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Evacuation dynamics considering pedestrians' movement behavior change with fire and smoke spreading

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ABSTRACT

This paper proposes an extended Floor-Field (FF) model to study the pedestrian evacuation dynamics with the influence of the fire and the smoke spreading. The spreading of smoke is from top to bottom, which leaves less and less room for the movement of pedestrians. And thus, the movement behavior of pedestrians is divided into three stages: normal walk, bent-over walk, and crawl. In the new model, the influence of the fire and the smoke on the movement of pedestrians is modeled by the fire floor field and the smoke floor field respectively. Numerical simulations are carried out to study the evacuation dynamics under fire and smoke. The influences of personnel density, fire location, exit width, fire spreading rate, and smoke spreading rate, on the evacuation efficiency are analyzed in detail. The simulation results show that the pedestrian evacuation dynamics is highly related to fire location in the room and the spreading rates of the fire and the smoke. Those results can bring some guidance to design the building structure and make the evacuation strategy in emergency situation.

1. Introduction

Fire is a kind of frequent disasters. When a fire occurs in the building, the rapid spread of the fire and smoke can cause a lot of property damages and casualties. According to statistics, in 2015, there were 338,000 fires in China, 1742 people were died and 1112 people were injured. Those disasters resulted in direct property loss of 3.95 billion RMB. How to reduce the casualties in large-scale activity places and public gathering places with the fire emergency is remarkable. It is also the important content of public security research.

In recent years, a large number of works have been done to investigate the pedestrian dynamics by using different models and many significant and valuable results are obtained. These models can be divided into two categories: the macroscopic model and the microscopic model. The macroscopic model mainly contains fluid dynamic model and queuing-theoretical model. The microscopic model could precisely describe individual behavior and thus is more realistic. It mainly contains social force model, lattice gas model and cellular automata model. Helbing and Molnàr (1995) and Helbing et al. (2000) studied the pedestrian evacuation using social force model, analyzed the phenomenon of "fast is slow", "arching before the exit". Li et al. (2015) used social force model studying the real-life 2013 Ya'an earthquake evacuation in China. Cellular automata model (Yamamoto et al., 2007; Fukui and Ishibashi, 1999; Alizadeh, 2011; Li and Han, 2015; Liao et al., 2014) and lattice gas model (Guo et al., 2013; Li et al., 2008) are also widely used in modeling evacuation dynamics, especially in emergency situations (Zhao et al., 2006; Zhou et al., 2009; Zheng et al., 2011; Tanimoto et al., 2010; Nguyen et al., 2013; Cirillo and Muntean, 2013; Cao et al., 2014), since they have the advantages of simple rules and fast computing. FF model (Kirchner and Schadschneider, 2002; Huang and Guo, 2008; Nishinari et al., 2004) is a typical evacuation model based on cellular automaton. In this model, the direction of pedestrians' movement is determined by the exits' position and the interaction between the pedestrians, namely, the static floor field and the dynamic floor field.

Zhao et al. (2006) studied the evacuation in emergency by using cellular automata. Zhou et al. (2009) studied the personnel movement in large building with fire, considering the effect of smoke. Tanimoto et al. (2010) established an improved cellular automata model to simulate the bottleneck evacuation under emergency situation. Isobe et al. (2004) tested and simulated the evacuation process in smoke-filled room. Nguyen et al. (2013) integrated the smoke effect and blind evacuation strategy within fire evacuation, the simulation results were confirmed by empirical data from the metro supermarket. Cirillo and Muntean (2013) studied the dynamics of pedestrians in regions with no visibility by using the

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lattice model. Cao et al. (2014) studied the effect of fire and smoke on evacuation, and simulated the pedestrian evacuation under fire emergency by using cellular automata model.

At present, most of the research on evacuation under fire ignored the dynamic spreading process of fire and smoke. Pedestrians' moving behavior is very different with and without fire and smoke spreading. If there is no fire and smoke, or the fire and smoke are assumed static, pedestrians will walk upright during the whole evacuation process. When the fire and smoke spread dynamically, pedestrians' movement behavior changes from walk to bent-over walk, crawl according to the surrounding environment. Nagai et al. (2006) studied the evacuation of crawlers and walkers from corridor through an exit. Yang et al. (2012) carried out experimental studyies on bent-over walking behavior of occupants in corridors, and obtained the evacuation characteristics of bent-over walkers. The pedestrians' movement behavior change—normal walk, bent-over walk, and crawl—is rarely mentioned in the previous articles. Our previous work (Zheng et al., 2011) introduced the fire spreading dynamics into the traditional FF model. This paper introduces the effect of both the fire and the smoke spreading during the evacuation process and proposes an extended FF model. The influence of the fire and smoke spreading on the evacuation dynamics is investigated.

The details of the extended model are introduced in Section 2. The scenarios for simulation are given in Section 3. The simulation results are analyzed in Section 4. At last the conclusion is given.

2. Model

2.1. FF model

In the FF model, pedestrians move to their target cells according to the selected probability, which is decided by static floor field and dynamic floor field.

The static floor field represents the attractiveness of the destination, which describes the shortest distance to the exits, it does not change with time and personnel movement during simulations. The dynamic floor field is the record of pedestrians' trails according to herding and panic behavior. Pedestrians are more likely to move to the cells which more pedestrians have passed. The dynamic floor field is similar to ants foraging. It is produced by the pedestrian movement and affects the movement of others in turn. When the pedestrian passes the cell, the value of dynamic floor field increases, but it diffuses and decays with time, and finally vanishes.

2.2. The extended FF model

When a fire occurs, pedestrians tend to move away from the fire and smoke. The transition probability is different from the traditional FF model, especially near the fire and smoke. In our previous work (Zheng et al., 2011), only the influence of fire spreading on the pedestrian evacuation is considered; this paper further introduces the influence of smoke spreading, and considers the change of pedestrians' movement behavior. The influence of the smoke is named as smoke floor field in this paper. We assume that all pedestrians are familiar with room structure and exit position, not considering the influence of vision scope caused by smoke. The transition probability of selecting the target cell (i,j) is calculated as follows,

$$P_{ij} = N(\exp(k_S S_{ij} + k_D D_{ij} - k_F F_{ij} - k_M M_{ij}))(1-\eta_{ij})\varepsilon_{ij} \tag{1}$$

N is the normalization for ensuring that $\Sigma p_{ij} = 1$. S_{ij}, D_{ij}, F_{ij}, M_{ij} denotes static, dynamic, fire, and smoke floor field, respectively. k_S, k_D, k_F, k_M are scaling parameters. η_{ij} indicates whether the cell (i,j) is occupied by wall, obstacles, or fire, the value is 1 when the cell is occupied, and it is 0 when the cell is empty. ε_{ij} indicates whether the cell (i,j) is occupied by a pedestrian, the value is 0 when the cell is occupied, and it is 1 when the cell is empty.

S_{ij} describes the shortest distance to the exits. It is set inversely proportional to the distance from the cell (i,j) to the exits. And it is calculated as follows,

$$S_{ij} = \frac{1/d_{ij}^{*}}{\sum_i \sum_j 1/d_{ij}^{*}} \tag{2}$$

Here, d_{ij}^{*} represents the shortest distance from the cell (i,j) to all the exits of the room.

