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# Evacuation dynamics with smoking diffusion in three dimension based on an extended Floor-Field model

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ABSTRACT

This paper proposes an extended Floor-Field (FF) model to study the pedestrian evacuation dynamics under the influence of smoke diffusing in three-dimension (3D). In addition to static and dynamic fields, the extended model adopts the smoke and herding fields to reflect pedestrian's smoke-avoiding behavior and herding behavior. The impact of smoke on pedestrians' health is also considered. The smoke will reduce the pedestrians' health point and finally impact their moving ability. Numerical simulations were carried out to study the evacuation dynamics. The influence of the smoke particles producing rate, the initial health point, the critical smoke concentration value, and the herding field on evacuation dynamics were analyzed in detail. Those results could bring some guidance to make the evacuation strategy in the smoke diffusing environment.



## 1. Introduction

If fire occurs in the crowd building, it may cause a lot of casualties and property loses. In 2016, there are 312,000 fires in China, 1582 people were died and 1065 people were injured. Those disasters resulted in direct property loss of 3.72 billion RMB. According to statistics [1], about 53% of the casualties in the fire are caused by the asphyxia and poisoning because of the smoke. How to reduce the causalities under smoke conditions is very necessary and important. It is also the important content of public security research.

Up to now, many models [2–37] were introduced to study the pedestrian dynamics, and many significant and valuable results had been obtained. These models can be divided into two categories: the macroscopic model and the microscopic model. The macroscopic [2–6] models deal with a spatially averaged representation of the pedestrian distribution, which is treated as a continuum in terms of the pedestrian density. It mainly contains fluid dynamic model and queuing-theoretical model. The microscopic models describe the time evolution of the position of each single pedestrian, addressed as a discrete particle. It mainly contains social force model [7–14], cellular automata model [15–19] and lattice gas model [20,21]. The microscopic model is more informative when considering much localized dynamics, in which the action of single individuals is relevant; conversely, the macroscopic model is appropriate when insights into the ensemble (collective) dynamics are required or when high densities are considered. Both the models are deduced out of common phenomenological assumptions; hence they are expected to reproduce analogous phenomenon. In this paper, we use the microscopic model to study the pedestrians' evacuation. FF model [22–24] is a typical pedestrian evacuation model in the framework of cellular automata. In this model, the pedestrians' moving behavior is determined by the exits' position and the interaction between

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pedestrians, namely, the static floor field and the dynamic floor field. Various extension works have been done to reproduce more realistic moving behaviors based on the FF models [25–30]. The model studied in this paper is an extension work of the FF model.

Besides evacuation under normal condition, many scholars have studied evacuation dynamics in emergency. Zhao et al. studied the evacuation in emergency using cellular automaton [38]. Tanimoto et al. established an improved cellular automata model to simulate the bottleneck evacuation under emergency situation [39]. Haghani et al. investigated the social dynamics during emergency escape of crowds and revisited the accuracy of distance-based attraction/repulsion force categorization [40]. Yang et al. investigated the influence of mass behavior on evacuation dynamics and mainly focused on the guided evacuation dynamics [41]. Some papers focus on the study of evacuation under fire and smoke conditions. Isobe et al. simulated the evacuation process in smoke-filled room [42]. Zhou et al. studied the personnel movement in large building with fire, considering the effect of smoke [43]. Yuan et al. proposed a numerical model based on cellular automaton, and simulated the crowd behavior in the evacuation from a smoke-filled compartment [44]. Yang et al. simulated the fire emergency evacuation with fire using an agent-based fire and human interaction model [45]. Nguyen et al. integrated the smoke effect and blind evacuation strategy into fire evacuation. The results were confirmed by empirical data from metro supermarket [46]. Cao et al. studied the effect of fire and smoke on evacuation, and simulated the pedestrian evacuation under fire emergency using cellular automata model [47]. Zhang et al. proposed the probabilistic model for safe evacuation under the effect of uncertain factors in fire [48]. Shen et al. introduced a model to study the collective behaviors in condition of fire with dense smoke, and the results show the moderate panic can reduce the escape time [49].

However, many research on evacuation under fire and smoke conditions ignored the dynamic diffusion process of the smoke. The smoke can affect the pedestrians in two ways. Firstly, the smoke contains some poisonous products, which can endanger pedestrians' health. Secondly, the pedestrians' visibility range can be reduced as the smoke concentration increases. In our previous work [50,51], we introduced the dynamic fire spreading into the evacuation, and divided pedestrians' movement into three stages: normal walk, bent-over walk, and crawl with the spreading of smoke. This paper simulates the 3D diffusion of the smoke, and introduces the limited vision and lethal effect of the smoke particles. The extended FF model is proposed to investigate the influence of the smoke diffusion on evacuation dynamics.

The details of the model are provided in Section 2. The scenarios for simulation are given in Section 3. The numerical simulation results are discussed in Section 4. At last the conclusion is given.

## 2. Model

### 2.1. Smoke diffusion model

In this paper, the particle system of unity 3d is used to model the smoke diffusion process. The particle updating rules are the same as that in Refs. [52,53], and they are briefly introduced as follows.

Step 1: particles produce. In each time interval, several particles are produced from the smoke resource.

Step 2: particles move. After the particles are produced, each of them moves according to the following equations.

$$a^t = F^t / M_P,\ V^t = V^{t-1} + a^{t-1},\ P^t = P^{t-1} + V^t. \tag{1}$$

Here, $P^t$, $V^t$, $a^t$ is the location, velocity, acceleration of the particle respectively at time interval $t$. $F^t$ is the resultant force for the smoke particle, such as the air buoyancy, wind, and so on. $M_P$ is the weight of the smoke particle.

Step 3: particles die. Each particle has a life cycle. The initial life point of each particle is set $I_0$, and it diffuses with time. When the life point of the particle is equal to or less than 0, it is considered to be dead and removed from the system.

$$I^t = I^{t-1} - \varphi\, dt \tag{2}$$

$I^t$ is the life point at time interval $t$. $\varphi$ is the reduction coefficient of life point.

Step 4: draw the particles. Draw the particles according to their properties.

### 2.2. The extended FF model

Here an extended FF model is proposed to simulate the evacuation dynamic under smoke diffusion condition. It is obviously that there will be smoke avoiding behavior in the evacuation process. That is to say, pedestrian is tend to move to the place with less smoke. Furthermore, the smoke would limit pedestrians' vision scope and damage pedestrians' respiratory passage. The former induces herding behavior and the latter affects pedestrians' moving ability.

As the concentration of the produced smoke particles increases, the vision scope of pedestrians becomes smaller. Then pedestrians cannot see any exit, and thus they tend to move following other pedestrians' movement. The direction that more pedestrians moving to is more attractive. Such behavior is the herding behavior.

While high temperature smoke was breathed into respiratory passage, pedestrian would be hard to breathe and wounded. His/her moving ability is affected and finally he/she could not move.

Those behaviors are captured in the proposed extended FF model. Here, Moor neighborhood is adopted, thus there are totally 8 neighbor cells (see Fig. 1(a)). Considering the possibility of non-moving option, there are 9 target cells in the next time interval (see Fig. 1(b)).