq. (22), because the coefficient by which the effective fields in ETFe are divided depends on the air velocity.

5. Consideration of a non-uniform environment

In order to adjust ETVSC to the non-uniform environment, the non-contact and contact surfaces are divided into \( i \) and \( j \) segments, respectively. The convective heat loss from the segment \( i \) \( C_i \) [W/m²] can be expressed as follows:
\[ C_i = h_{ci} F_{clei} f_i (tski - t_{ai}) \]  
(64)

where \( h_{ci} \) [W/(m²K)], \( F_{clei} \) [n.d.], \( f_i \) [n.d.], \( t_{ski} \) [°C], and \( t_{ai} \) [°C] are the convective heat transfer coefficient for segment \( i \), effective clothing thermal efficiency for segment \( i \), area ratio of the surface of segment \( i \) to the whole skin surface, skin temperature at segment \( i \), and air temperature around segment \( i \), respectively.

The heat loss from segment \( i \) by longwave radiation \( R_{Li} \) [W/m²] can be expressed as follows:
\[ R_{Li} = h_{ri} F_{clei} f_i (tski - t_{ri}) \]  
(65)

where \( h_{ri} \) [W/(m²K)] and \( t_{ri} \) [°C] are the radiant heat transfer coefficient for segment \( i \) and radiant temperature around segment \( i \), respectively.

The heat loss from segment \( i \) by evaporation \( E_i \) [W/m²] can be expressed as follows:
\[ E_i = w_i h'_{ei} f_i (p_{ski, s} - p_{ai}) \]  
(66)

where \( w_i \) [n.d.], \( h'_{ei} \) [W/(m²kPa)] \( p_{ski, s} \) [kPa], and \( p_{ai} \) [kPa] are the skin wettedness of segment \( i \), evaporative heat transfer coefficient including the actual clothing effect for segment \( i \), saturated water vapor pressure at \( t_{ski} \), and water vapor pressure at \( t_{ai} \), respectively.

Replacing \( t_{ski} \) by \( t_{sk} \), \( p_{ski} \) by \( p_{sk} \) and \( w_i \) by \( w \) yields the following equations:
\[ C_i = h_{ci} F_{clei} f_i (t_{sk} - t_{ai}) \]  
(67)
\[ R_{Li} = h_{ri} F_{clei} f_i (t_{sk} - t_{ri}) \]  
(68)
\[ E_i = wH'_{ei} f_i (p_{sk, s} - p_{ai}) \]  
(69)
\[ H_{ci} = h_{ci} \frac{t_{sk} - t_{ai}}{t_{ski} - t_{ai}} \]  
(70)
\[ H_{ri} = h_{ri} \frac{t_{sk} - t_{ri}}{t_{ski} - t_{ri}} \]  
(71)
\[ H'_{ei} = h'_{ei} \frac{w_i (p_{sk, s} - p_{ai})}{w (p_{ski, s} - p_{ai})} \]  
(72)

In the same manner as for Eq. (2), Eq. (24) and Eq. (31), assuming that the heat loss from segment \( i \) by convection, longwave radiation, and evaporation in the standard environment respectively correspond to the heat loss \( C_i \) when \( t_{ai} \) equals a hypothetical air temperature \( t_{vi} \) [°C], the heat loss \( R_{Li} \) when \( t_{ri} \) equals a hypothetical radiant temperature \( t_{ri} \) [°C], and the heat loss \( E_i \) when \( p_{ai} \) equals a hypothetical vapor pressure \( p_{vi} \) [kPa], the losses \( C_i, R_{Li}, \) and \( E_i \) can be expressed as follows:
\[ C_i = h_{co} F_{cleo} f_i (t_{sk} - t_{vi}) = h_{ci} F_{clei} f_i (t_{sk} - t_{ai}) = h_{ci} F_{clei} f_i (t_{ski} - t_{ai}) \]  
(73)
\[ R_{Li} = h_{re} F_{clei} f_i (t_{sk} - t_{ri}) = h_{ri} F_{clei} f_i (t_{ski} - t_{ri}) = h_{ri} F_{clei} f_i (t_{ski} - t_{ri}) \]  
(74)
\[ E_i = w_{co} f_i (p_{sk, s} - p_{vi}) = w_{ei} f_i (p_{sk, s} - p_{ai}) = w_{ei} f_i (p_{ski, s} - p_{ai}) \]  
(75)

