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Optimum energy use to satisfy indoor air quality needs

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ABSTRACT

Indoor air quality is important to occupant health. Ventilation is a widely used technique for improving indoor air quality. However, improper ventilation results in heat losses up to 70.0% and is often the source of energy usage problems. According to the final report of the HOPE [11], the simultaneous assurance of ventilation, energy reduction and occupant health remains a design challenge. In addition, CO_2 is a pollutant which is largely impacted by air exchange, the effects of which cannot be neglected in indoor air quality. Therefore, this study focuses on levels of CO_2 and calculates the makeup air rate and recirculation air rate of indoor spaces. The optimum ratio of makeup air and recirculation air is evaluated in Korea to maintain acceptable indoor air quality and to save energy.

1. Introduction

Indoor air quality has changed due to industrial development, attitude, and occupant lifestyles and directly or indirectly affects the health and well-being of building users [1–4]. Good indoor air quality is defined as air free of pollutants that can cause occupant irritation, discomfort, or health problems. Indoor thermal conditions and relative humidity, aspects of indoor air quality, also influence comfort and health [5]. Recently, more extensive use of insulation and tighter building designs using new methods and technologies as well as renewable energy sources have reduced heating and cooling demands. However, the reduced airflow increases pollutant concentrations in interior spaces [3,6,7].

Air exchange rate is extremely important for pollutant concentrations in indoor settings and is accomplished mainly through ventilation in order to control indoor air pollutants and to ensure pleasant and healthy indoor air quality [3,7–10]. However, the use of air exchange results in an approximate 70% building energy loss [11]. According to HOPE (2005), it is very difficult to simultaneously attain energy reduction and occupant health with regard to indoor air quality [11].

It is well known that natural ventilation is the most effective and energy-efficient method for use in residential homes [12]. However, countries, such as Korea, where little land is available for residential building projects and population density is high, rely significantly on high-rise and high-tech modern buildings as a solution for housing issues. The windows in these buildings are usually sealed for energy-efficiency, prohibiting ventilation through window cracks and/or building gaps [12]. However, the Indoor Air Quality Management Act has regulated that an ACH (air change per hour) of 0.7 or greater is required for new and remodeled residential buildings [1]. To comply with this law, the application of mechanical ventilation is almost mandatory to ensure indoor air quality [13].

In addition, CO_2 is a pollutant which is dominantly determined by air exchange and whose presence must be considered in indoor spaces [14]. Therefore, CO_2 pollution is a critical issue that cannot be neglected. In Korea, most energy use usually takes place in the summer and winter. Therefore, this study focuses on CO_2 levels and calculates the ratio of makeup air to recirculation air in the Korean summer and winter. The optimum ratio of makeup air to recirculation air is evaluated to maintain an acceptable indoor air quality and to save energy.

2. Research method

There are two important parameters associated with ventilation system use. One is airflow rate, such as the number of air changers per hour; the other are building parameters that control airflow characteristics, infiltration dependent on the number and features of doors and windows, type of HVAC system, and room size. Ventilation systems involve the exchange of polluted indoor air with external air using ventilation, thus improving indoor air quality to ensure occupant health. The air exchange rate helps to determine how quickly the polluted air is replaced by fresh external air. Therefore, air exchange rates are extremely important to reduce pollutant concentrations in indoor settings.

Elkilani and Bouhamra [3] showed that recirculation air and makeup air are critical energy-saving factors in ventilation systems, and their study suggests an optimum model for energy use and

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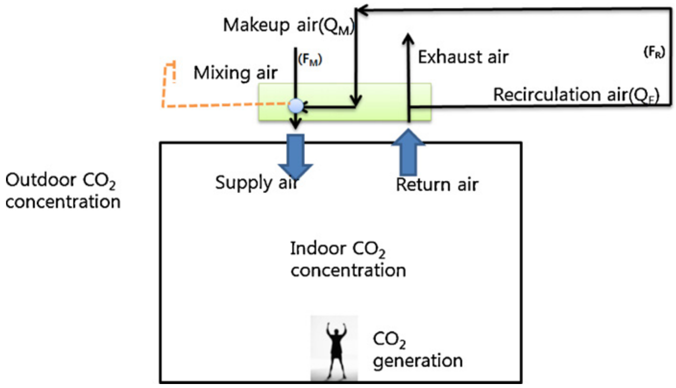

Fig. 1. A single ventilation system of cooling/heating load model.

indoor air quality (Fig. 1) [3]. Their model adheres to the required indoor air exchange rate, and the temperature of the mixed air formed through the combination of recirculation air and makeup air is lower (summer) or higher (winter) than that of the air taken in directly from the outside, resulting in reduction of cooling/heating loads. That is, its effectiveness in reducing the energy use associated with heating/cooling has been demonstrated. However, the pollutant concentration in the mixed air is higher than that of external air, requiring adjustments to the makeup to recirculation air ratio to ensure indoor air quality. Thus, the current study analyzes a method for minimizing energy consumption and assuring adequate indoor air quality.