D_{ij} represents the attraction between pedestrians. There are three steps to calculate the dynamic floor field.

Step1, Whenever someone passes through the cell $(i,\ j)$, $D_{ij} = D_{ij} + 1$.

Step2, Calculate the dynamic floor field according to decay and diffusion,

$$D_{ij} = (1-\lambda) * (1-\delta) * D_{ij} + \lambda * \frac{1-\delta}{8} * \left(\sum_{i=i-1}^{i+1} \sum_{j=j-1}^{j+1} D_{ij} - D_{ij}\right) \tag{3}$$

λ is the diffusion probability; δ is the decay probability.

Step3, Normalize, $D_{ij} = D_{ij}/\sum_i \sum_j D_{ij}$.

F_{ij} reflects the fire avoidance behavior, it is inversely proportional to the distance from cell (i,j) to the fire. It is calculated as follows,

$$F_{ij} = \frac{1/d_{ij}^{**}}{\sum_i \sum_j 1/d_{ij}^{**}} \tag{4}$$

Here, d_{ij}^{**} represents the shortest distance from the cell (i,j) to the edge of fire within the influence scope of fire. In this paper the influence scope of fire is 8 cells' length around the fire.

M_{ij} reflects the smoke avoidance behavior, it only exists in the cells which the smoke spreads over. It is inversely proportional to the distance from cell (i,j) to the smoke source (the fire). It is calculated as follows,

$$M_{ij} = \frac{1/d_{ij}^{***}}{\sum_i \sum_j (1/d_{ij}^{***})} \tag{5}$$

Here, d_{ij}^{***} represents the shortest distance from the cell (i,j) to the smoke source (the fire).

2.3. Update rules

The update rules of the extended FF model have the following structure.

(1) The model is updated in parallel.
(2) In each time step, calculate the static floor field S_{ij}, the dynamic floor field D_{ij}, the fire floor field F_{ij}, and the smoke floor field M_{ij} according to Section 2.2, and then calculate the target cell selection probability P_{ij}. The Moor neighborhood is adopted, as shown in Figs. 1 and 2.
(3) Without considering any external factors, the fire spreads to the surrounding with certain rate V_f m/s.
(4) Without considering any outside influence, the smoke produced by fire spreads upward on the early stage with the rate V_{mu} m/s. When the smoke is up to the top of room, it diffuses around horizontally with the rate V_{mp} m/s. With the smoke produced continuously, it spreads downward with the rate V_{md} from the top of room and eventually fills the whole room. The smoke spreading process is shown in Fig. 3.

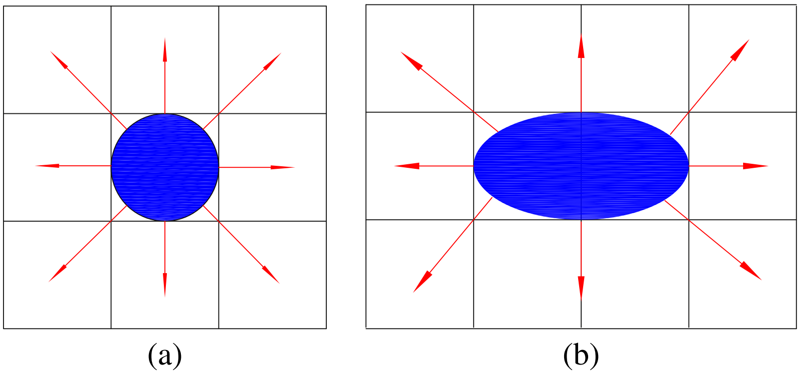


Fig. 1. Target cells at the next time step. The Moore neighborhood is used for this model. (a) The pedestrian walk normally. (b) The pedestrian walk bent-over or crawl.

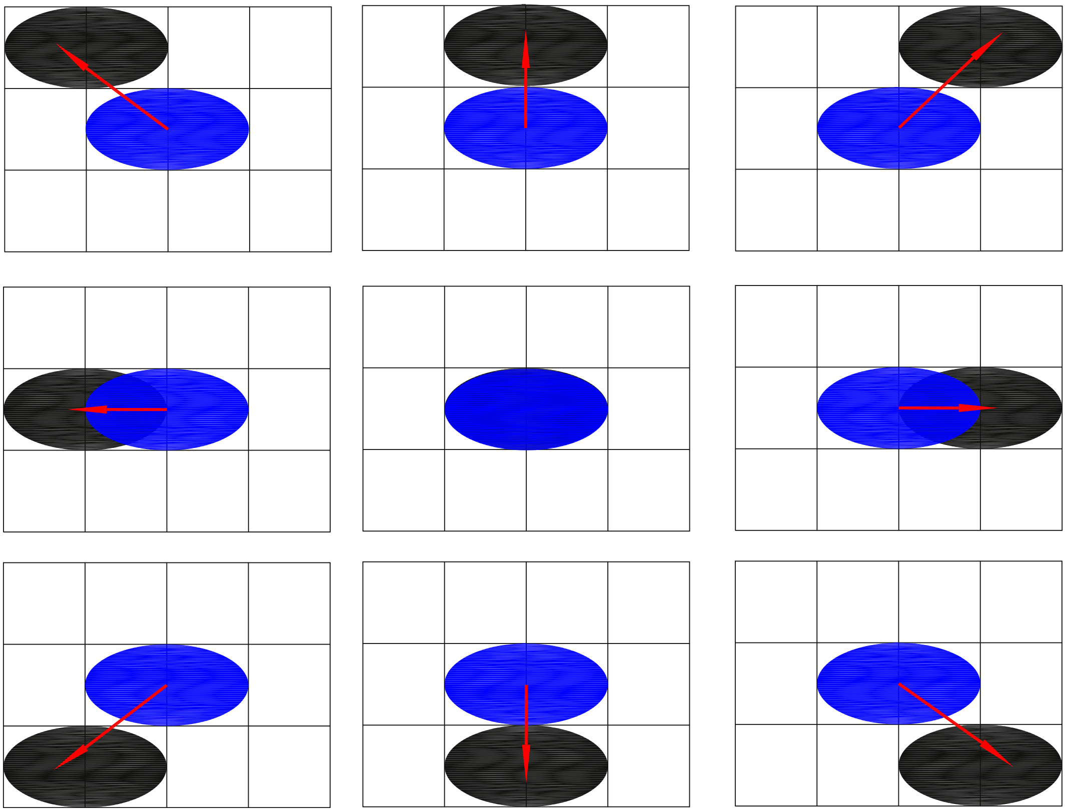


Fig. 2. Target cells (black ones) at the next time step when the pedestrian walk bent-over or crawl.