The net heat gain at segment \( i \) from shortwave radiation \( R_{Si} \) [W/m²] can be expressed using the net direct solar radiation to segment \( i \) \( R_{diri} \) [W/m²], the net diffuse solar radiation to segment \( i \) \( R_{diffi} \) [W/m²], and the net reflected solar radiation to segment \( i \) \( R_{refi} \) [W/m²]:
where $a_{hi}$ [n.d.], $f_{pi}$ [n.d.], $f_{cli}$ [n.d.], $q_{sky-hi}$ [n.d.], $f_{rdi}$ [n.d.] and $q_{ground-hi}$ [n.d.] are the solar absorptivity of segment $i$, projected area factor for segment $i$, clothing area factor for segment $i$, angle factor between segment $i$ and the sky surface, effective radiation area factor for segment $i$, and angle factor between segment $i$ and the ground surface, respectively.

In the same manner as mentioned above, OTVS$i$, i.e., OTVS for segment $i$, and ETVSi, i.e., ETVS for segment $i$, can be expressed as follows:

$$C_i + R_{Li} - R_{Si} + E_i = h_v f_i (t_{sk} - OTVS_i) + w_{leo} f_i (p_{sk,s} - p_{vi})$$

$$= h_v f_i [(t_{sk} + w_{leo} f_i p_{sk,s}) - (OTVS_i + w_{leo} f_i p_{vi})]$$

$$= h_v f_i [(t_{sk} + w_{leo} f_i p_{sk,s}) - (ETVS_i + 0.5 w_{leo} f_i p_{ETVS_i,s})]$$

$$OTVS_i = t_{ai} + \frac{TVFi}{h_v f_i} + \frac{ERFLi}{h_v f_i} + \frac{TVFri}{h_v f_i} + \frac{ERFSi}{h_v f_i}$$

$$ETVS_i = OTVS_i + \frac{w_{leo} f_i}{h_v f_i} (p_{vi} - 0.5 p_{ETVS_i,s})$$

$$= t_{ai} + \frac{TVFi}{h_v f_i} + \frac{ERFLi}{h_v f_i} + \frac{TVFri}{h_v f_i} + \frac{ERFSi}{h_v f_i} + \frac{SEHF_{ETVS_i}}{h_v f_i} + \frac{TVFei}{h_v f_i}$$

$$TVFi = h_{eo} F_{clo, f_i} (t_{vi} - t_{ai})$$

$$ERFLi = h_{ro} F_{clo, f_i} (t_{ri} - t_{ai})$$

$$TVFri = h_{ro} F_{clo, f_i} (t_{rvi} - t_{ri})$$

$$ERFSi = R_{Si} = f_i (R_{diri} + R_{diff} + R_{refi})$$

$$SEHF_{ETVS_i} = \frac{w_{eo} f_i (p_{ai} - 0.5 p_{ETVS_i,s})}{h_v f_i}$$

$$TVFei = w_{eo} f_i (p_{vi} - p_{ai})$$

where TVFi, ERFLi, TVFri, ERFSi, SEHFETVSi, and TVFei are the effective fields for segment $i$. According to Eq. (44) and Eq. (80), the sensible heat loss from the total non-contact area can be expressed as follows:

$$C + R_L - R_S = \Sigma(C_i + R_{Li} - R_{Si})$$

$$h_v f_n (t_{sk} - OTVS) = \Sigma h_v f_i (t_{sk} - OTVS_i)$$

The non-contact area ratio $f_n$ is equal to the sum of $f_i$, that is, $f_n = \Sigma f_i$. Hence,

$$OTVS = \frac{\Sigma h_v f_i OTVS_i}{h_v f_n}$$
Using the representative value \( t_{ao}[^\circ C] \) of air temperature in a non-uniform environment, OTVS can be expressed as follows:

\[
OTVS = t_{ao} + \frac{\sum NUATFi}{h_v f_n} + \frac{\sum TVFi}{h_v f_n} + \frac{\sum ERFLi}{h_v f_n} + \frac{\sum TVFri}{h_v f_n} + \frac{\sum ERFSi}{h_v f_n} \tag{92}
\]

\[
NUATFi = h_v f_i (t_{ai} - t_{ao}) \tag{93}
\]

NUATFi [W/m\(^2\)] represents the separate effect of the air temperature distribution and is defined as the net heat energy exchanged on segment i when the air temperature around segment i does not correspond to the representative air temperature. This paper refers to this quantity as the non-uniform air temperature field.

