A NEW COMPOSITE FIRE EVACUATION (CFE) MODEL BASED ON HUMAN BEHAVIOR

Chen Tao[1, 2], Yang Rui[1, 2], Sun Zhanhui[1, 2], Weng Wenguo[1, 2]
Email: chentao.a@tsinghua.edu.cn

[1] Center for Public Safety Research, Tsinghua University, Beijing, 100084, China
[2] Department of Engineering Physics, Tsinghua University, Beijing, 100084, China

ABSTRACT

Occupant evacuation dynamics is a kind of many-body system of strongly interacting persons. A great deal of factors should be taken into account in the study of fire evacuation, such as human behavior, fire products and architecture. To describe human behavior, there are two different evacuation models, the social force model and the lattice-gas model. Considering the impact of fire product upon people's physiology and psychology, the CFE (Composite Fire Evacuation) model is presented in this paper, which includes three sub models: lattice-gas model, social force model and pre-movement time model. And a direction potential field concept is introduced in the CFE model to solve the moving directionality of people. In the end, the fire case of Yiyuan dancing hall in Fuxin is simulated by the CFE model and the lattice-gas model based on the human characteristics of China.

KEYWORDS

Evacuation Model, Fire, Human Behavior, Case Study

INTRODUCTION

In recent years, the study of performance-based fire protection design and fire risk assessment develops rapidly in the world and it has been one of key issues in the research field of fire safety. One of the most important goals of these researches is to ensure the safety of life. To realize the rational and optimal fire protection design, proper calculation of the Required Safe Egress Time (RSET) is required.

It is thought that evacuation and fire development go irreversibly and synchronously along the same time-line. The fire development can be divided into several periods, such as breaking out, fire increasing, stable burning, fire decay and fire extinguishing. For human safety, the first two periods should be cared about mainly. Generally, an evacuation will go through the stages of perceiving a fire, preparing, evacuating, reaching safe place, etc. During the evacuation, there are two significant moments, the fire detecting time and the time of fire endangering human safety.

The key to guarantee the human safety in building is that the RSET must be smaller than the Available Safe Egress Time (ASET, viz. the time period from fire breaking out to endangering human safety). The universal criterion of safe evacuation time-line is shown in Figure 1.

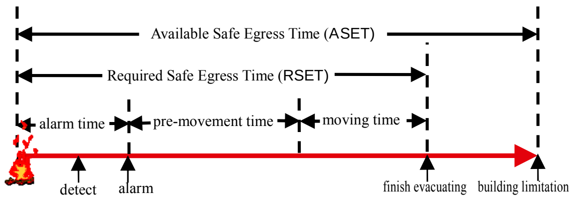


Figure 1 Universal criterion of safe evacuation time-line

The RSET means the time period from the moment of fire breaking out to the moment that all the people reach the safe area. The RSET includes the detecting and alarm time t_{alarm}, the pre-movement time tpre and the movement time t_{move}, where the t_{pre} consist of the recognition time t_{reg} and the response time t_{resp}, expressed as Eq. (1).

$$RSET = t_{alarm} + t_{pre} + t_{move} = t_{alarm} + (t_{reg} + t_{resp}) + t_{move} \quad (1)$$

The t_{alarm} can be estimated by the smoke spreading simulation and the characteristic of detection system, the t_{pre} is generally acquired from statistics, and the t_{move} can be predicted by the simple empirical formula or the evacuation model which mainly depends on crowd density, walking speed, width of exits, etc.

CFE MODEL

According to the representation methods of the enclosure (Gwynne et al. 1999), models can roughly be classified as coarse network models, fine net models or continuity models. In the coarse network model, each node may represent a room or corridor irrespective of its physical size. Nodes are connected by arcs representing actual connectivity (such as door, exit) within the structure. This model presents difficulties when incorporating local movement and navigation including overtaking, the resolution of local conflicts, and obstacle avoidance. Using the fine net approach the entire floor space of the enclosure is usually covered in a collection of tiles or nodes. It can show geometry form of the floor space, position of the inside barrier and people's accurate position, but it is difficult to simulate the crowded situation. Based on the systematic frame of multi-particles and self-driven, the continuity model (also called social force model) uses mechanics equations to simulate crowd dynamics. The individual has the ability of independent movement and making a response to surrounding environment in this model. This simulation can subtly realize pushing, panic and visual range (Helbing et al. 2000) at great cost of computing time, which will result in low computational efficiency.

