Constant evacuation time gap: Experimental study and modeling*

Ning Guo(郭宁)[1,†], Rui Jiang(姜锐)[2], Mao-Bin Hu(胡茂彬)[3], and Jian-Xun Ding(丁建勋)[1]

[1] School of Automotive and Transportation Engineering, Hefei University of Technology, Hefei 230009, China
[2] MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing Jiaotong University, Beijing 100044, China
[3] School of Engineering Science, University of Science and Technology of China, Hefei 230026, China

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In this paper, the evacuation dynamics in an artificial room with only one exit is investigated via experiments and modeling. Two sets of experiments are implemented, in which pedestrians are asked to escape individually. It is found that the average evacuation time gap is essentially constant. To model the evacuation dynamics, an improved social force model is proposed, in which it is assumed that the driving force of a pedestrian cannot be performed when the resultant physical force exceeds a threshold. Simulation results are in good agreement with the experimental ones.

Keywords: evacuation dynamics, social force model, no driving force

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1. Introduction

To describe and investigate evacuation dynamics, quite a few models have been proposed, which can be classified into macroscopic ones[1,2] and microscopic ones. Microscopic models treat pedestrians as discrete individuals, which can be further classified into two types. In the first type of model, such as the social force model,[3–5] the heuristics-based model,[6] the statistical mechanics-based model,[7] and steps model,[8] the continuous time and space have been adopted. While in the second type of model such as the lattice gas model and the floor field model,[9–13] the time and space are discretized. It is generally believed that panic is adverse to evacuation. Helbing *et al.*[4] took the panic degree into consideration, and found some evacuation phenomena such as "faster is slower" and "arch". Garcimartín *et al.*,[14] launched a controlled experiment to demonstrate the "faster is slower" effect, and found that competitive egress produced longer evacuation time.

The evacuation time gap is one significant characteristic to assess the escape dynamics. To our knowledge, the consistency of evacuation time gaps at different times of the escape process has not been studied. In this paper, we carry out experiments to study the influence of pedestrian number on evacuation time. To model the evacuation dynamics, an improved social force model is proposed, in which it is assumed that the driving force of a pedestrian cannot be fulfilled when the composition of physical forces exceeds a threshold because the pedestrian cannot keep his/her balance under this circumstance. The improved model is shown to be able to correctly reproduce the evacuation process while the original social force model fails to do so.

The remainder of this paper is organized as follows. In Section 2 the experimental setup and results are described. In Section 3 the models and simulation results are presented. Finally, some conclusions are drawn from the present study in Section 4.

2. Experiment

2.1. Experimental setup

The experiments were performed respectively on November 16, 2014 (50 graduate students, of them 39 male, 11 female) and on June 7, 2015 (100 undergraduates, of them 85male, 15 female) in Hefei University of Technology. Experiments were conducted in an artificial room with one exit. The sizes of the virtual room were 7 m×7 m and 10 m×10 m respectively, so that the pedestrian density is approximately the same. The width of the exit is 0.8 m. At the boundary of the virtual room some chairs and two rostrum tables were placed as walls, see Fig. 1.

Participants knew clearly where the exit was, and were asked to escape from the room as soon as possible, but not in a panic environment. It can be regarded as the case that the participants take part in evacuation drills. Before the evacuation, the individuals had uniform random distribution. If too many participants gather in one small area, the experimental commander would ask them to disperse to other place. Pushing by the arm and slight squeezing by the body were allowed in the experiments. Before each round of the experiment, the commander reminded that the participants should escape as if real disaster happened. But if there were some safety hazards, the commander would stop the experiment immediately. Fortunately, no danger happened in two experiments.

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†Corresponding author. E-mail: guoning_945@126.com
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The two sets of experiments were conducted with 12 and 20 replications respectively. The motion of each participant was recorded by video camera (SONY HDR-CX510E), and the evacuation times were recorded manually.

