ENVIRONMENTAL HOUSEHOLD ECO-ACCOUNT BOOK SYSTEM AND INDICATION OF THE EFFECT OF ENVIRONMENTAL FACTORS ON THE SENSATIONAL TEMPERATURE RELATED TO THE ENVIRONMENTAL CONTROL BEHAVIOR

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ABSTRACT

Residents' behavioral thermoregulation embodies the improvement effect of sensational temperature. From health and energy conservation, this is an important method of environmental control. If the effect of this can be expressed by sensational temperature, it may give environmental accounting indication for global warming prevention from the position of living design. It is necessary to include not only air temperature but also thermal radiation, air velocity, humidity and heat conduction in considering the thermal sense. Thus, in this study, conduction-corrected modified effective temperature (ETF), which is a new thermal environmental index incorporating heat conduction, is defined in order to make possible the evaluation of thermal environments that take into account behavioral thermoregulation. To verify this index, experiments were conducted. This sensational temperature index converts the effects of the following parameters into a temperature equivalent: air velocity, thermal radiation, contact material surface temperature and humidity. In addition, this new index is able to evaluate the effect of posture. This index has the features of a summation formula. Through the use of these parameters, it is possible to represent and quantify their composite influence on bodily sensation and the effects of discrete meteorological elements through an evaluation on an identical axis. The active means for controlling body temperature can alter the physical and physiological coefficients that describe the human body, which include the effects of air velocity, radiant temperature, clothing thermal insulation, metabolism and heat transfer area. Conduction-corrected modified effective temperature ETF will facilitate the design of specific control values of environmental factors. In addition, it will enable the expression of environmental control activities in terms of perceived temperature as well as energy, which enables the inclusion of environmental control activities in a household eco-account book system.

Keywords: Energy conservation, Environmental accounting, Environmental factor, Sensational temperature, Thermal environmental index

1. INTRODUCTION

In an indoor living space, active body temperature control is achieved by controlling the thermal environment through the adjustment of environmental conditions. For example, the thermal environment can be actively controlled by adjusting the room temperature or air speed by opening or closing a window, adjusting sunlight or thermal radiation by changing locations relative to a window or wall, adjusting the amount of clothing worn by removing or putting on clothes, or adjusting the heat transfer area by spreading out one's body or huddling up, to name a few.

Methods of regulating the thermal environmental that are important from the perspectives of health and energy conservation are air conditioning that utilizes thermal radiation without making use of an air medium, air conditioning that uses heat conduction (e.g., floor heating), and active behavioral thermoregulation such as altering body posture.

In spaces where air conditioning via thermal radiation or thermal conduction is used, the distance between the human body and the heated surface is small and the heat transfer area of the thermal radiation source (e.g., the floor surface in the case of floor heating) increases. Additionally, when sitting on the floor or lying down, much of the body surface is in direct contact with the floor surface, and as a result, the heat transfer area of the human body also increases (Kurazumi et al., 2008). Consequently, the influence of heat conduction and thermal radiation cannot be disregarded, and the effects on thermal sensation and thermal comfort in spaces in which only normal air temperature is controlled become comparatively strong.

Thermal environmental evaluation indices based on body heat balance are Effective Temperature (Houghten and Yaglou, 1923), Eupatheoscope (Dufton, 1929), Globe Temperature (Vernon, 1930), Température Résultante (Missenard, 1931), Equivalent Temperature (Bedford and Warner, 1934), Operative Temperature (Winslow et al., 1937), Heat Stress Index (Belding and Hatch, 1955), Equi-calorimetric Temperature (Matsuoka, 1960), Predicted Mean Vote (Fanger, 1970), Humid Operative Temperature (Nishi and Gagge, 1971), New Effective Temperature (Gagge et al., 1971), Corrected Humid Operative Temperature (Horikoshi and Kobayashi, 1985), and Modified Effective Temperature (Horikoshi et al.,1995). However, none of these thermal environmental evaluation indices include the role of heat conduction since these indices were designed to evaluate thermal environments in which light duties are performed while sitting in a chair in an office space.

In expressing multiple environmental factors as a single composite variable, the projection and planning of a thermal environment that considers the degree of incidence of reciprocal environmental factors is exceedingly difficult. Accordingly, Horikoshi and Kobayashi (1985) converted air velocity, thermal radiation, and humidity into an air temperature at a relative humidity of 100% and proposed a representative Corrected Humid Operative Temperature (HOTV) on a single evaluation axis. Moreover, Horikoshi et al. (1995) proposed the Modified Effective Temperature (ETV) similar to the New Effective Temperature (ET*) developed by Gagge et al. (1971) for a relative humidity of 50%, which is close to the humidity experienced in typical living spaces.

