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A Measurement Method of Air Movement and Radiant Temperature with Dry and Wet Kata Thermometers

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Abstract

The purpose of the present study is to discuss the formula attached to a Kata thermometer for calculating air movement, especially the convective and the radiative heat transfer coefficients in the formula and a calculating formula for radiant temperature by a Globe thermometer.

As a result of the present investigations, it is clarified that the calculating formula of air movement of the Kata thermometer can be applied only in a uniform thermal environment where the air temperature is equal to the radiant temperature and that although the value of Kata radiative heat transfer coefficient appears to be almost appropriate in a temperature range of our current living conditions, its convection coefficient seeems to be suspect.

On the other hand, with regard to the Globe thermometer, it is pointed out that the formula for calculating radiant temperature should be applied with due consideration of the value of air movement to be substituted.

Further, an approach for rational measurements of air movement and radiant temperature is proposed by using dry and wet Kata thermometers at the same time, in order to correct errors arising in the case of using the existing formulas attached to the Kata thermometer and Globe thermometer.

1. Introduction

The Kata thermometer is said to be available for measuring low air movement such as we find in an ordinary room in everyday life. The thermometer was invented as a man-thermal model by L. Hill in 1916. Since the apparatus is very small in comparison with a human body, it has an unusual sensibility for air movement and therefore at present it is used as an excellent anemometer useful for the measurement of low air movement by a reverse application of the special characteristics of the Kata thermometer.

In the present study, heat transfer coefficients, i. e., the convection and the radiation coefficients defined in the calculating formula of air movement, are discussed by comparing of the values obtained from dimensionless equations of convective heat transfer etc. It is also pointed out that the formula cannot be used in an ordinary thermal environment where air temperature is not equal to radiant temperature.

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On the other hand, the Globe thermometer invented by H. M. Vernon for measurement of the radiant thermal effect is used. It is pointed out that an error is generally contained in the radiant temperature calculated by substituting the value of air movement obtained from the existing formula of the Kata thermometer derived on the assumption that air temperature equals radiant temperature into the heat balance equation of the Globe thermometer.

Further, in order to cope with the discrepancy mentioned above, a method for measuring air movement and radiant temperature is proposed by applying dry and wet Kata thermometers at the same time.

2. List of symbols

H: cooling power of dry Kata thermometer, Kcal/m² h
H': cooling power of wet Kata thermometer, Kcal/m² h
F: Kata factor of dry Kata thermometer, Kcal/m²
F': Kata factor of wet Kata thermometer, Kcal/m²
t: measurement time of dry Kata thermometer, h
t': measurement time of wet Kata thermometer, h
α_r: radiative heat transfer coefficient, Kcal/m² h °C
α_c: Kata convective heat transfer coefficient, Kcal/m² h °C
α_{cK}: convective heat transfer coefficient defined in Eq (12), Kcal/m² h °C
α_{cG}: convective heat transfer coefficient defined in Eq (14), Kcal/m² h °C
α_{c1}: Kata local convective heat transfer coefficient, Kcal/m² h °C
α_{c2}: Kata local convective heat transfer coefficient, Kcal/m² h °C
$\bar{\alpha}_c$: mean convective heat transfer coefficient weighted by α_{c1}, α_{c2}, A_1 and A_2, Kcal/m² h °C
A_1: Kata local surface area, m²
A_2: Kata local surface area, m²
V: air movement, m/s
V_K: air movement obtained from Eq (12), m/s
V_G: air movement obtained from Eq (14), m/s
T_K: mean temperature of Kata thermometer, °C
T_G: reading of Globe thermometer, °C
T_a: ambient air temperature, °C
T_w: wet bulb temperature, °C
T_r: mean radiant temperature, °C
T_{rV}: mean radiant temperature based on V, °C
T_{rV_K}: mean radiant temperature based on V_K, °C
T_{rV_G}: mean radiant temperature based on V_G, °C
P_{Ks}: saturated vapor pressure at T_K, mmHg
P_a: vapor pressure of ambient air, mmHg
κ: modified Lewis coefficient, °C/mmHg
Nu: Nusselt number, N. D.
Re: Reynolds number, N. D.
$B, C, J, K, Q, f, m, n, m_G, n_G, m_K, n_K$: constants

3. Heat transfer coefficients of Kata thermometer

3–1 The formula attached to dry Kata thermometer for calculating air movement

L. Hill invented dry and wet Kata thermometers as shown in Fig. 1. The apparatus has a thick lower part of 16 mm in diameter and 3.8 cm length and the slender upper part has a 6.5 mm diameter and is 18 cm in length. Although at first the thermometer was made as a man-thermal model, at present it is widely used as an excellent anemometer especially useful for low and directionally unstable air movement found in a still ordinary room. Usually dry Kata thermometer is used and when ambient air temperature is high a wet Kata thermometer is applied in order to shorten the measurement time.

