Derivation of Equation for Personal Carbon Dioxide in Exhaled Breath Intended to Estimation of Building Ventilation

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Equation for CO_2 Production Rate Included in Exhaled Breath

$$P_{CO_2} = 1.589 \times 10^{-4} M$$

$$M = 94.4 A_D + 83.9 Met + 21.0 C_g - 149.7$$

Douglas bag method
Regression analysis
With approximately total 70 Japanese subjects

$$A_D = 0.007246 \times W_b^{0.425} \times H_b^{0.725}$$

P_{CO2} : Carbon dioxide production rate [m³/h]
M : metabolic rate [W]
A_D : body surface area [m²] (for Japanese adult)
C_g : coefficient of gender (0: female, 1: male)
W_b : body weight [kg]
H_b : body height [cm]

DERIVATION OF EQUATION FOR PERSONAL CARBON DIOXIDE IN EXHALED BREATH INTENDED TO ESTIMATION OF BUILDING VENTILATION

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ABSTRACT

Carbon dioxide included in exhaled breath is often used as a tracer gas when estimation of ventilation aspect in buildings with occupants is performed. Carbon dioxide produced by occupants is the key for the estimation. JIS A 1406 and ASTM D6245-12 refer personal carbon dioxide production rate. However JIS does not take into account personal attribute like as body height and weight. On the other hand, ASTM does not take into account gender difference and based on average westerner adult data. Hence, by using Douglas bag method with approximately total 70 voluntary Japanese subjects, a prediction equation for occupants' carbon dioxide production rate included in exhaled breath is developed. Moreover, the equation is tested in single zone with occupants aiming at accuracy testing. The results can allow predicting more correct carbon dioxide concentration produced by occupants', exhaled breath in single zone compared with the standards.

KEYWORDS

Ventilation, Exhaled breath, Carbon dioxide, Single zone, Douglas bag method

1 INTRODUCTION

Carbon dioxide included in exhaled breath is often used as a tracer gas when estimation of ventilation aspect in buildings with occupants is performed. Amount of carbon dioxide produced by the occupants is a key for this kind of estimation. Carbon dioxide production rate is shown in e.g. a Japanese Industrial Standard (JIS A 1406[1974], 2010) and an American Society for Testing and Materials International Standard (ASTM D6245-12, 2012).The JIS standard indicates a relationship between personal carbon dioxide production rate and RMR (relative metabolic rate) including gender difference, which shows female's production rate is 0.9 times of male's. The ASTM standard gives a relationship between personal carbon dioxide production rate and parameters, as body surface area and metabolic rate. These personal carbon dioxide production rates were referenced in other standard (e.g. SHASE-S102, 2011) and have been used for computing ventilation rate or air change rate in some previous works (e.g. Saito et al., 2002, Stavova et al., 2006). These carbon dioxide production rates in the standards are described simply, therefore they are useful for the estimation. However, the JIS's rate is not considered body height and weight. On the other hands, the ASTM's rate is not considered gender difference and is based on average westerner adult data with a fixed respiratory quotient value (RQ = 0.83).

Because of these backgrounds, this study aims at derivation of a prediction equation using variables such as *Met* and personal attribute for personal carbon dioxide production rate included in exhaled breath with Japanese subjects, aims and at accuracy testing of this equation at rooms with occupants in real use conditions.

2 DERIVATION OF EQUATION FOR PERSONAL CARBON DIOXIDE PRODUCTION RATE

2.1 Outline of the derivation

The derivation of an equation for carbon dioxide production rate was performed with obtained carbon dioxide production rate, Met, and subjects' personal attribute. Then, with using these obtained data, an equation was derived trough regression analysis.

2.2 Measurement

Using Douglas bag method, the measurement of carbon dioxide production rate was performed with total of approximately 70 voluntary people who were mainly university students. The testing activities and number of subjects are shown in Table 1 and testing instruments are shown in Table 2.

Metabolic value M and carbon dioxide production value V_{CO_2} are determined by the following equations (ISO8996, 2004) with using obtained data which are V_{O_2} and V_{CO_2}. Moreover, personal attribute, age, gender, body height and weight, were also obtained.