Therefore, to enable the use of a thermal environmental index to evaluate differences in posture, a mathematical description of a thermal environmental index that includes heat conduction is presented. In addition, to verify this index, experiments are conducted.

2. EFFECTS OF ENVIRONMENTAL FACTORS

2.1. Effects of airflow

The sensible heat exchange between the human body and the surrounding air due to convection can be expressed by the following equation.

$C_v = h_c\ (t_s - t_a)\ fcl\ Fcl\ f_{conv}$ (1)

Here, h_c: Convective heat transfer coefficient [W/m^{2}K], t_s: Convection-corrected mean skin temperature [°C], t_a: Air temperature [°C], fcl: Effective surface area of clothing [N. D.], Fcl: Thermal efficiency factor of clothing [N. D.], f_{conv}: Convective heat transfer area factor [N. D.].

To account for the effects of convection (air velocity), the thermal velocity field (TVF [W/m^2]) derived by Horikoshi and Kobayashi (1985) is used. This is used without modification for the convective heat transfer area. Rewriting equation 1 using standard air velocity and standard clothing yields the following equation.

$C_v = h_o (t_s - t_v)\ fcl\ Fclo\ f_{conv}$ (2)

$t_v = t_a + TVF_{hta} / h_o\ fcl\ Fclo\ f_{conv}$ (3)

$TVF_{hta} = (h_o\ fcl\ Fclo\ f_{conv} - h_c\ fcl\ Fcl\ f_{conv}) (t_s - t_a)$ (4)

Here, h_o: Convective heat transfer coefficient under the standard condition [W/m^{2}K], Fclo: Thermal efficiency factor of clothing under the standard condition [N. D.], t_v: Air temperature corrected by air velocity [°C], TVF_{hta}: Convective heat transfer area of the combined thermal velocity field [W/m^2], reflecting the valid temperature change not caused by air velocity.

2.2. Effects of thermal radiation

The sensible heat exchange by means of thermal radiation between the human body and the surrounding environment can be expressed as the following equation.

$R = h_r (t_s - t_r)\ fcl\ Fcl\ f_{rad}$ (5)

Here, h_r: Radiative heat transfer coefficient [W/m^{2}K], t_r: Mean radiant temperature [°C], f_{rad}: Radiant heat transfer area factor [N. D.].

To account for the effects of thermal radiation, the Effective Radiation Field (ERF [W/m^2]) based on the operative temperature (OT) derived by Gagge et al. (1967) is used. The ERF is not modified for the radiant heat transfer area. The quantity of heat exchange between the human body and the surrounding environment by means of convection and radiation can be expressed by the following equation.

$C_v + R = (h_o\ fcl\ Fclo\ f_{conv} + h_r\ fcl\ Fcl\ f_{rad}) (t_s - OT_v)$ (6)

$OT_v = t_a + TVF_{hta} / h_v + ERF_{hta} / h_v$ (7)

$ERF_{hta} = h_r\ fcl\ Fcl\ f_{rad} (t_r – t_a)$ (8)

$h_v = h_o\ fcl\ Fclo\ f_{conv} + h_r\ fcl\ Fcl\ f_{rad}$ (9)

Here, h_v: Combined heat transfer coefficient [W/m^{2}K], OT_v: Air-temperature-modified operative temperature [°C], ERF_{hta}: Radiant heat transfer area combined effective radiation field [W/m^2].

2.3. Effects of heat conduction

The quantity of heat exchange due to conduction between the human body and a contact surface can be expressed by the following equation.

$C_d = \lambda / \delta (t_c - t_b)\ Fcld\ f_{cond}$ (10)

Here, C_d: Conductive heat exchange at skin [W/m^2], λ: Heat conductivity [W/m K], δ: Thickness [m], t_c: Contact skin temperature [°C], t_b: Contact rear temperature [°C], f_{cond}:, Conductive heat transfer area factor [N. D.], Fcld: Thermal efficiency factor of clothing [N. D.].

Applying equation 11, which reflects the heat conductance of the contact material (m), to equation 10 and rewriting it gives equation 12.

$h_{dm} = \lambda / \delta$ (11)

Here, h_{dm}: Heat conductance [W/m^{2}K].

