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Simulation of Pedestrian Evacuation in a Room under Fire Emergency

Shu-chao Cao, Wei-guo Song*, Xiao-dong Liu, Nan Mu

State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230027, China

Abstract

An extended floor field model is proposed to simulate the pedestrian evacuation in a room by considering the smoke and fire effect under fire emergency. In this new model, the visibility floor field and temperature floor field are introduced, these extensions are important for evacuation simulations under fire circumstances. Through the numerical simulations, the influence of fire locations, type of burning materials, heat release rates and exit width on evacuation are analyzed. The results show these factors have great effects on evacuation, which may be useful to understand the pedestrian evacuation under fire emergency.

Keywords: pedestrian evacuation, fire, floor field model

1. Introduction

With the rapid development of economy and urban construction in recent decades, people's life safety is paid more and more attention, Once fire accident occurs in a crowd building, it may cause heavy casualties, for example, a fire at a commercial building in Luoyang, China, killed 309 in 2000, a nightclub fire in Rhode Island in 2003 killed 100 people, more than 194 people died at an overcrowded working-class nightclub in Buenos Aires, Argentina, in 2004, Brazil nightclub fire killed more than 200 people in 2013 recently. Due to the life losses under fire emergency, the study of evacuation under fire conditions is very necessary and important to reduce the casualties and losses.

Considering the danger of fire conditions, it is not possible to conduct fire evacuation experiments in reality, therefore, computer simulation becomes a very important and feasible tool with the development of computer technology, up to now, many evacuation models are introduced by different researchers, these model can be divided into two categories: the macroscopic model such as fluid dynamic model[1-3] and queuing-theoretical model[4-5], the microscopic model such as social force model[6-7], cellular automata model[8-11], lattice gas model[12-16]. Many scholars have studied the evacuation under fire or smoke conditions, Zheng et al.[17] investigated the dynamics of pedestrian evacuation with the influence of fire spreading, the fire floor field was introduced based on the floor field model[18-22]. Yuan et al.[23]proposed a numerical model based on cellular automaton to simulate the human behavior in emergency evacuation from a large smoke-filled compartment, the model considered the smoke effect in context of visibility. Yang et al.[24] used an agent-based fire and human interaction model to simulate fire emergency evacuation in an underground subway station. Emilio N. M. Cirillo and Adrian Muntean[25] studied the motion of pedestrians through obscure corridors where lack of visibility due to smoke and fog. Motonari Isobe et al.[14] modeled the evacuation process by means of experiments and simulation from a "smoky" room where people wore eye masks. Manh Hung Nguyen et al.[26]presented an agent-based

* Corresponding author. Tel.: +86-551-63606415; fax: +86-551-63601669.
E-mail address: wgsong@ustc.edu.cn

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evacuation model with smoke effect and blind evacuation strategy(SEBES), the simulation results are confirmed by the metro supermarket.

However, many researchers who studied the evacuation under fire conditions ignored the integrative factors of fire and smoke, the high temperature is the main effect of fire, and smoke can affect people in two ways, on the one hand, smoke

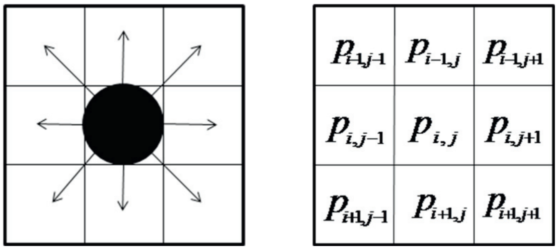


Fig. 1. Possible transitions and corresponding transition probabilities.

contains some poisonous products such as CO which undermines people's health, it is reported that two thirds of toll are due to the noxious fire products under fire emergency, on the other hand, pedestrian's visibility range can be reduced by smoke soot, then the velocity of pedestrian may be slower than normal environment. In this paper, an extended FF model considering the composite factors of fire and smoke is proposed to simulate evacuation in different fire situations, the fire simulation is carried out by FDS software, then the output data such as visibility, temperature and CO concentration from the slice file can be the input of evacuation model.