Based on the human behavior characteristic of people in China, CFE (Composite Fire Evacuation) model has been described in this paper, which includes three sub models: lattice-gas model, social force model and pre-movement time model. The impact of fire products upon people's physiology and psychology has also been considered in this model. The CFE model comprehends the advantage of the lattice-gas model which is high computational efficiency, and the social force model, which is fine simulation of crowd dynamics. It adopts the lattice-gas approach in low crowd density areas and uses the social force model to simulate the panic and crowded behavior in high crowd density areas.

Lattice-gas sub-model

Traditional lattice-gas model is a kind of discrete non-linear kinetics system based on the fluid molecular kinetic theory (Li et al. 1994), and it is the embodiment and application of cellular automaton in statistical physics and fluid mechanics. In a microscopic scale, the model describes a large number of particles with the same quality moving and interacting in the regular discrete nets following a certain collision rule, and it will simulate the complicated physical phenomenon in the macroscopic scale. In a word, it is a physical model with discrete time, space and target.

Each human individual have a certain body size which can be expressed by the area of people's horizontal projection. In this model, the size of lattice is fixed through the area of people's horizontal projection and the statistics value of shoulder width. It is indicated that the average area of pedestrian horizontal projection is $0.113m^2$ in Russia (Predtechenskii et al. 1971), $0.1458\text{-}0.1862m^2$ in Austria (Kendik 1985) and $0.12\text{-}0.19m^2$ in Germany (Schneider 2001). According to "Chinese adult's physique determines standard", the statistical averages of adult's height and weight are shown in Table 1 (Yu 1997). About the proportionate relationship of the human body, it is indicated that the shoulder width is 1/4 of the height. So, the average shoulder width of Chinese can be calculated, shown in Table 1. According to the above statement, each grid of the lattice is set as 0.5m×0.5m. The grid area is $0.25m^2$ which is sufficient to contain one person.

Table 1 Mean values of Chinese adult's height, weight and shoulder width

Age bracket		18-20	21-25	26-30	31-35	36-40
Height (cm)	M	169.9	170.2	170.1	169.8	169.6
	F	158.8	159.2	159.4	159.0	158.9
Weight (kg)	M	59.2	61.2	63.2	64.6	65.7
	F	51.1	51.3	53.5	54.9	56.5
Shoulder width (cm)	M	42.5	42.6	42.5	42.5	42.4
	F	39.7	39.8	39.9	39.8	39.7
Age bracket		41-45	46-50	51-55	56-60	
Height (cm)	M	168.9	167.8	167.8	167.6	
	F	158.2	157.7	157.4		
Weight (kg)	M	66.2	66.0	66.2	66.3	
	F	58.1	58.8	58.5		
Shoulder width (cm)	M	42.2	42.0	42.0	41.9	
	F	39.6	39.4	39.4		

Except for certain quality and body size, a human individual is a special particle with ideology. Especially in fire emergency, people's actions have obvious directionality, viz. fleeing from the hazardous area and evacuating to the safe zone or outdoors. The traditional collision rule based on momentum conservation can not describe people's action characteristics accurately. To solve the moving directionality of people, the lattice-gas model in this paper introduces a direction potential field concept. It means that each lattice has a direction potential. The individual in the CFE model will move from the lattice with higher potential to that with lower potential.

The direction potential field can not only express the relative distance to the exit but also reflect familiar degree of evacuee to the structure of the building, the escape route and the safety exit. It can even show the trend of far away from dangerous area. Figure 2 gives a demonstration of net dividing and direction potential field initializing for the 5m×5m square room with two exits. Figure 2(a) is the sketch map of net dividing, position of exits and fire point. In Figure 2(b), only relative distance to the exit is considered in the direction potential field. The direction tendencies of exit 1 and 2 are set as 0, and the highest direction potential is 9 in this room. Figure 2(c) shows different familiar degree of evacuee to different exits, which results in the change of direction potential field. Here, the direction potential of exit 1 is 0 and that of exit 2 is 5, which means exit 1 is in common use. And the highest value of direction potential has changed into 11. The influence of fire region is expressed by Figure 2(d). The direction potential of fire region in the CFE model is usually set as the highest value, which represents the tendency of keeping away from hazardous area.