The heat loss from segment j by conduction \( C_{dj} \) [W/m\(^2\)] can be expressed as follows:

\[
C_{dj} = \frac{\lambda_j}{l_j} F_{cldj} f_j (t_{skj} - t_{bj}) \tag{94}
\]

where \( \lambda_j \) [W/(mK)], \( l_j \) [m], \( F_{cldj} \) [n.d.], \( f_j \) [n.d.], \( t_{skj}[^\circ C] \), and \( t_b[^\circ C] \), are the heat conductivity of the contact material at segment j, thickness of the contact material at segment j, thermal efficiency factor of clothing with respect to the heat conduction at segment j, area ratio of the surface of segment j to the whole skin surface, skin temperature at segment i, and rear surface temperature of the contact material at segment j, respectively.

Replacing \( t_{skj} \) by \( t_{sk} \) and \( t_{bj} \) by the contact surface temperature of the material at segment j \( t_{dj}[^\circ C] \) yields the following:

\[
C_{dj} = h_{dj} F_{cldj} f_j (t_{sk} - t_{dj}) \tag{95}
\]

\[
h_{dj} = \frac{\lambda_j (t_{skj} - t_{bj})}{l_j (t_{sk} - t_{dj})} \tag{96}
\]

Assuming that the heat loss from segment j by conduction in this standard environment corresponds to the heat loss \( C_d \) given in Eq. (95) while \( t_{dj} \) equals a hypothetical surface temperature of the standard contact material at segment j \( t_{djo}[^\circ C] \), the loss \( C_{dj} \) can be expressed as follows:

\[
C_{dj} = h_{do} f_j (t_{sk} - t_{djo}) \tag{97}
\]

The total sensible heat loss including heat conduction can be expressed as follows:

\[
C + R_L - R_S + C_d = \Sigma(C_i + R_{Li} - R_{Si}) + \Sigma C_{dj} \\
= h_v f_n (t_{sk} - OTVS) + \Sigma h_{do} f_j (t_{sk} - t_{djo}) \\
= h_u (t_{sk} - OTVSC) \tag{98}
\]

\[
OTVSC = \frac{h_v f_n OTVS + \Sigma h_{do} f_j t_{djo}}{h_u} \tag{99}
\]

\[
h_u = h_v f_n + \Sigma h_{do} f_j = h_v f_n + h_{do} f_d \tag{100}
\]
This is the redefinition of OTVSC. The coefficient \( h_u \) in Eq. (100) corresponds to that in Eq. (59), since the contact area ratio \( f_d \) is equal to the sum of \( f_j \), that is, \( f_d = \sum f_j \). The SECF \( j \) that refers to \( t_{ao} \) does not necessarily correspond to the SECF in Eq. (60) that refers to \( t_u \), even when the contact area is not divided. When the non-contact area as well as the contact area is not divided, \( t_{ao} \) corresponds to \( t_u \), and SECF \( j \) corresponds to SECF.

Adding the evaporative heat loss of Eq. (75) to Eq. (98) yields the following:

\[
C + R_L - R_S + Cd + E = h_u (t_{sk} - OTVSC) + \sum E_i
\]

\[
= h_u \left[ (t_{sk} + \sum \frac{wh_{co} f_i}{h_u} p_{sk, i}) - (OTVSC + \sum \frac{wh_{co} f_i}{h_u} p_{vi}) \right]
\]

\[
= h_u \left[ (t_{sk} + \sum \frac{wh_{co} f_i}{h_u} p_{sk, i}) - (ETVSC + 0.5 \sum \frac{wh_{co} f_i}{h_u} p_{ETVSC, i}) \right]
\]

(102)

ETVSC = OTVSC + \sum \frac{wh_{co} f_i}{h_u} (p_{vi} - 0.5p_{ETVSC, i})

\[
= t_{ao} + \sum \frac{SNUATF_i}{h_u} + \sum \frac{TVF_i}{h_u} + \sum \frac{ERFL_i}{h_u} + \sum \frac{TVF_i}{h_u}
\]

\[
+ \sum \frac{ERFS_i}{h_u} + \sum \frac{SEHF_{ETVSC}}{h_u} + \sum \frac{TVF_e}{h_u} + \sum \frac{SECF_j}{h_u}
\]

(103)

\[
SEHF_{ETVSC} = wh_{co} f_i (p_{ai} - 0.5p_{ETVSC, i})
\]

This is the redefinition of ETVSC. As for Eq. (103), each effective temperature difference is separated into a number of segments. That is, this ETVSC can indicate the separate effects of various environmental factors including solar radiation and heat conduction on each segment, even for a non-uniform environment, as well as the universal effect. This paper refers to this index as the universal effective temperature ETU.