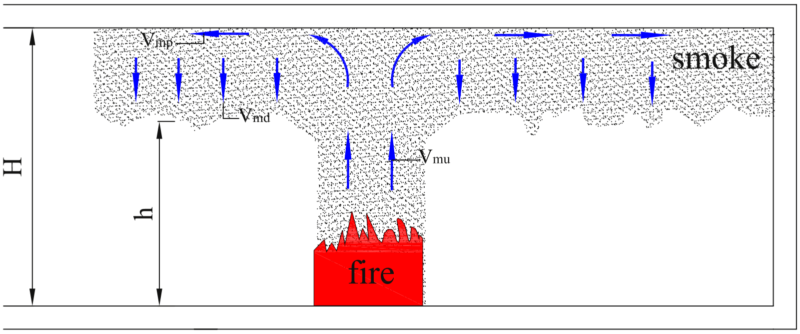


Fig. 3. The smoke spreading process.

(5) Pedestrians' movement behavior is divided into three stages according to the smoke spreading process, as shown in Fig. 4. The height of the smoke from the ground is set as h. The first stage, $h > h_1$, pedestrians walk normally; each pedestrian only occupies one cell, as shown in Fig. 1(a). The second stage, $h_2 < h < h_1$, pedestrians walk bent-over; each pedestrian occupies two cells, as shown in Fig. 1(b). The third stage, $h < h_2$, pedestrians crawl; each pedestrian also occupies two cells, as shown in Fig. 1(b).

(6) Each pedestrian moves to a target cell randomly based on the transition probability P_{ij}.

When two or more pedestrians compete for the same target cell, a conflict is formed. In this case, all involved pedestrians keep still with probability $\mu \in [0, 1]$, and one of the pedestrians moves to the target cell with probability $1 - \mu$. When one pedestrian occupies one cell, 8 cells around cell (i, j) should be checked for the conflict (see Fig. 5(a)). When one pedestrian occupies two cells, 14 cells around cell (i, j) should be checked for the conflict (see Fig. 5(b)).

3. Scenarios

In this paper, we investigate a simple case that pedestrians evacuate from a room with size of 12 m $*$ 12 m, and the height of the room is 3.6 m. Both the length and width of each cell are 0.4 m, and the room is defined as the size of 30 cells $*$ 30 cells. Fig. 6 shows three configurations for numerical simulation. Configuration I, there are two exits in the left wall. Configurations II, there are two exits, one in the left wall, and the other in the right wall. Configuration III, there is one exit in the left wall. The exit width is set as W.

The initial fire location is analyzed in three cases: on the left of the room, namely the cell (4, 16); in the middle of the room, namely the cell (16, 16); on the right of the room, namely the cell (26, 16). Each cell has five states, empty, occupied by the pedestrian, occupied by fire, occupied by smoke, occupied by the pedestrian and smoke. The pedestrian movement speed is set refer to the paper written by Yang et al. (2012). On the first stage, pedestrians walk normally, the maximum speed is 1.5 m/s, and each time step corresponds to 4/15 s. On the second stage, pedestrians walk bent-over, the maximum speed is 1.0 m/s, and each time step corresponds to 6/15 s. On the third stage, pedestrians crawl, the maximum speed is 0.75 m/s, and each time step corresponds to 8/15 s. When the fire spreads to the entire room, the pedestrians who did not escape from the room are named as "not-escaped pedestrians".

4. Simulation results

Pedestrians are distributed randomly in the room initially, and the number of pedestrians is set as N. Each scenario is carried out 10 times, and then the average value is obtained to analyze the results. The parameters are set as $\lambda = 0.2$, $\delta = 0.2$, $\mu = 0.1$, $k_D = 10$, $k_S = 6000$, $k_F = 600$, $k_M = 100$, $h_1 = 1.6$ m, $h_2 = 0.8$ m.

4.1. Simulation of evacuation process

Firstly, we analyze the floor field distribution in the room. Fig. 7 shows the static floor field, the closer to the exit, the larger it is. Fig. 8 shows the fire floor field, the closer to the fire, the larger it is. Fig. 9 shows the smoke floor field, it only exists in the area the smoke spreads to, and the closer to the smoke source, the larger it is.

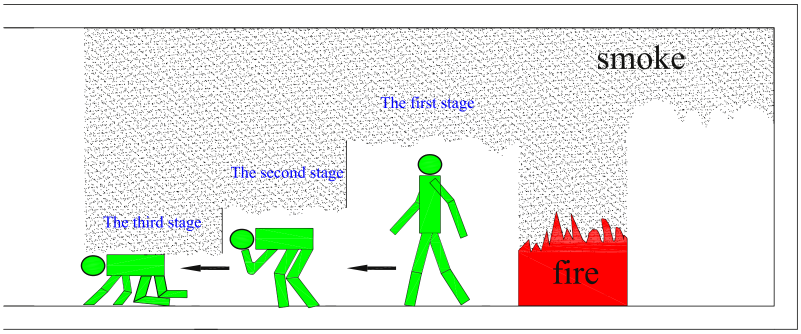
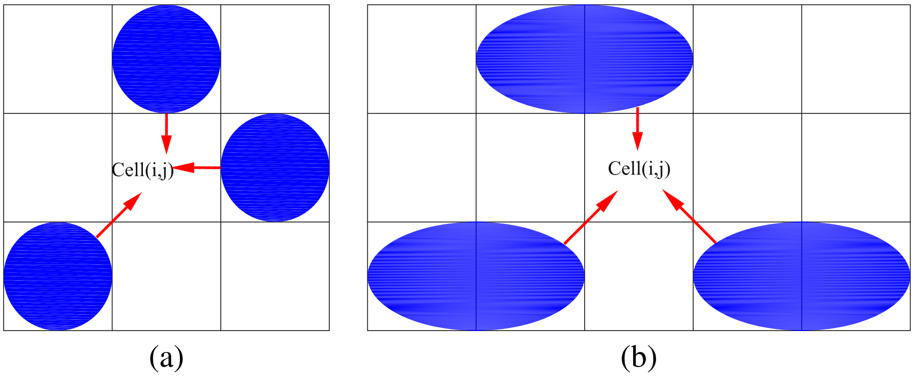


Fig. 4. The pedestrians' movement behavior.



(a) (b)

Fig. 5. Occurrence of confliction. (a) The pedestrian walk normally. (b) The pedestrian walk bent-over or crawl.

