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Morphological and dynamical aspects of the room evacuation process

D.R. Parisi[a,*], C.O. Dorso[b]

[a] *Urbix Technologies Research Division, Centro de Incubación FADU, Subsuelo Pabellón 3, Ciudad Universitaria, 1428 Buenos Aires, Argentina*
[b] *Departamento de Física-Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Pabellón 1 Ciudad Universitaria, 1428 Buenos Aires, Argentina*

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Abstract

We study the evacuation of a set of 200 pedestrians from a room under a state of panic. The dynamics of the pedestrians is given by the Social Force Model. The degree of panic is controlled by a parameter v_d which represents the velocity at which pedestrians wish to move. We show that the "faster is slower effect" can be understood in terms of the works performed by the different forces present in the system and the role played by dissipative terms in the model. Beyond the maximum flow rate the "granular cluster" mass distribution displays a transition from exponentially decaying to "U-shaped" as this value of v_d evacuation efficiency begins to decrease rapidly.

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

1. Introduction

The problem of the evacuation of pedestrians from a room under panic conditions is of obvious importance. The proper understanding of the evacuation dynamics will allow, for example, to improve the design of pedestrian facilities, making them more comfortable and safer. The dynamics of the evacuation through a narrow door during an emergency is a complex problem not well understood yet, that might be characterized by the occurrence of very dramatic blocking effects.

In recent years, several computer models pointing toward the simulation of pedestrian dynamics have been developed [1]. Pedestrian flow through a bottleneck [2] and clogging in a T-shaped channel [3] have been studied using lattice-gas models with biased random walkers. More general self-driven particle systems with simple interactions have been studied by Vicsek [4], Albano [5] and Czirók [6].

*Corresponding author.
E-mail address: dparisi@urbix.com.ar (D.R. Parisi).

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An important topic to be considered in evacuation problems is the effect of pedestrians panic on the evacuation efficiency. One model that is able to take into account, at least qualitatively, some aspects of panic is the so-called "Social Force Model", proposed by Helbing and Molnar [7]. This model considers the discrete nature of the "pedestrian fluid" for which the dynamics is generated by realistic interaction forces. The time evolution of the position of each pedestrian can be calculated and the physical parameters of each individual (mass, shoulder width, desired velocity, target, etc.), can be fixed. The main characteristic of this model (see Section 1) is that the pedestrians are represented by self-propelled particles, i.e., particles have a target and they are willing to move at a given velocity (hereafter the desire velocity) toward it. The state of panic of the pedestrians is related to the value of this velocity. The higher the degree of panic, the faster they will be willing to move. The model also includes conservative repulsive forces (social term) and dissipative ones (see Section 1). Among the latter we mention contact forces which may cause high pressures capable of pushing down a brick wall, or to asphyxiate people in the crowd. These characteristics cannot be properly taken into account with cellular automata approaches or traditional models using continuous fluid approximations.

Considering the room evacuation of 200 pedestrian through a narrow door, Helbing et al. have shown [8] that the evacuation time (t_e) defined as the total time needed by the pedestrians to empty the room, is a function of the desired velocity v_d. The resulting function ($t_s(v_d)$) has a minimum at the, so-called, desired velocity threshold (v_{dt}) such that below it, t_e is a decreasing function of v_d, while above the tendency is reversed. This result means that the evacuation process is optimum at moderate values of v_d. This behavior is called the "faster is slower effect".

In a previous work [9], we analyzed the "faster is slower effect" induced by increasing desired velocities. Analyzing the problem from a microscopic point of view, it could be shown that the "faster is slower effect" could be related to the appearance in the discharge curve of increasing clogging delays which are strongly correlated with the formation of arch-like metastable structures that block the exit and that we, correspondingly, call "blocking clusters". It must be noted that in this case, the evacuation process is nonstationary, the number of pedestrians inside the room decreases as a function of time and correspondingly, the pressure and other dynamic properties of the system are also time-dependent.

In the present work we develop a stationary version of the problem. In this case, pedestrians are reinserted into the room as they leave it, in this way the state of maximum jamming is maintained a long time. This stationary situation allows, on the one hand, to study some features that cannot be revealed in the nonstationary case. On the other hand a stationary state can be expected to take place, at least approximately, in the case of the evacuation of a high building in which pedestrians from a given floor leave it while others from the next upper floor populate it or in the case when people need to leave a museum or exhibition area made up of a sequence of rooms. So, the analysis presented in this work can be viewed as a first step toward the analysis of this kind of situation.

Along this work, several macroscopic quantities are calculated in order to unveil the nature of the slowing down effects once a given threshold for the desired velocity v_d is surpassed. We have calculated works done by the whole system forces on different sets of particles. We have also performed a fragment mass distribution analysis resorting to "granular clusters" definition and we have related the morphological structure of the system with the main observables.

This work is organized as follows. In Section 2 we briefly review the "Social Force Model" proposed by Helbing et al. In Section 3 we describe the simulations made. In Section 4 we analyze the results of the simulations from a dynamic and morphological point of view. Finally in Section 5 we present our conclusions.