A calculating formula of air movement attached to the dry Kata thermometer is given by the following equations and a nomogram has also set forth based on Eq (1) and Eq (2)[1].

$$V \leqq 1: \quad V=\left(\frac{\dfrac{H}{36.5-T_a}-7.20}{14.40}\right)^2 \qquad (1)$$

$$V \geqq 1: \quad V=\left(\frac{\dfrac{H}{36.5-T_a}-4.68}{16.92}\right)^2 \qquad (2)$$

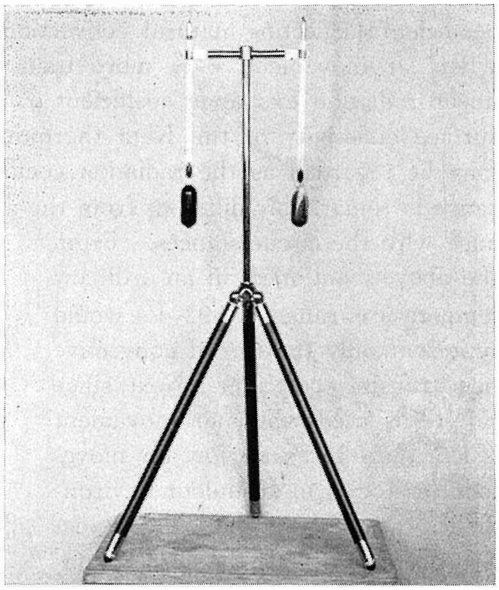

Fig. 1. Dry and Wet Kata thermometers.

Eq (1) and Eq (2) may be transformed to Eq (1)′ and Eq (2)′

$$V \leqq 1: \quad H=(14.40\sqrt{V}+7.20)(36.5-T_a) \qquad (1)'$$

$$V \geqq 1: \quad H=(16.92\sqrt{V}+4.68)(36.5-T_a) \qquad (2)'$$

Eqs (1)′ and (2)′ indicate that in a steady state released heat is propotional to the difference of the Kata mean temperature 36.5°C and ambient air temperature T_a (the equations show that air temperature equals surrounding radiant temperature) and that $14.40\sqrt{V}+7.20$ and $16.92\sqrt{V}+4.68$ are equivalent to the Kata heat transfer coefficients.

3–2 Convective and radiative heat transfer coefficients of Kata thermometer

In a general thermal environment where the air temperature is not equal to the radiant temperature, a heat balance equation for the dry Kata thermometer is as follows in a steady state, separating and expressing heat losses by convection and radiation.

$$H=\alpha_c(36.5-T_a)+\alpha_r(36.5-T_r) \qquad (3)$$

Eq (4) is derived as a special case of Eq (3), only when the air temperature is equal to the radiant temperature.

$$H=(\alpha_c+\alpha_r)(36.5-T_a) \tag{4}$$

The form of Eq (4) is similar to that of Eq (1)′ or Eq (2)′. From this, in a usual living room where the air temperature does not equal the radiant temperature, if Eq (1)′ and Eq (2)′, namely Eq (1) and Eq (2) of the air movement calculating formulas are applied, errors can be contained in the value of air movement obtained.

Let us examine the heat transfer coefficients in Eq (1)′ and Eq (2)′. It may be safe to say that convection coefficient of Eq (2)′ shows only the forced convection coefficient neglecting natural convection, since Eq (2)′ is the formula to be applied when air movement V is more than 1 m/s. Further, since the concrete value of linear radiation exchange coefficient α_r is almost $\alpha_r=4.5\sim5.0$ Kcal/m²h°C considering surface emissivity of the Kata thermometer in a daily living area,[2] 4.68 in Eq (2)′ may be regarded as the radiation coefficient itself. However, when the temperature range is remarkably different from the above, the value α_r must be changed in accordance with the circumstances. From the above-mentioned, in an ordinary temperature range, $16.92\sqrt{V}$ would represent only the forced convective heat transfer coefficient. Next, since Eq (1)′ is used when air movement is less than 1 m/s, in low air movement as found in an indoor environment, the effect of natural convection coexisting with the forced convection cannot be generally ignored. In the common state in Eq (1)′ and Eq (2)′, that is, in the case of air movement $V=1$ m/s, examining and comparing the coefficients of the two equations, $\alpha_c=2.52+14.40\sqrt{V}$ considering both natural and forced convection would be assumed as the convective heat transfer coefficient in Eq (1)′.