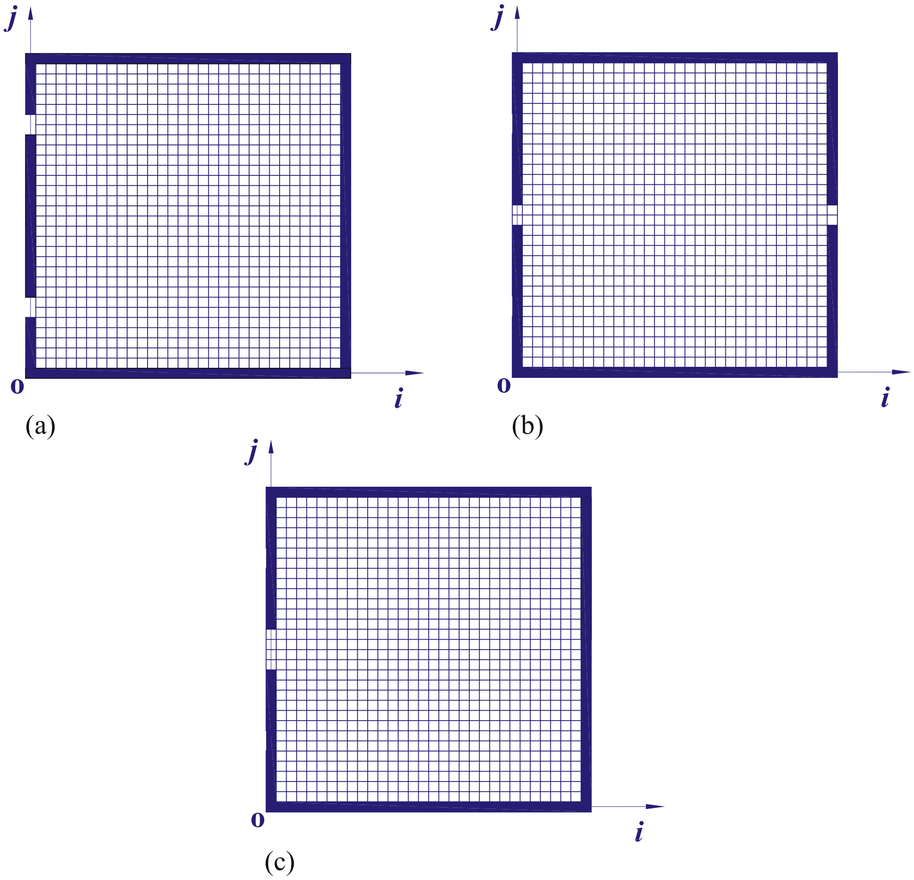


Fig. 6. The room structure. (a) Configuration I. (b) Configuration II. (c) Configuration III.

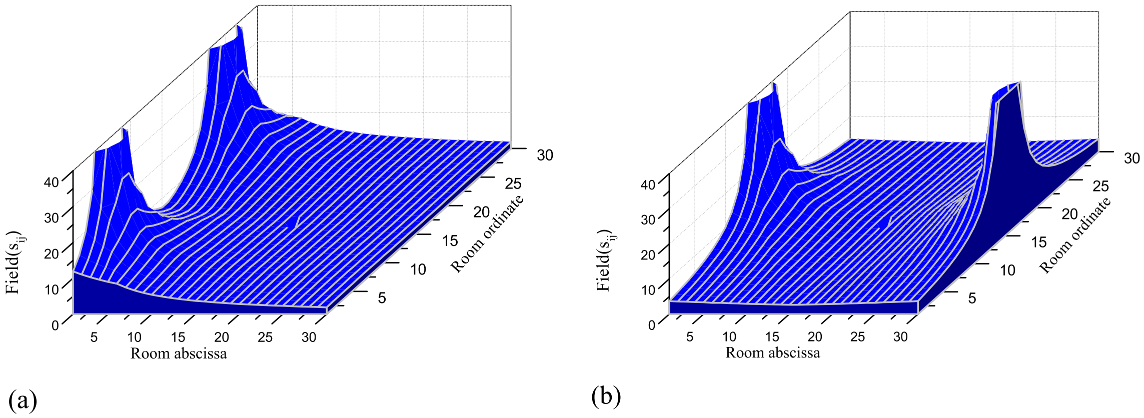


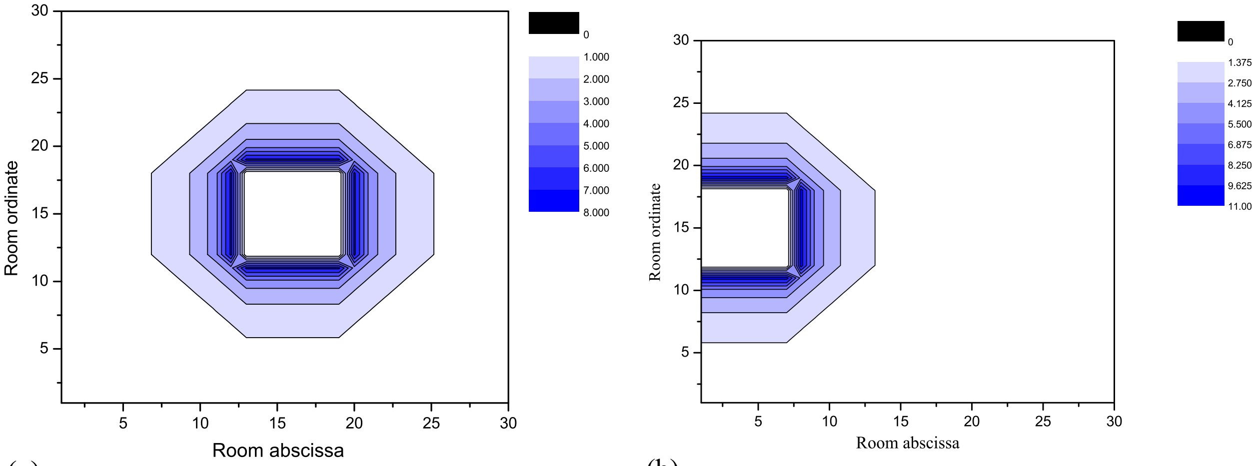
Fig. 7. The static floor field in room. *Field* $(S_{ij}) = k_S * S_{ij}$. (a) The room structure is as Configuration I. (b) The room structure is as Configuration II.

The evacuation process is studied by plotting scenarios at different time step. Fig. 10 shows evacuation scenarios at time steps $t = 10$, 25, 40, 54, 70, and 85. We can see that, the fire and the smoke spread around, and the concentration of smoke is stronger with time. Pedestrians escape from fire and smoke, and move toward the exits. As the smoke spreads, pedestrians' movement behavior changes from walk to walk bent-over and then crawl. Pedestrians who are covered by fire are not-escaped pedestrians.

4.2. The effect of smoke

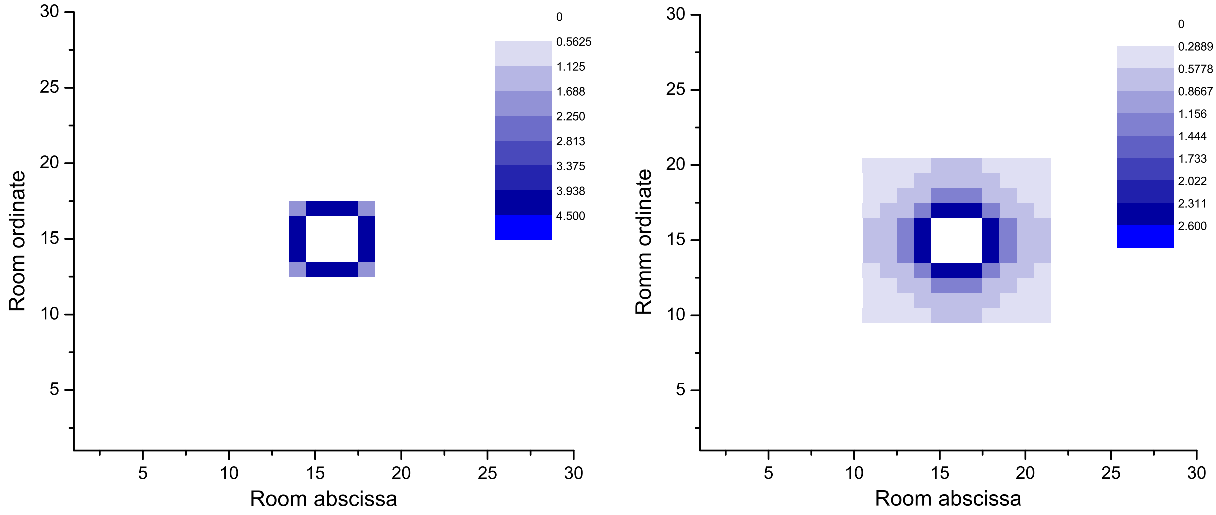
If the effect of smoke is not considered, pedestrians walk normally from the beginning to the end, without bent-over walk, and crawl. When the effect of smoke is introduced, the movement behavior of pedestrians is divided into three stages. The effect of smoke is the highlight of innovation in this paper.