2. The model

In this work we use a slightly modified version of the "Social Force Model" proposed by Helbing and coworkers [8].

In this model the dynamics of each particle (p_i) is driven by three forces with different properties, they are:

1. "Desire Force" ($\mathbf{F}_{Di}$): This is the force responsible for the self-propelled characteristic of the particles, indicating where its target is located and at which desired velocity the particle will try to reach it.

The corresponding expression for this force is

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

In this equation m_i is the particle mass, $\mathbf{v}_i$ and v_{di} are the actual and the desired velocities, respectively; $\mathbf{e}_i$ is the unit vector pointing to the desired target (particles inside the room have their targets located at the closest position over the line of the exit door), τ is a constant related to the relaxation time of the particle to achieve v_d.

2. "Social Force" ($\mathbf{F}_{Si}$): This is a long range repulsive interaction representing the fact that people like to stay away from each other.

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

with N_p being the total number of pedestrians in the system, A and B are constants that determine the strength and range of the social interaction, $\mathbf{e}_{ij}^n$ is the unit vector pointing from particle p_j to p_i, this direction is the "normal" direction between two particles, and ε_{ij} is defined as

$$\varepsilon_{ij} = r_{ij} - (R_i + R_j), \tag{3}$$

where r_{ij} is the distance between the centers of particles p_i and p_j. R_i and R_j are the corresponding particle radius.

3. "Granular Force" ($\mathbf{F}_{Gi}$): This is a contact force which is repulsive and dissipative.

$$\mathbf{F}_{Gi} = \sum_{j=1, j\neq i}^{N_p} \lfloor(-\varepsilon_{ij}k_n - \gamma v_{ij}^n)\mathbf{e}_{ij}^n + (v_{ij}^t \varepsilon_{ij} k_t)\mathbf{e}_{ij}^t\rfloor g(\varepsilon_{ij}). \tag{4}$$

Here, $\mathbf{e}_{ij}^n$ is the same as in $\mathbf{F}_{Si}$, while the tangential unit vector ($\mathbf{e}_{ij}^t$) indicates the corresponding perpendicular direction (such that $\mathbf{e}_{ij}^t \cdot \mathbf{e}_{ij}^n = 0$), k_n and k_t are the normal and tangential elastic restorative constants, γ is the damping constant (the Helbing's original model did not consider the non-conservative term associated to this constant), v_{ij}^n is the normal projection of the relative velocity seen from p_j ($\mathbf{v}_{ij} = \mathbf{v}_i - \mathbf{v}_j$), v_{ij}^t 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. In numerical simulations, the initial condition is built by choosing the particles coordinates uniformly distributed inside the room such that $\varepsilon_{ij} > 0$ for all pairs ij. The initial velocities were randomly generated inside the range of $1.0 \pm 0.005\,\mathrm{m/s}$.

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

All the forces act in the plane as the model is 2-D, then, particles are disks and boundaries are lines.

3. Numerical simulations

In order to explore the room evacuation dynamics with the model described above, we have performed a series of numerical simulations varying v_d which means that we are exploring different degrees of "panic". As mentioned above, in this approach, high values of v_d represent a high level of panic. Following the bibliography [8], the model parameters used were $\tau = 0.5\,\mathrm{s}$, $A = 2000\,\mathrm{N}$, $B = 0.08\,\mathrm{m}$, $k_n = 1.2 \times 10^5\,\mathrm{N/m}$, $k_t = 2.4 \times 10^5\,\mathrm{kg/m/s}$, $m = 80 \pm 10\,\mathrm{kg}$ and $\gamma = 100\,\mathrm{kg/s}$. These parameters were determined in Ref. [8] in order to reproduce the known experimental value of the flow rate through a narrow door at low desired velocity. It remains an open question if these parameters are good for higher v_d. Its verification would require experiments in which pedestrians should be exposed to dangerous situations, and then, they cannot be performed.

The geometry of the room was fixed as a 20 m by 20 m square with an exit door of width $L = 1.2\,\mathrm{m}$. Pedestrians shoulder widths (particles' diameter) were uniformly distributed between 0.5 and 0.58 m, i.e., the linear dimension of the exit is slightly larger than two times the maximum pedestrian shoulder width. In all the simulations we have fixed the size of the crowd to be 200 individuals.

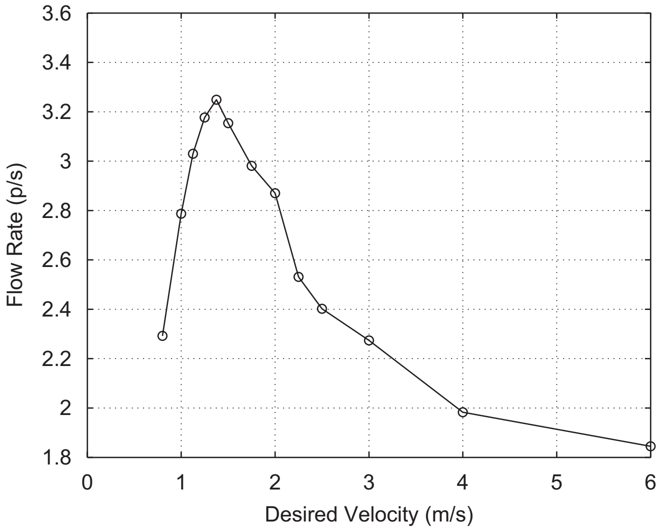

Fig. 1. Flow rate of the evacuation system as a function of v_d. The maximum is reached at $v_{dt} = 1.375\,\mathrm{m/s}$.