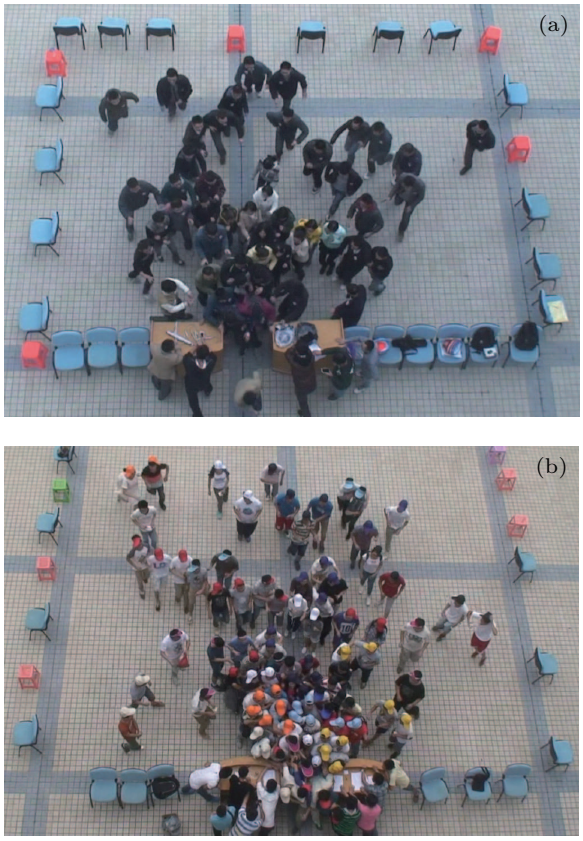


Fig. 1. (color online) Snapshots at the beginning of experiments: (a) 50 pedestrians and (b) 100 pedestrians.

2.2. Experimental results

Tables 1 and 2 show the evacuation times in the two sets of experiments. The average evacuation time in the first set of experiments is 16.96 s, and the standard deviation is 0.89 s. The second set of experiments has larger average evacuation time 32.02 s, which is nearly twice that of the first set of experiments, and the standard deviation (1.79 s) is larger.

Table 1. Evacuation times (unit: second) in the first set of experiments.

First set of experiments							
No.	Time	No.	Time	No.	Time	No.	Time
1	16.96	4	16.02	7	16.00	10	17.64
2	17.97	5	16.70	8	16.01	11	15.80
3	18.44	6	17.72	9	17.50	12	16.78
Average time		16.96		Standard deviation		0.89	
Simulation							
Average time		16.92		Standard deviation		1.02	

Figure 2 shows the distribution of evacuation time gaps. It can be seen that the distribution for each set of experiments keeps basically consistent, and has a peak value around 0.3 s. As a result, the standard deviations of the evacuation time gap are 0.1776 s and 0.1815 s respectively. The small proportion of low evacuation time gap (0.1 s) means that few pedestrians can escape from the room simultaneously, due to the exit width. In addition, the small proportion of high evacuation time gap (> 0.6 s) shows that few arches emerge in the evacuation process.

Table 2. Evacuation times (unit: second) in the second set of experiments.

Second set of experiments							
No.	Time	No.	Time	No.	Time	No.	Time
1	32.25	6	32.46	11	35.03	16	33.38
2	28.4	7	30.72	12	32.10	17	34.14
3	29.92	8	33.28	13	33.39	18	33.98
4	30.62	9	30.37	14	32.85	19	31.41
5	33.40	10	29.38	15	30.29	20	33.1
Average time		32.02		Standard deviation		1.79	
Simulation							
Average time		31.96		Standard deviation		1.90	

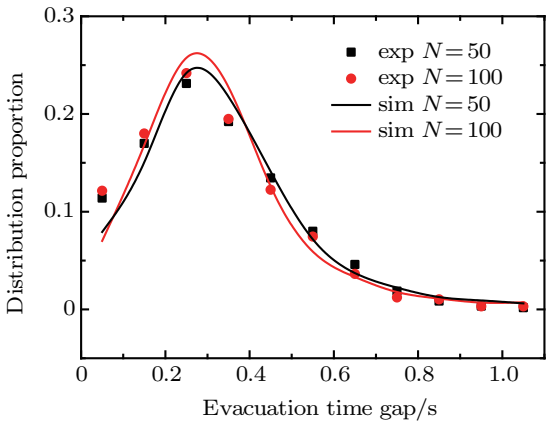


Fig. 2. (color online) Evacuation time gap distribution.