Table 2 shows whether each thermal index can indicate the universal and separate effects simultaneously, can take the solar radiation into consideration, can take the heat conduction into consideration, and can be applied to a non-uniform environment. As shown in Table 2, ETU is the only index that has all four features. Many other indices, e.g., \( t_{eqi} \) [20], OT* [21], PCC [22], PET [23, 24], and Local-SET* [25], have been also proposed. The \( t_{eqi} \) and Local-SET* are suitable for use in non-uniform conditions, not in the outdoors with solar radiation. PCC and PET are suitable for use in the outdoors, not in non-uniform conditions. OT* is suitable for use in situations involving sitting on the floor with heat conduction, not in the outdoors. And, these five indices cannot indicate the universal and separate effects simultaneously.
6. Conclusion

This paper proposed a new thermal index, i.e., the universal effective temperature ETU, defined as the hypothetical air temperature of an isothermal environment at 50% relative humidity, a velocity of 0.1 m/s (a convective heat transfer coefficient of 3.0 W/(m²K)), a radiant heat transfer coefficient of 4.5 W/(m²K) and a clothing insulation of 0 clo, in which a human body would have the same heat exchange at the skin surface as in an actual indoor or outdoor environment, where the human body may transfer the heat energy of solar radiation and/or conduction and/or whose factors may be non-uniform. ETU, as the universal effect of all environmental factors, and the effective fields, representing the separate effects of each environmental factor, can be expressed mathematically as follows:

\[
ETU = t_{ao} + \sum NUATFi \frac{1}{h_u} + \sum TVFi \frac{1}{h_u} + \sum ERFLi \frac{1}{h_u} + \sum TVFri \frac{1}{h_u} + \sum ERFSi \frac{1}{h_u} + \sum SEHFj \frac{1}{h_u} + \sum TVFei \frac{1}{h_u} + \sum SECFj \frac{1}{h_u}
\]

\[
NUATFi = h_v f_i (t_{ai} - t_{ao})
\]

\[
TVFi = h_{co} F_{cleo} f_i (t_{vi} - t_{ai})
\]

\[
ERFLi = h_{ro} F_{cleo} f_i (t_{ri} - t_{ai})
\]

\[
TVFri = h_{ro} F_{cleo} f_i (t_{rvi} - t_{ri})
\]

\[
ERFSi = R_{Si} = f_i (R_{diri} + R_{difi} + R_{refi})
\]

\[
SEHF_i = wh_{eo} f_i (p_{ai} - 0.5 p_{ETU,s})
\]

\[
TVFei = wh_{eo} f_i (p_{vi} - p_{ai})
\]

\[
SECFj = h_{do} f_j (t_{dai} - t_{ao})
\]

As shown in these equations, ETU is the summation of the representative air temperature plus the effective temperature differences from the representative air temperature caused by the non-uniform air temperature field (NUATFi), thermal velocity field (TVFi), effective longwave radiant field (ERFLi), radiation-related TVF (TVFri), effective shortwave radiant field (ERFSi), effective humid field (SEHFj), evaporation-related TVF (TVFei), and standard effective conduction field (SECFj) for segment i or j. NUATFi indicates the effect of the air temperature distribution with reference to the representative air temperature. TVFi indicates the effect of air velocity. ERFLi indicates the effect of longwave radiation with reference to the air temperature. TVFri indicates the net effect of longwave radiation caused by the differences of the actual velocity and clothing from the standard conditions. ERFSi indicates the effect of solar radiation. SEHFj indicates the effect of humidity with reference to 50% relative humidity at ETU. TVFei indicates the net effect of evaporation caused by the differences of the actual velocity and clothing from the standard conditions. SECFj indicates the effect of heat conduction with reference to the standard material. The derivation of
universal ETU, which is accompanied by the effective temperature differences, can help us to understand how much each of the environmental factors affects the human thermal comfort. Furthermore, the application of ETU is unrestricted, as it can be used in indoor or outdoor environments, uniform or non-uniform environments, and with or without heat conduction.

References
[26] G. Jendritzky, A. Maarouf, H. Staiger, Looking for a Universal Thermal Climate Index UTCI

<table>
<thead>
<tr>
<th>Measured conditions</th>
<th>19 August 2010/12:00</th>
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Fig. 1 Calculated results of the original ETVS

Fig. 2 Calculated results of the modified ETVS
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<th>Q3</th>
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Q1: Can it indicate universal and separate effects of the environmental factors simultaneously?
Q2: Can it take solar radiation into consideration?
Q3: Can it take heat conduction into consideration?
Q4: Can it be applied to non-uniform thermal environments?