In the usual nonstationary case, it is found that during the evacuation process there exists a time at which maximum jamming is reached. In this state, the biggest granular clusters can be found. It was shown in a previous work [9] that granular clusters are needed as substrate for blocking clusters which are the structures responsible for the decrease of the efficiency of evacuation process for high v_d. So, the rate at which the room is evacuated is related to the pedestrian jamming in the inner neighborhood of the exit door. This effect, which we fully describe below, is difficult to study in the nonstationary case because the maximum jamming lasts for a short time. In view of this difficulty we have implemented a stationary case in which the above mentioned maximum jamming remains constant. This has been accomplished by reinserting particles that have left the room, back inside of it. Outgoing pedestrians that have reached 3 m away from the exit door are instantaneously placed inside the room at a random position not closer than 1.5 m from any other pedestrian.

Under steady-state conditions the most relevant observable is the flow rate (number of particles leaving the room per unit time) which is constant along time. So, we choose this quantity to characterize the evacuation performance of the system for each value of v_d.

Steady-state simulations were performed for the following mean values of v_d: 0.8, 1.0, 1.125, 1.25, 1.375, 1.5, 1.75, 2.0, 2.25, 2.5, 3.0, 4.0 and 6.0. In each case, a uniform velocity distribution of 3% around the mean value was considered. The simulation time was 1000 s in all cases.

The state of the system which corresponds to the most efficient evacuation, is characterized by that value of v_d for which the flow rate attains a maximum. In Fig. 1 we show the behavior of the flow rate as a function of v_d. It can be seen that it displays a maximum at an intermediate value of v_d that we call v_{dt} (desired velocity threshold).

This behavior is qualitatively similar to the one found for the evacuation time as a function of v_d in the nonstationary case, but quantitatively different. In the nonstationary case, $v_{dt} = 2.0\,\mathrm{m/s}$ while in the stationary problem here analyzed, $v_{dt} = 1.375\,\mathrm{m/s}$. This difference is natural since in one case we have a time-dependent (pressures, number of particles, cluster size and distribution, etc.) process while in the other we are dealing with the stationary case.

It would be possible to obtain similar v_{dt} if in the stationary case particles were reinjected in a more diluted way or if the total number of particles were reduced.

4. Results

Once the numerical simulations are performed we calculate different properties of the system. As has been mentioned above the morphological properties i.e., the cluster structures that appear within it, are relevant.

Moreover, we have found it fruitful to calculate dynamic variables in a given region within the system away from the outer limits of the crowd. This quantities are defined in the next subsection. In the following ones we present the results of the dynamic calculations.

4.1. Some definitions

In this section we define magnitudes which we have found useful in order to explore the system properties. Some of them have been already defined in previous works: [9,11].

4.1.1. Granular cluster

In order to explore the morphological structure of the system under study, we define a ‘‘granular cluster’’ (C_g) in the following way: given a particle p_i of radius R_i and a cluster C_g [12],

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

where (p_j) indicates the jth particle and R_j is its radius. This means that C_g is a set of particles that interact not only through social but also via granular forces.

4.1.2. Blocking cluster

Just before the exit, the contact forces are able to produce arch-like blocking clusters [9] (see Fig. 2).

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 by 3 to more than 10 particles.

4.1.3. Bulk of the crowd

There are some properties of the system that are not well defined near the borders of the crowd inside the room, basically due to the discontinuities produced by pedestrians which suffer a transition from free state to jamming state and vice versa.

So, in order to avoid border effects, we define the bulk of the system formed by pedestrian who are inside the room within $L_{12} = 4(2R_{min})$ and $L_{23} = 10(2R_{min})$ from the center of the exit door, corresponding to the region A2 shown in Fig. 3. Here $2R_{min}$ is the minimum particle diameter.

The results presented in next sections do not depend on the exact value of the limits chosen (L_{12} and L_{23}). This means that the results and conclusions are valid for a wide range of limits of region A2 as long as they are far enough from the borders of the jamming pedestrians.

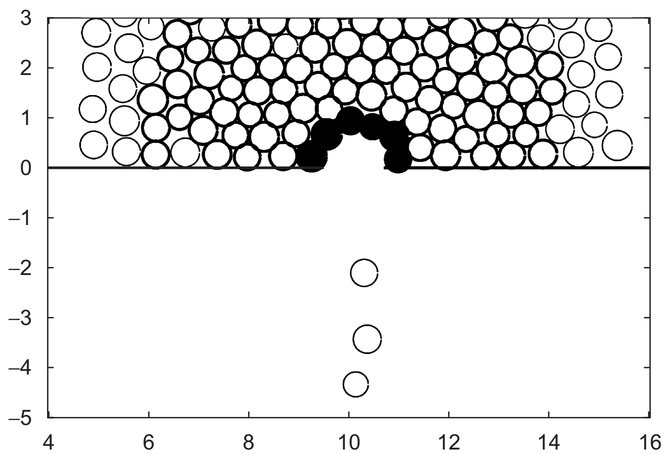

Fig. 2. A typical blocking cluster (black particles). Particles belonging to any arbitrary cluster >1 are drawn with wider lines.