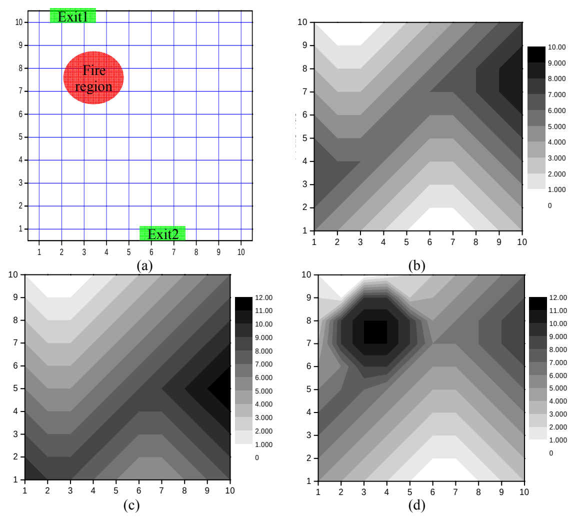


Figure 2 Net dividing and direction potential field initializing in the 5m×5m square room

Social force sub-model

During fire emergency, people's behavior is generally complicated and unordered. But given relatively simple and loose environment, people's behavior can be described by probability, which lead to the development of gas-kinetic model (Helbing 1992). Lewin has proposed another method to simulate people's behavior (Lewin 1992). It is thought that the behavior should be changed by the influence of "social force". According to the concept of social force, Helbing, et al. have proposed a dynamics model to describe people's psychology and crowded behavior (Helbing et al. 2000). In this model, the behaviour in a crowd will be influenced by two different forces, socio-psychological and physical force.

It is supposed that individual i, who is in dangerous area at a certain moment t, expects to evacuate to the safe area with speed $v_i^0(t)$ and direction $\vec{e}_i^{\,0}(t)$. His social psychology force can be described by Eq. (2), where $\vec{v}_i(t)$ means the actual speed, m_i is the weight and τ_i is the characteristic acceleration time to describe his accelerating ability.

$$\vec{f}_{i0}(t) = m_i \frac{v_i^0(t)\vec{e}_i^{\,0}(t) - \vec{v}_i(t)}{\tau_i} \tag{2}$$

The physics environment force includes $\vec{f}_{ij}$ (the force among people) and $\vec{f}_{iw}$ (the force between people and barrier). The kinetic equation to describe evacuating velocity in the social force sub-model can be expressed as:

$$m_i \frac{d\vec{v}_i}{dt} = m_i \frac{v_i^0(t)\vec{e}_i^{\,0}(t) - \vec{v}_i(t)}{\tau_i} + \sum_{j \neq i} \vec{f}_{ij} + \sum_{w} \vec{f}_{iw} \tag{3}$$

Pre-movement time sub-model

In the pre-movement time sub model, a Gaussian distribution function is used to describe the pre-movement time t_{pre} (Jia et al. 2002), expressed by

$$f = \frac{1}{\sqrt{2\pi} t_{pre,\sigma}} \exp\left[-\frac{(t_{pre} - t_{pre,\mu})^2}{2 t_{pre,\sigma}^{\ 2}}\right] \tag{4}$$

The five main factors which influence $t_{pre,\mu}$ (standard pre-movement time) are: people's state, building characteristic, present position of people, fire intensity, fire detecting and warning facility. The calculation formula of $t_{pre,\mu}$ is

$$t_{pre,\mu} = \overline{t}_{pre} b(a + c + d + e) \tag{5}$$

where $\overline{t}_{pre}$ and $t_{pre,\sigma}$ are mean value and mean variance of $t_{pre,\mu}$.

The five factors can be expressed by dimensionless parameters a, b, c, d and e separately, whose values are shown in Table 2.