Evacuation time gap between two consecutive pedestrians varies in the evacuation process. Figure 3 shows the average evacuation time gap between the i-th escaped pedestrian and the $(i+1)$-th escaped pedestrian. The average time gap is an indicator to reflect concentration trend, which can undermine the randomness and fluctuation due to the differences in individuality and condition. The average is a common method in evacuation study, such as in the Garcimartín *et al.*'s work.[15] The time gap is essentially constant in both sets of experiments. This implies that the evacuation time gap essentially does not depend on the number of pedestrians that have not yet escaped. Note that the panic condition cannot be built in the experiment, so no faster-is-slower or deadlock emerges near the exit. In the real panic, the life instinct may cause different dynamic characteristics. The experiment is more similar to the real case, when pedestrians leave the stadium in a hurry after one public activity. Therefore, the experimental conclusion has limited application range.

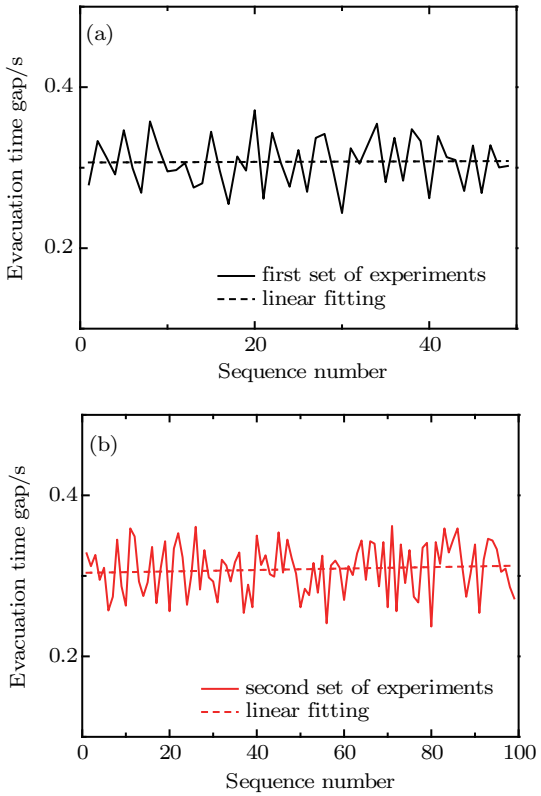


Fig. 3. (color online) Variations of average evacuation time gap between consecutive pedestrians with sequence number in (a) first set $N = 50$ and (b) second set of experiments $N = 100$. The results are averaged over 12 replications and the 20 replications respectively. The dash lines are linear fitting results and are guides for the eyes.

3. Model and simulation

3.1. Social force model

We simulate the evacuation dynamics of the 50-pedestrian experiment by using the original social force model. In the social force model, the motion of a pedestrian is described by three different components: driving force, repulsive force between pedestrians, and repulsive force between pedestrian and wall. The equation of motion is as follows:

$$m_i \frac{\mathrm{d}\boldsymbol{v}_i}{\mathrm{d}t} = \boldsymbol{f}_i^0 + \sum_j \boldsymbol{f}_{ij} + \sum_W \boldsymbol{f}_i^{\mathrm{wall}}. \tag{1}$$

Here m_i is the mass of pedestrian i. The driving force $\boldsymbol{f}_i^0$ represents the pedestrian motivation to walk in a given direction with desired speed, which reads

$$\boldsymbol{f}_i^0 = m_i \frac{v_i^0 \boldsymbol{e}_i^0 - \boldsymbol{v}_i(t)}{\tau}. \tag{2}$$

Here v_i^0 and $\boldsymbol{e}_i^0$ are respectively the magnitude and direction of the pedestrian desired speed. $\boldsymbol{v}_i(t)$ is the current speed, and τ denotes the relaxation time.