4.2. Kinetic energy

The average over time of the kinetic energy of particles inside the region A2 was calculated using

$$\langle E_{A2}\rangle = \frac{1}{N(t_2-t_1)}\sum_{i\varepsilon A2}\sum_{t_1\leqslant t_k\leqslant t_2} E_{it_k} \tag{6}$$

where $N(t_2-t_1)$ is the number of measurement performed between the time limits.

Where E_{it_k} is the kinetic energy of particle i at the instant t_k, $t_1 = 20\,\text{s}$ and $t_2 = 1000\,\text{s}$.

Fig. 4 shows $\langle E_A\rangle$ for different values of v_d.

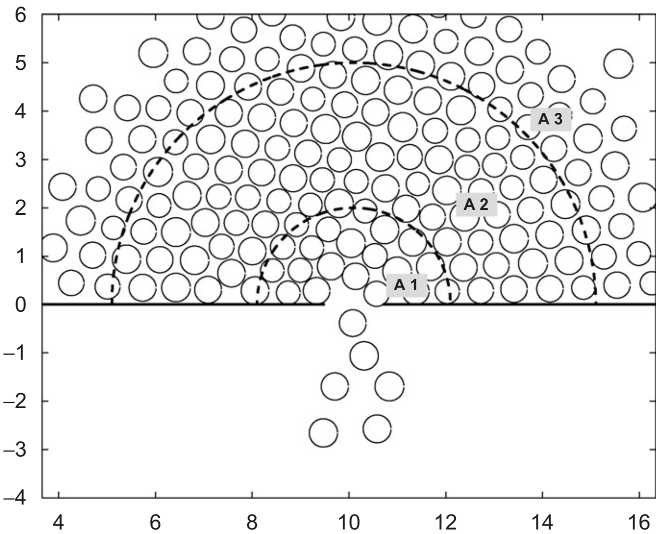

Fig. 3. Definition of areas to avoid border effects. Area A2 is define to be the bulk of the system and areas A1 and A3 are considered borders.

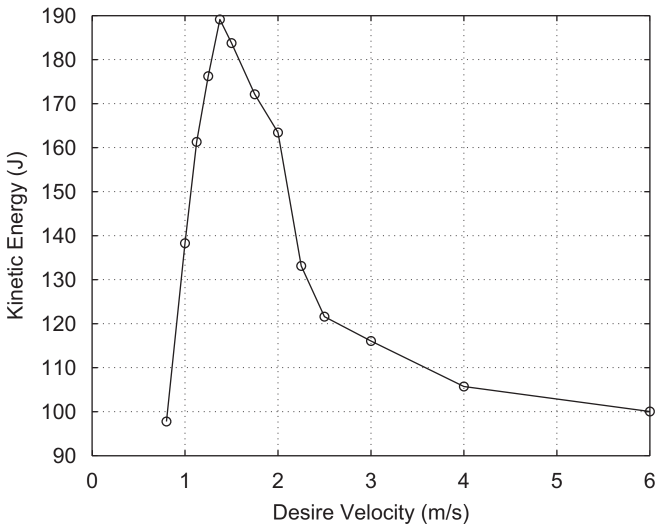

Fig. 4. Average kinetic energy of particles in region A2 as a function of v_d. The maximum is reached at $v_{dt} = 1.375\,\text{m/s}$.

It can be seen that its shape is similar to the flow rate curve, displaying a maximum at the same value of $v_{dt} = 1.375\,\mathrm{m/s}$.

This implies that the maximum flow rate is attained when the bulk of pedestrians inside the room has maximum mobility.

It also indicates that particles in region A2 are representative of the phenomena that we are investigating in this work, i.e., the "faster is slower effect".

4.3. Work done on the bulk

In order to find an explanation for the maximum flow rate observed in the system, we looked at the work done on particles belonging to the bulk (particles inside region A2) by all the system forces (walls and all the others particles belonging to A1, A2 and A3).

The total work done on particles inside A2 is

$$W_{A2} = \sum_{i \varepsilon A2} W_i, \tag{7}$$

where

$$W_i = \int_{t_1}^{t_2} \mathbf{F}_i \mathbf{v}_i \, \mathrm{d}t = \int_{t_1}^{t_2} (\mathbf{F}_{Di} + \mathbf{F}_{Si} + \mathbf{F}_{Gi}) \mathbf{v}_i \, \mathrm{d}t; \tag{8}$$

the three terms on the r.h.s. of the equation have the form given by Eqs. (1), (2) and (4), respectively, considering the interactions of pedestrian i with walls and all of the other pedestrians. In order to avoid any transient effect, t_1 was chosen equal than 20 s, when all the dynamic variables become stable, and $t_2 = 1000\,\mathrm{s}$.