Fig. 11 indicates the difference of evacuation dynamics considering and not considering the effect of smoke. Case I, not consider the effect of smoke, pedestrians walk normally all the time. Case II, consider the effect of smoke, pedestrians' movement behavior changes as the smoke spreads. One can see that the number of pedestrians in room decreases as time increases in both cases. In the early stage, the smoke is less, and it does not affect pedestrians' moving behavior, thus the evacuation dynamics of the two cases are the same. Later, the smoke spreads downward and makes pedestrians bent-over. The moving speed of the pedestrian



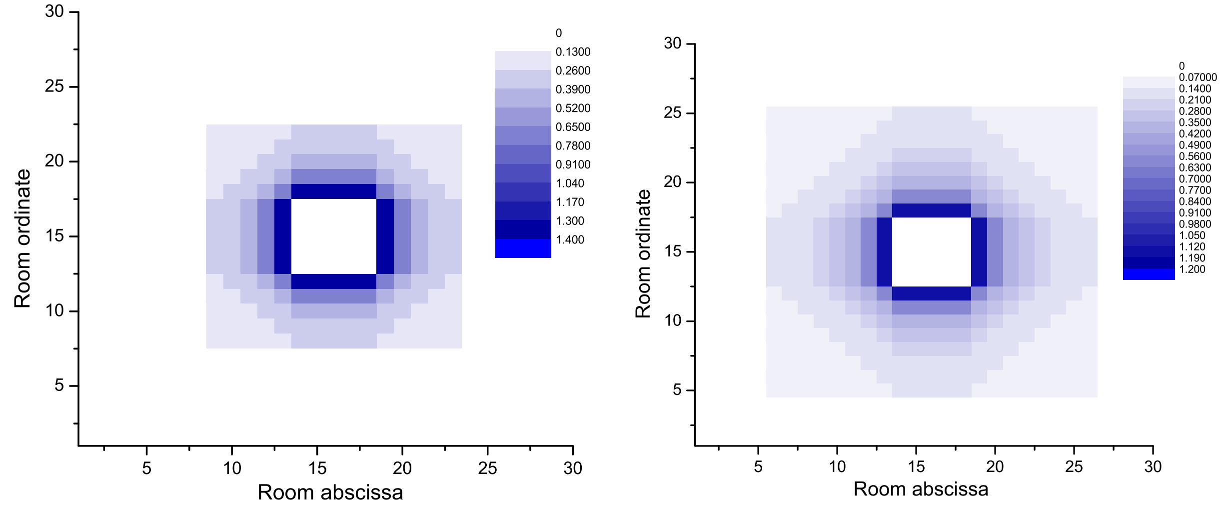
(a) (b)

Fig. 8. The fire floor field in room at time step $t = 30$. *Field* $(F_{ij}) = k_F * F_{ij}$. (a) Fire occurs in the middle of the room (cell (16, 16)). (b) Fire occurs on the left of the room (cell (4, 16)). Here, $V_f = 0.15$ m/s.



(a) $t = 10$

(b) $t = 15$



(c) $t = 20$

(d) $t = 25$

Fig. 9. The smoke floor field in room at time steps (a) $t = 10$, (b) $t = 15$, (c) $t = 20$, (d) $t = 25$, respectively. The fire occurs in the middle of the room (cell (16, 16)). The deeper the color, the larger the smoke floor field is. *Field* $(M_{ij}) = k_M * M_{ij}$. Here $V_{mu} = 3$ m/s, $V_{mp} = 0.75$ m/s, $V_{md} = 0.5$ m/s.

