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STUDY OF THE DYNAMICS OF FIRE AND SMOKE CONTROL IN CASE OF EVACUATION IN HIGH BUILDINGS, BASED ON CONTINUOUS MODEL FDS+EVAC

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ABSTRACT

To understand the fire behaviour depending on the structure of the building, it is extremely important, not only to analyse and interpret the ventilation systems, but also to understand the forms of support for smoke control and analyse the best strategy evacuation in case of emergency of zones of high flow of occupants.

With the evolution of hardware and software, the technique of numerical simulation has been widely applied in the simulation of reconstruction of fire, making it a useful tool in analyzing the design features, ultimately improving the speed of evacuation of occupants.

So this article is a brief review of the methods of smoke control based on 3D simulation of the dynamics of fire with a case study applied to a 21-storey building with an area of 2060m^2 (Technological Department of Wuhan University of Technology, Hubei-China). In order to introduce the study based on continuous model FDS+Evac, some examples of simulation scenarios of fire in one of the building stairwells are presented. Also, natural ventilation, pressurization and dilution, are simulated as tested, with the aim of obtaining the optimal solution. Furthermore, the results are analyzed and compared. Finally, it is also addressing continuation studies.

INTRODUCTION

When there is a fire in a high building, for precautionary reasons, it's not advisable to use the elevators, so the stairs are the only way to evacuate a building, so within the stairwell environment, the visibility is a key factor for the occupants in case of emergency to safely evacuate the building. Due to numerous fires in high buildings, a change in mindset has been required to complete evacuation of buildings, the delay of the occupants due to queuing on the stairs, may result in exposure of occupants to the stairwell environment for long time. Then it is therefore imperative for the exit stairs, to be smoke-free in the highest possible proportion, and incorporate design features that improve the output speed of the occupants through the stairs [7].

On a related note to the security of a high building, a design in stair pressurization system has been used to prevent the entry of smoke on the stairs [9]. The stack effect can be highly possible to occur, especially in some countries in Europe and America, which usually happen due to differences in temperature between the inside and the outside, above 30°C [4]. In these types of buildings are more specific to more than 25 floors, the stairwell pressurization systems, are more complex to design, particularly related to the impact of the stack effect in maintaining uniform pressure in relation to the height of the building [5].

Despite this, the effectiveness of a stair pressurization system, depends mainly on keeping doors predominantly closed, so you can maintain a pressure differential where necessary, and thus prevents the entry of smoke inside the stairwell [1]. Keeping the doors open during the egress of occupant, can become a problem particularly during a full evacuation of the building, or issues relating to structural damage to the stairs, would also severely compromise system performance.

The study model proposed in this paper particularly examines design issues associated with pressurizing systems of stairwells, and also analyses a potential alternative approach, namely, models involving supply & exhaust of high rates of air streams, providing clean air into the stairwell and thus the possibility of the maximum dilution of any fumes that may be present [8]. The model shows that this system can control the different pressure on the top floor, and consequently the reduction of smoke on the stairs, in this sense, it is considered practical to build stairs in high buildings.

