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Evaluating emergency ventilation strategies under different contaminant source locations and evacuation modes by efficiency factor of contaminant source (EFCS)

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ABSTRACT

Emergency ventilation plays an important role in protecting occupants when a hazardous contaminant is released indoors. A number of studies have been conducted to better understand how to protect indoor occupants with effective ventilation strategies. However, little attention has been paid to the impact of the non-uniform and time-dependent distribution of occupants during evacuation. A new concept, Efficiency Factor of Contaminant Source (EFCS), has recently been proposed to evaluate the performance of emergency ventilation by comprehensively considering the spatial and temporal distributions of both the contaminant and occupants. This paper aims to: (1) propose and demonstrate a procedure for determining an optimal ventilation strategy by using EFCS; (2) examine the effects of source locations, ventilation modes, and evacuation modes on the performance of emergency ventilation. One hundred cases with ten ventilation modes, two evacuation modes, and five source locations were investigated numerically. The results show that the EFCS concept can provide a reasonable way to evaluate the performance of emergency ventilation. The threats of different source locations may vary over a large range, and certain measures should be taken to monitor and prevent the releases at high threat locations. A system equipped with multiple ventilation modes is necessary since no universal ventilation mode can successfully mitigate all hazardous situations. The effects of an evacuation mode may be more significant than that of a ventilation mode under certain situations.

1. Introduction

With the occurrence of chemical and biological terrorism and the accidental release of toxic chemicals in indoor environments, more and more people have recognized that emergency ventilation is of great importance to protect indoor occupants. In comparison with the normal ventilation for thermal comfort and indoor air quality (IAQ), emergency ventilation pays more attention to the safety of occupants during the short period of time after the contaminant is released. It is a common practice in traditional emergency ventilation to protect occupants by increasing the airflow rate during an event [1], such as using auxiliary ventilation to rapidly exhaust smoke from a burning building. However the influence of a contaminant on indoor occupants not only depends on the airflow rate but also on the contaminant source location, airflow pattern, and temporal and spatial distribution of occupants during emergency events. As a result, merely increasing the airflow rate may have opposite effect. A previous study shows that improving airflow pattern maybe a better solution for pollutant removal rather than simply increasing airflow rate [2].

Since the performance of emergency ventilation is determined by many factors, it is extremely complicated to determine an optimal ventilation strategy or design an effective ventilation system without a reasonable evaluating index. To date, a number of commonly used indices, such as age of air [3], air exchange efficiency (AEE) [3,4], contaminant removal efficiency [5], and scale for ventilation efficiency (SVE) [6,7], have been developed for evaluating a ventilation system's steady-state performance. However, a suddenly released contaminant will influence the indoor environment over a relatively short period of time. Thus an index that

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Abbreviations: AMG, Algebraic Multigrid; BEC, Basic Exposure Cell; CFD, Computational Fluid Dynamics; EC, Exposure Cell; EFCS, Efficiency Factor of Contaminant Source; FVM, Finite Volume Method; RANS, Reynolds Averaged Navier-Stokes; SGEM, Spatial-Grid Evacuation Model; SIMPLE, Semi-Implicit Method for Pressure-Linked Equations.

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Nomenclature

BEC_i	*i*th basic exposure cell [–]
EC_i	*i*th exposure cell [–]
$\overline{C}_i(t)$	equivalent concentration of EC_i at time t [mg/m^3]
$\overline{C}_{n,i}(t)$	volume-weighted-average concentration of n layers [mg/m^3]
$\overline{C}^j_i(t)$	volume-averaged concentration in the jth layer of EC_i at time t [mg/m^3]
$\overline{C}_R$	average exhausted concentration of contaminant under steady-state conditions [mg/m^3]
m	identifying number of the individual [–]
N	total number of exposure cells [–]
w_j	weighted coefficient to reflect the differences of contact exposure along the height direction [–]
EFCS3(τ)	Efficiency Factor of Contaminant Source 3 (EFCS3) which reflects the influence of contaminant source on all the occupants in the period τ [–]
$PNC_i(t)$	number of occupants in EC_i at time t [–]
$x(m,t)$	coordinate of the occupant m at time step t in x direction [m]
$y(m,t)$	coordinate of the occupant m at time step t in y direction [m]
$u\rightarrow$	velocity vector [m/s]
U_m	velocity component of the occupant m in x direction [m/s]
V_m	velocity component of the occupant m in y direction [m/s]
S_ϕ	contaminant source term [mg/(m^3 s)]
t	time [s]
Δt	time step [s]
τ	a period of time [s]
Greek symbols	
ϕ	contaminant concentration [mg/m^3]
Γ_ϕ	contaminant diffusion coefficient in the air [m^2/s]