The rest of this paper is organized as follows. In section 2, we provide an overview of the extended floor field model, different scenarios are set in section 3. Numerical simulations are carried out and the results are discussed in section 4. Finally, in section 5, we close the paper by summarizing our findings and discussing our future research in the area.

2. Model

2.1. An extended FF model

In this model, the visibility and temperature floor fields are introduced based on the original model[17], and the Moor neighborhood is adopted, each pedestrian could select one of the eight possible directions as in Fig 1, the transition probability of selecting a neighborhood cell (i,j) are calculated as follows:

$$p_{ij} = N\exp(k_S S_{ij} + k_D D_{ij} - k_F F_{ij} + k_V V_{ij} - k_T T_{ij})(1-n_{ij})\alpha_{ij} \tag{1}$$

N is the normalization for ensuring that $\sum p_{ij}=1$. k_S, k_D, k_F, k_V, k_T are parameters for scaling the floor fields, n_{ij} indicates whether the cell (i,j) is occupied, it is 1 if the cell is occupied and 0 otherwise. α_{ij} is related to the existence of obstacle or fire in the cell, the value is 0 if the cell is occupied by obstacle or fire and 1 otherwise.

(1) The static floor field S_{ij} which is initialized at the beginning of the model run describes the shortest distance to the exit, it is set inversely proportional to the distance from the exit.

(2) The dynamic floor field D_{ij} diffusing and decaying with the time is a virtual trace left by the pedestrian similar to the pheromone in chemotaxis.

(3) The fire repulsvie field F_{ij} which is calculated inversely proportional to the distance from the fire location represents the effect of the fire location within the certain range. The spread of fire is not considered in this model because the spread of smoke is faster and more serious than the fire spread in the reality.

(4) The visibility floor field V_{ij} reflecting the influence of visibility to pedestrian evacuation is introduced in this model, the expression as follows:

$$V_{ij} = V / V_0 \tag{2}$$

V is the visibility of cells, we set V_0=6m because when the visibility is smaller than 6m, the velocity of pedestrians will be affected badly.

(5) The temperature floor field T_{ij} representing the factor of temperature in the room during evacuation is proposed in the extended model, FDS can export the temperature data.

$$T_{ij} = T / T_0 \tag{3}$$

T is the temperature data, T_0=20℃ represents the environment temperature.
(6) The pedestrian's health is calculated as follows:

$$p_h = p_h - \frac{C_{co}}{W_{co}} * dt \tag{4}$$

p_h is the health of pedestrian and the initial value is 1, C_{co} is the CO concentration, W_{co} is a constant dose, the value is 27000 ppm.min, dt is the size of one timestep.

2.2. Basic update rules

The update rules of our model have the following structure:
(1) The model is updated in parallel.
(2) The static floor field which is updated every timestep is not kept unchanged in this model. If the pedestrian located in one cell can't see the exit due to the bad visibility, then the static floor value of this cell is zero, pedestrians prefer to select the cell which has good visibility.
(3) The range of fire repulsive field is 8 cells from the fire location. If the distance between the pedestrian and fire location is larger than this range, the influence of fire repulsive field is zero. Pedestrian can't cross the range within one cell from the fire location because of the high risk of that area.
(4) Each pedestrian chooses a target cell randomly based on the transition probability p_{ij}.
(5) The health of pedestrian is updated every timestep, when the value of health is below zero, we assume that the pedestrian dies.
(6) The data of visibility, temperature and CO concentration can be got from the FDS, which are read and updated by program every three timesteps.

3. Scenarios

The size of the room is 12m*12m inside, which is discretized into 30cells*30cells, the corresponding cell is 0.4m*0.4m, the single exit whose width is 0.8m is located in the center of right wall as in Fig 2(a), the initial static floor field as in Fig 2(b).