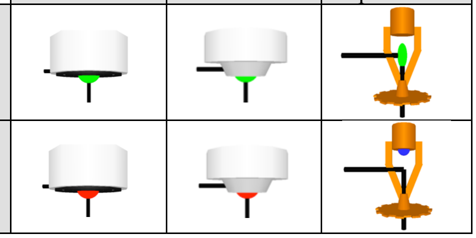
PROJECTS BASED ON STANDARD PERFORMANCE CODES

The methodology of the project based on performance, consists to use engineering methods to achieve protection against fire where the objective is to save lives. This cannot be considered as a new approach in engineering applications, given that the concept was first implemented in 1963, where this approach was then converted to a 5 stage framework (*Goal*, *Functional requirement*, *Performance requirement*, *Verification* and *Pre-accepted solutions*) called NKB level, for the use in 5 countries in northern Europe. Later in 1980 & 1984, these criteria were promulgated by the International Standardization Organization (ISO), in building codes (ISO 6420-1980/BS 6019:1980 & ISO 6421-1984). This implementation was then followed by other countries such as the United Kingdom Building Regulations (1991), the New Zealand building code (1992), United States, performance in the seismic resistance of buildings (1995), in Australia Building Codes Board (1996) and Japan's building Standard Law (1998). With the evolution of years and the rapid development of modern hardware and software technology, under the help of computer programs, the method of numerical simulation has been widely applied in the development of fire and evacuation in large buildings [11, 2].

As the Fire Dynamics Simulator (FDS), which is a Computational Fluid Dynamics software, fire conduction model and fluid flow. This software solves numerically a form of the Navier-Stokes equations appropriate for heat conduction and low-speed flow, with emphasis on heat transfer from fires and smoke. Also, it appears the Smokeview (SMV), as a supplemental 3D visualization program, which reads code structures of output files, and shows results of FDS and also produces animations on the computer screen. We also can view and extract, vector representation gas flow, temperature zones, air circulation, movement of particles, propagation and statistical data in graphs format. Both FDS and SMV applications are developed by the National Institute of Standards and Technology (NIST) of the USA Department of Commerce, in cooperation with (VTT) Technical Research Centre of Finland and are all free software.

The FDS also includes an analysis of fire detectors and water-spraying fire-extinguishing system function modules (see Tab.1), which can be used to study the influence of safety installations to fire development. Their results were validated by many experiments, which have made it widely used in the field of fire safety engineering [6]. In this sense, the software used to simulate the dynamics of fire and smoke spread in this work was {FDS_5.5.3} and {SMV_5.6}.

Tab. 1 - Fire detectors, Smoke and Spray model

	Smoke detector	Heat detector	Sprinkler pendent
Inactive			
Active			

FDS, NUMERICAL SIMULATION

The Physical Model

This work focused on the study of one of the stairwells of a 21-storey building in Wuhan-Hubei-China with an area of 2060m^2. Thus, Fig.1 shows the geometric model designed.

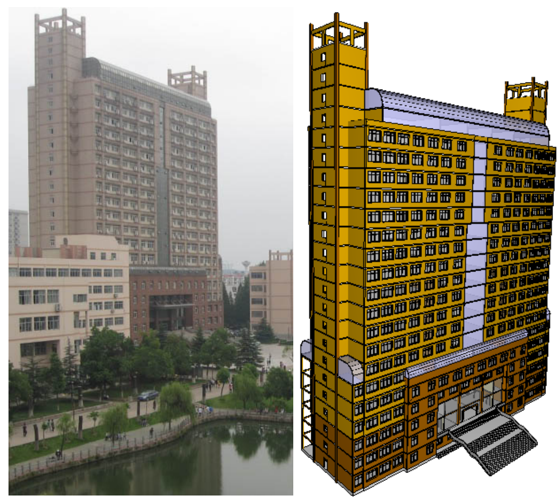


Fig. 1 - Geometric model under study, (real picture – FDS model)

In geometric modeling tested herein, the outside temperature in winter was assumed to be -3 °C. Based on standard document stipulated by the Chinese code GB50045-95 [3], the minimum output width of the stairs shall not be less than the values described in Tab.2.

Tab. 2 - Minimum width of escape stairs.

Building type	Minimum exit width	
Apartments	1,1m	44”
Hospitals	1,3m	52”
Others	1,2m	48”

The width of the main exit and measures of stairs per floor studied in this work are presented in Tab.3, and in Fig.2, is shown a partial image of the modeled stairwell.

Tab. 3 - Measurements of the staircase project.

