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

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ABSTRACT

Indoor carbon dioxide (CO_2) concentrations have been used in the fields of building ventilation and indoor air quality (IAQ) for decades. Specific applications include the estimation of ventilation rates, control of outdoor air ventilation rates based on indoor CO_2 as an indicator of occupancy, and use of CO_2 as an IAQ performance metric. All of these applications require values for the CO_2 generation rates of the occupants of the space or building being considered. Human CO_2 generation rates depend on their level of physical activity as well as their sex, age, and body size. Historically and currently, these rates have been based on formula and data from the literature that are many decades old. In many cases, a single value for an adult on the order of 0.3 L/min is used independent of individual characteristics that are known to impact CO_2 generation rates. While the fields of human metabolism and exercise physiology have been studying human energy use, oxygen consumption and CO_2 generation for many decades, that knowledge has not been incorporated by the ventilation and IAQ communities. This paper describes the known dependencies of CO_2 generation rates on occupant characteristics and presents a calculation method for estimating these generation rates based on these concepts. This method is more robust and up-to-date than previously-established calculation procedures and will support more accurate values of CO_2 generation rates for use in ventilation and IAQ applications. The paper also compares the CO_2 generation rates using the new approach to those from the approach commonly used today as well as the resulting steady-state concentrations for different space types.

KEYWORDS

Carbon dioxide; human metabolism; physical activity

1 INTRODUCTION

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 (Persily 2015). 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.

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.

2 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):

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

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:

$$A_D = 0.203 H^{0.725} W^{0.425} \tag{2}$$

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 (Black et al., 1986). Based on data on human nutrition in the U.S, specifically the ratios of fat, protein and carbohydrate intake (Wright and Wang, 2010), RQ equals about 0.85.

Equation 1 first appeared in the Thermal Comfort chapter of the ASHRAE Fundamentals Handbook in 1989. That discussion, as well as the current discussion in the handbook, references Nishi (1981), which presents that equation as a means of measuring the metabolic rate of an individual. Nishi does not discuss the basis of this equation nor provide references. The ASHRAE 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 ASHRAE 2013), with similar data contained in ISO standard 8996 (ISO, 2004). As noted later in this paper, there are more recent and comprehensive sources of metabolic rate data.

The above equations and data are currently being used to estimate CO_2 generation rates within the field of ventilation and IAQ. For example, ASTM D6245 presents these equations and notes that for an average-sized adult (A_D = 1.8 m^3) engaged in office work at 1.2 met, the corresponding CO_2 generation rate is 0.0052 L/s (ASTM 2012). For a child (A_D = 1 m^2) at the same level of physical activity, the corresponding CO_2 generation rate is 0.0029 L/s. Note that discussions of the application of Equation 1 to ventilation and IAQ do not generally consider effects of air density on CO_2 generation rates, simply presenting these rates in volumetric units without specifying the air temperature or pressure.

3 ESTMATION OF CO_2 GENERATION RATES

This section describes a new approach to estimating CO_2 generation rates from building occupants based on concepts from the fields of human metabolism and exercise physiology, as described in more detail in Persily and de Jonge (2017). This approach uses the basal metabolic rate (*BMR*) of the individual(s) of interest combined with their level of physical activity. This approach contrasts with Equation 1, which only considers body surface area and level of physical activity.
The first step in this new approach is to estimate the *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. For example, the *BMR* of an 85 kg male between 30 y

and 60 y old is 7.73 MJ/day and 6.09 MJ/day for a 75 kg female in this same age range.

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
18 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

After estimating the value of *BMR*, the next step is to estimate their level of physical activity in terms of the value of *M* that corresponds to the activities in which they are involved. There are two primary references for obtaining information on 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 a factor that characterizes the specific activity. The FAO report refers to this factor as the physical activity ratio (*PAR*), while the web-based compendium refers it as the metabolic equivalent using the term *MET*. In this paper, the variable *M* (in dimensionless units of met) is used to describe the ratio of the human energy use associated with a particular physical activity to the BMR of that individual. Persily and de Jonge (2017) contains tables of values of *M* for various activities from the FAO report and the web-based compendium.

Once 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 (Lusk, 1924). The exact conversion depends on the relative oxidation of carbohydrates and fat, but given the variation in the other factors used to calculate CO_2 generation rates, a value of 0.206 L is a reasonable approximation. 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 (discussed above), corresponds to 0.00048 L/s of CO_2 production. A *BMR* value of 7.73 MJ/day, mentioned above for an 85 kg male between 30 y and 60 y of age, therefore corresponds to 0.0037 L/s of CO_2 production. Using a physical activity level of 1.5 met for sitting tasks, light effort (e.g. office work) results in a CO_2 generation rate of 0.0056 L/s, which is close to the value of 0.0052 L/s cited in ASHRAE Standard 62.1 and ASTM D6245 for an adult.