$C_d = h_d (t_s - t_f)\ Fcld\ f_{cond}$ (12)

$h_d = h_{dm} (t_c - t_b) / (t_s - t_f)$ (13)

Here, t_f: Surface temperature of the contacted material [°C], h_d: Resultant heat conductance [W/m^{2}K], f_{cond}: Conductive heat transfer area factor [N. D.].

The convection between the human body and the surrounding environment and the quantity of heat exchange due to thermal radiation and conduction can be expressed by the following equation.

$C_v + R + C_d = (h_o\ fcl\ Fclo\ f_{conv} + h_r\ fcl\ Fcl\ f_{rad} + h_d\ Fcld\ f_{cond}) (t_s - OT_f)$ (14)

$OT_f = t_a + TVF_{hta} / h_f + ERF_{hta} / h_f + ECF_{hta} / h_f$ (15)

$ECF_{hta} = h_d\ Fcld\ f_{cond} (t_f - t_a)$ (16)

$h_f = h_o\ fcl\ Fclo\ f_{conv} + h_r\ fcl\ Fcl\ f_{rad} + h_d\ Fcld\ f_{cond}$ (17)

Here, h_f: Sensible heat transfer coefficient [W/m^{2}K], OT_f: Conduction-combined modified operative temperature [°C], ECF_{hta}: Heat transfer area combined effective conduction field [W/m^2].
ECF_{hta} is considered to be a field that reflects the effective temperature change arising from heat conduction from the contact surface to the human body and defines an effective conduction field including the influence of the conductive heat transfer area; that is, the heat transfer area combined with the effective conduction field. The units are W/m^2.
OT_f is the weighted average OT derived from the heat transfer coefficient of the air-velocity-corrected air temperature t_v, the mean radiant temperature t_r, and the contact region surface temperature t_f. By conversion of the respective effects of thermal convection, thermal radiation and heat conduction into the convective heat transfer area combined with the thermal velocity field, the radiant heat transfer area combined with the effective radiation field and the heat transfer area combined with the effective conduction field, they can be expressed by a sum of the temperatures. This is considered to be an OT modified in response to heat conduction and is defined as the conduction-modified corrected operative temperature OT_f. This reflects the effect conveyed to the human body according to conduction, using air temperature as a basis.

2.4. Effects of latent heat from the skin surface of the human body

The latent heat release from the human body into the surrounding environment due to evaporation can be expressed by the following equation.
$E = L\ b\ w\ h_c\ fcl\ Fpcl\ (t_s - t_d)$ (18)
Here, L: Lewis relation coefficient [°C/kPa], b: Constant of linearization [kPa/°C], w: Skin wetness [N. D.], Fpcl: Permeation efficiency factor of clothing [N. D.], t_d: Dew-point temperature [°C].
Concerning the influence of humidity, the reduced-effective humid field (RHF [W/m^2]) is determined based on the corrected HOTV of Horikoshi et al. (1991).
Thus, the heat exchange between the human body and the surrounding environment due to convection, thermal radiation, conduction and evaporation can be expressed by the following equation.
$C_v + R + C_d + E = (h_o\ fcl\ Fclo\ f_{conv} + h_r\ fcl\ Fcl\ f_{rad} + h_d\ Fcld\ f_{cond} + L\ b\ w\ h_c\ fcl\ Fpcl)(t_s - HOTF)$ (19)
$HOTF = t_a + TVF_{hta} / h_k + ERF_{hta} / h_k - RHF / h_k$ (20)
$RHF = L\ b\ w\ h_c\ fcl\ Fpcl\ (t_a - t_d)$ (21)
$h_k = h_o\ fcl\ Fclo\ f_{conv} + h_r\ fcl\ Fcl\ f_{rad} + h_d\ Fcld\ f_{cond} + L\ b\ w\ h_c\ fcl\ Fpcl$ (22)
Here, h_k: Humid-combined heat transfer coefficient [W/m^{2}K], HOTF: Conduction-modified corrected humid operative temperature [°C], RHF: Reduced-effective humid field [W/m^2].
RHF (Horikoshi et al., 1991) reflects the effects of humidity on the human body in relation to a relative humidity of 100% and an air temperature t_a.
HOTF is a kind of weighted average OT derived from the heat transfer rate of the air-velocity–corrected air temperature t_v, the mean radiant temperature t_r, the contact-region surface temperature t_f, and the dew-point temperature t_d. By conversion of the respective effects of air velocity, thermal radiation, heat conduction and humidity into the corrected thermal velocity field TVF_{hta}, the corrected effective radiation field ERF_{hta}, the effective conduction field ECF_{hta} and reduced-effective humid field RHF, they can be expressed by a sum of the temperatures. This is assumed to be the modified Humid Operative Temperature (HOT), which is corrected in response to heat conduction and is defined as the conduction-modified corrected humid operative temperature (HOTF [°C]).
In a typical living environment, relative humidity is rarely 100%. Accordingly, the level of humidity is converted to a level similar to that actually encountered in a typical living environment. HOTF is transformed by the same method as that used by Fobelets and Gagge (1988), and a conversion based on a relative humidity of 50% is carried out. It is assumed that the total enthalpy is equal, and rewriting equation 19 gives equation 23.
$C_v + R + C_d + E = h_f\ (t_s - HOTF) + L\ w\ h_c\ fcl\ Fpcl\ (p_s^* - p_{HOTF}^*)$ (23)
$HOTF = OT_f + L\ w\ h_c\ fcl\ Fpcl\ (p_a - p_{HOTVf}^*) / h_f$ (24)
Here, p_a: Water vapor pressure at the air temperature [kPa], p_s^*: Saturated water vapor pressure at the skin temperature [kPa], p_{HOTF}^*: Saturated water vapor pressure at the conduction-modified corrected humid operative temperature [kPa].