The fire locations are located at the top left corner and near the exit respectively in different scenarios. The burning materials are wood (the yield of soot y_s=0.015g/g), polystyrene foams (the yield of soot y_s=0.18g/g), which are classified into two types according to the soot yield. Eight different heat release rates are studied in this paper. Two types of pedestrian are modeled: the slow pedestrian whose velocity is 1.3m/s, and the fast pedestrian whose velocity is twice as much as the slow pedestrian is 2.6m/s, each timestep is 0.3s, so the fast pedestrian is updated twice and the slow pedestrian is updated once within a timestep in the model, but when the visibility is smaller than 3m or the health of pedestrian becomes 0.5 or below, the velocity of fast pedestrian is cut in half, all the pedestrians are slow pedestrians at that case. The ratio of fast pedestrian to the slow pedestrian is 1:1 in the simulation. The pre-evacuation time we set is 20s in this model, which means pedestrian will begin evacuating from the room after the fire lasts for 20s.

4. Simulation results

The parameters are set as k_S=0.6, k_D=0.2, k_F=0.2, k_V=1.2, k_T=2. Next different scenarios will be studied in this paper, the pedestrians are distributed randomly in the room, each scenario is carried out 10 times, and then the average value is used after calculation.

4.1. The effect of fire locations

Three scenarios are set to study the effect of different fire locations on evacuation in this part, scenario (a) room without fire, (b) room which fire occurred at the top left corner cell(5,5), (c) room which fire occurred near the exit (26,10), the scenarios in the model and FDS are showed in Fig 3(a) and Fig 3(b), simulation results are displayed in Fig 4.

Firstly, in Fig 4, the evacuation time is increasing with the increase of the initial density in the room for different scenarios, obviously, the more pedestrian will need more time to evacuate from the room. Secondly, the evacuation time from a room without fire is smaller than from a room with fire at the same density, the fire effect is reflected in the model. Thirdly, compared to scenario (b), the evacuation from scenario (c) is more dangerous and difficult. Pedestrians will avoid the fire and tend to keep away from the fire during the evacuation, but one side of the exit are affected badly by the fire in

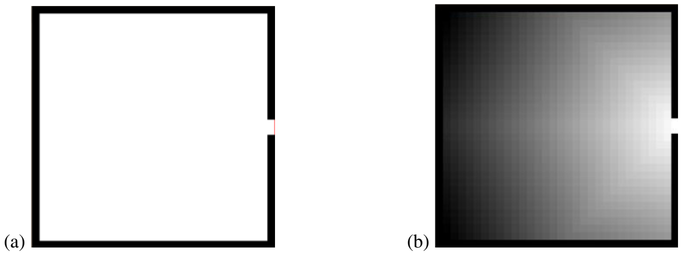


Fig. 2. (a)The structure of the room and (b) the initial static floor field, the larger of the static value, the whiter of the color, the exit cells have the greatest static value.

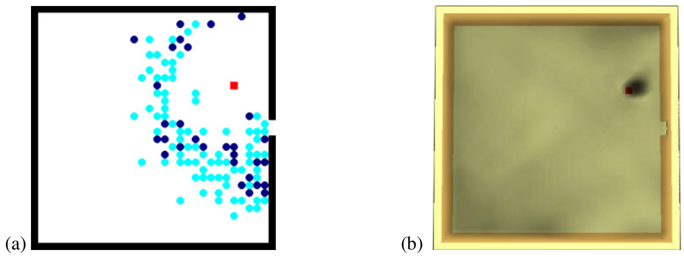


Fig. 3. (a)The evacuation scenario in the model. Red, blue and navy stand the fire location, slow pedestrian and fast pedestrian respectively, (b) the fire scenario in smokeview of FDS

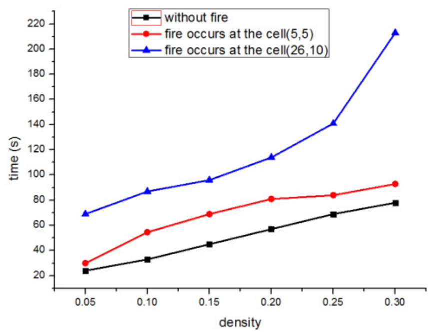


Fig. 4. Simulation of different fire locations, the burning material is wood and the heat release rate is 1000kw/m^2.

scenario (c), people can only evacuate from the other side of exit which is far away from the fire location, so the evacuation from scenario (c) is impeded and needs more time than evacuation from scenario (b).

