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A New Approach to Estimating Carbon Dioxide Generation Rates from Building Occupants

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Indoor CO_2 concentrations have been prominent in discussions of building ventilation and indoor air quality (IAQ) since the 18th century. More recent discussions have focused on the impacts of CO_2 on building occupants as well as the use of indoor CO_2 to estimate ventilation rates and to control outdoor air ventilation. While the rates at which building occupants generate CO_2 are key to these applications, the rates currently in use are not based on recent references or a thorough consideration of the impacts of occupant characteristics. However, the fields of human metabolism and exercise physiology have studied human activity for many decades, focusing on rates of energy expenditure, oxygen consumption and CO_2 generation, as well as the individual factors that affect these rates. These factors include sex, age, height, weight and body composition, with fitness level and diet composition also affecting energy expenditure and the ratio of O_2 consumed to CO_2 produced. This paper applies the principles of these fields to yield an updated approach to estimating CO_2 generation rates from building occupants, which is described in detail in Persily and de Jonge (2017).

CURRENT APPROACH TO ESTIMATE CO_2 GENERATION RATES

The ventilation and IAQ fields have long used the following equation to estimate CO_2 generation rates from building occupants (ASHRAE 2017):

$$V_{CO2} = \frac{0.00276 A_D M\ RQ}{(0.23RQ + 0.77)} \quad (1)$$

where V_{CO2} is the CO_2 generation rate per person (L/s); A_D is the DuBois surface area of the individual (m^2); M is the level of physical activity, sometimes referred to as the metabolic rate (met); and RQ is the respiratory quotient. A_D is estimated from height H in m and body mass W in kg as follows:

$$A_D = 0.203 H^{0.725} W^{0.425} \quad (2)$$

The respiratory quotient, RQ, is the ratio of the volumetric rate at which CO_2 is produced to the rate at which oxygen is consumed, and its value depends primarily on diet. Based on data on human nutrition in the U.S, RQ equals about 0.85.

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Equation 1 first appeared in the Thermal Comfort chapter of the ASHRAE Fundamentals Handbook in 1989. That discussion, as well as the discussion in the 2017 handbook, references a 1981 paper by Nishi, which does not discuss the basis of this equation nor provide references. The Fundamentals Handbook also contains a table of metabolic rates for various activities, which has remained unchanged since the 1977 edition. These values are based on references predominantly from the 1960s, though some are even older. The same metabolic rate values are contained in the ASHRAE thermal comfort standard (Standard 55).

NEW APPROACH ESTMATION OF CO_2 GENERATION RATES

The new approach to estimating CO_2 generation rates from building occupants is based on concepts from the fields of human metabolism and exercise physiology. The first step in this new approach is to estimate the basal metabolic rate (*BMR*) of the individuals of interest. Equations for estimating *BMR* values as a function of sex, age and body mass are presented in Schofield (1985) and shown in Table 1.

After estimating the value of *BMR*, the next step is to estimate the occupants' level of physical activity as expressed by the value of *M*. There are two primary references for energy requirements for different physical activities. The first is a report prepared by the Food and Agriculture Organization of the United Nations (FAO), the World Health Organization (WHO) and the United Nations University (UNU), which discusses human energy requirements as a function of age and other individual characteristics (FAO, 2001). The second is a web-based compendium of physical activities (Ainsworth et al., 2011a; Ainsworth et al., 2011b). The rate of energy use of an individual, or group of individuals, engaged in a specific activity is estimated by multiplying the *BMR* value for that individual or group by the value of M for the activity. Persily and de Jonge (2017) contains tables of *M* values for various activities from the FAO report and the web-based compendium.

after the *BMR* value and the value of *M* for the relevant activity have been determined, their product in units of MJ/day is converted to L of oxygen consumed per unit time. This conversion is based on the conversion of 1 kcal (0.0042 MJ) of energy use to 0.206 L of oxygen consumption. This conversion results in 1 MJ/day of energy use corresponding to 0.00057 L/s of oxygen consumption, which based on a respiratory quotient *RQ* of 0.85, corresponds to 0.00048 L/s of CO_2 production. Based on this approach, the CO_2 generation rate can be expressed in L/s at an air pressure of 101 kPa and a temperature of 273 K, with *BMR* in units of MJ/day and *M* in met and assuming RQ equals 0.85, using Equation (3).

$$V_{CO2} = BMR\ M\ 0.000484 \qquad (3)$$

Equation (4) shows the CO_2 generation rate for other values of T and P.

$$V_{CO2} = RQ\ BMR\ M\ (\frac{T}{P})\ 0.000211 \qquad (4)$$

Persily and de Jonge (2017) contains a table of CO_2 generation rates for a number of M values over a range of ages for both males and females.

DISCUSSION

This new approach for estimating CO_2 generation rates from individuals is based on concepts from the fields of human metabolism and exercise physiology, as well as more recent data than currently used in the fields of ventilation and IAQ. It is intended to replace the equation that has been used for decades within the ventilation and IAQ communities (Equation 1 in this paper) and offers important advantages. First, the previous equation is based on a 1981 reference that provides no explanation of its basis, while the new approach is derived using principles of human metabolism and energy expenditure. Also, the new approach characterizes body size using mass rather than surface area, which in practice is estimated not measured. Body mass is easily measured and data on body mass distributions are readily available. The new approach also explicitly accounts for the sex and age of the individuals being considered, which is not the case with Equation 1.

Based on the initial and limited analysis conducted to date, the use of the new method and the new physical activity data yields significant differences in CO_2 generation rates and resulting steady-state concentrations in some circumstances, in some cases higher and in others lower. More space types and occupancy characteristics need to be investigated before any general trends are revealed.

The approach presented in this paper for estimating CO_2 generation rates from building occupants constitutes a significant advance in the analysis of IAQ and ventilation and should be considered in future applications of CO_2 in ventilation and IAQ studies and standards. In addition, the sources of physical activity data identified should be incorporated into the references that currently use older and much more limited data sources, i.e., ASHRAE Standard 55, the ASHRAE Fundamentals Handbook, and ASTM D6245.

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Table 1

BMR values (Schofield 1985). (m is body mass in units of kg)

	BMR (MJ/day)	
Age (y)	**Males**	**Females**
< 3	0.249 m − 0.127	0.244 m – 0.130
3 to 10	0.095 m + 2.110	0.085 m + 2.033
10 to 18	0.074 m + 2.754	0.056 m + 2.898
8 to 30	0.063 m + 2.896	0.062 m + 2.036
30 to 60	0.048 m + 3.653	0.034 m + 3.538
>= 60	0.049 m + 2.459	0.038 m + 2.755