The repulsive force $\boldsymbol{f}_{ij}$ describes the interaction between pedestrian i and other pedestrians, which includes socio-psychological force to stay away from others and physical contact force, and is expressed as

$$\boldsymbol{f}_{ij} = A \cdot \exp[(r_{ij} - d_{ij})/B]\boldsymbol{n}_{ij} + g(r_{ij} - d_{ij}) \times (k\boldsymbol{n}_{ij} + \kappa \Delta v_{ji}^q \boldsymbol{q}_{ij}), \tag{3}$$

$$g(x) = \begin{cases} x, & x > 0, \\ 0, & x \le 0. \end{cases} \tag{4}$$

In Eq. (3), the first term on the right-hand side denotes the socio-psychological force, and the second term represents the physical contact force. Pedestrians i and j are regarded as cylinders with radius r_i and r_j, respectively. The r_{ij} denotes the sum of the radius of the two pedestrians, namely $r_{ij} = r_i + r_j$. The d_{ij} is the distance between the centers of the two pedestrians. $\boldsymbol{n}_{ij}$ represents the unit normal vector from pedestrian j to i, and $\boldsymbol{q}_{ij}$ means the unit tangential vector. They are expressed as follows:

$$\boldsymbol{n}_{ij} = \left(\frac{x_i - x_j}{d_{ij}}, \frac{y_i - y_j}{d_{ij}} \right), \tag{5}$$

$$\boldsymbol{q}_{ij} = \left(-\frac{y_i - y_j}{d_{ij}}, \frac{x_i - x_j}{d_{ij}} \right), \tag{6}$$

where x_i, x_j and y_i, y_j are respectively the horizontal and vertical coordinates of the centers of the two pedestrians. The Δv_{ji}^q means the tangential velocity,

$$\Delta v_{ji}^q = (\boldsymbol{v}_j - \boldsymbol{v}_i) \cdot \boldsymbol{q}_{ij}, \tag{7}$$

where $k\boldsymbol{n}_{ij}$ and $\kappa \Delta v_{ji}^q \boldsymbol{q}_{ij}$ are body pressure and friction force respectively. A, B, k, and κ are four parameters.

The repulsive force $\boldsymbol{f}_i^{\mathrm{wall}}$ from the wall is modeled analogously as

$$\boldsymbol{f}_i^{\mathrm{wall}} = A \cdot \exp[(r_i - d_i^{\mathrm{wall}})/B]\boldsymbol{n}_i^{\mathrm{wall}} + g(r_i - d_i^{\mathrm{wall}}) \times (k\boldsymbol{n}_i^{\mathrm{wall}} + \kappa \Delta v_i^q \boldsymbol{q}_i^{\mathrm{wall}}). \tag{8}$$

Here, d_i^{wall} means vertical distance to the wall, $\boldsymbol{n}_i^{\mathrm{wall}}$ denotes the unit normal vector from the wall to pedestrian i, and $\boldsymbol{q}_i^{\mathrm{wall}}$ is the unit vector tangential to the wall. The tangential velocity $\Delta v_i^q = -\boldsymbol{v}_i \cdot \boldsymbol{q}_i^{\mathrm{wall}}$, since speed of the wall is zero.

In the simulation, we set $A = 0$, i.e., we neglect the socio-psychological repulsive force, because pedestrians do not care to stay away from others in the evacuation process. Other parameters are calibrated and they are $m_i = 60$ kg, $v_i^0 = 1.5$ m/s, $r_i = 0.225$ m, $\tau = 0.5$ s, $k = 7.2 \times 10^4$ kg·s^{-2}, and $\kappa = 60$ kg·m^{-1}·s^{-1}. The uniform random distribution is used. With these parameters, the average evacuation time of 50 pedestrians from a 7 m×7 m room is 17.44 s, which is in good agreement with the experimental result. However, as can be seen from Fig. 4, instead of being essentially constant, the evacuation time gap gradually increases. Also, the average evacuation time of 100 pedestrians is 25.87 s, which is significantly different from the experimental result. It is due to the accumulation effect of driving force. The driving force transmits to the exit area by the body contact, such as pushing or squeezing. More pedestrians in the room generate larger accumulation, facilitating the evacuation process. When the pedestrians are fewer, the accumulation effect weakens, slowing down evacuation efficiency.

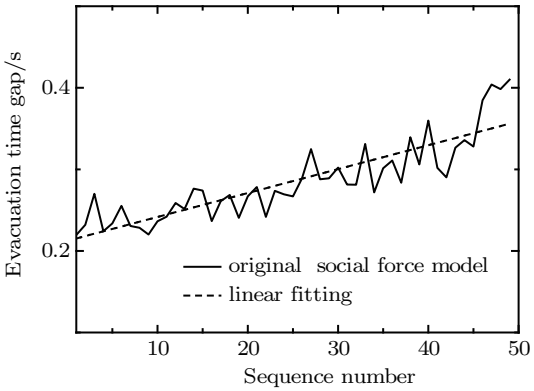


Fig. 4. Variation of average evacuation time gap between consecutive pedestrians with sequence number in simulation results of escaping individually in the original social force model. The simulation results are averaged over 50 replications.

