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Long-term prediction of dynamic distribution of passive contaminant in complex recirculating ventilation system

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ABSTRACT

Recirculating ventilation systems may act as carriers of hazardous substances. The long-term prediction of the dynamic distribution of contaminants in this type of system is crucial for the evaluation of pollution and further design of more efficient ventilation systems. However, few convenient methods can predict the dynamic distribution of contaminants, because the dynamic supply air concentrations resulting from air recirculation are unknown, especially over long time periods, such as months or years. In this study, a novel method is proposed to predict the dynamic distribution of contaminants over a long time period in a complex recirculating ventilation system, where an algebraic expression based on the indices of the response coefficient is applied to account for the relationship between the contaminant distribution inside the room and various boundary conditions. The method is established by obtaining comprehensive mathematical descriptions of the relationships between concentrations of contaminants in the air handling units, supply air inlets, return air outlets, and fresh air. Hourly supply air concentrations can be easily obtained by solving a matrix, and the dynamic distribution of contaminants is then calculated using an expression based on the response coefficient. The reliability of the proposed method is analyzed by both experimental and numerical methods. A simplified method is suggested to accelerate the time-consuming calculation of the response coefficient. The proposed method is beneficial for predicting three-dimensional dynamic distribution of contaminants in complex ventilation systems with an acceptable accuracy and time cost.

1. Introduction

People spend more than 90% of their time in enclosed environments, including vehicles and rooms of buildings [1,2]. Therefore, effectively controlling the pollution from various types of indoor and outdoor sources of hazardous substances is crucial for the health and safety of human beings [3]. Buildings are vulnerable to pollutants such as chemical and biological agents [4–7]. Moreover, events in the last decade, such as the outbreaks of Severe Acute Respiratory Syndrome (SARS, 2003) and the H1N1 Type A influenza (2009), have revealed the importance of taking more active measures to protect the environment in buildings [8,9]. Furthermore, the increasingly serious hazy weather (i.e., fine particulate matter), especially in China, in recent years has greatly raised awareness of the need to maintain an acceptable indoor air quality [10].

Ventilation systems play an important role in controlling indoor environment, specifically air temperature, humidity, and pollutant concentration. However, in most buildings with central air conditioning and ventilating systems, a large portion of old indoor air is recirculated to the air handling unit (AHU) to save energy [11–13]. The ventilation systems in these situations, therefore, act as carriers of hazardous substances [14]. The contaminants released in one room may be transported with return air into neighboring rooms or even distant rooms through the ventilation system, causing widespread exposure to a hazardous environment. Therefore, accurately predicting the dynamic distribution of contaminants in buildings with complex ventilation systems that utilize air recirculation during long time periods, such as months and years, can contribute to the overall evaluation of the exposure level of occupants to pollution, and inform the future design of more efficient ventilation systems.