Width of exit stair	Stairs per floor		
1,2m	Length	5,8m	232”
	Width	2,8m	11”
	Height	3,3m	132”

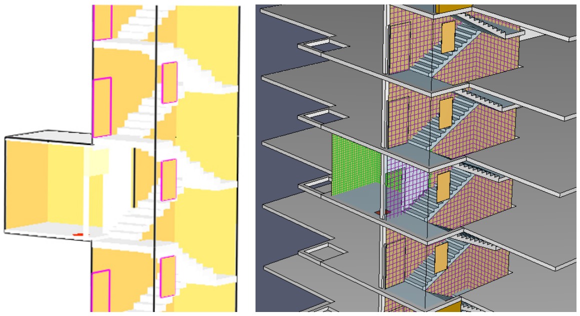


Fig. 2 - Partial model of the stairwell (SMV - FDS)

The Simulation Scenario

To explain the scenario, we would begin by pointing out that the simulation of the fire occurred in the technology department of Wuhan University of Technology, Hubei-China, specifically in the lobby to the access of one of the side stairs of the building, on the 12th floor. Initially the power of the fire is 5000$_{KW}$, equivalent to 5$_{MW}$. The building environment temperature in winter on the day of the event was considered -3°C outdoor, and to define the inner temperature of 18°C was used "*init region*" within the site. In this article, a study is made of ventilation and analysis during a 5$_{mn}$ simulation for three different states: when all the doors and windows are closed, semi-open and open.

In the simulation in which the doors and windows are all open, is used the "*open surfaces*" in the openings. The access door to fully opened stairwells, has an area of 2,76m^2 for each door (equivalent to a total of 52,44m^2), and the windows of the type (*aluminum sliding window*), with only 50% of the total area open and half closed, with a total air leakage of 0,5644m^2 for each window (equivalent to a total of 10,7236m^2). Including doors and windows open, we have a total area of air leakage equivalent to 63,1636m^2. For simulation with everything closed, we used "*obstructions*" that fill the size of the doors and windows with a total area of leak approximately 0,0140m^2, for each door (equivalent to a total of 0,266m^2) and for windows, the area of total leakage for each window is 0,0088m^2 (equivalent to a total of 0.1672m^2). Thus, including doors and windows closed, we have a total area of air leak equivalent to 0,4332m^2. Finally, the semi-open simulation is organized doors and windows alternately between floors, specifically open in pairs floors with the exception of the floor where the incident occurred and closed on odd floors to the three cases of measurement (Natural ventilation, Pressurization and Dilution).

- Natural ventilation, here the study is done without any preventive measure be taken. According to the standard document stipulated by the Chinese code GB50045-95, the total area of the open windows of the stairwell for each 5 floors must not be less than 2m^2 [3]. The building under study in this paper contains a window on each floor, directly to outside of (1,4m * 0,8m).

- Pressurization, the pressurization system of the staircase, provides a ventilation to inside the stairwell of 18000m^3/h, through 5 "*fans*" positioned alternately (floor 8, 10, 12, 14 and 16) on floors nearest of fire, where each one provides a air flow of approximately 1m^3/s.

- Dilution, in this system the amount of air drawn is equal to the amount that is provided by the "*fans*". In the case of dilution, extraction of air is taken through five "*exhausts*", wherein each one extracts 1m^3/s of air.

The visibility at the time of evacuation, is a very important factor, so it is analyzed that the rate of decrease of light and the visibility is used to describe the situation of the evolution of smoke in the simulation, both given by the following equations [10]:

$$I/I0 = \exp(-KL)$$

where:

- I - light intensity at the time of exit from the space;
- I0 - light intensity at the time of going into space;
- I/I0 - balopticon rate of the space in %;
- K - decreased rate of light, 1/m;
- L - the length of the space, m.

The decrease in the rate of light is a variable dependent on the mass of smoke per unit volume, as follows:

$$K = Km * Ms$$

where:

- Km - rate of decrease of light per unit mass of smoke, m^2/kg;
- Ms - mass of smoke per unit volume, kg/m^3.