4.2. The effect of burning materials

Different burning materials have different physicochemical and thermal physical properties, so the effect of different burning materials on pedestrian evacuation can be investigated. In view of the reason that wood is the raw material of furniture and polystyrene is used for foam insulation in the room, so we choose two burning materials: (a) wood, the yield of soot y_s=0.015g/g and the yield of CO y_s=0.004g/g, (b) polystyrene foams, the yield of soot y_s=0.18g/g and the yield of CO y_s=0.06g/g. The total pedestrian in the room in this two scenarios is 200, simulation result is showed in Fig 5.

From Fig 5 we can see that, the whole evacuation in two scenarios can be divided into three phases: the initial phase, the middle phase and the final phase. The distinction of evacuation in two scenarios is not obvious at the initial phase before 27s, because the fire is very small at the inception, which has little influence on the pedestrian evacuation process in both scenarios, the visibility is good enough for pedestrians to find the exit and the fire temperature is not high at this phase. But

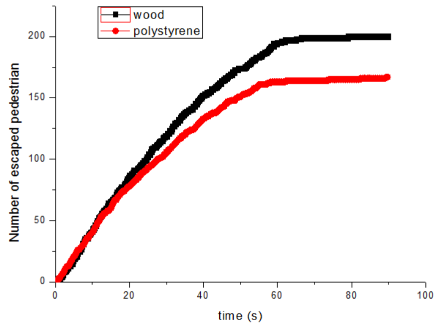
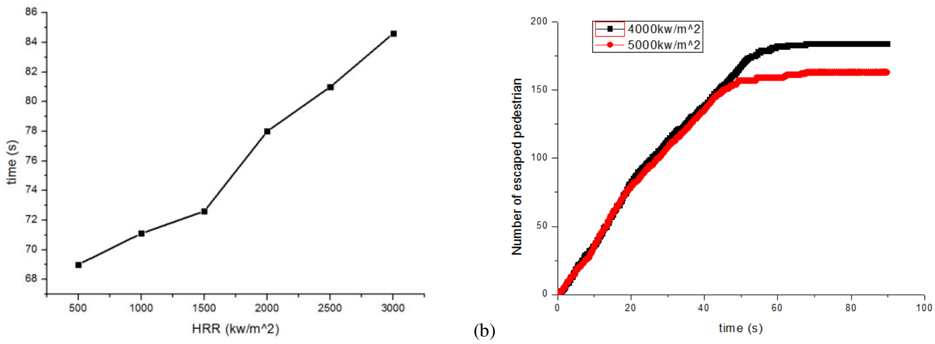


Fig. 5. Different burning materials, the heat release rate is 1000kw/m^2 in two scenarios and fire occurs at the cell (10,10).



(a) (b)

Fig. 6. Effect of different HRR on evacuation, the fire occurs at the cell (10,10) and the burning material is wood.

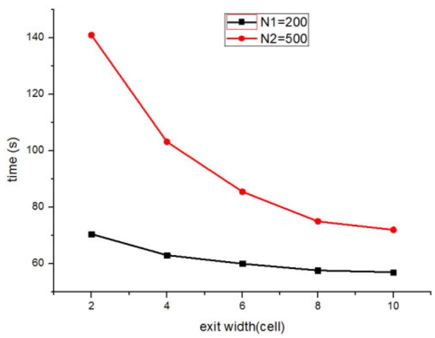


Fig. 7. The effect of different exit width on evacuation, the fire occurs at the cell (10,10), the burning material is wood and the HRR is 1000kw/m^2.

as the time goes on, the difference between two scenarios is displayed, the evacuation in scenario (a) is faster than scenario (b) at the middle phase between 27s and 57s, the reason is that the visibility is reduced dramatically in scenario (b) because of the bigger yield of soot which can reduce the opticality in scenario (b), the yield of soot of the polystyrene is more than ten times of the wood. At the final phase, the visibility is bad in both scenarios, so the evacuations are very slow and the left pedestrians can't find the exit, at last, all the pedestrians are evacuated from the room after the 76.8s in scenario (a) while 33 pedestrians are left in scenario (b) after the 90s. The results indicate that the smoke has great effect on the pedestrian evacuation, meanwhile, it reminds us that a fire occurs in a room decorated with foam materials can result in serious consequences because of the high yield of soot and CO gas.