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Nomenclature

$\overline{C^0}$	average concentration of the initial contaminant [kg/m^3]
$C^p(0)$	contaminant concentration of point p at moment 0 [kg/m^3]
$C^p(j\Delta\tau)$	contaminant concentration of point p at the jth time step [kg/m^3]
$C_e^{n_C,0}$	average concentration from all of the outlets at the steady state, when the emission rate from the n_C^{th} contaminant source is $S^{n_C,0}$ [kg/m^3]
$C_o^{n_f^{n_r}}(j\Delta\tau)$	concentration in the $n_f^{n_r}$ th fresh air inlet in the n_r^{th} room [kg/m^3]
$C_{od}[(j-I^{n_f^{n_r}})\Delta\tau]$	outdoor air concentration at the $(j-I^{n_f^{n_r}})^{\text{th}}$ time step [kg/m^3]
$C_R^{n_r,n_u}(j\Delta\tau)$	return air concentration in the n_u^{th} GAHU from the n_r^{th} room at the jth time step [kg/m^3]
$C_R^{n_u,T}(j\Delta\tau)$	total return air concentration in the n_u^{th} GAHU at the jth time step [kg/m^3]
$C_{R,in}^{n_R^{n_r,n_u}}(j\Delta\tau)$	concentration in the $n_R^{n_r,n_u}$ th outlet for the n_u^{th} GAHU in the n_r^{th} room [kg/m^3]
$C_S^{n_S}(\tau)$	contaminant concentration in supply air from the n_S^{th} inlet at moment τ [kg/m^3]
$C_S^{n_S,0}$	contaminant concentration in supply air from the n_S^{th} inlet at the 0$^{\text{th}}$ time step [kg/m^3]
$C_S^{n_S^{n_r,n_u}}(j\Delta\tau)$	concentration in the $n_S^{n_r,n_u}$ th inlet for the n_u^{th} GAHU in the n_r^{th} room [kg/m^3]
$C_S^{n_u}(j\Delta\tau)$	supply air concentration of the n_u^{th} GAHU at the jth time step [kg/m^3]
$CON^{n_u}(j\Delta\tau)$	known item caused by the concentrations in supply air and fresh air, and emission rate of contaminant source at the previous time steps, considering the time delay in part of the air ducts [kg/m^3]
f^{n_u}	fresh air ratio of the n_u^{th} GAHU $^{[-]}$
$I^{n_f^{n_r}}$	delayed time step for the transport of contaminant from the outdoor air opening to the $n_f^{n_r}$ th inlet [−]
$I^{n_R^{n_r,n_u}}$	delayed time step for the transport of contaminant from the $n_R^{n_r,n_u}$ th outlet to the n_u^{th} GAHU [−]
$I^{n_S^{n_r,n_u}}$	delayed time step for the transport of contaminant from the n_u^{th} GAHU to the $n_S^{n_r,n_u}$ th inlet [−]
N_C	number of contaminant sources [−]
$N_C^{n_r}$	number of contaminant sources in the n_r^{th} room [−]
$N_f^{n_r}$	number of direct fresh air inlets in the n_r^{th} room [−]
N_r	number of independent rooms [−]
$N_R^{n_r,n_u}$	number of return air outlets for the n_u^{th} GAHU in the n_r^{th} room [−]
$N_{R1}^{n_r,n_u}$	number of return air outlets with neglected time delay [−]
N_S	number of supply air inlets [−]
$N_S^{n_r,n_u}$	number of supply air inlets for the n_u^{th} GAHU in the n_r^{th} room [−]
$N_{S1}^{n_r,n_u}$	number of supply air inlets with neglected time delay [−]
N_u	number of GAHUs [−]
Q	ventilation rate of the room [m^3/s]
Q^{n_r}	ventilation rate of then_r^{th} room [m^3/s]
$Q_F^{n_u}$	fresh air flow rate of the n_u^{th} GAHU [m^3/s]
$Q_R^{n_u}$	return air flow rate of the n_u^{th} GAHU [m^3/s]
$Q_S^{n_u}$	supply air flow rate of the n_u^{th} GAHU [m^3/s]
$r^{n_R^{n_r,n_u}}$	ratio of return air flow rate in the $n_R^{n_r,n_u}$ th outlet of the n_u^{th} GAHU from the n_r^{th} room to the total return air flow rate of the n_u^{th} GAHU from the n_r^{th} room [−]
$R_R^{n_r,n_u}$	ratio of return air flow rate of the n_u^{th} GAHU from the n_r^{th} room to the total return air flow rate of the n_u^{th} GAHU [−]
$S^{n_C}(\tau)$	emission rate from the n_C^{th} contaminant source at moment τ [kg/s]
$S^{n_C,0}$	emission rate from the n_C^{th} contaminant source at the 0$^{\text{th}}$ time step [kg/s]
$S^{n_C^{n_r}}(i\Delta\tau)$	emission rate from the $n_C^{n_r}$ th contaminant source at the ith time step [kg/s]
V	volume of the room [m3]
$Y_C^{n_C,p}(j\Delta\tau)$	RCCS at an arbitrary point p from the n_C^{th} contaminant source at the jth time step [−]
$Y_{DF}^{n_f^{n_r},n_R^{n_r,n_u}}[(j-i)\Delta\tau]$	RCSA at the $n_R^{n_r,n_u}$ th outlet from the $n_f^{n_r}$ th fresh air inlet at the $(j-i)^{\text{th}}$ time step [−]
$Y_I^p(j\Delta\tau)$	RCID at an arbitrary point p from the initial concentration distribution at the jth time step [−]
$Y_S^{n_S,p}(j\Delta\tau)$	RCSA at an arbitrary point p from the n_S^{th} inlet at the jth time step [−]

Greek symbols

η^{n_u}	purification efficiency of contaminant in then_u^{th} GAHU [−]
$\eta_f^{n_r}$	purification efficiency of contaminant in fresh air in the n_r^{th} room [−]
T	transient time [s]
$\Delta\tau$	time interval [s]

Abbreviations

AHU	Air Handling Unit
CFD	Computational Fluid Dynamics
FCU	Fan Coil Unit
GAHU	Generalized Air Handling Unit
RAC	Room Air Conditioner
RCCS	Response Coefficient to Contaminant Source
RCID	Response Coefficient to Initial Distribution
RCSA	Response Coefficient to Supply Air

Computational fluid dynamics (CFD) has been widely utilized to predict the spatial and temporal distribution of indoor contaminants. Numerous studies have used CFD simulations to study ventilation and air quality [15–20]. Other attempts have been conducted to improve the computing speed of CFD [21–23]. Most of the existing work related to CFD has focused on one room, where all of the boundary conditions are known. However, in many actual buildings, different rooms are always connected with each other through ventilation systems that recirculate air. As the concentration of contaminant in return air is unknown, the concentration of contaminant in supply air is unknown as well; therefore, the predictions of the CFD simulations are usually inaccurate [24].

Multizone airflow network models can solve the issue of contaminant variations in the entire building, as they assume that the concentration of contaminants in each room is uniform [25–27]. For a specific condition of contaminant release, the concentration of the contaminant at an arbitrary position in the room is uniform for ideal mixing ventilation; however, the concentrations of the contaminant at different indoor positions and in return air or exhaust air outlets are actually different for different airflow