The computation was made using a discretized version of the last equation:

$$W_i = \sum_{t_k} \mathbf{F}_i(t_k) \mathbf{v}_i(t_k)\, \Delta t, \tag{9}$$

where t_k runs over the discrete time steps of length Δt.

In Fig. 5 we show the net work done on particles in region A2. It can be seen that a maximum is reached at v_{dt} at which the flow rate is maximum.

The maximum flow rate can be directly related to the maximum work done by the system forces on particles in the bulk.

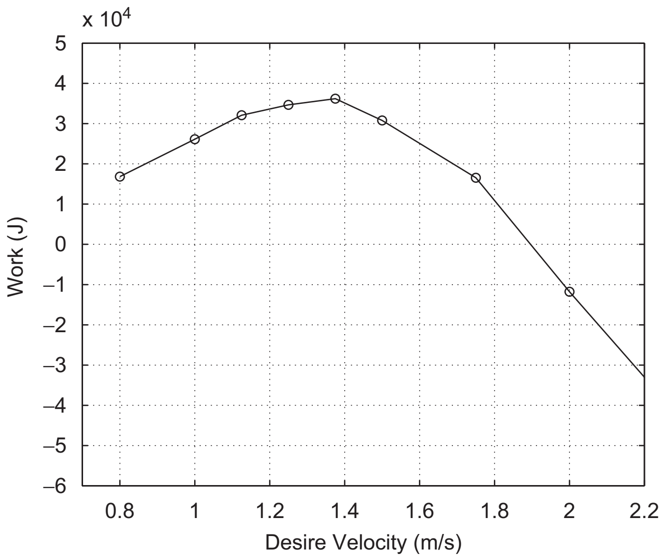

Fig. 5. Zoom over the maximum work done by all the system forces on particles in area A2.

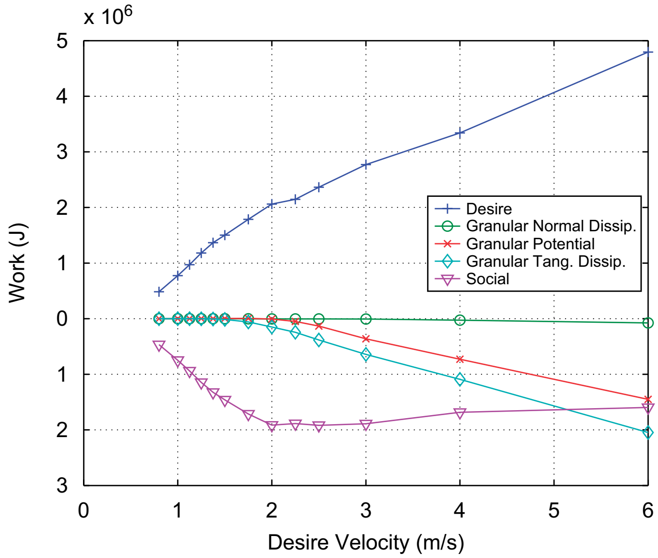

Fig. 6. Decomposition of the work done on particles in region A2 by the different kind of forces.

This is a dynamic consequence of the blocking cluster structures formed near the exit door which have been reported in Ref. [9].

We now show in Fig. 6 how the work W_{A2} is composed.

The only force producing an input of energy in the system is the desire force which is the responsible for the self-propelled characteristics of pedestrians. The rest of the forces do negative work indicating that particles are stopped by dissipation and repulsive interactions.

The role of granular forces, in particular the tangential component which is a dissipative force, is crucial in order to obtain the maximum mentioned above. To show that, the following analysis is presented.

In order to evaluate the importance of each kind of work for obtaining the behavior is shown in Fig. 5, we look at the sum of four out of the five work contributions. Fig. 7 shows the four cases resulting when one of the negative works is removed from the calculation.

It must be noted that the only case in which the local maximum disappears is when the work done by granular tangential force is neglected. This result indicates that the existence of granular tangential dissipative interaction is a necessary condition in order to obtain the typical behavior of having an maximum at moderated v_d. This fact is a strong evidence that the friction of granular force has an important role in the ‘‘faster is slower’’ effect.

To end this section we want to note that the fact that the system reaches a stationary state is not in contradiction with the fact that the total work is not equal to zero. Actually this is the case in a stationary, open and nonconservative system like particles in region A2. Each particle loses kinetic energy due to the work done by the nonconservative forces, but there is a continuous flow of particles (entering and going out of region A2) which produces a stationary flow of slowing down particles.

4.4. Granular cluster analysis

As it has been already shown in a previous work, the morphological structure of the system plays a crucial role in its behavior. The presence of blocking structures strongly influences the evacuation. Because blocking clusters need as a substrate configurational clusters, we first analyze the latter.