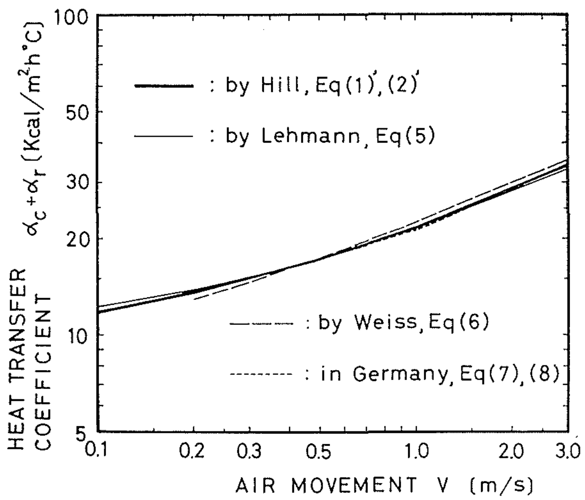

Fig. 2. Comparison of heat transfer coefficients for Kata thermometer.

The Kata thermometer coefficients by Lehmann, Weiss and others[1] in addition to Hill's proposal have been set forth and these relations are shown in Fig. 2.

$$\text{by Lehmann}: \quad \alpha_c+\alpha_r=12.24\,V^{0.622}+9.36 \tag{5}$$

$$\text{by Weiss } (V\geqq0.2\text{ m/s}): \quad \alpha_c+\alpha_r=17.64\sqrt{V}+5.04 \tag{6}$$

$$\text{in Germany } (V\leqq1\text{ m/s}): \quad \alpha_c+\alpha_r=13.86\sqrt{V}+7.38 \tag{7}$$

$$(V\geqq1\text{ m/s}): \quad \alpha_c+\alpha_r=17.46\sqrt{V}+3.78 \tag{8}$$

As stated previously, the upper slender part and the lower thick part of Kata thermometer are 6.5 mm and 16 mm in diameter respectively. If dimensionless equations of the forced convection for a cylinder by McAdams[3], Douglas-Churchill[4] and Hilpert[5] are applied to these diameters, we obtained the loci in Fig. 3. As shown in Fig. 3, considerable discrepancies are noted among the Kata property line and the loci drawn by dimensionless equations.

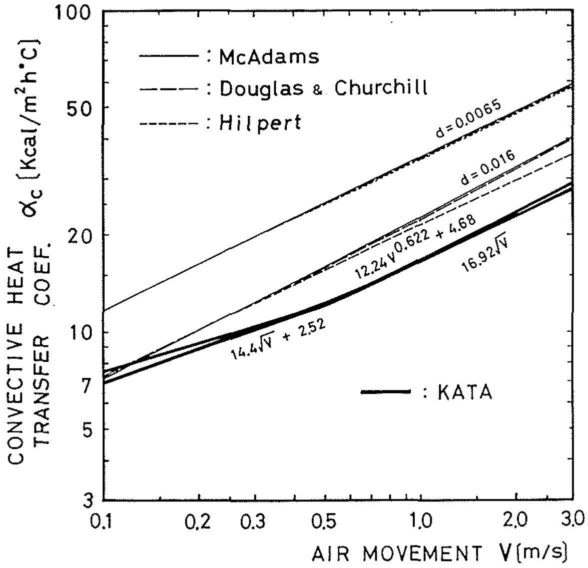

Fig. 3. Convective heat transfer coefficients of Kata thermometer and a cylinder.