To quantify the effect, we define a pressure-like parameter P as the magnitude of repulsive physical contact forces between pedestrian i and other pedestrians, and it is expressed as

$$P_i(t) = \frac{1}{m_i} \sum_{j=1, j\neq i}^{N} \left| \boldsymbol{f}_{ij}(t) \right|, \tag{9}$$

where N is the number of pedestrians still not yet escaped.

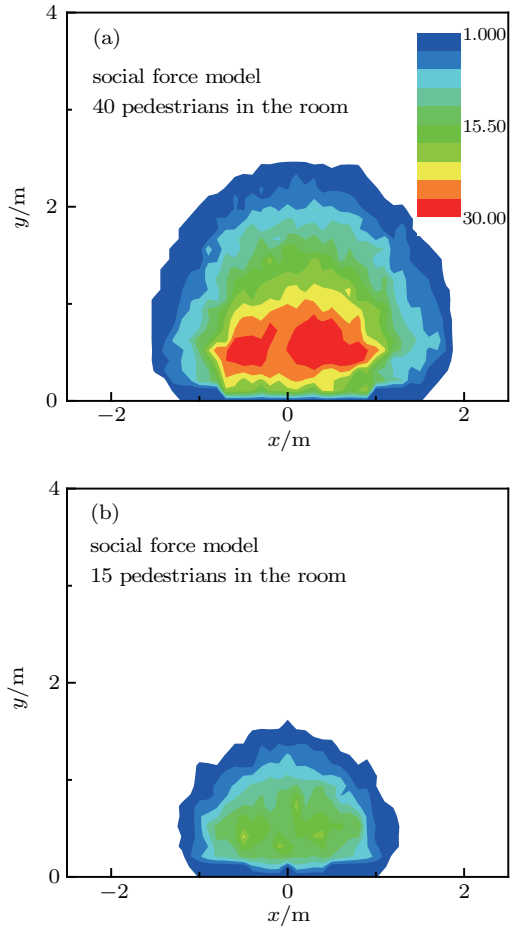


Fig. 5. (color online) Simulation results of distribution of the pressure-like parameter P (unit: m/s^2). Initially there are 50 pedestrians in the room simulated by the original social force model.

Figures 5(a) and 5(b) show the distributions of P, which are averaged over 50 replications. Generally speaking, the closer to the door, the larger P is. Moreover, with more pedestrians escaped from the room (Fig. 5(b)), the magnitude of P in the vicinity of the door remarkably decreases. When P is large, pedestrians near the door will be pushed by large force. Therefore, they escape quickly. With the decrease of P, the pushing force decreases, lowering down the movement speed. To some extent, this result is like the fluid dynamic problem. Suppose that there is a tap at the bottom of a barrel. The less the water in the barrel, the smaller the flow speed from the tap is, because the pressure near the tap lowers down. Here the driving force of pedestrian is analogous to the gravity of water, and the pressure-like parameter P is analogous to the pressure of water in the barrel.

3.2. Improved social force model

Now we propose an improved social force model to overcome the deficiency presented above. When squeezed in the crowd, a pedestrian can be pushed away if the resultant contact force from other pedestrians and walls is large. Under this circumstance, the pedestrian would not be able to perform the driving force temporarily. Based on this fact, the driving force is modified as follows:

$$\boldsymbol{f}_i^0 = \begin{cases} m_i \dfrac{v_i^0 \boldsymbol{e}_i^0 - \boldsymbol{v}_i(t)}{\tau}, & f_i^{\text{contact}} \leq f_{\text{c}}, \\ 0, & f_i^{\text{contact}} > f_{\text{c}}. \end{cases} \tag{10}$$

Here

$$f_i^{\text{contact}} = \left| \sum_j \boldsymbol{f}_{ij} + \sum_W \boldsymbol{f}_i^{\text{wall}} \right| \tag{11}$$

means the resultant physical force. The f_{c} is a threshold parameter. Note that Parisi *et al.*[16] have proposed a self-stopping mechanism in a normal situation, in which pedestrians prefer to keep a distance from others so that they proactively stop performing the driving force when getting close to others. In contrast, in our model, escaping pedestrians are not able to perform the driving force passively when getting squeezed.

