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Microscopic dynamics of pedestrian evacuation

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Abstract

In the present work, we studied the room evacuation problem using the social force model introduced by Helbing and coworkers. This model allows to explore different degree of panic. The 'faster is slower' effect induced by panic is analyzed. It can be explained in terms of increasing clogging delays probability which shows a strong correlation with certain structures that we call 'blocking clusters'. Also, the influence of the exit door size over the evacuation efficiency is briefly discussed.

PACS: 46.10.+z; 34.10.+x; 89.50.+r

Keywords: Panic evacuation; Social force model; Discrete pedestrian simulation

1. Introduction

The problem of evacuation is of obvious importance in common life. In last years, several computer models that simulate pedestrian evacuation were developed [1]. They are compatible with the corresponding country regulations. However, the problem of evacuation under emergency situations is not treated properly in engineering design codes where the flow rate of pedestrian going out through an exit door of width L is considered a linear function of L. Under normal evacuation conditions (no panic) a $L = 2\,\mathrm{m}$ door may have the double evacuation capacity than a $L = 1\,\mathrm{m}$ door.

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Nevertheless, under panic situation this is no longer valid, because panic can cause very dramatic blocking effects.

Pedestrian flow through a bottleneck [2] and clogging in T-shape channel [3] have been studied previously using the lattice-gas model of biased random walkers. More general self-driven particle systems with simple interactions were studied by Vicsek et al. [4], Albano [5] and Czirók et al. [6]. Phase transitions were found for all these systems.

In the present work we will study the room evacuation problem. Since the 'Social Force Model' proposed by Helbing and Molnar [7] we have a realistic model for panic simulation. This model takes into account the discrete nature of the 'pedestrian fluid' allowing to set individual physical parameters (mass, shoulder width, desired velocity and target, etc.). Real scale interaction forces can be calculated, in particular the contact forces which may cause high pressures capable of pushing down a wall of bricks or to asphyxiate people inside the crowd. The above characteristics cannot be considered with cellular automata approaches or traditional models using continuous fluid approximations.

The understanding of the evacuation dynamics will allow to design more comfortable and safe pedestrian facilities.

Also, special devices that speed up the evacuation processes could be created. A simple example is to place a column near the exit as proposed by Helbing et al. [8]. More sophisticated devices could be developed based on a validated panic model.

The aim of the present paper is to investigate the microscopic mechanism involved in the efficiency of the room evacuation process.

This work is organized as follows. In Section 2 we present the 'Social Force Model' postulated by Helbing et al. [8]. Section 3 describes the simulations made. In Section 4 the results of the simulations with variable desired velocity and fix door width are shown and interpreted. Section 5 briefly discuss the influence on the evacuation efficiency if the exit door width are increased. Finally in Section 6 we present our conclusions.

2. The model

In this paper we make use of the 'Social Force Model' model proposed by Helbing et al. [8]. In this model the dynamics of each particle (p_i) is fixed by three kind of forces: 'Desired Force' ($\mathbf{F}_{Di}$), 'Social Force' ($\mathbf{F}_{Si}$) and 'Granular Force' ($\mathbf{F}_{Gi}$). The corresponding expressions are shown in the next equations

$$\mathbf{F}_{Di} = m_i \frac{(v_i - v_{di})\mathbf{e}_i}{\tau} , \tag{1}$$

$$\mathbf{F}_{Si} = \sum_{j=1, j\neq i}^{N_p} A \exp\left(\frac{-\varepsilon_{ij}}{B}\right)\mathbf{e}_{ij}^n , \tag{2}$$

$$\mathbf{F}_{Gi} = \sum_{j=1, j\neq i}^{N_p} \lfloor(-\varepsilon_{ij}k_n - \gamma \mathbf{v}_{ij}^n)\mathbf{e}_{ij}^n + (\mathbf{v}_{ij}^t \varepsilon_{ij} k_t)\mathbf{e}_{ij}^t\rfloor g(\varepsilon_{ij}) , \tag{3}$$