Table 1. Constants for Eq (9)

Re	*B*	*C*	*n*
0.1～ 1000	0.52	0.43	0.52
1000～50000	—	0.24	0.60

Table 2. Constants for Eq (10)

Re	*B*	*K*	*C*
2～ 500	0.43	0.48	—
500～250000	—	0.46	0.00128

Table 3. Constants for Eq (11)

Re	*C*	*n*
4～ 40	0.821	0.385
40～ 4000	0.615	0.466
4000～40000	0.174	0.618

McAdams : $Nu = B + C \cdot Re^n$ (9)

Douglas-Churchill : $Nu = B + K \cdot Re^{0.5} + C \cdot Re$ (10)

Hilpert : $Nu = C \cdot Re^n$ (11)

It has been reported that when a cylinder is small in diameter, the forced convection is hardly affected by natural convection, even if the air movement is still[6]. And the dimensionless numbers in Eqs (9), (10) and (11) were fixed on the basis of the values of a property of matter at 30°C.

Although the flow condition around the Kata thermometer with a complicated form may be imagined to be different from that around a simple cylinder, the Kata property line of convective coefficient differs considerable from the theoretical loci obtained by the assumption of the two diameters of the upper and the lower parts of the Kata thermometer in a greater range of air movement. One of the reasons why the difference among Kata property line and the theoretical loci is caused may be as follows: the air temperature in the test chamber used when heat transfer coefficients in Eq (1)′ and Eq (2)′ were decided may have been different from the radiant temperature of the surrounding walls in the chamber.

4. A measurement method of air movement and radiant temperature with dry and wet Kata thermometers

4-1 Examination of ordinary measurement methods of air movement and radiant temperature

The Kata formula for calculating air movement was defined on the assumption that the air temperature is equal to the radiant temperature and a general equation of its heat balance may be as follows.

$$H=(\alpha_{cK}+\alpha_r)(T_K-T_a)$$
$$=(m_K V_K^{n_K}+\alpha_r)(T_K-T_a) \qquad (12)$$

However, in an environment where the air temperature is not equal to the radiant temperature, we must use the following heat balance equation in which the terms of convection and radiation heat losses are divided.

$$H=\alpha_c(T_K-T_a)+\alpha_r(T_K-T_r)$$
$$=mV^n(T_K-T_a)+\alpha_r(T_K-T_r) \qquad (13)$$

On the other hand, a heat balance equation of general form for the Globe thermometer is expressed by the following equation.[7]

$$0=\alpha_{cG}(T_G-T_a)+\alpha_r(T_G-T_r)$$
$$=m_G V_G^{n_G}(T_G-T_a)+\alpha_r(T_G-T_r) \qquad (14)$$

When Kata and Globe thermometers are used in any thermal environment, we obtain the relations tabulated below.[8]

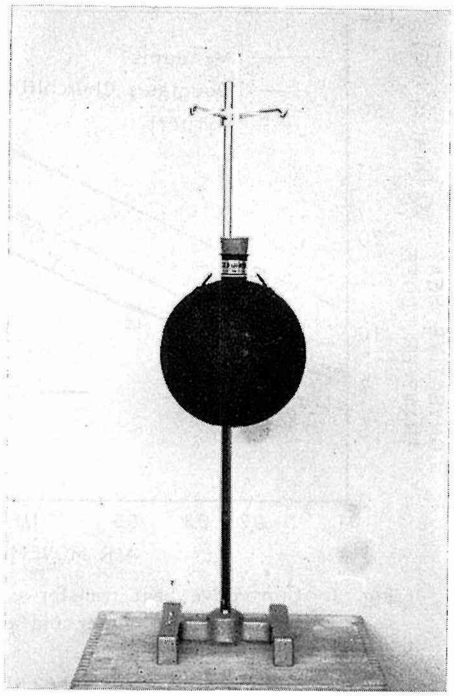

Fig. 4. Globe thermometer.

As listed in Table 4, although trouble does not arise when the environment is thermally uniform, in an environment where the air temperature is higher than the radiant temperature, the value of air movement obtained from Eq (12), i. e., Kata formulas (1) and (2) would result in an overestimation of the actual value and further, the radiant temperature calculated by substituting the overestimated value of air movement would be higher than the actual radiant temperature. As mentioned above, the value obtained by using Eq (1) and Eq (2) or the nomogragh made based on these equations would have errors, if we use these in a non-uniform temperature environment of daily life.