Making use of the definition of granular cluster given in Section 4.1.1, we study the morphology of the complete system inside the room (including areas A1–A3). First, we calculate the cluster size distribution for various values of v_d. In Fig. 8 we show such distributions for $v_d = 1.375$, 2.25, 2.5 and 3.0 m/s.

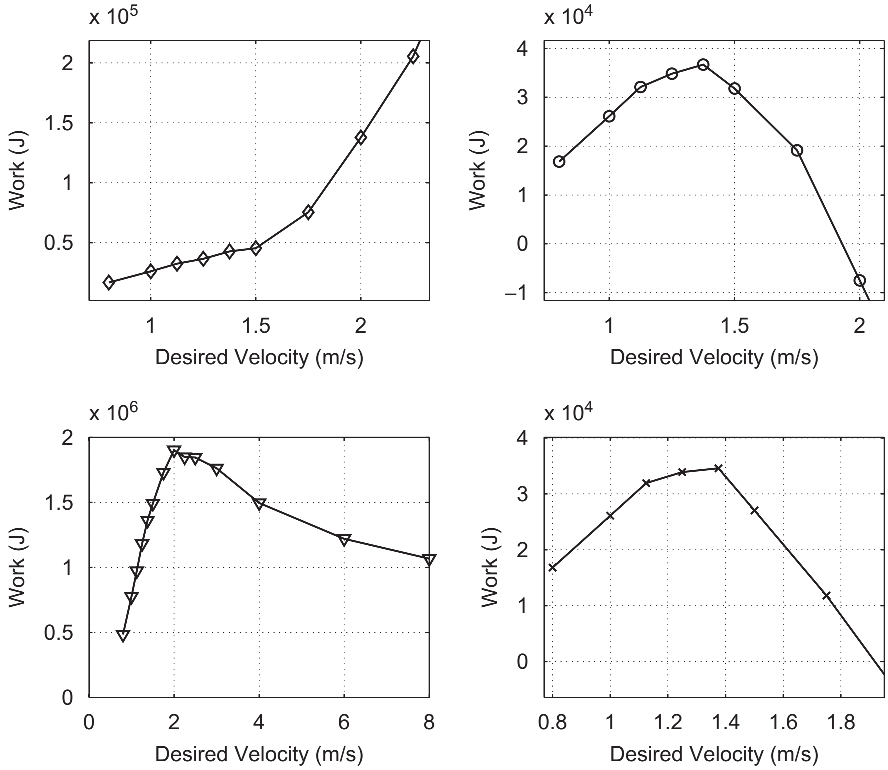

Fig. 7. Work done by the system forces on particles in area A2 ignoring the contributions of: granular tangential (upper left), granular normal dissipative (upper right), social (bottom left) and granular normal potential (bottom right) works.

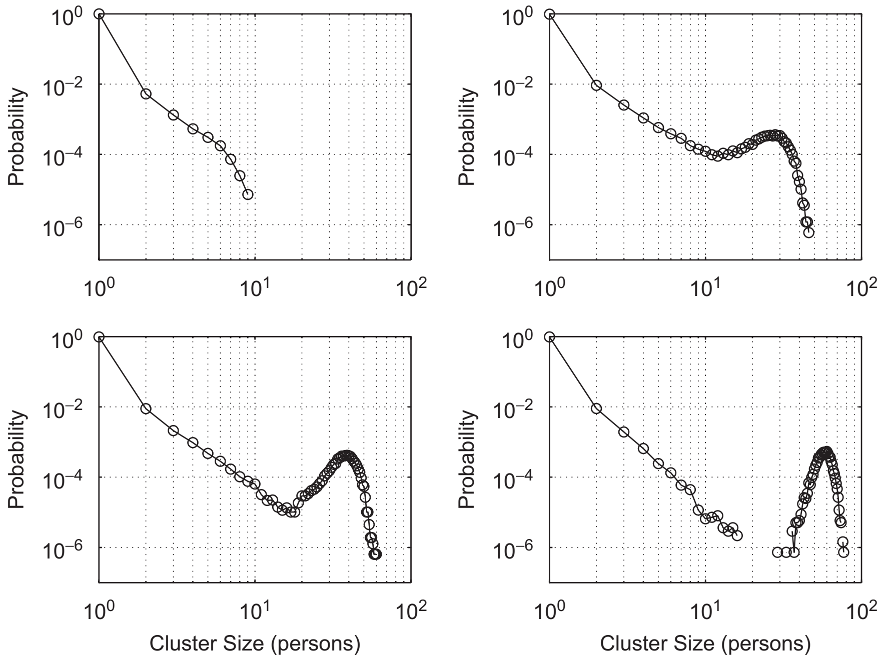

Fig. 8. Cluster size distributions for $v_d = 1.375$ (upper left), 2.25 (upper right), 2.5 (bottom left) and 3.0 m/s (bottom right).

It can be seen that the shape of the distributions changes from rapidly decaying (at low v_d), which means that large fragments are quite improbable, to U-shaped (for high v_d), in this latter case large fragments turn out to be highly probable. By highly probable we mean that there will be a big cluster at almost all times.