where

$$\varepsilon_{ij} = r_{ij} - (R_i + R_j) \quad (4)$$

and m_i is the particle mass, v_i and v_{di} are its actual and desired velocities, respectively, $\mathbf{e}_i$ is the versor pointing to the desired target, τ is a constant related with the relaxation time of the particle to achieve his v_d, N_p is the total number of people in the system, A and B are constants that state the strength and reach of the social interaction, $\mathbf{e}^n_{ij}$ is the versor pointing from particle p_j to p_i, this direction is the 'normal' direction between two particles, the tangential versor ($\mathbf{e}^t_{ij}$) indicates the corresponding perpendicular direction, r_{ij} is the distance between the centers of p_i and p_j, R_i is the particle radius, k_n and k_t are the normal and tangential elastic restitutive constants, γ is the damping constant (the Helbing's original model did not consider the non-conservative term associated to this constant), v^n_{ij} is the normal projection of the relative velocity seen from p_j ($\mathbf{v}_{ij} = \mathbf{v}_i - \mathbf{v}_j$), v^t_{ij} is the tangential projection of the relative velocity, and the function $g(\varepsilon_{ij})$ is: $g = 1$ if $\varepsilon_{ij} < 0$ or $g = 0$ otherwise. Particles were initialized uniformly distributed inside the room in such a way that $\varepsilon_{ij} > 0$ for all pair ij and with also uniformly distributed initial velocities inside the range $1.0 \pm 0.005\,\mathrm{m/s}$.

The interaction of particles with walls and vertex through social and granular forces are computed in an analogous way.

3. Numerical simulations

In order to further explore the room evacuation dynamics with the above model we have performed a series of simulations varying v_d and the exit door width (L). For each value of L, the total number of people inside the room was varied in order to get similar jamming effects just before the exit.

The equations of motion were solved using a velocity Verlet Algorithm [9] with a time step of $\mathrm{d}t = 10^{-4}\,\mathrm{s}$. This time step is low enough to obtain stable results in the sense that if $\mathrm{d}t$ is reduced to $\mathrm{d}t' < \mathrm{d}t$ very similar trajectories of the particles are obtained, solving the equations of motion of the system with the same initial conditions.

Following Helbing, the model parameters used were $\tau = 0.5\,\mathrm{s}$, $A = 1000\,\mathrm{N}$, $B = 0.08\,\mathrm{m}$, $k_n = 1.2\ 10^5\,\mathrm{N/m}$, $k_t = 2.4\ 10^5\,\mathrm{kg/m/s}$ and $\gamma = 100\,\mathrm{kg/s}$.

The geometry of the room was a $20\,\mathrm{m} \times 20\,\mathrm{m}$ square. Pedestrian shoulder width were uniformly distributed between $(0.5\,\mathrm{m}, 0.58\,\mathrm{m})$.

Around 14 runs were performed, with 200 particles and $L = 1.2\,\mathrm{m}$, for each of the following values of v_d: 0.8, 1.0, 1.5, 1.75, 2.0, 2.25, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0 and 8.0 m/s. In each case the desired velocities for the 200 particles were uniformly distributed inside a range of $v_d \pm 0.05\,\mathrm{m/s}$.

Another set of 14 runs were made with $v_d = 4\,\mathrm{m/s}$ for each of the following door widths (L): 1.2, 1.8, 2.4, 3.0, 3.6 and 4.2 m with $N_p = 200$, 260, 320, 380, 440 and 500 particles, respectively.

4. Evacuation time versus desired velocity

Helbing and coworkers have analyzed different properties of the model above-described. In what is relevant to this work they have shown that, in the room evacuation problem, the total evacuation time curve has a typical functional behavior, displaying a minimum at moderate values of v_d. We will denote this minimum as the desired velocity threshold v_{dt}. For velocities above and below, the evacuation time increases, which means that a very interesting phenomenon takes place, above the threshold the largest the value of v_d the longer it takes to evacuate a room.

The importance of such a behavior is clear if one thinks on situations in which the crowd is in a state of panic. A state of panic is associated with higher values of v_d. When we analyze the evacuation time in our simulations the behavior described by Helbing is recovered. In Fig. 1 we show such a curve. In this figure we are showing the variation of such a curve when one considers different amounts of pedestrians who have already left the room. It can be seen that the general shape is conserved.