Equation 24 is a definition distinct from the conduction-modified corrected humid operative temperature (HOTF) defined by equation 20. Performing a conversion as well as using both ET* (Gagge et al., 1971) and ETV (Horikoshi et al., 1995) in equation 24 at a relative humidity of 50% provides equation 25.

$ETF = OT_f + L\ w\ h_c\ fcl\ Fpcl\ (p_a - 0.5\ p_{ETF}^*) / h_f$ (25)

Here, ETF: Conduction-corrected modified effective temperature [°C], p_{ETF}^*: Saturated water vapor pressure in conduction-corrected modified effective temperature [kPa].

ETF expresses the temperature at 50% relative humidity that maintains a constant enthalpy of the human body equivalent to the HOTF under the same HOTF thermal environmental conditions, referencing air velocity, standard clothing, air temperature, mean radiant temperature, contact material surface temperature.

When humidity is 50%, the effective humid field (EHF [W/m^2]) is used, which is based on the modified effective temperature ETV derived by Horikoshi et al. (1995).

Based on this approach, equation 25 is rewritten to provide equation 26.

$ETF = t_a + TVF_{hta} / h_f + ERF_{hta} / h_f + ECF_{hta} / h_f + EHF_{ETF} / h_f$ (26)

$EHF_{ETF} = L\ w\ h_c\ fcl\ Fpcl\ (p_a - 0.5\ p_{ETF}^*)$ (27)

Here, EHF_{ETF}: Effective humid field in conduction corrected modified effective temperature [W/m^2].

The effective humid field at the ETF expresses the effects on the human body of a relative humidity of 50%. The effects of the humidity are converted into a temperature, which is obtained by removing EHF_{ETF} using the sensible heat transfer coefficient h_f that describes the effects of convection, thermal radiation and conduction.

ETF can convert the effects of air velocity, radiant temperature, contact material surface temperature and humidity into a temperature equivalent, and as a result, the summation of each factor with air temperature becomes possible. Consequently, it is possible to quantify the composite effects as well as the discrete effects of each meteorological element on the same evaluation axis.

3. VERIFICATION OF CONDUCTION-CORRECTED MODIFIED EFFECTIVE TEMPERATURE ETF

3.1 Experimental design

An artificial climate chamber was used in the experiment, which was a booth composed of woven fabric. A floor heating device constructed from crafted carbon panel heating elements (2.0 m x 2.0 m) was placed inside the booth.

The thermal environmental conditions consisted of 3 air temperatures of 24ºC, 26ºC and 28ºC, and 3 floor temperatures of 31ºC, 35ºC, and ambient temperature. Thus, there were 9 different combinations of air and floor temperatures. A constant air velocity (an air flow of 0.2 m/s or less) and a relative humidity (50%) were maintained for all conditions.

The subjects wore only bikini-style bathing suits to maintain a near-naked condition. They were also at rest. The 8 postures were adopted by the subjects during the experiment: standing, sitting in a chair, kneeling on both knees (*seiza*), sitting cross-legged, sitting sideways, sitting with knees held against the chest, sitting with legs extended and in a lateral posture.