4.3. The effect of heat release rate

In this part, we set eight heat release rates to study the effect of different heat release rates to the pedestrian evacuation. The burning material is wood, scenario (a) HRR=500kw/m^2, (b) HRR=1000kw/m^2, (c) HRR=1500kw/m^2, (d) HRR=2000kw/m^2, (e) HRR=2500kw/m^2, (f) HRR=3000kw/m^2, (g) HRR=4000kw/m^2, (h) HRR=5000kw/m^2. 200 pedestrians are distributed randomly in the room.

The heat release rate mainly influences the temperature floor field and visibility floor field in the room, the larger of HRR, the fast the temperature increases and the more soot produces. Pedestrians are inclined to choose the cell of low temperature and good visibility in the model, as showed in Fig 6(a), with the increase of HRR, the evacuation time from the room is growing, but the rate of increase is not fast at the beginning when compared to the later period. When the HRR exceeds 3000kw/m^2, some pedestrians can not evacuate from the room because of the bad visibility at last stage, in Fig 6(b), the evacuations are both very fast before 60s, however, the curves become very smooth in the following, which means it is difficult and slow for pedestrians to evacuate from the room. The number of non-escaped pedestrian is 16 and 37 in scenario (g) and (h) respectively within 90s, therefore, we can find the evacuation is highly related to the heat release rate.

4.4. The effect of exit width

During the evacuation simulation above, we find that the congestion near the exit will occur when the initial pedestrian density in the room is high, so the effect of exit width on the evacuation under fire emergency should be discussed. Two scenarios are set in this part: scenario (a) number of the total pedestrian N1=200, (b) number of total pedestrian N2=500. The fire occurs at the cell (10,10) and the burning material is wood.

As showed in Fig 7, at first, the evacuation needs more time in scenario (a) than in scenario (b) with the same exit width because of the higher pedestrian density in the former scenario. The evacuation time can be reduced with the increment of the exit width in scenario (a) and (b), because it is obvious that the congestion near the exit can be relieved when the exit becomes wider. We also see that the influence of exit width at high density in scenario (b) is greater than at low density in scenario (a), but the rate and degree of the decrease becomes slow with the increase of the exit width in two scenarios, which means the exit width is not the dominant factor during the evacuation when the width of exit is very large, the exit is underused at that case in the simulation. Therefore, in view of the safety of pedestrian evacuation under fire emergency and the artistic aspect of the building, the exit width should be considered seriously in architectural design.

5. Conclusions and future work

In this study, an extended floor field model is proposed with considering the effect of smoke and fire on pedestrian evacuation. Firstly the evacuations in a room with fire and without fire scenarios are compared to study the fire effect on pedestrians. After that, the effects of fire locations, burning materials, heat release rate and exit width are discussed, the results show as follows:

(1) The evacuation is more difficult and dangerous under fire emergency, especially when the fire occurs near the exit, which can impede the pedestrian evacuation obviously.

(2) The burning material which has a high yield of soot and CO gas severely affects the evacuation because of the dramatic reduction of visibility after the fire occurs.

(3) The heat release rate has great effect on the temperature and visibility in the room. The larger the heat release rate is, the more evacuation time the pedestrians need.

(4) To some extent, the increase of exit width can reduce the evacuation time, however, when the width of exit is large enough, the decrease of evacuation time doesn't occur, so the exit width should be taken seriously in architectural design especially in crowd buildings.

Although the smoke and fire factors are considered in this model, some other factors may be ignored. In the future, some expansion work should be made, such as considering the velocity change and the psychological factors of the pedestrians under fire emergency.

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