Further information can be gained if we look at the discharge curve, i.e., the number of particles that have left the room as a function of time. In this curve horizontal lines denote the time difference between two successive particles which leave the room. These time differences will be referred as ‘‘delays’’ (see Section 4.1). In Fig. 2 we show this curve for a single realization at three different values of v_d, namely 0.8, 2.0 and 6.0 m/s. It can be easily recognized that at larger values of v_d the occurrence of abnormally large delays becomes more probable particularly in the early stages of the evolution of the system. This effect can be further explored if we look at the distribution of delays when 10–160 people were evacuated. This is

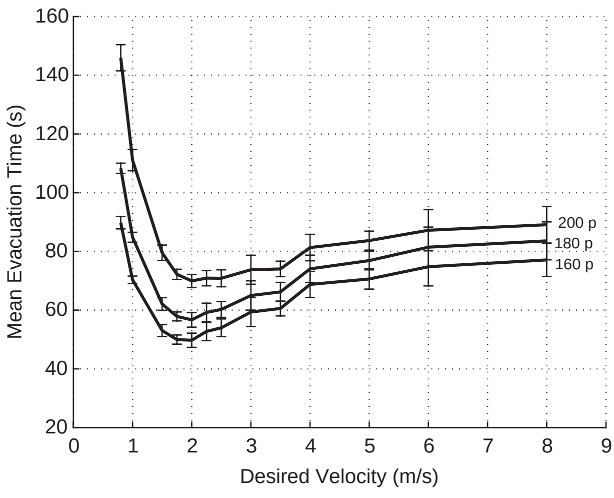

Fig. 1. Mean evacuation time as function of the v_d for all the 200 people and for the first 180 and 160 persons.

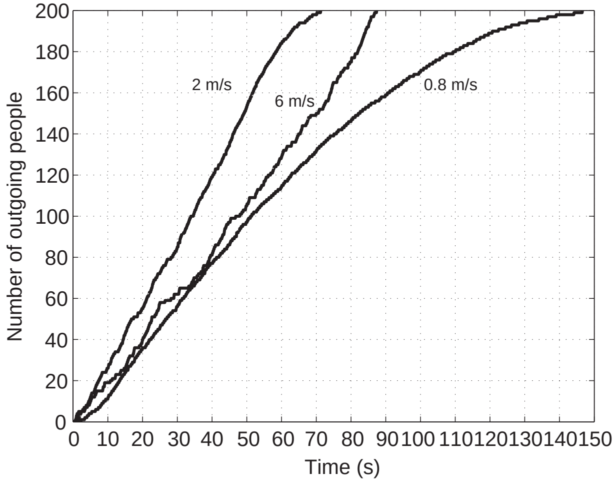

Fig. 2. This figure shows the so-called discharge curve, i.e. the time at which each particle leaves the room. This curves are calculated from a single simulation for three different values of v_d namely 0.8, 2.0 and 6.0 m/s. Note that the curve corresponding to the highest v_d has a less smooth shape. This is related to the presence of large clogging delays (see text).

displayed in Fig. 3. In this figure it is clear that the tails of the distributions grow larger the larger the value of v_d.

Through the examination of animations of the evolutions performed it was clear that the larger the value of v_d the higher the tendency of particles to get stacked in the vicinity of the door precluding them to cross it and other particles to approach it. In Section 4.1 we will perform a cluster analysis of the configurations and show it is correlation with the emergence of delays.

4.1. Clogging delay and granular clusters

As stated in Section 4, simulations show that there are different kinds of delays between two successive outgoing individuals. This effect is known as clogging and we call "clogging delay" to the period of time between two outgoing people. Fig. 4 shows the mean clogging delay for the evacuation of 200 people and for the values of v_d analyzed in this work. As it can be expected the total evacuation time is directly related to the mean clogging delay. However, the clogging delays at both sides of v_{dt} ($v_{dt} = 2\,\mathrm{m/s}$) have very different nature.

In order to find the reason for this asymmetry we define a "granular cluster" (C_g) as

$$C_g : p_i \varepsilon C_g \;\Leftrightarrow\; \exists j \varepsilon C_g / r_{ij} < (R_i + R_j)\,, \tag{5}$$

where (p_i) indicate the ith particle (or person) and R is his radius. That means, C_g is a set of particles that interact not only with social and desired force, but also with granular forces.