Before the experiment, the subjects stayed in a seated posture and at rest for 60 minutes or more in the pre-test booth having the same air/wall temperature and relative humidity as the test booth. Then the subjects were swiftly moved to a test booth where they were placed in an exposure position and exposed to a set of thermal environmental conditions for 30 minutes.

The subjects were 3 healthy adult women. In accordance with the Declaration of Helsinki, all subjects were given detailed information regarding the experiments and informed consent to participate in the study was obtained.

The thermal environmental conditions of air temperature, humidity, air temperature distribution in the vertical direction, air velocity and surface temperature on the different surfaces were measured.

The conditions of the subjects were evaluated by measuring sublingual temperature, skin temperature, weight loss, sensible heat flux from skin surfaces.

3.2 Results and Discussion

Fig. 1 shows the relationship between air temperature and mean skin temperature for physiological reactions after 30-minute exposures to the various thermal environmental conditions. The results indicate that mean skin temperature tends to rise when the air temperature rises. It was confirmed that at a given temperature, the mean skin temperature tends to rise if the floor surface and heat transfer conduction area increase in size. The presence of parameters such as thermal environmental conditions and posture conditions were amply demonstrated.

Next, conduction-corrected modified effective temperature ETF, which is capable of expressing the effects of conduction and radiation, will be considered. Fig. 1 shows the relationship between ETF and mean skin temperature for physiological reactions after 30-minute exposures to the various thermal environmental conditions. When ETF increased, the mean skin temperature also increased.

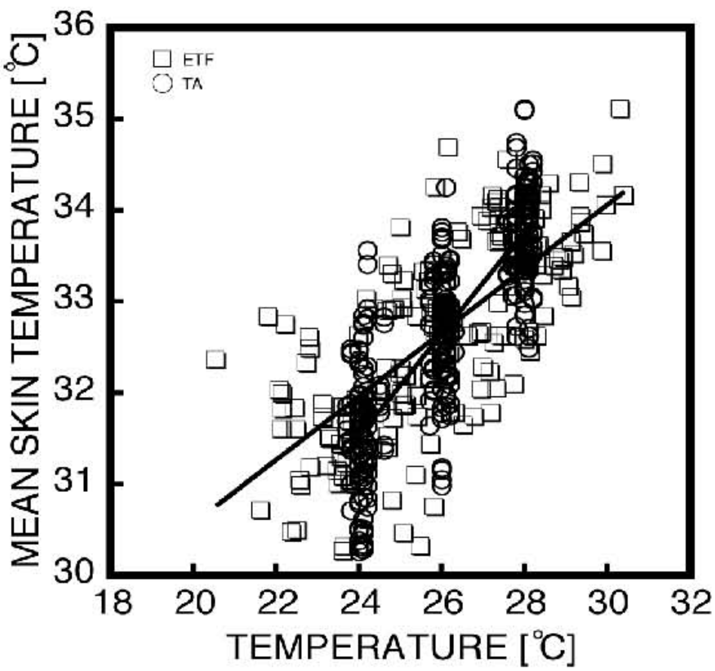

Fig. 1 Relationship between thermal environmental evaluation indices (conduction-corrected modified effective temperature ETF, air temperature TA) and conduction-corrected mean skin temperature.

In tests of subjects in a lateral posture at an air temperature at 28ºC, in which the floor and the human body are in intimate contact, it was found that a 35ºC floor temperature raised the air temperature by 2.5ºC. In contrast, in tests of subjects kneeling on both knees (*seiza*), sitting cross-legged or sitting sideways at equal floor and air temperature of 24ºC, the air temperature decreased by 2ºC (although there were discrepancies). Compared to the air temperature above, it is clear that ETF expresses the effects of heat conduction. ETF allows for additive expression of the effects of heat conduction.

By including air temperature, air velocity, thermal radiation, humidity and heat conduction on the evaluation axis of the thermal environment, it is possible to clarify the relationship between thermal environmental conditions and mean skin temperature in greater detail than when using air temperature.

Based on these results, it has been established that conduction-corrected modified effective temperature ETF converts the effects of air velocity, thermal radiation, humidity and heat conduction into a temperature equivalent and is a thermal environmental index capable of additive expression independent of air temperature. Moreover, ETF is a thermal environmental index that can comprehensively express air temperature, air velocity, thermal radiation, humidity and heat conduction.

