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Returning and net escape probabilities of contaminant at a local point in indoor environment

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ABSTRACT

The quantified recirculation of a contaminant in a local domain is an essential property of the ventilation efficiency in a room. The returning probability of a contaminant (α) generated in a local domain and its net escape probability (NEP) are essential information for understanding the structure of the contaminant concentration distribution in a room and for controlling the indoor air quality. Here, we propose the fundamental definitions of α and NEP and discuss their potential relation with the net escape velocity (NEV) concept. NEP is defined at a local point and/or local domain as the probability that a contaminant is exhausted directly through an exhaust outlet and does not re-circulate to the target local point/domain again. In a computational fluid dynamics (CFD) simulation, the minimum local domain in a room corresponds to the control volume (C.V.) of discretization; hence, NEP in a C.V. is assumed as the probability in a point without volume. In this study, the calculation results of α, NEP, and NEV distributions in a simple two-dimensional model room and a three-dimensional room with push-pull type ventilation system are demonstrated and discussed.

1. Introduction

Ventilation is an essential factor to maintain indoor air quality at a certain level. Increasing the ventilation rate leads to decreasing contaminant concentration level in an indoor environment. In general, ventilation represents the exchange of contaminated indoor air with less contaminated/fresh outdoor air. Here we assume the outdoor air is clean. However, an increase in ventilation rate causes an increase in energy consumption of an HVAC (heating, ventilating, and air-conditioning) system; hence, this is a trade-off problem in indoor environmental design [1–4]. Ventilation is comprehensive, and multiple issues and several primary impacts of ventilation have been identified with regard to the control of indoor air quality, comfort, performance, freshness, and energy consumption [5,6]. Therefore, many researchers have investigated on effective methods of ventilation not only for residential spaces but also for industrial buildings [7,8]. In the case of pharmaceutical industries, a very effective method of removing contaminants from a room, such as cleanroom techniques, is required. Push-pull type ventilation systems offer an appropriate mechanism for controlling the contaminants generated in a local area of a room. This system consists of a push hood and an exhaust hood (a pull hood), which enable uniform air flow over a considerable distance. In addition, a uniform low-velocity supply of air enters the working space from the push hood and the exhaust is directed outside the room through the pull hood. It creates a separate volume inside the room and achieves a more efficient ventilation in a part of that room. Therefore, people can work comfortably anywhere in the workspaces throughout this local ventilation zone. Recently, a study on pollutant control in residential kitchens based on the push-pull ventilation system has been performed [9]. Several review studies have reported results about the ventilation effectiveness and its impact on the control of the indoor air quality. For instance, Cao et al. reviewed the scientific literature on the relationship between airflow distribution and ventilation effectiveness [10], and Liddament provided technical information related to ventilation effectiveness [11]. The review paper by Li at el [12]. pointed out that there was insufficient data to specify the relation between ventilation, airflow pattern in building, and the spread of infectious diseases.

According to the specification codes, e.g., those in Japan and the

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Republic of Korea, the ventilation rate in a residential room shall be controlled to be a minimum of 0.5 ACH (air changes per hour) and more. On the other hand, the ventilation rate shall maintain the authorized threshold of contaminant concentration level in relation to the performance-based code. The purpose of this performance-based ventilation in residential spaces is to assure a healthy indoor air quality level. In particular, the control of air quality at a local domain, e.g., an occupied zone, becomes essentially important. The air quality control in a local domain or at a local point has been categorized as the study of ventilation efficiency or ventilation effectiveness, and fruitful research results have been achieved by several researchers [13–18]. At the beginning of 1980, a new index for evaluating ventilation efficiency, the age of air concept, was proposed by Sandberg to discuss directly the efficiency in the distribution of fresh air from a supply inlet to a certain point in a room [13,14]. This age of air concept has been widely adopted in ventilation design and is also used for constituting various indices of ventilation effectiveness, e.g., contaminant removal efficiency, air exchange efficiency, and normalized contaminant concentration in an occupied zone [7]. Kato and Murakami proposed a calculation procedure for the age of air distribution in a room by using a steady state flow and contaminant-concentration distribution analysis, which is based on computational fluid dynamics (CFD), a simulation technique, and the age of air is defined as the index for ventilation efficiency No. 3 (SVE3) concept [15]. In some recent work, the age of air concept and air change efficiency (ACE) were used to investigate the local air quality/thermal comfort in indoor environments [19–23]. Meanwhile, a couple of indices for the ventilation efficiency were introduced, for example, an index to evaluate the effectiveness of ventilation using the mean concentration of the contaminant in the ventilated space, the purging flow rate (PFR) concept, which was proposed and calculated by Davidson and Olsson [24]. In addition, the visitation frequency (VF) concept proposed by Csanady [25] represents how many times a contaminant particle enters the local domain. The indoor ventilation efficiency indices described above were also applied to investigate and evaluate pollutant concentration distributions for the design of urban climatology [26–32]. However, there are some limitations to the practical use of these indices. The PFR can only be used with the contaminant concentration assumed as spatially uniform in the CFD analysis, and the VF should be expressed with the average staying time of particles in a local domain [16,17].