Thus, the visibility calculation as follows:

$$S = C/K$$

where:

- S - visibility, m;
- C - proportional module, C is 8 for the illuminants, and 3 for the reflectors. In this case C is 3.

Thus, the analyzes performed with the use of a dynamic reading plane "*slice*", the Fig.3, 4 and 5 show the rates of ***visibility***, after the fire which took $4{,}5_{mn}$ in three ventilation conditions, in which windows and doors were closed, semi-open or completely open.

- With natural ventilation system, it is noticed that the smoke tends to occupy most of the stairs, due to heat pressure and stack effects;

- In the pressurization system, we perceive, that the smoke was prevented from entering the staircase;

- For the dilution system, only a little smoke was allowed to enter the staircase

Analyzing comparatively the different ventilation systems, we realize that the natural ventilation system provides a measure of escape less favorable than the dilution system, which in turn improves the environment for evacuation, however, with the permission of some smoke entry on the stairs, under the stack effect produced by negative pressure. While there is some open doors, accelerates the flow under the stack effect so that there is a rapid rise of smoke, while on the other hand, a certain amount of smoke is pushed out of the stairs to enter the upper level. Thus we see that both effects are approximately equal and neutralized, which does not allow us to see great changes of visibility in reading plans.

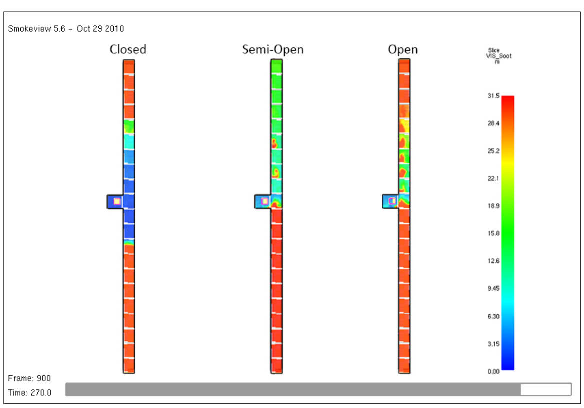


Fig. 3 - Visibility in the Natural Ventilation System

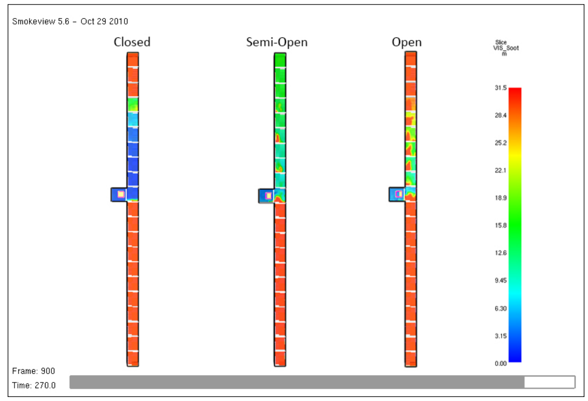


Fig. 4 - Visibility in the Pressurization System

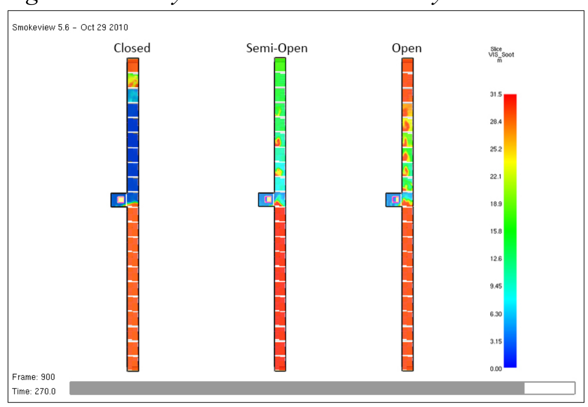
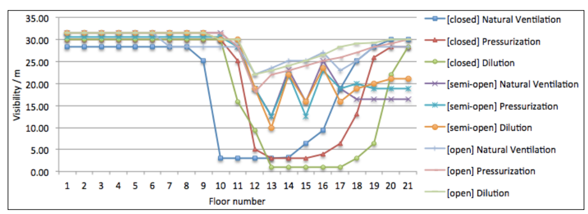