Table 2 Values of dimensionless parameters in pre-movement time sub-model

Dimensionless Parameter		**Characteristic and Value**				
a	People's state	Waking	Resting	Sleeping		
		1	1.2	1.5		
b	Building characteristic	Market or amusement place	Office or Factory building	House or School dormitory	Hotel or Apartment	Hospital or Sanatorium
		0.5	1.0	1.2~1.5	1.6~1.8	≈2.0
c	Position of people	The number of rooms to the fire room / 10				
d	Fire intensity	large	middle	small		
		-0.1	0	0.1		
e	Fire detecting and warning facility	Pronunciation broadcasting	Recording alarm	Alarm bell: Accurate	Alarm bell: Inaccurate	None
		-0.2	-0.1	-0.1	0.2	0.1

CASE STUDY

Since 1991 in China, the twelve extraordinarily serious fire tragedies have caused about 1,552 deaths, each of which devitalized more than 50 people's lives. Among them, the fire of Yiyuan dancing hall in Fuxin resulted in 233 deaths. Taking this fire as an example, FDS is used to simulate the fire scene and to calculate and confirm ASET, and RSET is calculated by the CFE model. The number of death can be calculated by comparing of ASET and RSET.

Fire scene

The fire accident of Yiyuan dancing hall in Fuxin took place at 13:30 on November 27, 1994. There were 304 people in the dance hall when the fire broke out. It caused 233 deaths, 133 men and 100 women. Four people were severely injured and sixteen people were slightly injured. Among the 231 deceased whose identities were verified, there were 84 workers, 75 students and 61 job-waiting youth. According to the statistic, most of the deceased were young people, 61 people between 14 and 17 years old and 159 people between 18 and 25 years old (Anno., Anno. A).

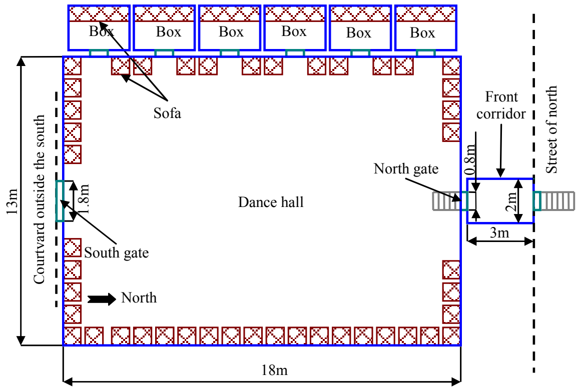
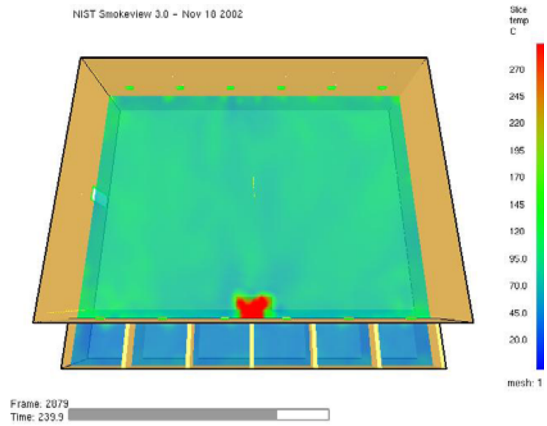


Figure 3 The plan sketch of Yiyuan dancing hall in Fuxin

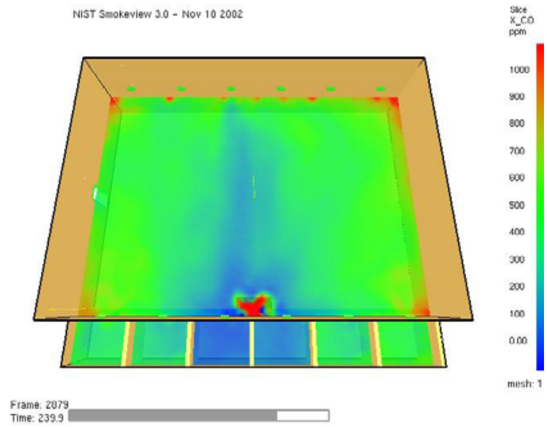
The area of Yiyuan dancing hall is 280m^2. Figure 3 shows the Yiyuan dancing hall. The hall is 18 meters long, 13 meters wide and 5 meters high, with six boxes in the west which are 2.76 meters long, 2 meters wide and 2.4 meters high. The width of the boxes' doors is 0.8m, and the north gate is 0.8m, the south gate is 1.8m (unfortunately, the south gate was closed during the fire). All the exits are 2 meters high. The building wall is fitted with the woven Dacron and cotton with both upper and lower ends nailing and pigeonholing. The top of the building is decorated by wooden-ply board. There are 56 sofas against the wall with synthetic leather as surface material and polyurethane as filling.