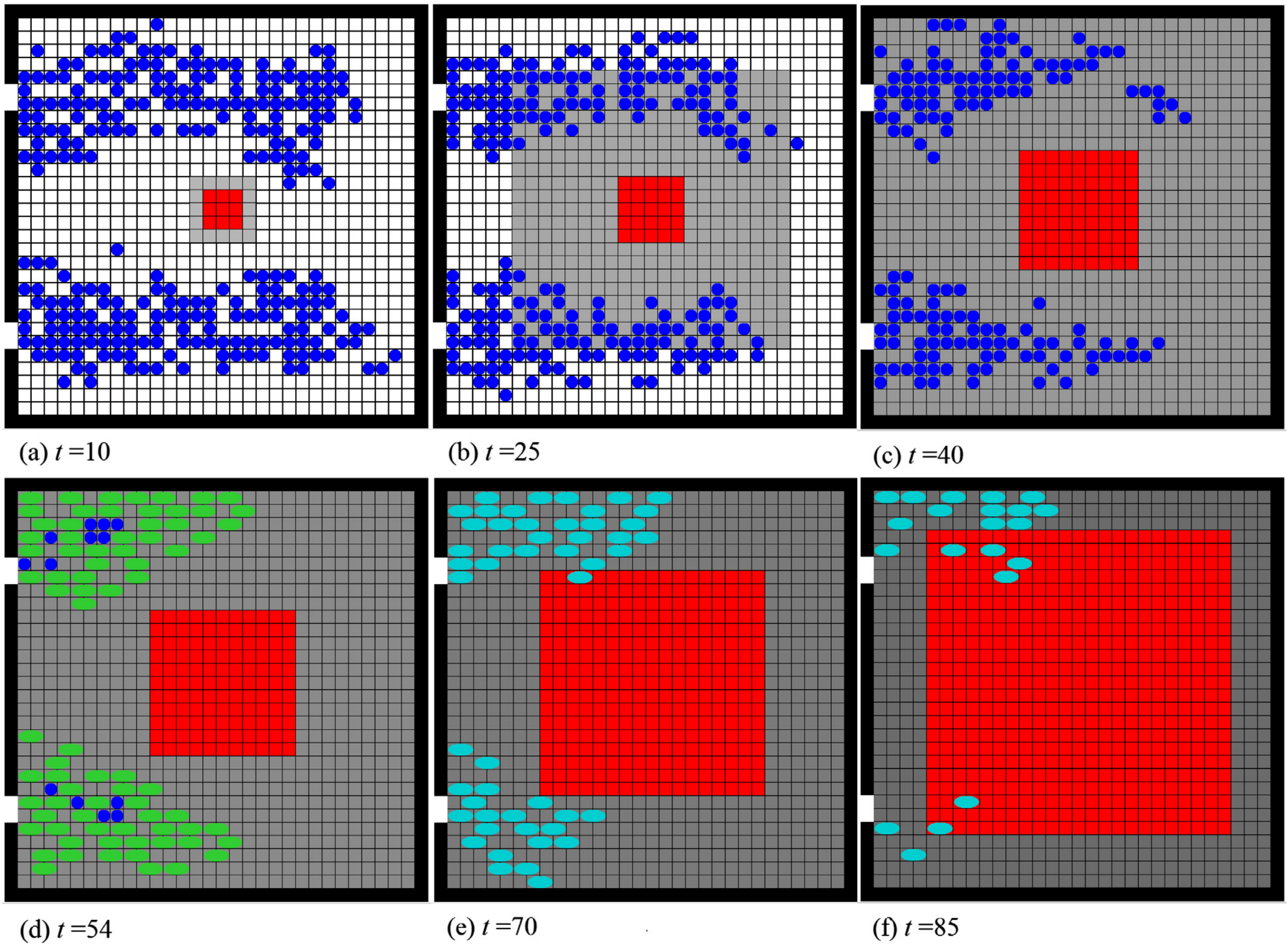


Fig. 10. Snapshots of evacuation. The scenarios are at the time step (a) t = 10, (b) t = 25, (c) t = 40, (d) t = 54, (e) t = 70, (f) t = 85, respectively. The fire occurs in the middle of the room (cell (16, 16)). Here red represents fire, and gray represents smoke. Deepen gray means the smoke is thickened. Blue ones show pedestrians who walk normally, green ones show pedestrians who walk bent-over, and cyan ones show pedestrians who crawl. The parameters are N = 300, W = 0.8 m, V_f = 0.15 m/s, V_{mu} = 3 m/s, V_{mp} = 0.75 m/s, V_{md} = 0.5 m/s. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

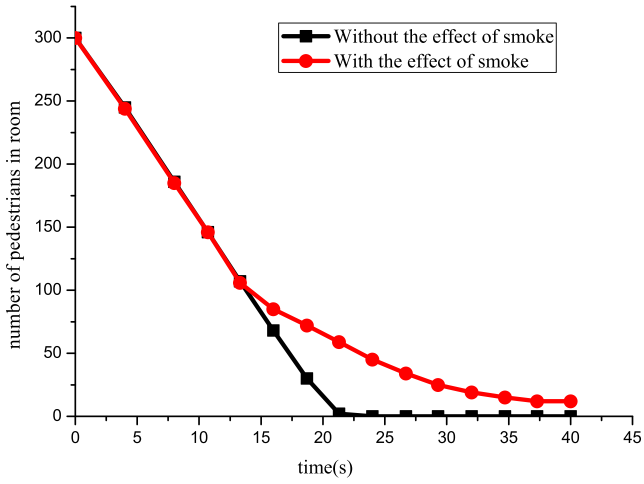


Fig. 11. The number of pedestrians in the room as a function of time. The room structure is as Configuration I. The fire occurs in the middle of the room (cell (16, 16)). The parameters are N = 300, W = 0.8 m, V_f = 0.15 m/s, V_{mu} = 3 m/s, V_{mp} = 0.75 - m/s, V_{md} = 0.5 m/s.

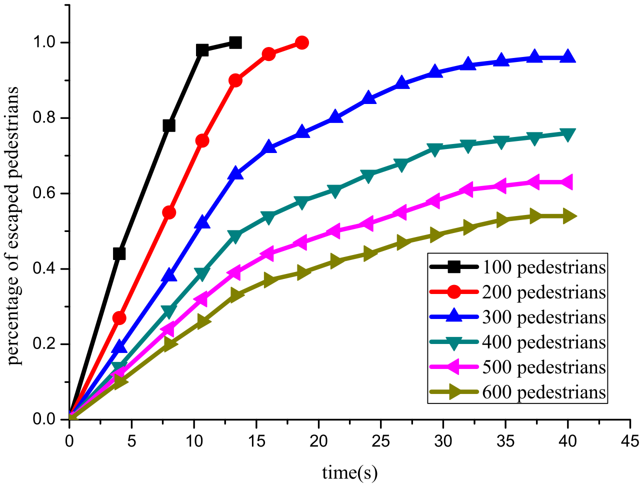


Fig. 12. The percentage of escaped pedestrians as a function of time. The room structure is as Configuration I, fire occurs in the middle of the room (cell (16, 16)). The parameters are W = 0.8 m, V_f = 0.15 m/s, V_{mu} = 3 m/s, V_{mp} = 0.75 m/s, V_{md} = 0.5 m/s.