Fig. 5 - Visibility in the Dilution System



Graf. 1 - Visibility in 3 ventilation conditions, when closed, semi-open and open

In order to frame the interpretations above are considered minimum visibilities of 5m for unfamiliar and 13m for people that are familiar with the building [10]. So the Graf.1 shows in three states (closed, semi-open and open) that:

- In natural ventilation system the visibility hovers around:

  - *Closed*: from 10th till 14th floor the visibility is less than 5m, in 15th and 16th the visibilities vary around 10m, slightly less than the required code, and from 17th the visibility exceeds 18m;

  - *Semi-open*: with the exception of the 13th floor with 12,6m, the others floors visibility exceeds 15m;

- *Open*: in this case the visibility is more than 20m.

- Given the pressurization system, exerting a pressure that prevents the smoke from entering the stairwell, so the visibility is:

  - *Closed*: between 12th to 16th floor the visibility is less than 5m, in 17th and 18th is between 5m to 13m and the others is greater than 25m;

  - *Semi-open*: with the exception of the 13th and 15th floor with 12,6m, the others floors visibility exceeds 15m.

  - *Open*: with the aid of the circulation of air flows, the visibility is more than 18m.

- While the dilution system, the visibility is:

  - *Closed*: the lowest visibility occurred between 13th to 18th floor with less than 3,5m, the 12th is 9,45m, allowing visibility exceeding 15m in other floors.

  - *Semi-open*: with the exception of the 13th floor with 10m, the other floors visibility exceeds 15m.

  - *Open*: here, the visibility is clearly greater than 21m.

Now on the other hand, looking at ***differential pressure*** of the fire that remained burning for 4,5min, where is perceived by Fig.6, 7 and 8, with all doors and windows closed, in three different ventilation conditions, the stack effect caused by the temperature difference between the inside and the outside, obviously occurred in stairwell.