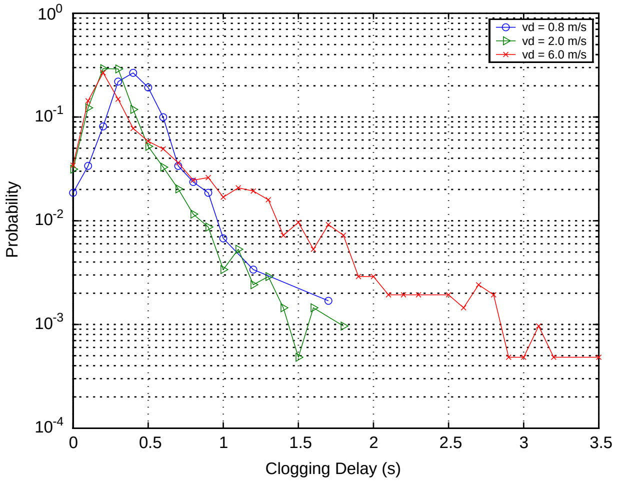

Fig. 3. Distribution of clogging delays up to 160 people evacuated for the same values of v_d as in the previous figure. It can be seen that as the v_d gets larger the clogging delay distribution develop a tail at larger times.

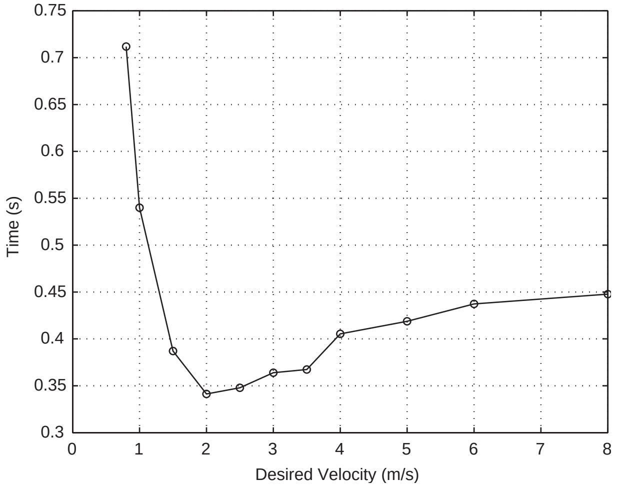

Fig. 4. Mean clogging time delay for the evacuation of 200 people as a function of v_d.

In Fig. 5 the probability of finding a granular cluster with more than 10 persons for each v_d can be seen.

Note that granular clusters greater than 10 persons begin to have a non-negligible probability for $v_d > v_{dt}$. This is a clear evidence that granular interaction become dominant for high v_d. On the other hand, for low v_d granular interactions are rarely observed.

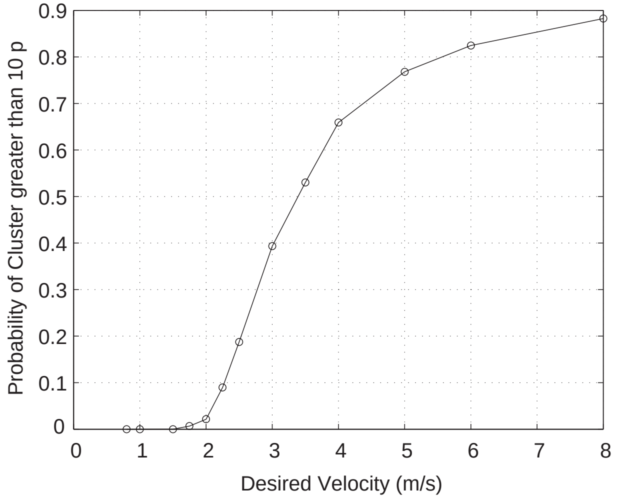

Fig. 5. Existence probability of clusters with more than 10 particles versus v_d.

In the region of $v_d < 2\,\mathrm{m/s}$ only social repulsion is relevant. The low desired velocities generate low desired forces which are not strong enough to overcome the social potential, so people do not touch each other.

Based on the asymmetry found respect to granular and social interactions we will call "social clogging" and "granular clogging" to both types of clogging, respectively.

In the following subsections the mentioned difference is further investigated.

4.2. Low desired velocities

For low v_d ($< v_{dt}$) the behavior of the system is what one would expect since the faster the people move (as v_d increase) the faster they can evacuate the room. In this region the behavior of the evacuation time curve is modeled by two effects: the value of v_d and the social clogging.

In order to corroborate this affirmation let us define a "mean geometric flow rate" as the flow rate that would be achieved if pedestrian did not feel any social repulsion and they were organized in an ordered geometrical way. An illustration of this situation would be a "transportation belt" where people move all at the same velocity and they stand very close.