If methods based on sensational temperature can be used in the design and control of thermal environments, it will contribute to the comfort and health of individuals in that environment. Thermal perception—hot, cold, and comfort—are often discussed in terms of environmental temperature, and correlation equations are used in the environmental control of space.

A sensational temperature index using the ETF can convert the effects of air velocity, radiant temperature, contact material surface temperature and humidity into a temperature equivalent, and as a result, the summation of these temperatures is possible. In addition, this new index is able to evaluate the effect of posture.

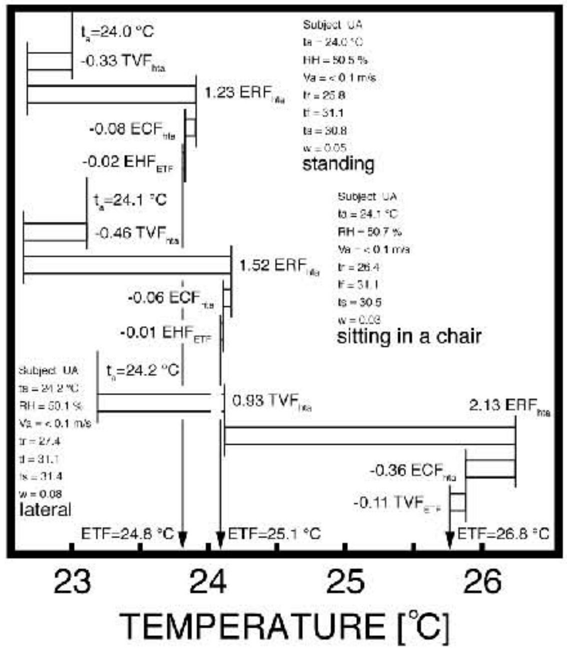

Fig. 2 Indication of independent and combined effects of thermal environmental factors. Conduction-corrected modified effective temperature ETF can be expressed as the sum of air temperature plus the effective temperature differences caused by air velocity, thermal radiation, contact material surface temperature (heat conduction), and humidity.

Fig. 2 shows that ETF is the sum of air temperature plus the effective temperature differences caused by air velocity, thermal radiation, contact material surface temperature (heat conduction), and humidity.

This example illustrates that the separate effects of individual thermal environmental variables as well as their combined effect can be expressed as a sum of the modifying temperature deviations with respect to air temperature.

In an indoor living space, active body temperature control is achieved by controlling the thermal environment through the adjustment of environmental conditions. For example, the thermal environment can be actively controlled by adjusting the room temperature or air speed by opening or closing a window, adjusting sunlight or thermal radiation by changing locations relative to a window or wall, adjusting the amount of clothing worn by removing or putting on clothes, or adjusting the heat transfer area by spreading out one's body or huddling up, to name a few. These active means for controlling body temperature can alter the physical and physiological coefficients that describe the human body, which include the effects of air velocity, radiant temperature, clothing thermal insulation, metabolism and heat transfer area.

Consequently, *the heat transfer area combined thermal velocity field,* TVF_{hta}, *the heat transfer area combined effective radiation field,* ERF_{hta}, *the heat transfer area combined effective conductive field,* ECF_{hta} and *the effective humid field in conduction corrected modified effective temperature,* EHF_{ETF} are calculated. As a result, the effects on the improvement of the sensational temperature are clarified by the transformed values that are converted into temperature equivalents. In addition, it is possible to use the transformed values ofTVF_{hta}, ERF_{hta}, ECF_{hta} and EHF_{ETF}, in air conditioning control techniques for maintaining the thermal condition of the target in the environmental controls.

4. CONCLUSION

In this study, it was shown that ETF is a thermal environmental index that converts air velocity, thermal radiation, humidity and heat conduction into temperature equivalents and is capable of additive expression independent of air temperature. Furthermore, ETF is a thermal environmental index that comprehensively expresses the effects of air temperature, air velocity, thermal radiation, humidity and heat conduction.

ETF has a strong relationship with mean skin temperature and was shown to be an effective thermal environmental evaluation index. The evaluation of posture parameters has confirmed a good correlation between ETF and thermal perception, whole-body thermal sensation, and whole-body thermal comfort.

Conduction-corrected modified effective temperature ETF will facilitate the design of specific control values of environmental factors. In addition, it will enable the expression of environmental control activities in terms of sensational temperature as well as energy, which enables the inclusion of environmental control activities in a household eco-account book system.

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