Next, we present simulation results of the improved social force model. Calibration shows that $f_{\text{c}} = 600$ N, $v_i^0 = 1.8$ m/s, and other parameters are the same as those used before. As can be seen from Tables 1 and 2, the average evacuation time is 17.48 s and 32.01 s, which are in pretty good agreement with the experimental results. Figure 2 shows that simulation results of the distribution of evacuation time gaps are in consistent with the experimental ones.

More importantly, figure 6 shows that the evacuation time gap is essentially a constant as observed in the experiments. The distribution of the pressure-like parameter P is shown in Fig. 7, which is remarkably different from that in the original model. One can see that magnitude of P in the vicinity of the

door is essentially independent of the number of pedestrians that have not yet escaped. If the pushing force is temporarily too large, the pedestrian has to keep the body balance to avoid possible falling-down. In this condition, the pedestrian has no mind going forward, and breaks the increase of the pushing force from congestion boundary to congestion center. Therefore, the pushing force keeps constant, and time gap keeps constant, too. This result is analogous to the grain flow problem. The flow rate of sandglass remains constant. As shown in Fig. 8, the more the pedestrians in the room, the more the pedestrians not able to perform the driving force is. Consequently, the evacuation time gap essentially does not change.

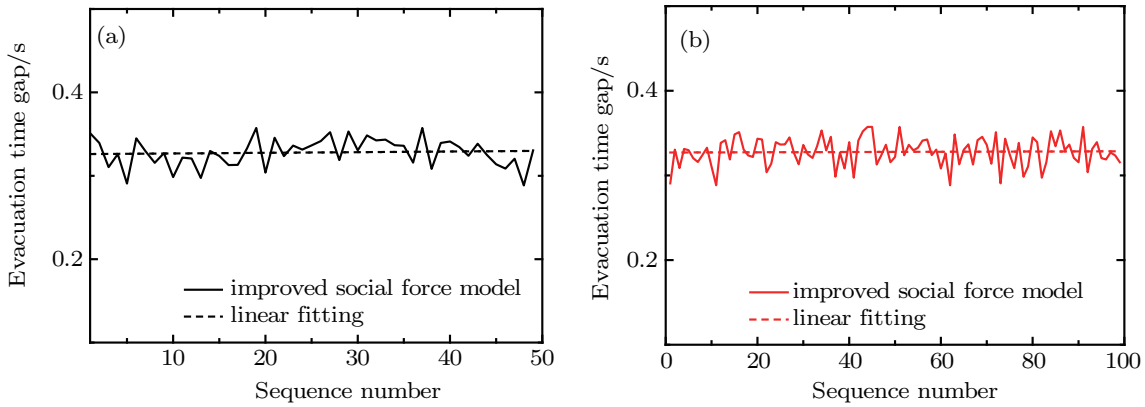


Fig. 6. (color online) Simulation results of average evacuation time gap between consecutive pedestrians by the improved social force model, in which pedestrians escape individually in the cases of (a) $N = 50$ and (b) $N = 100$.