In this picture, two people can get out simultaneously (because the maximum shoulder diameter is half the door width) followed by other two and so on. The mean time needed to cross the door is $0.54\,\mathrm{m}/v_d$ so the mean geometric flow rate could be written as $Q_g = 2/0.54\,\mathrm{m}/v_d$. Then the evacuation time of 200 people can be calculated as $t_{eg} = 200/Q_g$. If we compare the results obtained by applying this formula with the ones obtained in our simulation we find that, at low v_d, t_{eg} is nearly twice the simulated t_e.

Table 1

v_d	t_e	t_{eg}	$\frac{t_e}{t_{eg}}$
0.8	146	135	1.08
1.0	111	108	1.03
1.5	79.5	72	1.10
2.0	69.9	54	1.30
2.5	70.8	43	1.64
3.0	73.7	36	2.05
3.5	74	31	2.40
4.0	81.3	27	3.10

The reason for such a discrepancy is that simulations show that in general the probability of two persons going out simultaneously is very low for small values of v_d ($\sim 10^{-3}$) while for higher values of v_d it approaches 10^{-2}.

So people leave the room one at a time. Then the mean geometric flow rate should be rewritten as $Q_g = 1/0.54\,\text{m}/v_d$. This effect is due to the social repulsion which does not allow two people to stand very close one from another.

Table 1 shows the simulated and geometric evacuation time for 200 people for various v_d.

It can be seen that $t_e \sim t_{eg}$ until $v_d = 2\,\text{m/s}$ at which the ratio $\frac{t_e}{t_{eg}}$ begins to rise. This clearly states that for $v_d < 2\,\text{m/s}$ the evacuation time is governed by the v_d and the fact that social repulsion forces people to leave the room one by one.

On the other hand, for $v_d > 2\,\text{m/s}$ the simulated evacuation time begins to be greater than the corresponding t_{eg} indicating that a change in regime takes place.

The clogging delays observed in the region $v_d < 2\,\text{m/s}$ are due to the low people density (which do not touch each other) governed by social repulsion. The main effect of such an interaction is, as already mentioned, that people leave the room one at a time, but it can also happen that two or three people stand for a while "wandering around" before one of them finally succeeds in leaving the room. This phenomenon occur because an unstable equilibrium is reached between the desired and social forces near the door. And it can be interpreted as an "excess of politeness".

Summarizing, in the case studied in this subsection, pedestrian are able to faster evacuate the room by increasing v_d keeping the probability of personal contact low and friction negligible.

4.3. High desired velocities

In the region of $v_d > 2\,\text{m/s}$ the behavior of the system is more complex and less intuitive. At variance with the behavior found in the previous section, the faster the people wish to move the slower they can evacuate the room. This is known as the "Faster is slower effect".

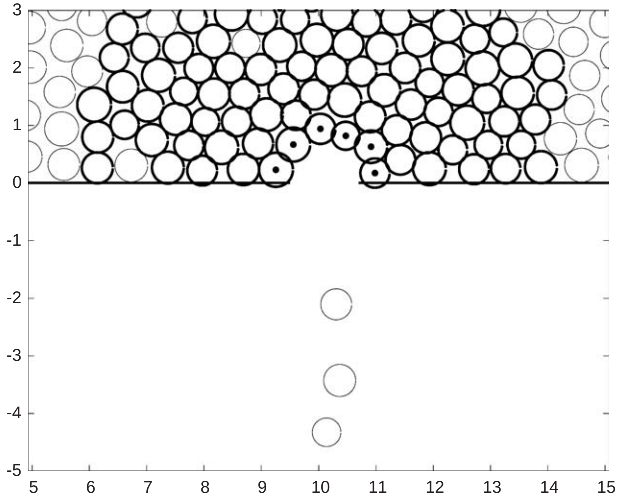

Fig. 6. A typical blocking cluster (particles with centers). Particles belonging to any arbitrary cluster are drawn with wider lines.

When $v_d > 2\,\mathrm{m/s}$ the desired force gets high values which overcome the social potential, producing contacts between particles. As a consequence, as already said in Section 4.1, granular forces begin to play a role.

Just before the exit, the contact forces are able to produce arch like blocking clusters as shown in Fig. 6. A "blocking cluster" (C_{bc}) is defined as the subset of clusterized particles closest to the door whose first and last component particles are in contact with the walls at both sides of the door.

These blocking clusters can be more or less stable and can last up to 6 s in our simulations and they can be composed of 3 to 10 individuals.