We observe that the value of v_{dt} at which the change in behavior of the flow rate takes place (the flow rate change its tendency at $v_{dt} = 1.375\,\mathrm{m/s}$) corresponds to a cluster size distribution well inside the rapidly decaying region.

More information can be gained if we now calculate the average size of the biggest fragment ($\langle BF \rangle$) as a function of v_d.

$$\langle BF \rangle = \frac{1}{N} \sum_{i=1,N} BF_i, \tag{10}$$

where the sum runs over all the time steps at which fragments are calculated and BF_i is the biggest fragment found a each time step. The results of such a calculation are displayed in Fig. 9. It can be readily seen that as v_d increases the $\langle BF \rangle$ also increases.

If we look at the mean number of clusters greater than one (Fig. 10), a maximum at $v_d = 2\,\mathrm{m/s}$ can be observed. This maximum can be associated with a frontier between the small clusters domain for $v_d < 2\,\mathrm{m/s}$ and the bigger clusters domain for $v_d > 2\,\mathrm{m/s}$.

We can also look at the second moment (M_2) of the cluster size distribution without the maximum cluster [10,11], we see that it displays a sharp maximum at $v_d = 2.25\,\mathrm{m/s}$ (Fig. 11).

Such kind of behavior deserves a more detailed analysis and is currently under way.

Finally, we can look at the blocking cluster probability as a function of v_d (Fig. 12) which confirms the result, obtained in the nonstationary case [9], that the higher the v_d the most probable is the presence of a blocking cluster, verifying that the presence of blocking clusters and big granular clusters are correlated, indicating that the decline of the evacuation efficiency can be related to the existence of blocking clusters.

4.5. Regimes

In previous sections the existence of two interesting points in the flow rate curve versus v_d was shown. The first one is $v_{dt} = 1.375\,\mathrm{m/s}$ at which the flow rate, the kinetic energy and the total work of the bulk reach their maximum value. The second one is $v_d = 2.25\,\mathrm{m/s}$, in this point the granular clusters size distribution displays a maximum of M_2.

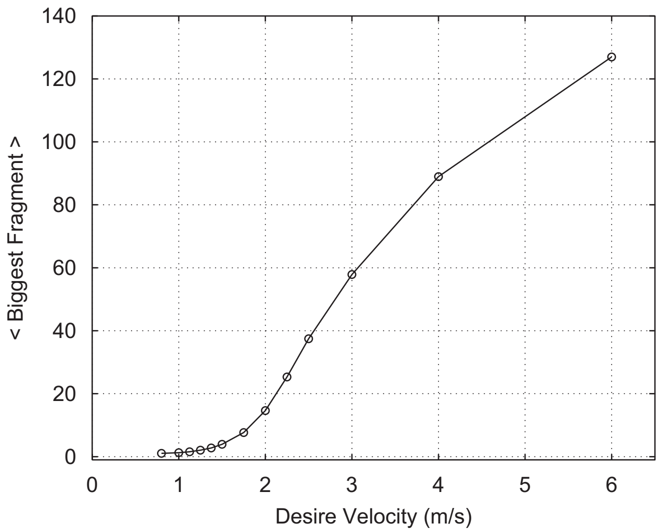

Fig. 9. Biggest fragment as defined in Eq. (10) as a function of v_d.

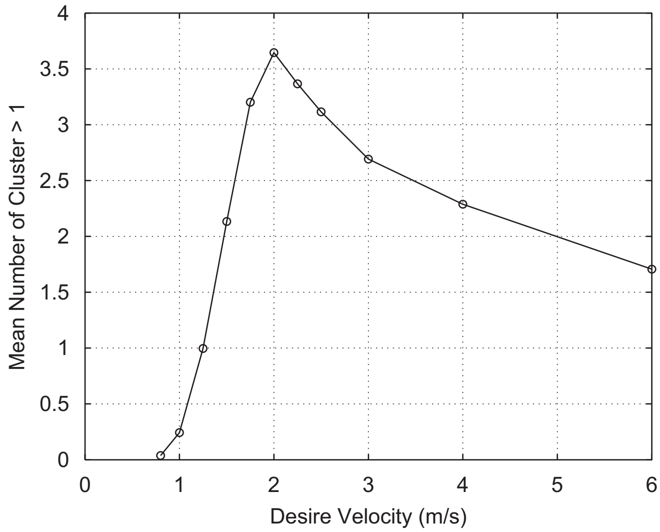

Fig. 10. Multiplicity of clusters greater than one.

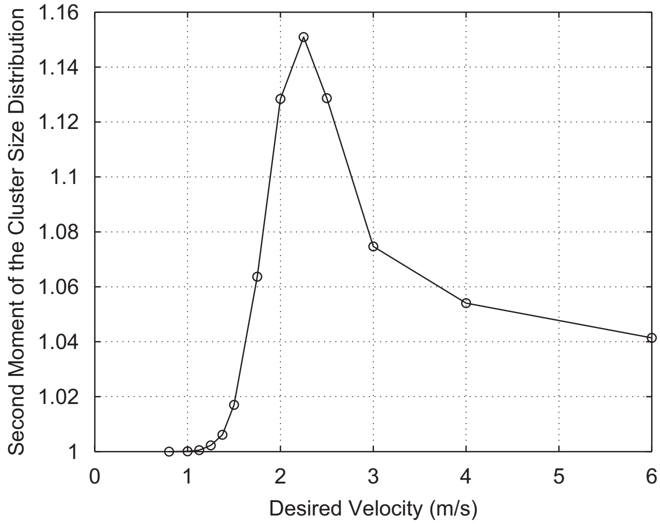

Fig. 11. Second moment of the cluster size distribution without the maximum cluster.