can be used to quantify the influence of the contaminant on the indoor environment over a finite period of time is required. To accommodate this requirement, we have presented several indices, including Accessibility of Supply Air (ASA), Accessibility of Contaminant Source (ACS), and Integrated Accessibility of Contaminant Source (IACS), in our previous studies [8-10]. The major advance of these indices is that they can be used in an unsteady state. However, they are still not appropriate for emergency ventilation since they cannot reflect the influence of a contaminant on occupants when the occupant distribution is changing with time during the evacuation. As a preliminary study, we used the IACS index concept to numerically analyze the influence of the contaminant source location, occupant distribution and air distribution on the emergency ventilation strategy [11]. However, the evacuation process was neglected in the study due to the inherent limitations of IACS.

To reasonably evaluate the emergency ventilation by considering the evacuation process, we further proposed a new concept of Efficiency Factor of Contaminant Source (EFCS) [12]. EFCS is a set of indices, including EFCS1–EFCS3, which reflects the occupants' relative exposure to the contaminant over time immediately after the contaminant was released. These indices comprehensively consider the spatial and temporal distribution of the contaminant and occupants in order to facilitate the evaluation of ventilation performance from multiple aspects. Suppose a room under study is discretized into finite spatial volumes. EFCS1 indicates the relative exposure of all the occupants to the contaminant distributed in each of the spatial volumes. With EFCS1, the relative exposure of all the occupants is distributed into the each spatial volume. EFCS2 indicates the relative exposure of each occupant to the contaminant distributed in the whole room. With EFCS2, the relative exposure of all the occupants is distributed into the each occupant. EFCS3 indicates the relative exposure of all the occupants to the contaminant distributed in the whole room. With EFCS3, the distributed values of EFCS1 and EFCS2 are accumulated into a single lumped value to represent the overall risk of exposure to all the occupants throughout the emergency event. All the three indices are the functions of the flow characteristic, occupant distribution, and source location, while independent of the intensity and composition of the contaminant source. Since EFCS3 is a single lumped value to represent the whole relative exposure of all the occupants, it is simpler to understand and easier to use than EFCS1 and EFCS2. Therefore, we have selected EFCS3 to evaluate different ventilation strategies in this study. The principal advantage of EFCS3 over IACS is that it successfully takes into account the temporal development of occupant distribution during the evacuation process. Moreover, using EFCS3 as a common metric, it is possible for us to focus on the effects of ventilation modes, evacuation modes, and source locations.

The objectives of the present study are to: (1) propose and demonstrate a procedure for determining an optimal ventilation strategy for an occupied room under different evacuation modes and contaminant source locations by using EFCS3 as an evaluating index; (2) examine the effects of source locations, ventilation modes, and evacuation modes on the performance of emergency ventilation, which aims to minimize the influence of contaminant on indoor occupants. One hundred scenarios, which are the combinations of ten ventilation modes, two evacuation modes, and five contaminant source locations, are investigated numerically.

2. Research approach

In order to quantify the effects of emergency ventilation and evacuation strategies for different source locations, we employed EFCS3 as an evaluation index, which incorporates the temporal and spatial distributions of contaminant and occupants in emergency events. The contaminant dispersion and evacuation process were simulated by a computational fluid dynamic (CFD) and a spatial-grid evacuation model (SGEM), respectively.

2.1. Developing process of emergency event

The developing process of a typical emergency event is illustrated in Fig. 1. Assume contaminants indoors were suddenly released at time t_0, and then dispersed in the air. A certain period of time would be required to identify the release and to determine corresponding response strategies. Suppose the response strategies were started at time t_1. That is, the occupants were instructed to start evacuating at time t_1, while the ventilation mode was switched. The time period from t_0 to t_1 is called pre-evacuation period. Before time t_1, the ventilation system was operated in normal mode. Therefore, the flow field remained steady. After time t_1, the ventilation system was switched from the normal mode to an emergency mode. As a result, the flow field is switching to a new steady-state.