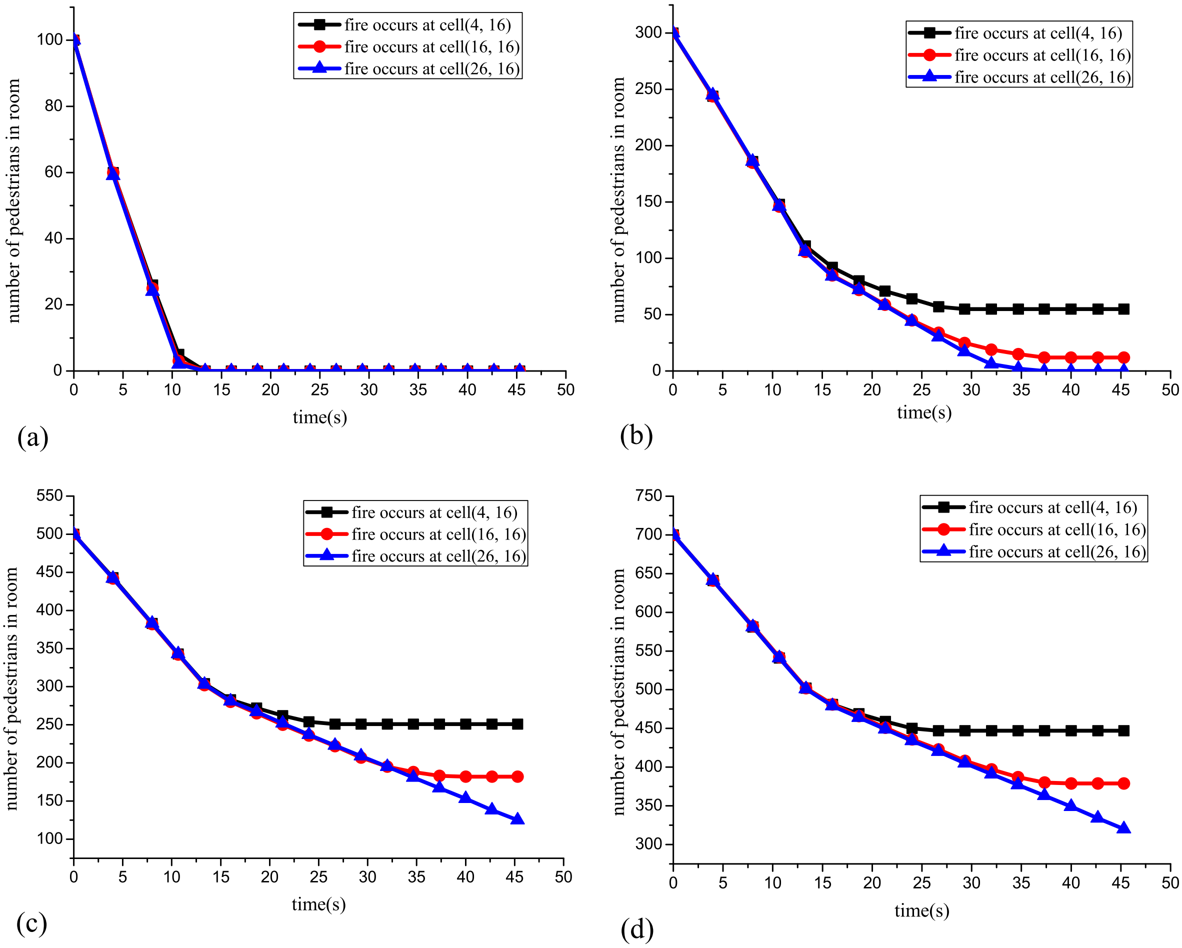


Fig. 13. The number of pedestrians in room as a function of time for different fire locations. The room structure is as Configuration I. Parameters $W = 0.8$ m, $V_f = 0.15$ m/s, $V_{mu} = 3$ m/s, $V_{mp} = 0.75$ m/s, $V_{md} = 0.5$ m/s, (a) $N = 100$, (b) $N = 300$, (c) $N = 500$, (d) $N = 700$.

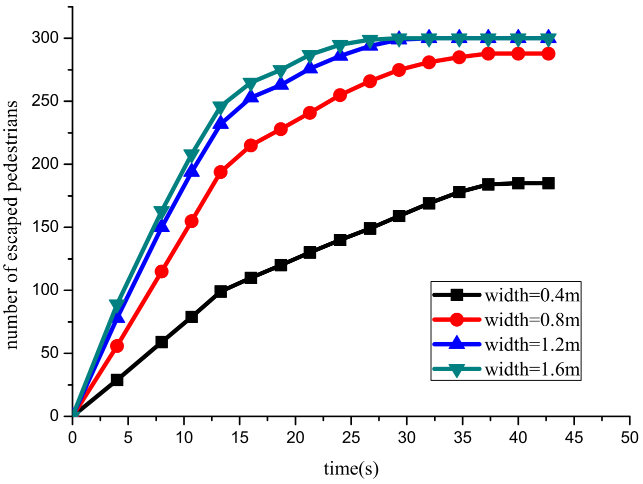


Fig. 14. The number of escape pedestrians as a function of time for different exit widths. The room structure is as Configuration I, fire occurs in the middle of the room (cell (16, 16)). The parameters are $N = 300$, $V_f = 0.15$ m/s, $V_{mu} = 3$ m/s, $V_{mp} = 0.75$ m/s, $V_{md} = 0.5$ m/s.

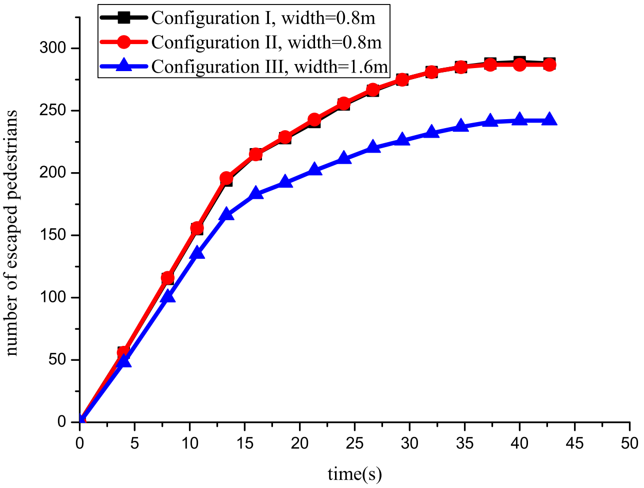


Fig. 15. The number of escaped pedestrians as a function of time for different exit settings. The fire occurs in the middle of the room (cell (16, 16)). The exit is set as Configuration I, Configuration II, Configuration III respectively. Parameters $N = 300$, $V_f = 0.15$ m/s, $V_{mu} = 3$ m/s, $V_{mp} = 0.75$ m/s, $V_{md} = 0.5$ m/s.

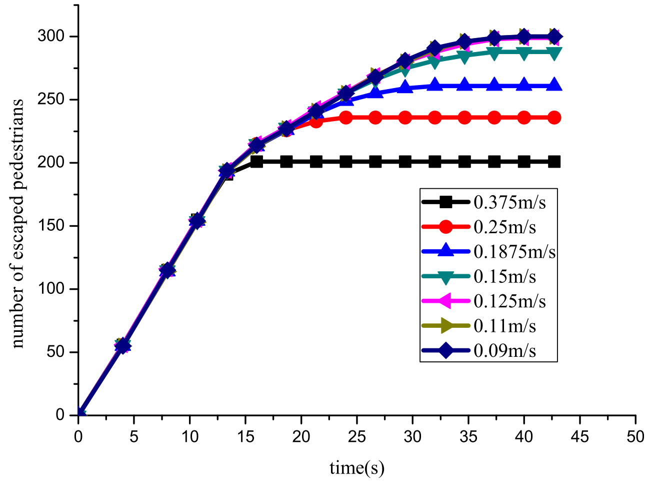


Fig. 16. The number of escaped pedestrians as a function of time for different fire spread rates. The room structure is as Configuration I, fire occurs in the middle of the room (cell (16, 16)). Parameters $N = 300$, $W = 0.8$ m, $V_{mu} = 3$ m/s, $V_{mp} = 0.75$ m/s, $V_{md} = 0.5$ m/s.

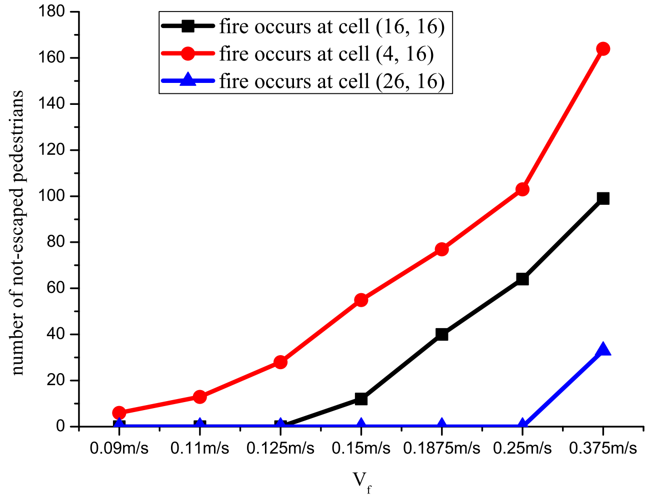


Fig. 17. The number of not-escaped pedestrians as a function of the fire spread rate V_f. The room structure is set as Configuration I. Parameters $N = 300$, $W = 0.8$ m, $V_{mu} = 3$ m/s, $V_{mp} = 0.75$ m/s, $V_{md} = 0.5$ m/s.

decreases and the evacuation rate reduces. Thus the number of pedestrians in room in Case II is higher than that in Case I.