Table 1: testing activities and number of subjects

Activity	Seated, quiet	Walking (2km/h)	Walking(4km/h)
Work period	10 minutes	5 minutes	3 minutes
Number of Subjects*	23(9)	23(9)	23(9)

*total 69 people, ( ) means internal numbers of female

Table 2: testing instruments

Douglas bag	Volume: 100L	TK-11288
Gas analyser	CO_2 NDIR 0-5/10/20 vol% O_2 zirconia process 0-5/10/25 vol%	PG-240

$$RQ = \frac{V_{CO_2}}{V_{O_2}} \quad (1)$$

$$\mathrm{EE} = (0.23RQ + 0.77)5.88 \quad (2)$$

$$M = EE \times V_{O_2} \quad (3)$$

Where

- RQ is the respiratory quotient
- V_{O_2} is the oxygen consumption rate [L/h]
- V_{CO_2} is the carbon dioxide production rate [L/h]
- EE is the energetic equivalent [Wh/LO_2]
- M is the metabolic rate [W]

2.3 Regression analysis

The measured data was selected into for 51 subjects' data for the regression analysis, by considering to the aspect of the RQ value referred in former works like as the followings. RQ varies from 0.7 to 1.0(e.g. Herman, 2007). RQ equals 0.83 for an average adult engaged in light or sedentary activities (ASTM D6245-12 2012). RQ = 0.83 applies to a normal diet mix of fat, carbohydrate, and protein (ASHRAE Standard 62.1, 2010)

The whole measured values range approximately from 0.6 to 1.2. Only the data ranges from 0.7 to 1.0 were used as the selected data. Therefore, the selected *RQ* values finally range from 0.78 to 0.99 and the average value is 0.93 for seated quiet, 0.92 for walking at 2km/h and 0.91 for walking at 4km/h. Hence these measured *RQ* values are larger than the ASTM's and ASHRAE's theoretical fixed values.

(1) Relationship between carbon dioxide production rate and metabolic rate

The relationship between carbon dioxide production rate P_{CO_2} in m³/h and metabolic value *M*, simple correlation, is shown in Figure 1. The equations (1), (2) and (3) show that the metabolic rate *M* is determined by using oxygen consumption rate V_{O_2} and carbon dioxide production rate V_{CO_2}. Even without oxygen consumption rate V_{O_2} this relationship has strong correlation and the relationship can be expressed by equation (4). Thus this equation within metabolic rate as a variable can be considered as basic equation for the prediction of personal carbon dioxide production rate.

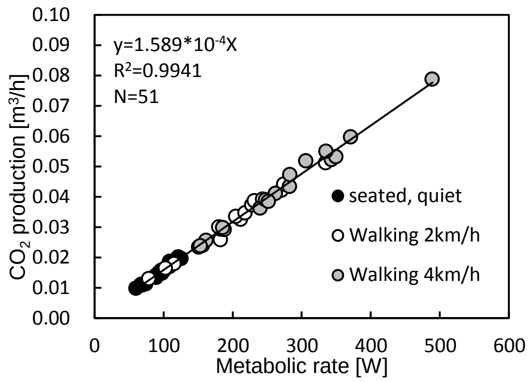

Figure 1: Relationship between carbon dioxide production rate and metabolic value

$$P_{CO_2} = 1.589 \times 10^{-4} M \quad (4)$$

Where

P_{CO_2} is the carbon dioxide production rate [m³/h]

(2) Relationship between metabolic rate and body height and weight

Relationship between metabolic rate *M* and body surface area A_D is shown in Figure 2. The body surface area is given by equation (5) (SHASE Handbook, 2010). This equation is based on Japanese adults' data.

From regression analysis results with explanatory variables as the BMI (body-mass index), height and weight themselves, and body surface area, the body surface area A_D has the strongest correlation with metabolic rate as same as previous works (e.g. ASTM D6245-12 2012, Persily, 1997) .

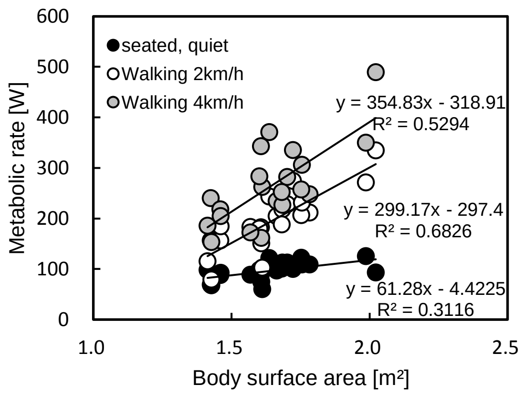

Figure 2: Relationship between metabolic rate and body surface area

$$A_D = 0.007246 \times W_b^{0.425} \times H_b^{0.725} \qquad (5)$$

Where
 A_D is the body surface area [m^2] (for Japanese adult)
 W_b is the body weight [kg]
 H_b is the body height [cm]

(3) Relationship between metabolic rate and Met

Figure 3 indicates relationship between metabolic rate and *Met* given by equation (6). *Met*, which is generally used as an index of occupants' activity, is calculated by substituting each subject's metabolic rate obtained under the condition of "seated, quiet" as M_S into this equation. The coefficient of determination R^2 shown in Figure 3 is approximately 0.82.