In order to quantify the relationship between blocking cluster and clogging delay we define the "arch-clogging" correlation coefficient as follows

$$c_{ac} = \frac{1}{N}\sum_{cd=1}^{N} f(t_2^{bc}, t_1^{cd}, t_2^{cd}) \,, \tag{6}$$

where N is the total number of clogging delays in each run t_2^{bc} is the time at which some arbitrary blocking cluster brakes down, t_1^{cd} is the time at which the associated clogging delay starts, t_2^{cd} is the time at which this clogging delay finishes. "Associated" means that the first particle that exits the room at time t_2^{cd} (when the clogging delay finished) must be one of the particles that belonged to the blocking cluster broken at t_2^{bc}. The function f is equal to 1 if $t_1^{cd} \leqslant t_2^{bc} \leqslant t_2^{cd}$ and is otherwise equal to zero.

In Fig. 7 the number of Clogging delays as a function of the v_d and for different bins in time of delay are shown. It can be seen that the slow v_d dynamics is dominated by clogging delays between 0.3 and 1.0 s. As the v_d increases, clogging delays between 0.1 and 0.3 s become more important.

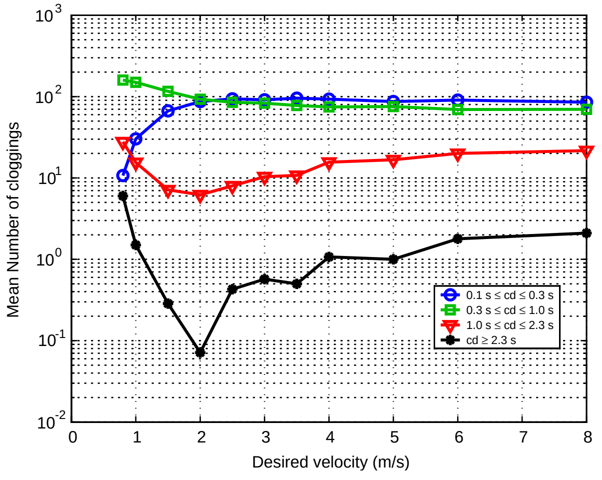

Fig. 7. Mean number of clogging delays within the defined bins for different v_d.

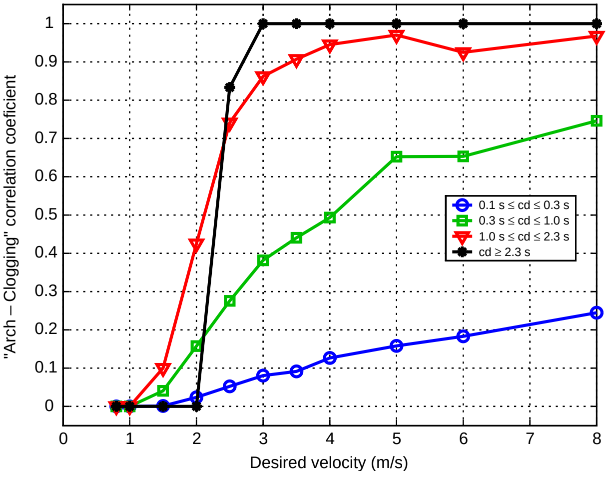

Fig. 8. Arch-clogging correlation coefficient as defined in Eq. (6) versus v_d.

We now present the results of the calculation of c_{ac}, Fig. 8 shows the c_{ac} coefficient for different clogging delay ranges. The meaning of a c_{ac} of 0.6 is that the 60% of the clogging delay (between the considered range) were produced by blocking clusters and the 40% left are social clogging.

It can be seen that the correlation between the presence of a blocking cluster and a clogging delay is almost one for delays longer or equal to 2.3 s and v_d bigger than 2.0 m/s, which is the optimal velocity for evacuation. Below this velocity all "long delays" are due to social clogging.

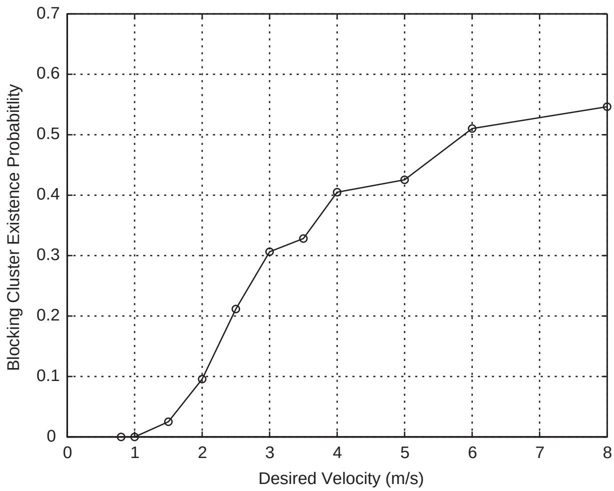

Fig. 9. Blocking cluster existence probability as a function of v_d.