4.3. The effect of pedestrian density

Fig. 12 indicates the percentage of escaped pedestrians as a function of time for different pedestrian density in the room. One can see that, the percentage of escaped pedestrians increases with time no matter what the initial pedestrian density is. When the initial density is large enough, not all pedestrians can escape from the room, some of them have no time to escape before the fire spreads to the whole room. Limited by the exits' capacity, the larger the initial density is, the smaller the percentage of escaped pedestrians.

4.4. The effect of fire location

Fig. 13 indicates the number of pedestrians in room as a function of time for different fire locations. The paper studies three scenarios, fire occurs on the left of room (near the exit, cell (4, 16)), fire occurs in the middle of room (cell (16, 16)), fire occurs on the right of room (cell (26, 16)). One can see that, the number of pedestrians in the room is the same in the three scenarios in the initial period when fire has not yet spread to the exits. When the density is low (see Fig. 13(a)), all the pedestrians can escape from the room with little time, the fire location has little effect on the evacuation. When the density becomes larger (see Fig. 13(b), (c) and (d)), the closer the fire occurs to the exits, the larger the effect on the evacuation. Because when fire occurs near the exits, it spreads around the exits quickly, and hinders the pedestrian evacuation sharply. When the density value is larger enough (see Fig. 13(c) and (d)), no matter where the fire occurs, not all pedestrians can evacuate successfully. When the fire occurs near the exits, the number of not-escaped pedestrians is larger.

4.5. The effect of exit width and location

Fig. 14 indicates the number of escaped pedestrians as a function of time for different exit widths. One can see that, the number of escaped pedestrians increases with the exit width. When the width of each exit increases to 1.2 m, all pedestrians can escape from the room safely.

Fig. 15 shows the number of escaped pedestrians as a function of time for different exit settings. One can see that, the evacuation process is almost the same in Configuration I and Configuration II.

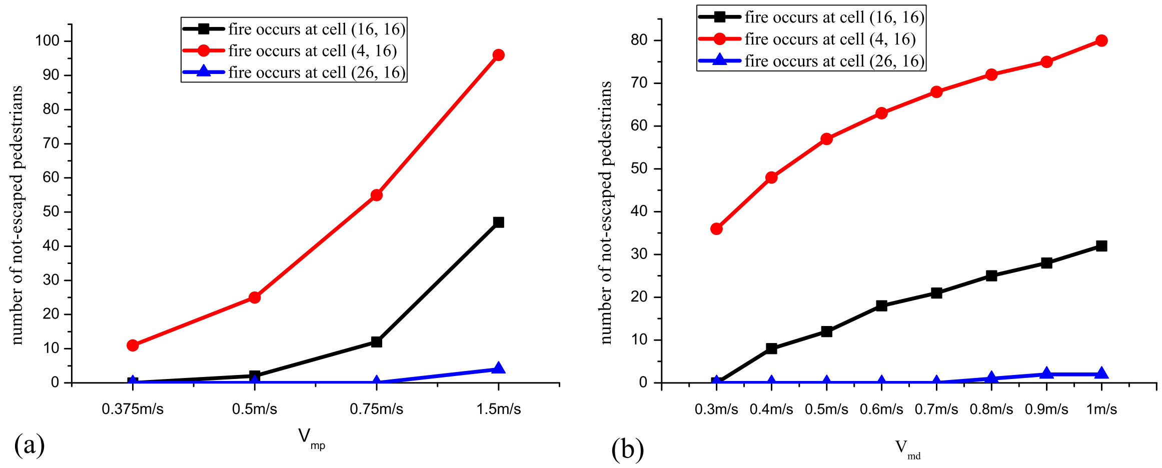


Fig. 18. The number of not-escaped pedestrians as a function of the smoke spread rate. The room structure is set as Configuration I. (a) $V_{md} = 0.5$ m/s, for the different V_{mp}; (b) $V_{mp} = 0.75$ m/s, for the V_{md}. Parameters $N = 300$, $W = 0.8$ m, $V_f = 0.15$ m/s, $V_{mu} = 3$ m/s.

Because when the fire occurs in the middle of the room, the time of the fire spreading to each exit is the same in the two configurations, and pedestrians have the same time to evacuate. Our previous work (Zheng et al. (2011)) informed that when fire occurs in room, without considering the pedestrians' movement behavior change, two exits are more beneficial than one exit with equal width of the sum of the two exits. The same conclusion can be got here, One can see from Fig. 15, Configuration I and Configuration II is better than Configuration III for evacuation.

4.6. The effect of fire spread rate

Fig. 16 indicates the relationship of fire spread rate and pedestrian evacuation. One can see that, in early stage of evacuation, fire spread rate has little effect on pedestrian evacuation, because in this stage, the fire has not spread to the exits and pedestrians can escape smoothly. The smaller the fire spread rate, the later the fire spreads to the exits, and the number of escaped pedestrians is larger.

Fig. 17 shows the relationship between the number of not-escaped pedestrians and fire spread rate for different fire locations. We can see that, wherever the fire occurs, the number of not-escaped pedestrians grows with the fire spread rate increases. When fire occurs near the exits, the number of not-escaped pedestrians is larger. So we should place slow-burning materials in room and the flammable materials should be set far away from the exits.

4.7. The effect of smoke spread rate

Fig. 18 shows the relationship between the number of not-escaped pedestrians and the smoke spread rate with different fire locations. We can see that, the number of not-escaped pedestrians grows as the smoke spread rate increases. Because the time of smoke diffusing horizontally covers a large proportion of the smoke spread process, the change of V_{mp} has larger effect than the change of V_{md} on evacuation. No matter what the smoke spread rate is, the number of not-escaped pedestrians is larger when the fire location is near the exits.

5. Conclusions

This paper presented an extended FF model with the fire and the smoke spreading. The impacts of the smoke on the movement behavior of pedestrians were considered in the new model. With the influence of smoke, pedestrians have to leave their heads out of the smoke and thus pedestrians' behavior always varies from normal walk, bent-over walk, to crawl. The effects of smoke, pedestrian density, fire location, exit width, exit location, fire spread rate and smoke spread rate on evacuation dynamics were analyzed with simulation results. It was shown that:

(1) The movement behavior change caused by the smoke spreading seriously affects pedestrians' evacuation efficiency. The evacuation dynamics are quite different with and without smoke. It is important to consider the influence of smoke fully in the building structure designing and evacuation strategy planning.
(2) The bigger the pedestrian density, fire spread rate, and smoke spread rate are, the more difficult the evacuation is. We should not place inflammable material in room.
(3) The farther the distance from the fire to the exits is, the smaller the effects of fire and smoke on evacuation are.

The fire and the smoke spreading process and pedestrians' evacuation behavior are very complex. The works in this paper assumed that the fire and the smoke spread in a very simple way. In future studies, the complex spreading dynamics of the fire and the smoke will be described. And pedestrians' special psychology, and impulsive behavior will also be considered. Furthermore, the effect of fire temperature and the harm smoke on evacuation will be investigated.

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