In consequence three regimes can be defined: (1) below v_{dt}, (2) between $v_{dt} = 1.375\,\mathrm{m/s}$ and $v_d = 2.25\,\mathrm{m/s}$ and (3) above $v_d = 2.25\,\mathrm{m/s}$.

In regime "1" the dominant interaction is the social repulsion. Here the behavior of the system is what one would expect since the faster the individuals want to move, the faster they can evacuate the room. No jamming take place because the Desire Force is weak enough for not being able to overcame the Social Repulsion Force. As a consequence, granular clusters are very rare and the probability of obtaining a blocking cluster is negligible.

Regime "2" is characterized by a linear decrease of the evacuation efficiency as v_d increases. The blocking cluster probability begins to grow linearly but with a high slope indicating that granular forces became more and more important. Also we know from Section 4.4 that in this region granular clusters of different sizes begin to dominate. And the number of clusters greater than one continues growing. At this regimen W_{A2} decreases but it is still positive.

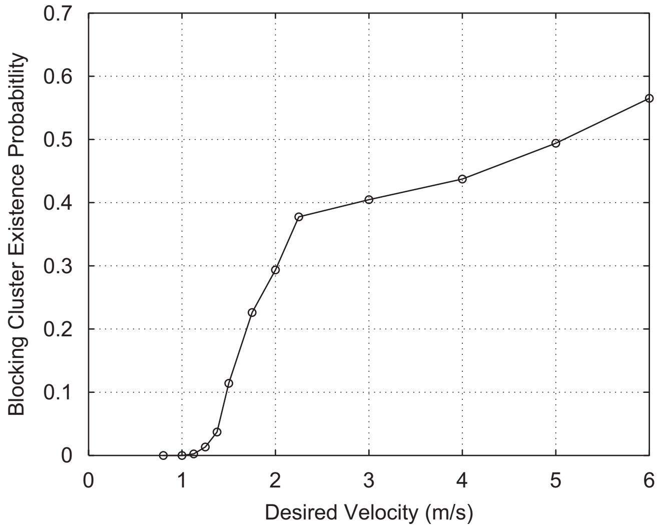

Fig. 12. Dependence of the blocking cluster existence probability on v_d.

In regime "3" the flow rate and the kinetic energy begin to decrease rapidly. The mean number of granular clusters greater than one begins to decrease. The granular cluster size distributions are dominated by the big cluster. The blocking cluster probability continues with a linear behavior but the slope changes to a minor one.

The work done on particles inside A2 (W_{A2}) became negative indicating that stopping (repulsive and dissipative) forces are dominant. Besides, looking at Fig. 6 it can be seen that granular forces are important while social repulsion remains stable as v_d increases in this regime 3.

The last two regimes have in common that the blocking clusters make the exit difficult to access, decreasing the evacuation performance of the system (the flow rate gets worse as v_d increases).

However, in practical terms, the point at v_{dt} (the maximum flow rate) is less important than the point at $v_d = 2.25\,\mathrm{m/s}$. Because if the system enters regime 3 the efficiency decreases rapidly giving rise to much more dramatic consequences. Moreover this is the starting point of the velocity range that we can associate with panic.

5. 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 one exit door. We have performed a series of numerical simulations of a system of particles interacting via the social force model in a stationary state as a function of the so-called "desired velocity".

By studying the flow rate of pedestrians through the exit door we have found that the "faster is slower effect" is present, i.e., the optimum desired velocity corresponds to a moderate value of the v_d of the pedestrians.

By defining the bulk of the system as the pedestrians in a region which is not at the boundaries of the jamming particles we have found that the optimum evacuation is attained when the work done by all the system forces on the bulk attains its maximum.

Then the maximum flow rate can be directly related to the maximum work done by the system forces on particles in the bulk of the system. This is a dynamic consequence of the blocking cluster structures formed near the exit door reported in Ref. [9].

It was shown that the role of granular forces, in particular the tangential component which is a dissipative force, is crucial in order to obtain the maximum mentioned above. This fact is a strong evidence of the assumption that the friction of granular force has an important role in the "faster is slower effect".

Besides the state of maximum flow rate there are another important state at $v_d > 2\,\mathrm{m/s}$ at which a transition occurs in the granular clusters size distribution from many small clusters to a few bigger clusters.

The fact that the cluster mass distribution displays a transition from exponentially decaying to "U-shaped" is of crucial importance because the evacuation efficiency begins to decrease rapidly when we enter into the "U-shaped" regime, which can produce very dramatic consequences.

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