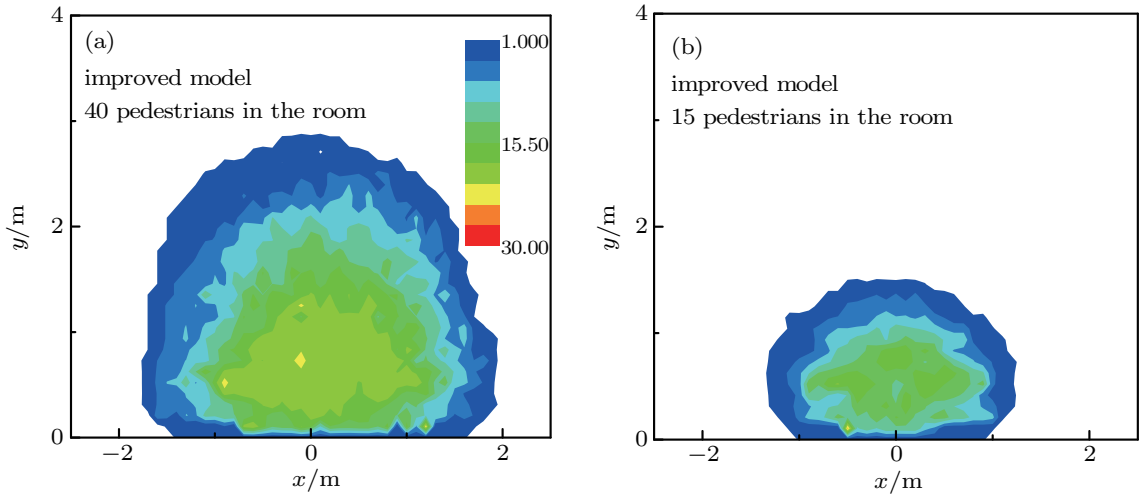


Fig. 7. (color online) Simulation results of distribution of the pressure-like parameter P (unit: m/s^2). Initially there are 50 pedestrians in the room simulated by the improved model.

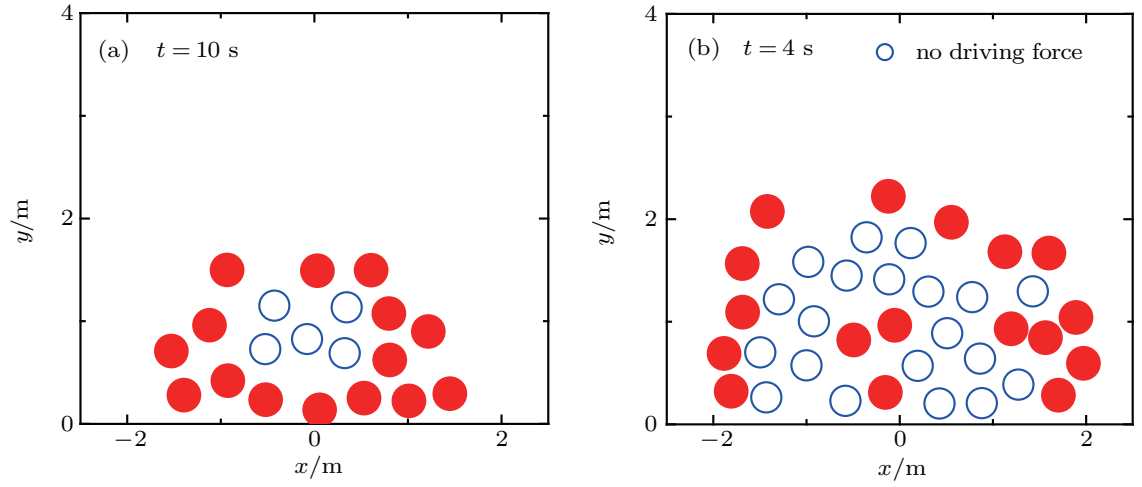


Fig. 8. (color online) Two snapshots of the evacuation process in one replication of the simulation. Initially there are 50 pedestrians in the room, and they escape individually. The red dots (blue circles) mean that pedestrians are able (unable) to perform the driving force at the moment.

4. Conclusions

In this paper, we experimentally study the evacuation dynamics. Two sets of experiments are conducted, in which pedestrians are asked to escape individually. The experiments show that the average evacuation time gap is essentially constant.

We perform the simulation of the evacuation process by using the social force model. It shows that the model fails to reproduce the constant average evacuation time gap due to accumulation effect of driving force. We propose an improved model to overcome the deficiency in the original social force model, in which it is assumed that the driving force of a pedestrian cannot be performed when the resultant physical force exceeds a threshold. Simulation results are in good agreement with the experimental ones.

Our study only considers the evacuation in a room with only one exit, and pedestrians know the environment well. In our future work, more experiments should be performed to examine other conditions, e.g., the effects of exit width and location, the effect of a real wall, the influence of view range. Our study focuses on evacuation when the congestions and arches emerge. If the room is too big, or very few pedestrians are the room, there will not exist the congestion, and the initial distribution may have great effects on evacuation time and time gap. More studies on low density are also necessary. Real cases in the disaster can also been investigated by the closed circuit television.

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