ASET calculated by FDS

To simulate the ventilation effect of the window break in FDS model, 6 vents with 0.08m^2 area are set up evenly in both sides of the hall, which are 2.0m height to the floor. According to the experiment database of NIST (National Institute of Standard & Technology), U.S.A., the largest fire power of one armchair is 2.25MW (Anno. B). It is supposed that the fire taking place in the dance hall is αt^2fire with 0.046889kW/s^2 of fire growth rate and there are always two sofas burning steadily in the largest fire power at any moment of spreading course after the fire is steady. Then, in the simulation of FDS, the area of fire is set as 2m^2 to satisfy the horizontal area of two armchairs. The fire material was adopted polyurethane, and the power of fire after burning steadily is 2.25MW/m^2. It can be found from the hypothesis that the fire source in FDS doesn't include the woven Dacron and cotton hanging on the wall. Since the burning rate of these chemical upholstery fabrics is very fast, it is considered that the supposed fire in this paper is relatively conservative. Figure 4 shows the calculation result of FDS at 6 minutes after the start of the fire: the value of temperature and CO density distribution map at the horizontal height of 1.6m, which is the height from the floor to the mouth of person of average length.



(a) Temperature (℃)



(b) CO density (ppm)

Figure 4 Temperature and CO density distribution map at 1.6m height (240s)

It is supposed in this paper that the temperature higher than 80℃ or the concentration of CO more than 800ppm will cause injury to the human body. The simulation results of FDS show that the average temperature at the horizontal height of 1.6m will be higher than 80℃ in about 220s, and CO density will reach 800ppm in about 280s. Thus, ASET is confirmed as 220s by the simulation of FDS.

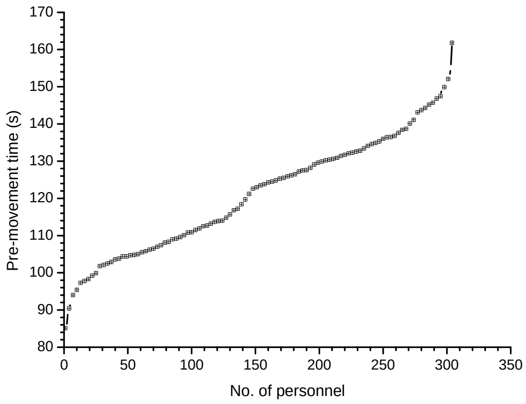
Evacuation simulation and analysis

It is described by Helbing et al. (2000) that the influence radius among human individual is 5m in the social force model. Consider that the high crowd density area generally appears near the bottleneck such as the exit and stair (Chen et al. 2003), in this case study, the social force sub-model is used to describe the panic and crowded behavior within 5m range near the north door and the lattice-gas sub-model will simulate evacuation in other low density areas.

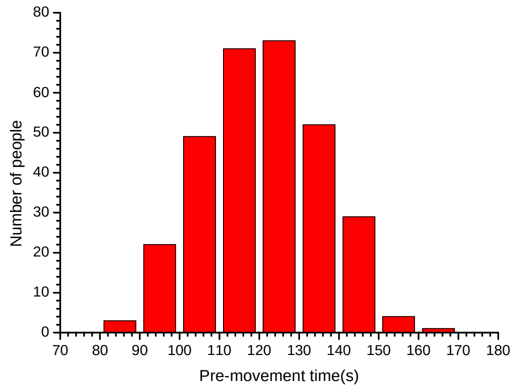
In the simulating of the CFE model, people's weight, shoulder width and speed are all regarded as normal distribution. According to the statistical information about the people in the dancing hall and the data of Table 1, the choice of people's parameters in the CFE model is selected as described in Table 3.