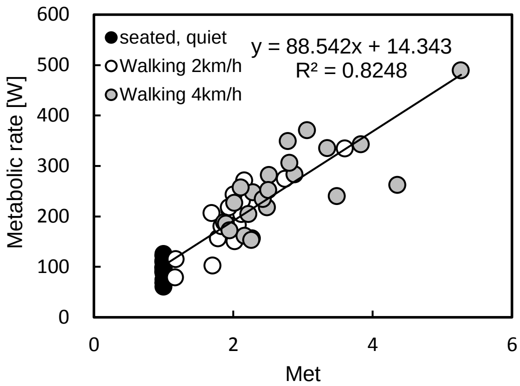

Figure 3: Relationship between metabolic rate and Met

$$Met = \frac{M}{M_S} \qquad (6)$$

Where
 M_S is the metabolic rate of relax seated [W]

2.4 Determination of equation for personal carbon dioxide production rate

Metabolic rate is given by equation (7) which also has coefficient of gender as a variable. Subject's age was not employed in the equation, because most of subjects were similar ages. The coefficient of determination did not increase even when subject's age was taken as variables.

Relationship between measured metabolic rate and calculated metabolic rate using equation (7) is shown in Figure 4, in which R^2 is approximately 0.88 and the RMSE is 33.1.

$$M = 94.4A_D + 83.9Met + 21.0C_g - 149.7 \qquad (7)$$

Where
 C_g is the coefficient of gender (0: female, 1: male)

Finally, the prediction equation for personal carbon dioxide production rate is derived as equation (8) using equation (4) and (7). Figure 5 represents relationship between measured carbon dioxide production rate and calculated carbon dioxide production rate by using equation (8). The trends agree with measured result as shown in the figure in which the R^2 is approximately 0.88 and the RMSE is 0.006.

$$P_{CO_2} = 1.589 \times 10^{-4}\left(94.4A_D + 83.9Met + 21.0C_g - 149.7\right) \quad (8)$$

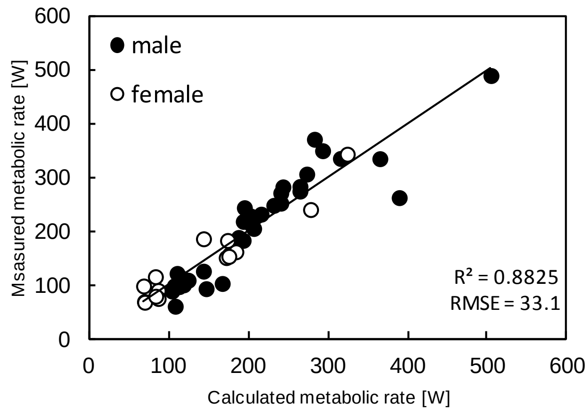

Figure 4: Relationship between measured metabolic rate and calculated metabolic rate

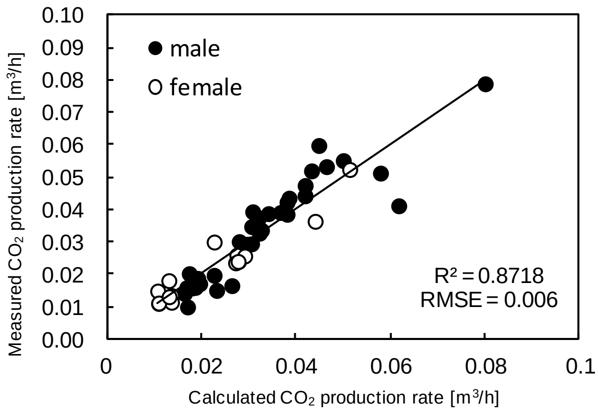

Figure 5: Relationship between measured carbon dioxide production rate and calculated carbon dioxide production rate

2.5 Comparison of carbon dioxide production rate of the equation, ASTM and JIS

Figure 6 shows carbon dioxide production rate of present work calculated by using the equation (8), of ASTM and of JIS. The ASTM's rate is calculated by equation (9) and (10) with RQ is 0.83 as the fixed value. Japanese average adult's body height and weight are put into the equation (8) and (10) to calculate the rate. Originally, the JIS shows relationship between carbon dioxide production rate and *RMR* (relative metabolic rate), which can be transformed into *Met* by using equation (11) (Herman, 2007).