Table 4. Relation of air temperature, radiant temperature and air movement obtained from Eqs (12), (13) and (14)

$T_a>T_r$	$T_a=T_r$	$T_a<T_r$
$V_K>V=V_G$ $T_{rV_K}>T_{rV}=T_{rV_G}$	$V_K=V=V_G$ $T_{rV_K}=T_{rV}=T_{rV_G}$	$V_K<V=V_G$ $T_{rV_K}<T_{rV}=T_{rV_G}$

4-2 A measurement method of air movement and radiant temperature with dry and wet Kata thermometers

In order to remove the defects as described above, a measurement principle of air movement and radiant temperature are described as follows by using dry and wet Kata thermometers at the same time.[9]

In an ordinary room of non-uniform temperature, the heat balance equations for dry and wet Kata thermometers are in a steady state as follows.

$$\text{Dry Kata}: \quad H = \frac{F}{t} = \alpha_c(T_K - T_a) + \alpha_r(T_K - T_r) \tag{15}$$

$$\text{Wet Kata}: \quad H' = \frac{F'}{t'} = \alpha_c(T_K - T_a) + \alpha_r(T_K - T_r) + \kappa\alpha_c(P_{Ks} - P_a) \tag{16}$$

From Eq (15) and Eq (16), convective heat transfer coefficient α_c which is a function of air movement V and mean radiant temperature T_r are given by the following equations, if convective and radiative heat transfer coefficients in Eq (15) and Eq (16) are assumed to be nearly equal respectively.

$$\alpha_c = \frac{H' - H}{\kappa(P_{Ks} - P_a)} \tag{17}$$

$$T_r = T_K - \frac{H}{\alpha_r} + \frac{(T_K - T_a)(H' - H)}{\kappa(P_{Ks} - P_a)\,\alpha_r} \tag{18}$$

If we could obtain a concrete relation between air movement and convection coefficient regarding the Kata thermometer, regardless of whether the air temperature is equal to the radiant temperature or not, we can obtain the appropriate values of air movement and mean radiant temperature at the same time, since the right sides of Eq (17) and Eq (18) are all values which can be measured beforehand.

As a simplification, temporarily let us assume that Kata mean convective eocfficient lies between the convective coefficients equivalent to the cylinders of 6.5 mm and 16 mm in diameter, whose values are the diameters of Kata upper and lower parts and Eq (19) is defined under the above assumptions.

$$\bar{\alpha}_c = \frac{\alpha_{c1}A_1 + \alpha_{c2}A_2}{A_1 + A_2} \tag{19}$$

For instance, if the values of diameters, lengths and surface areas which are

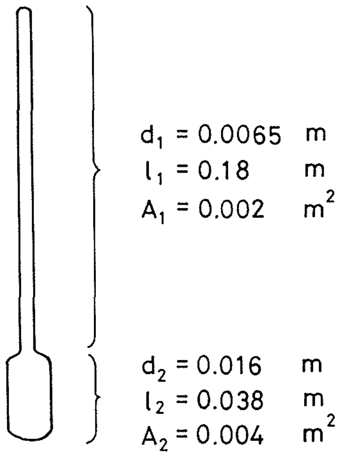

Fig 5. Diameters, length and surface areas of the upper and the lower parts of Kata thermometer.

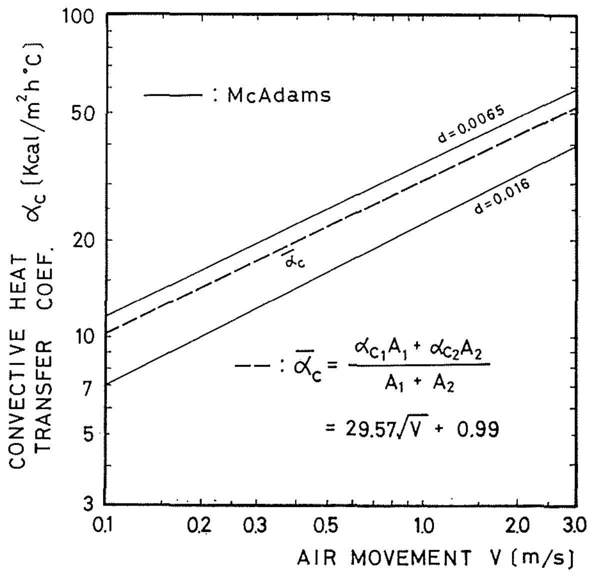

Fig. 6. Locus of Eq (19).