Table 3 People's parameters in the CFE model

SEX		**M**	**F**
Number		174	130
Weight (kg)	**Mean**	60	51
	Variance	1	1
Shoulder Width (cm)	**Mean**	47.5	44.7
	Variance	3	3
Speed (m/s)	**Normal**	1.0	1.0
	Expect	5.0	4.0
	Variance	0.2	0.2
Pre-movement time(s)	$\overline{t}_{pre}$	240	
	$t_{pre,\sigma}$	10	



(a) Pre-movement time of different person



(b) Distribution

Figure 5 Pre-movement time calculated by pre-movement time sub-model

The dancing hall is a public place of entertainment for people who are awake without fire detecting and warning facilities, and the fire is assumed to be large. According to Table 2, the value of the dimensionless parameter *a*, *b*, *d* and *e* is 1, 0.5, -0.1, 0.1 respectively. The value of *c* is calculated based on the topological structure of building. Thus, the pre-movement time of people in this building is calculated by the pre-movement time sub-model. Figure 5(a) presents pre-movement time of different persons, and Figure 5(b) is the distribution of pre-movement time, which is a normal distribution. From Figure 5, the biggest and smallest pre-movement time are 170s and 85s.

Based on the parameter selection, the simulatiom result of the CFE model is presented by the solid line in Figure 6. For comparison, the analog result is also obtained by the simple lattice-gas model, which is expressed by dotted line in Figure 6. It is shown that the evacuation efficiency calculated by the CFE model is relatively low. It is probably contributes to this model's ability of describing the phenomena of pushing and shoving among individuals near the north gate, which reflects that people are eager to evacuate to the safe area during a fire.

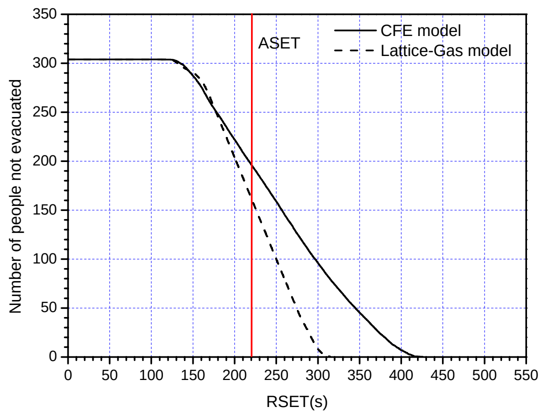


Figure 6 The simulation result of evacuating from north gate during fire

Regarding 220s as dangerous moment which is the ASET calculated by the simulation of FDS, 162 persons will die from the simulation of simple lattice-gas model and the number of death will be 197 from the CFE model. It seems that the simulation result of the CFE model is closer to the real case situation. One of the most probable reason is the difference in simulation ability about crowd situations of these two kinds of models. The ability of the simple lattice-gas model to describe the interacting among individual is not strong enough to simulate the evacuating situation in the high crowd density area accurately, especially in case where the exit is small and congestion is likely to occur.

The number of 197 deaths in accident of Yiyuan dancing hall simulated by the CFE model is smaller than the real death number of 233. The authors consider that it is mainly due to the neglect of the chemical fiber cloth decorating to the wall in the assumption of the fire scene. Thus, the fire situation calculated in FDS simulation is not as dangerous as the actual conditions. The neglect leads to the deviation of ASET and influences the simulation result of people's death finally.

CONCLUSION

The CFE model is built based on the analysis of Chinese people's behavior characteristic, which includes three sub models: lattice-gas model, social force model and pre-movement time model. The impact of fire products upon people's physiology and psychology has been considered in this model. Evacuation during fire can be simulated by the CFE model, and the result can predict RSET. With the help of FDS model to calculate ASET, it is possible to perform risk assessment or analyze the fire case for the certain building or environment.

After the simulation and analysis of the CFE model and simple lattice-gas model, it seems that the simulation result of the CFE model is closer to the real case situation. The reason is that the CFE model can simulate the condition of pushing and shoving among individual accurately. This condition reflects the psychology that people in a fire are eager to evacuate to the safe area as quickly as possible, and it usually causes congestion near the exit and reduces the efficiency of evacuating, which is described as the 'fast-is-slow effect' by Helbing (2000).

In the future, video material on escape panics will be used to validate the CFE model. The authors are now studying the impact of CO and high-temperature of fire exhaust gases on people, the interpersonal interactions which include direction, velocity, acoustic information exchange, etc.

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