Figure 6 indicates that present work's carbon dioxide production rate is larger than JIS's rate and the difference is 0.008m^3/h (8L/h) at 1.0Met. The present work's rate is also larger than ASTM's rate under the range of *Met* = 3. The difference at 1.0 Met is 0.004m^3/h (4L/h).

$$F = RQ\frac{0.00276A_{DB}Met}{(0.23RQ + 0.77)} \quad (9)$$

$$A_{DB} = 0.203 \times W^{0.425} \times H^{0.725} \quad (10)$$

Where

A_{DB} is the DuBois body surface area [m^2]
F the carbon dioxide production rate [L/h]
W is the body weight [kg]
H is the body height [m]

$$RMR = 1.2 \times (Met - 1) \tag{11}$$

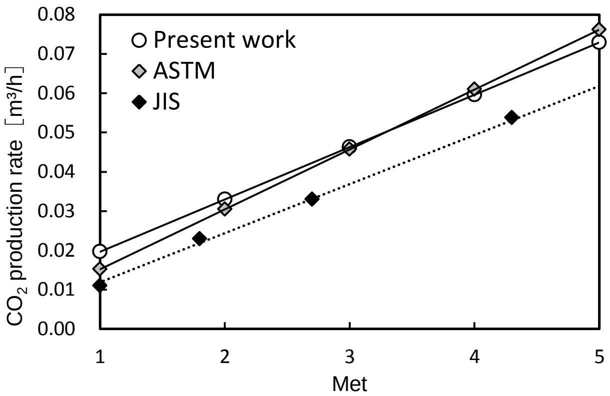

Figure 6: carbon dioxide production rate of present work, ASTM 6245-12 and JIS A1406 (using average Japanese adult's body height and weight)

3 ACCURACY TESTING IN SINGLE ZONE

3.1 Measurement for accuracy testing

As shown in the above, there are certain differences of carbon dioxide production rate between the equation and shown in the ASTM and the JIS. Therefore, by measuring carbon dioxides concentration under condition of known ventilation rate in rooms considered as single zone, the accuracy of the equation was tested.

Condition of the measurement is shown in Table 3. The room-A was occupied by a lecturer and university students for lecture. The room-B was occupied by university students for self-schooling. The room-A employs mechanical ventilation fans included in an air handling unit and its ventilation rate was measured by decay method using carbon dioxide concentration after leaving all occupants. The room-B employs mechanical fans, however, only an experimental exhaust fan, whose air flow rate can be given even in situ situation, was operated during the measurement.

Personal attribute, which are age, gender, body height and weight, of occupants were obtained. Additionally, Occupants' activities, which were *Met* = 1.0 and 1.2, were determined by visual judgment.

Table 3: Condition of measurement

Case	A-1	A-2	B-1
Name of room	room-A		room-B
air volume of room [m^3]	468		141
Ventilation rate of room [m^3/h]	1,300*		140**
Number of occupants	58	61	6
Outdoor CO_2 conc. [ppm]	413	403	400

*rate of mechanical ventilation employed in AHU measured by decay method
**set by using additional experimental exhaust fan

3.2 Measurement results and discussion

Measured carbon dioxide concentration and computed results given by using equation (12) are shown in Figure 7, 8 and 9. Carbon dioxide concentration measurement instruments were placed at the centre of the room-A and next to the suction part of the experimental exhaust fan in the room-B. The measurement interval was 30 seconds.

$$\frac{dC_i}{dt} V_i = \sum P_{CO_2} + Q_{io}(C_o - C_i) \tag{12}$$

Where

C_i concentration of carbon dioxide of target room [m^3/m^3]

C_o concentration of carbon dioxide of outdoor [m^3/m^3]

Q_{io} ventilation rate [m^3/h]

As shown in these diagrams, the trends of present work's concentration are almost similar to the measurement values except occasional risings especially in the room A compared with other computed values. The occasional risings are considered to be caused by non-uniform mixing state of carbon dioxide and incompleteness of visual judgement for occupants' activities. However, the present work's concentration of the room B, considered as being nearly uniform concentration condition, is almost accordance with measured concentration. In these diagrams, RMSE of the each computed concentration is shown, and they indicate that present work using equation (8) gives the most correct carbon dioxide concentration compared with the other ways.