shown in Fig. 5 are substituted into Eq (19) and McAdams' dimensionless equation of forced convection are applied, a concrete relation between mean convective heat transfer coefficient $\bar{\alpha}_c$ and air movement V is written by the following equation.

$$\bar{\alpha}_c = JV^{\frac{1}{f}} + Q \tag{20}$$

$$= 29.57\sqrt{V} + 0.99 \tag{21}$$

From Eqs (17) and (21), we can calculate the value of air movement as follows.

$$V = \left\{ \frac{1}{J} \left[\frac{H' - H}{\kappa (P_{Ks} - P_a)} - Q \right] \right\}^f \tag{22}$$

$$= \left\{ \frac{0.02(H' - H)}{45.8 - P_a} - 0.03 \right\}^2 \tag{23}$$

We can obtain the actual values of air movement and mean radiant temperature by Eq (18) and Eq (22), regardless of whether air temperature equals radiant temperature or not. As a matter of course, we can use the equation of convection coefficient defined by Hill or other more precise convection coefficients in place of Eq (21).

4-3 The calculating formula of air movement attached to the wet Kata thermometer

In a high temperature environment, the wet Kata thermometer is used instead of the dry Kata thermometer to shorten measurement time. The formula is as follows.[10]

$$V \leqq 1: \quad V = \left(\frac{\frac{H'}{36.5 - T_w} - 12.6}{30.6} \right)^3 \tag{24}$$

$$V \geqq 1: \quad V = \left(\frac{\frac{H'}{36.5 - T_w} - 3.6}{39.6} \right)^3 \tag{25}$$

Eq (24) and Eq (25) indicate that air movement V can be obtained by values of wet bulb temperature T_w and cooling power H' alone regardless of air temperature T_a and radiant temperature T_r. However, if a formula for calculating air movement is derived from the heat balance equation (16) regarding the wet Kata thermometer and the relation equation (20) between the convective coefficient and air movement, we can obtain Eq (26).

$$V = \left\{ \frac{1}{J} \left[\frac{H' - \alpha_r (T_K - T_r)}{(T_K - T_a) + \kappa (P_{Ks} - P_a)} - Q \right] \right\}^f \tag{26}$$

Eq (26) contains dry bulb temperature T_a (=air temperature) and radiant temperature T_r in addition to ambient vapor pressure P_a. Which is a function of wet bulb temperature T_w. Therefore, even if the air temperature is equal to the radiant temperature, it would be only in an accidental condition that we could obtain a simple form like Eq (24) or Eq (25).

5. Conclusions

Kata thermometer has been used as an excellent anemometer to measure low air movement in an ordinary room under still air conditions. However, since the calculating formula of air movement was derived on the assumption that the air temperature is equal to the radiant temperature, it seems that the value measured in a daily life environment where air temperature is not equal to radiant temperature would contain errors. Although the radiative heat transfer coefficient in the formula seems to be regarded nearly appropriate in the temperature range of a daily life, this value should cause errors, if used in lower or higher temperature regions. Further, in order to discuss the Kata convective heat transfer coefficient, as an attempt, dimensionless equations by McAdams, Douglas-Churchill and Hilpert were applied to the diameters of the upper and the lower part of the Kata thermometer, although there is some suspicion for applying simply dimensionless equations of convection heat transfer of a cylinder to the flow around the Kata thermometer with a complicated form.

As a result, the locus of the Kata convection coefficient does not lie between the loci of convection coefficients of cylinders equivalent to a pair of diameters of the Kata thermometer, especially in a high air movement range, a considerable different tendency was seen between the Kata coefficient and the coefficients obtained from dimensionless equations.

On the other hand, although we use Globe thermometer to measure radiant temperature, if the radiant temperature is calculated by substituting the value of the air movement obtained from the Kata thermometer into a heat balance equation of Globe thermometer, it follows errors and the general tendency was discussed.

A principle for measuring air movement and radiant temperature was proposed by using dry and wet Kata thermometers at the same time, in an attempt to improve on the irrationality above mentioned. It is possible to obtain air movement and radiant temperature consistently, regardless of whether the air temperature is equal to the radiant temperature or not, since we have used heat balance equations of dry and wet Kata thermometers which are different from the equations used at present.

It seems to be necessary to ascertain the exact value of the Kata heat transfer coefficient by laboratory work in a controlled test-chamber. And the Kata factor, the Kata mean temperature and so forth will be questions for further discussion.

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