Based on the approach just described, 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, using Equations (3) and (4).

$$V_{CO2} = RQ\ BMR\ M\ 0.000569 \tag{3}$$

Assuming RQ equals 0.85, Equation 3 can be expressed as:

$$V_{CO2} = BMR\ M\ 0.000484 \tag{4}$$

Adjustments to other values of air pressure and temperature are described in Persily and de Jonge (2017), with Equation (5) showing the CO_2 generation rate for other values of T and P.

$$V_{CO2} = RQ\ BMR\ M\ (\frac{T}{P})\ 0.000211 \qquad (5)$$

In order to facilitate use of these calculations, Table 2 contains CO_2 generation rates for a number of *M* values over a range of ages for both males and females. The mean body mass values are based on data in the EPA Exposure Factors Handbook, specifically the values in Tables 8-4 for males and 8-5 for females (EPA, 2011). These values are most accurate, but still inherently approximate, when applied to a group of individuals and will not generally be accurate for a single individual.

Table 2. CO_2 generation rates for ranges of ages and level of physical activity

			CO_2 generation rate (L/s)						
Age (y)	**Mean mass (kg)**	***BMR* (MJ/day)**	Level of physical activity (met)						
			1.0	1.2	1.4	1.6	2.0	3.0	4.0
Males									
< 1	8.0	1.86	0.0009	0.0011	0.0013	0.0014	0.0018	0.0027	0.0036
1 to <3	12.8	3.05	0.0015	0.0018	0.0021	0.0024	0.0030	0.0044	0.0059
3 to < 6	18.8	3.90	0.0019	0.0023	0.0026	0.0030	0.0038	0.0057	0.0075
6 to < 11	31.9	5.14	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0100
11 to < 16	57.6	7.02	0.0034	0.0041	0.0048	0.0054	0.0068	0.0102	0.0136
16 to < 21	77.3	7.77	0.0037	0.0045	0.0053	0.0060	0.0075	0.0113	0.0150
21 to < 30	84.9	8.24	0.0039	0.0048	0.0056	0.0064	0.0080	0.0120	0.0160
30 to < 40	87.0	7.83	0.0037	0.0046	0.0053	0.0061	0.0076	0.0114	0.0152
40 to < 50	90.5	8.00	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0155
50 to < 60	89.5	7.95	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0154
60 to < 70	89.5	6.84	0.0033	0.0040	0.0046	0.0053	0.0066	0.0099	0.0133
70 to < 80	83.9	6.57	0.0031	0.0038	0.0045	0.0051	0.0064	0.0095	0.0127
>= 80	76.1	6.19	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
Females									
< 1	7.7	1.75	0.0008	0.0010	0.0012	0.0014	0.0017	0.0025	0.0034
1 to <3	12.3	2.88	0.0014	0.0017	0.0020	0.0022	0.0028	0.0042	0.0056
3 to < 6	18.3	3.59	0.0017	0.0021	0.0024	0.0028	0.0035	0.0052	0.0070
6 to < 11	31.7	4.73	0.0023	0.0027	0.0032	0.0037	0.0046	0.0069	0.0092
11 to < 16	55.9	6.03	0.0029	0.0035	0.0041	0.0047	0.0058	0.0088	0.0117
16 to < 21	65.9	6.12	0.0029	0.0036	0.0042	0.0047	0.0059	0.0089	0.0119
21 to < 30	71.9	6.49	0.0031	0.0038	0.0044	0.0050	0.0063	0.0094	0.0126
30 to < 40	74.8	6.08	0.0029	0.0035	0.0041	0.0047	0.0059	0.0088	0.0118
40 to < 50	77.1	6.16	0.0029	0.0036	0.0042	0.0048	0.0060	0.0090	0.0119
50 to < 60	77.5	6.17	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
60 to < 70	76.8	5.67	0.0027	0.0033	0.0038	0.0044	0.0055	0.0082	0.0110
70 to < 80	70.8	5.45	0.0026	0.0032	0.0037	0.0042	0.0053	0.0079	0.0106
>= 80	64.1	5.19	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0101

4 DISCUSSION

While the approach described in this paper for estimating CO_2 generation rates from individuals has the advantages that it is based on principles of human metabolism and exercise physiology, as well as using more recent data on levels of physical activity, it is not yet clear how much it will impact applications of indoor CO_2 to building ventilation and IAQ. Analyses are needed to understand the impact on CO_2 demand control ventilation system setpoints, as well as the associated energy use. Other analyses are also needed to investigate how these updated CO_2 generation rates will impact the use of CO_2 as an IAQ metric. As an initial step in those analyses, CO_2 generation rates using the new approach are compared to those from the approaches commonly used today, as well as the resulting steady-state concentrations, for different space types.