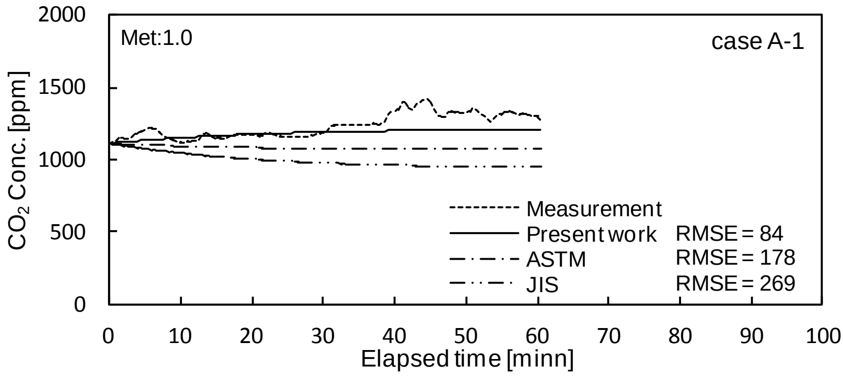

Figure 7: CO_2 concentration in case A-1

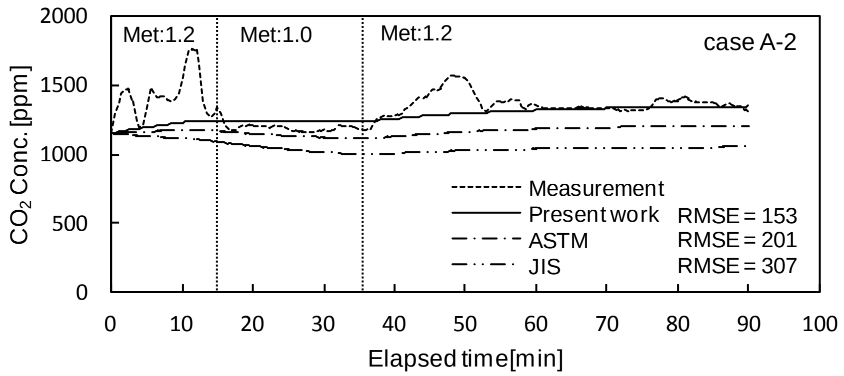

Figure 8: CO_2 concentration in case A-2

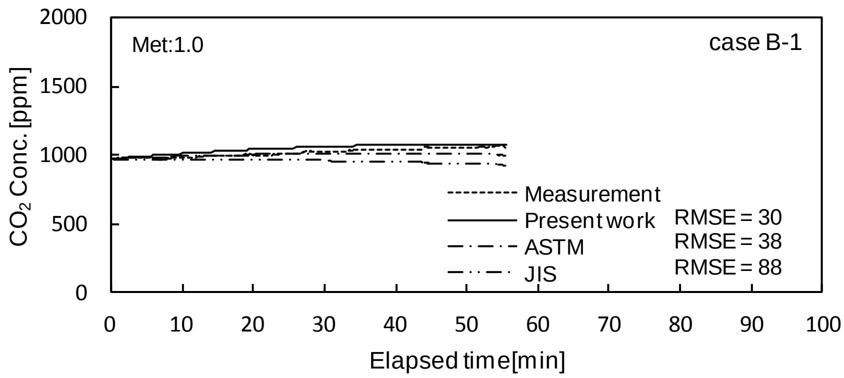

Figure 9: CO_2 concentration in case B-1

4 CONCLUSION

Based on data obtained by Douglas bag method with approximately total 70 voluntary Japanese subjects, a prediction equation for occupants' carbon dioxide production rate included in exhaled breath is developed. This equation has variables, such as *Met* and personal attribute (body height, body weight and gender). Therefore, the equation has certain advantages, like as taking gender difference into the formula and based on multiple Japanese subjects' data, compared with the personal carbon dioxide production rates shown in JIS A 1406^{1974} and ASTM D6245-12.

From measurement results operated at single zones, computed carbon dioxide concentration of present work shows the closest to the measurement value compared with the other standards' value under the condition of occupants' *Met* is 1.0 or 1.2. Therefore these results can allow predicting more correct carbon dioxide concentration produced by occupants', especially Japanese occupants', exhaled breath in single zone. Higher *Met* testing, and more measurement in buildings including within multi zone will be warranted.

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