In addition, this study also focused on CO_2 concentration. Kusiak and Li [15] stated that the equilibrium CO_2 concentration in a single room can be determined based on the number of occupants and the supply of outside air [15]. The steady-state indoor CO_2 concentration is obtained from the mass balance in Eq. (1), where C_{in} is the indoor CO_2 concentration, G is the CO_2 generation rate, C_{out} is the outdoor CO_2 concentration, V is the indoor volume (m^3), and W is the air pollutant adsorption rate.

$$V\frac{dC_{in}}{dt} = G + Q(C_{out} - C_{in}) - W \quad (1)$$

Applying the optimum energy use model (Fig. 1) of recirculation air and makeup air suggested by Elkilani and Bouhamra [3], the basic ventilation formula (1) is converted into Eq. (2) [16,17]. In addition, we assume no pollutant deposition, no exfiltration, and no air cleaning in the course of our study. In Eq. (2), Q_M is the makeup air flow rate (m^3/h), Q_R is the recirculation air flow rate (m^3/h), F_M is the makeup filter removal fraction, F_R is the recirculation filter removal fraction, and S is the CO_2 generation term (mg/h).

$$V\frac{dC_{in}}{dt} = Q_M((1 - F_M)C_{out} - C_{in}) - Q_R F_R C_{in} + S \quad (2)$$

Assuming a steady state, Eq. (2) is transformed into Eq. (3), where k is mixing factor, which we assumed to be 0.7 [3].

$$C_{in}\left(k\frac{Q_M}{V} + k\frac{Q_R F_R}{V}\right) = \left[k\frac{Q_M}{V}(1 - F_M)\right] C_{out} + \frac{S}{V} \quad (3)$$

In this study, indoor air quality (IAQ) and indoor temperature are controlled, and cooling/heating loads are determined through the makeup to recirculation air ratio of the HVAC system. As suggested in Fig. 1, it is because some of the warm indoor air escapes to the outdoors, while some of the outdoor air enters into the indoor space. This outdoor air that enters the indoor space is combined with the makeup air to form mixed air, the temperature of which is higher than that of the makeup air and lower than that of the recirculation air. Eq. (4) is used to calculate the temperature of the mixed air [3], where T_{in} is the indoor temperature, T_{out} is the outdoor temperature, and T_i is the mixed air temperature.

$$T_{in} + \frac{Q_M}{Q_R}T_{out} = \left(\frac{Q_M}{Q_R} + 1\right)T_i \quad (4)$$

As shown through the above equation, as the makeup to recirculation air ratio (Q_M/Q_R) increases, the indoor temperature decreases and the heating load increases [3]. This relationship allows for the determination of energy consumption. The heating load calculation is shown below in Eq. (5), where Q is the ventilation rate, ρ is the air density (1.3 kg/m^3), and cp is specific heat capacity of air at a constant pressure (1.2 kj/m^3 k).

$$q_c = Q\rho cp(T_{out} - T_{in}) \quad (5)$$

3. Experimental conditions

The capital region of Seoul (Fig. 2), the capital city of Korea, includes Seoul itself, satellite cities, such as Incheon, Suwon, Seongnam, Uijeongbu, Anyang, Bucheon and Gwangmyeong, and 19 districts of Gyeonggi Province, all within a 70.0 km radius of Seoul itself. The area of this capital region is 11,685.0 km^2, constituting 11.8% of the area of the entire country and housing more than 40.0% of the country's population. Therefore, the residence types and ventilation methods used in the country of Korea can be represented by the population of the capital region. This study analyzes indoor air quality and optimum energy use based on the capital region of Seoul, Korea.

The capital region of Korea has grown in terms of quantitative size, with a constant increase in population after the industrial movement in the 1960–1970s, resulting in overcrowding in the region. To address this problem, construction of high-rise buildings has rapidly increased to efficiently utilize the land in the downtown areas. Therefore, high-rise multi-purpose buildings have become a new residence type due to the development of architectural technology beginning in the year 2000 [18]. In addition, the construction of many high-rise residence buildings makes natural ventilation difficult. Thus, the introduction of mechanical ventilation to remove indoor pollutants and ensure occupant health has become a common practice [19].

Meanwhile, the architecture field is focused on low-energy construction due to global warming and high oil prices. However, Korea depends on imported energy for more than 97.0% of its needs, with 18.0% of this energy being consumed in residential buildings [20]. Therefore, improvements in energy consumption are of increasing concern in Korea, and this study uses the model introduced in Section 2 to ensure indoor air quality in the design of a mechanical ventilation system to optimize energy consumption.

To do so, three main factors should be considered, the weather of the region, the desired comfortable body temperature during cooling/heating and the indoor/outdoor air quality based on CO_2 concentration. The Seoul region has a monsoon-influenced humid continental climate. Summer is generally hot and humid, with monsoons taking place from June until September and having a daily average temperature of 22.0–30.0 °C. Conversely, winter is often very cold and has a daily average temperature of −7.0 to 1.0 °C [21]. In addition, the most comfortable indoor temperature for occupants was taken from the study of Li et al. [22]. The most comfortable indoor temperature for occupants is based on the analysis of data collected over 20 years in Korea. The summer temperature corresponding to a neutral thermal sensation of 0 was 24.7 °C, and that for winter was 22.5 °C [21]. However, considering the recent energy saving policy, the indoor temperature must be set to 26.0 °C or higher in summer and 20.0 °C or lower in winter (Te-specified standard). Therefore, the analyses in this study were conducted based on these values. Furthermore, in terms of