Table 3 presents values of CO_2 generation rates and steady state indoor CO_2 concentrations (above outdoor) for three different space types, calculated three different ways. The columns labelled "Standard values" employ the default CO_2 generation rates provided in ASTM D6245, 0.0052 L/s for adults and 0.0029 L/s for children, both assuming 1.2 met of physical activity. Ideally, a user of that standard would not rely on these typical values but would instead calculate them for the spaces they are considering, using an appropriate body surface area and met level. However, it is also possible that some use these average values without considering the occupants in their specific situation. The values labelled "Equation 1 (Nishi)" use equation 1 in this paper, which accounts for surface area A_D and met level M. For the Office and Conference room, M is assumed to equal 1.4, based on the more recent physical activity data referenced in this paper. The body surface area A_D is assumed to equal 2.0 m^2, based on mean values for adult males and females (EPA 2011). The classroom values are assume an occupancy of 24 students (1.2 met, 0.8 m^2) and 1 teacher (1.6 met, 2 m^2). The values labelled "Equation 4" use the values in Table 2 of this paper for the occupants as just described. The last three columns of Table 3 present steady-state values of the indoor minus outdoor CO_2 concentration, using the average CO_2 generation rates for each space and assuming they are ventilated in accordance with ASHRAE Standard 62.1 (ASHRAE 2016), per the values in the second column of the table.

Table 3. Comparison of CO_2 Generation Rates and Steady-State Indoor Concentrations

		Average CO_2 Generation Rate (L/s per person)			**Steady-State Indoor – Outdoor CO_2 Concentration (mg/m^3)**		
Space type	Outdoor air ventilation per Standard 62.1 (L/s per person)	"Standard" values	Equation 1 (Nishi)	Equation 4 in this paper	"Standard" values	Nishi Equation	Equation 4
Office	8.5	0.0052	0.0068	0.0048	1120	1465	1039
Conference room	3.1	0.0052	0.0068	0.0048	3071	4018	2850
Classroom (5 to 8 y)	7.4	0.0030	0.0026	0.0030	740	631	746

In comparing the CO_2 generation rates in Table 3, the values calculated using Equation 4 of this paper are about 8 % lower than the "Standard values" for the Office and Conference room and the same for the Classroom. However, they are close to 40 % less than the value from the Nishi equation for the Office and Conference room and about 15 % higher for Classroom. The steady-state concentrations using Equation 4 are about 7 % lower than the "Standard values" in the Office and Conference room and very close in the Classroom. Compared to the Nishi equation, the concentrations using Equation 4 are about 30 % less in the Office and Conference room. The values using Equation 4 are close to 20 % higher than the Nishi values in the Classroom. Based on this very limited analysis, the use of the new method embodied in Equation 4 and the new physical activity data can yield differences CO_2 generation rates and steady-state concentrations, in some cases higher and in others lower. More space types and occupancy characteristics need to be investigated before any general trends are revealed, but it seems clear that the new method will yield significantly different results in many cases.

5 CONCLUSIONS

The approach described in this paper 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 those 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. As new data on body mass become available, these data can be used to adjust CO_2 generation rates accordingly. Similarly, new information on *BMR* values and approaches to their estimation can also be easily applied to these calculations.

The CO_2 generation rate estimation method described here is applicable to groups of individuals, as the theory behind the method and the data are based on groups, not single individuals. If the rate of energy consumption or CO_2 generation of a specific individual is needed, it must be measured for that individual to account for differences that can exist due to body composition, diet, genetics and other factors. When considering a population of individuals in a building or space, the average values derived using the described approach will be more reliable than for a single individual. However, that reliability should be increased by characterizing the specific population of interest in terms of sex, age, body mass and activity level. Methods for performing such characterizations in a standardized fashion are not described in this paper. The increased accuracy of CO_2 generation estimates that may be achieved by doing so have not been studied, but additional research would be useful to demonstrate their value.

Based on the initial and limited analysis presented in this paper, the use of the new method embodied in Equation 4 and the new physical activity data, can yield 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, but it seems clear that the new method will yield significantly different results in many cases.

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, ISO Standard 8996, and ASTM D6245 (ASHRE 2013, ASHRAE 2017, ISO 2004, ASTM 2012).

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