For shorter clogging delays the competition between social clogging and blocking clusters is evident. In particular for the shortest bin considered ($0.1 \leqslant cd \leqslant 0.3$) blocking clusters are responsible for at most 30% of the clogging delays.

From this analysis it is clear why, above the threshold velocity v_{dt} "Faster is slower". As the v_d is increased the probability of apperance of a blocking cluster increases (see Fig. 9). This is due to the fact that at these velocities the granular forces play a more important role and can generate clusters which block the exit of particles. The monotonous increase of the mean clogging delay for v_d larger than v_{dt} in Fig. 4 can be traced to the increase in the mean number of the large clogging delays (see Fig. 7) which turnout to be strongly correlated to the presence of blocking clusters (see Fig. 8).

5. Effect of door size variation

The analysis performed so far focused in a given size door. It is quite obvious that the role of blocking clusters will depend on the size of the door (i.e., the bigger the door the lower the probability of finding blocking clusters and then the less important the "Faster is slower" effect).

In what follows we show some preliminary results from simulations in which the size of the door is increased. For this analysis, the number of particles inside the room is a function of the size of the door. The number of particles chosen for each case is such that the average number of particles forming clusters is approximately constant, for the cases analyzed. The doors sizes used and the corresponding number of particles are those stated in Section 3. The desired velocity was fixed at $v_d = 4\,\mathrm{m/s}$.

In Fig. 10 we show the probability of finding a blocking cluster as a function of the size of the door.

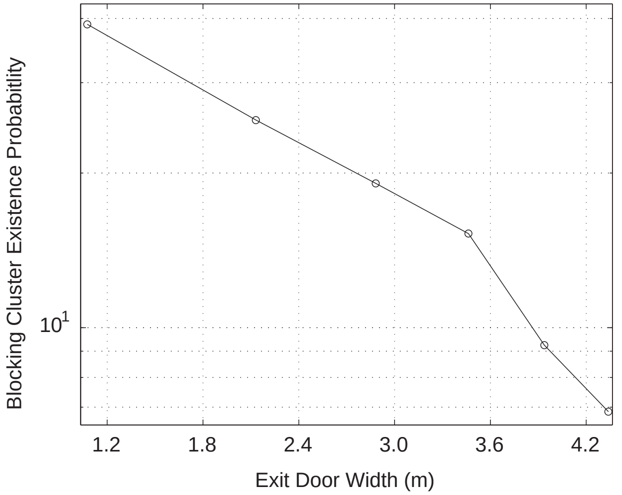

Fig. 10. Log–log plot of the blocking cluster existence probability as a function of the door width.

It can be seen that, as common sense would indicate, the probability of finding a blocking cluster vanishes with the size of the door. Nevertheless, it is interesting that this probability goes to zero only for very wide doors.

However, another important fact not shown in the figure, is that the stability of blocking cluster decrease with the increasing exit door width.

These both effects combined makes the mean evacuation time to decrease exponentially when the door size is increased.

Further analysis are needed to fully explore this issue and are currently under development.

6. Conclusions

In this work we have focused on the microscopic analysis of the evacuation dynamics of self-driven particles confined in a square container with an exit door.

In most of the work we have fixed the number of particles in 200 and the width of the door has been taken as 1.2 m. It has been confirmed that the evacuation time (t_e) is a function of the desired velocity v_d. As already shown by Helbing et al. we have found that there exists a threshold value of v_d such that below it, t_e is a decreasing function of v_d while above the tendency is reversed.

By analyzing the structure of the clusters that are formed in the system and introducing the concept of blocking clusters we have been able to trace this change in behavior to the increase in the probability of long clogging delays. These long time clogging delays are correlated with the formation of blocking clusters.

From the dynamical point of view the key effect is the increasing role of dissipative granular forces which become strong enough just above the v_{dt} to make the probability of formation of clusters non-negligible.

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