Ventilation efficiency and/or ventilation effectiveness could be important concepts to optimize indoor air quality, building energy consumption, and ventilation rate at a local domain in indoor environments, beyond the perfect mixing concept that is based on uniformity and homogeneity of the contaminant concentration in the entire room [13]. The essential transporter of the contaminant is the indoor air/fluid, and the contaminant concentration distributions are governed by a scalar transport equation coupled with the momentum and mass transport equations for a fluid, i.e., the Navier–Stokes and the continuity equations, respectively. In this scenario, the contaminant transport efficiency in indoor air is expressed by total flux, i.e., the convective and diffusive fluxes of the contaminant in a local domain [10,17]. With respect to the interaction between the local domain and its surrounding room environment, the total flux, which governs the contaminant transportation efficiency, could be separated into two components: (i) contaminant directly exhausted through an exhaust outlet in the room (and with no-return to the target local domain) and (ii) contaminant returned to the target local domain at least once by a recirculating flow in the room. Considering the control volume (C.V.) of the CFD simulation as the minimum resolution scale for a numerical analysis, we propose the net escape velocity (NEV) concept. The NEV defines the velocity scale of a contaminant (scalar) transporter for evaluating the local contaminant concentration at a point (equivalent to the volume-averaged contaminant concentration at the C.V.). This NEV concept is directly defined by the inflow and outflow fluxes of the contaminant against the target C.V [10,17]. Recently, the application of the NEV concept for investigating regional ventilation has received increasing attention [33–35]. However, this NEV concept remains uncertain with respect to the description/understanding of the relationship between the ambient space and target C.V. especially in terms of the returning/escape probability of a contaminant at the target C.V. The question may be phrased as “how many contaminants directly exhaust through an exhaust outlet, and how many contaminants return to the target C.V.?” Therefore, this study attempts quantitatively to address the returning/escape probability of a contaminant at the target C.V. through the relation between inflow and outflow fluxes at the C.V.

According to this background and scenario, we develop a new concept of ventilation index, the net escape probability (NEP), which represents the probability that the contaminant be exhausted directly through a room exhaust outlet and does not recirculate to the target local domain again. This NEP concept, which is defined in a local point (C.V. for the CFD analysis) is considered as complementary to the NEV concept. In this study, we introduce the definition and calculation procedure of the NEP by the CFD technique, and report the calculation results of NEP distribution in two-dimensional and three-dimensional model rooms, in which the contaminant is constantly generated in the target local domain. The specific relation between NEP and NEV is also discussed.

2. Definition of net escape probability

Here, we assume the C.V. of the CFD analysis as the target local domain to simplify the following discussion. The C.V. indeed has volume, but it is the minimum and finest space in view of the numerical resolution; hence, a C.V. may be assumed as approximately a point in the space. This assumption might be reasonable because the uniformity in the C.V. is mathematically secured by applying the finite volume method of CFD [36,37]. Further, the contaminant is assumed to be generated only at the target C.V.

When the amount of contaminant generated per unit time and volume is set to be q [kg/m^3/s], the total amount of contaminant generation in the C.V. becomes qV_{CV} [kg/s]. Here, V_{CV} is the volume of the target C.V. [m^3]. When the inflow flux into the C.V. per unit area and unit time is F_{inflow} [kg/m^2/s] (this flux represents the total flux and consists of convective and diffusive flux), the amount of contaminant that flows into the C.V. becomes $F_{inflow} \cdot A_{inflow}$ [kg/s]. A_{inflow} is the area through the inflow flux in the target C.V. [m^2].

Here, we define the returning probability α, which represents the probability that a contaminant returns to the target local domain (here, C.V.) under the condition that a contaminant is generated in the C.V.

If the returning probability α to the target local domain, i.e., the C.V. is assumed as constant (this means that the flow and the diffusion fields are at a steady state, and the local domain is reasonably small), this returning probability can be calculated by the summation of the geometric series of returning probability to the target local domain.

$$qV_{CV}\sum_{n=1}^{\infty}\alpha^n = qV_{CV}\frac{\alpha}{1-\alpha} = F_{inflow}\cdot A_{inflow} \tag{1}$$

Actually, the existence of an inflow flux against the target C.V. represents the return of the contaminant that is generated in the target C.V. along with the re-circulating flow in the room.