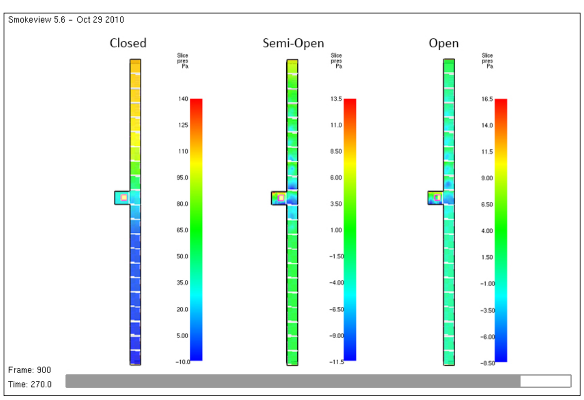


Fig. 6 - Differential Pressure in Natural Ventilation System

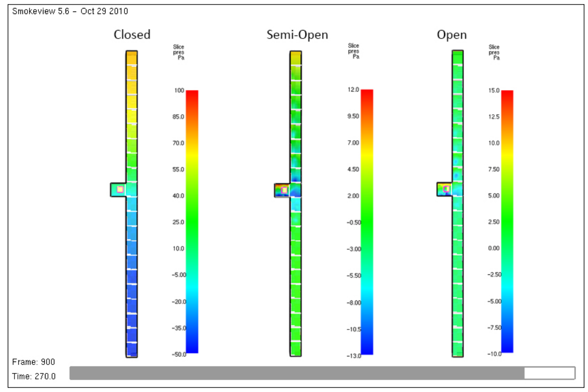


Fig. 7 - Differential Pressure in Pressurization System

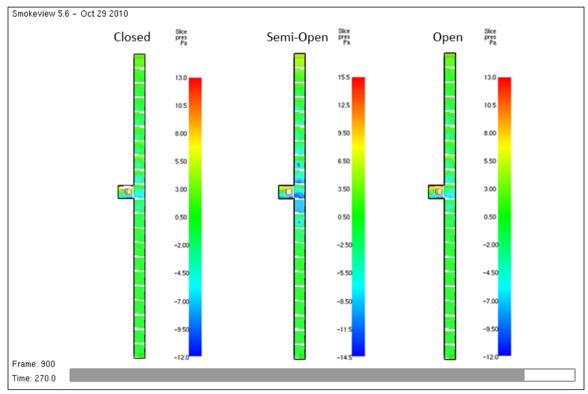
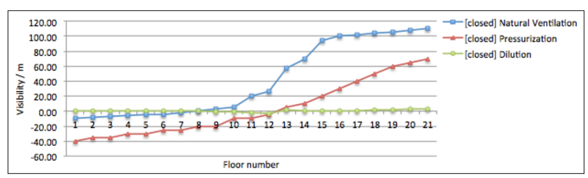


Fig. 8 - Differential Pressure in Dilution System



Graf. 2 - Differential Pressure in 3 conditions of ventilation in the closed state

One realizes that a negative pressure caused by stack effect occurred in the first 8 floors below the 12th floor, meaning that if the fire appears in these stories, the smoke quickly spread to the stairs. In this analysis, the Graf.2 exemplifies the three ventilation conditions for the state in which all doors and windows are closed.

- In natural ventilation, pressurization when in the closed state reaches the bottom of a pressure 0_{Pa} at the top reaches 110_{Pa}. If this pressure increases at the bottom, it tends to be much higher in the upper part, consequently very high pressures, difficult to open the doors, affecting the evacuation. If we consider the open state, we find that the pressure is evenly distributed when the most pressure is less than 6_{Pa}.

- On the other hand, the pressurization in the closed state, exerts a very high pressure on the top of the staircase, thus creating a difficulty to open the exit door. While the measurement of pressure is -40_{Pa} on the first floor, however it tends to achieve 70_{Pa} on top. The result of this system is still unsatisfactory since it is not easy to open the door.

- The dilution system, although the negative pressures occurring in the closed state, but uniformly distributed on the height change, thus the best result is given that the highest pressure is less than 4_{Pa}. With some doors open in three conditions, the pressure was slightly lower in each stairwell.

Result Analysis

According to what has been mentioned in Section 3.2 and summarized in Tab.4, was run 9 simulation of 5mn each on, using a machine with OS Windows 8, 64bit, processor intel(R) Core (TM) i7-3537U CPU @ 2.50GHz, 8.00GB RAM, GeForce GT 740M Graphics memory 4095MB. Also the same table summarizes the ratings of the three cases of ventilation, for the simulation reading of visibility and differential pressure.

Tab. 4 - Summary of 2 types of reading and evaluation of the simulation results

Visibility & Pressure differential	Natural ventilation	Closed
		Semi-open
		Open
	Pressurization	Closed
		Semi-open
		Open
	Dilution	Closed
		Semi-open
		Open
Ventilation system	**Pressure differential**	**Visibility**
Natural ventilation	Acceptable	Unacceptable
Pressurization	Unacceptable	Very good
Dilution	Very good	Acceptable

According to Tab.4 and considering the closed, semi-open and open state, the objective is to improve the maximum visibility evacuation function of ventilation systems in order to enforce optimal requirements. In this sense, we can increase the amount of ventilation so that it reaches the ideal requirements. In the high buildings and considering the cases of large temperature difference between the indoor and the outdoor, the pressurization system, it is recommended that buildings be built a zone of refuge dividing the staircase in the middle, so as to weaken the pressure difference between the first and last floor, caused by stack effect.

CONCLUSION

As already mentioned in paragraph 2 of this paper, we used the {FDS_5.5.3} to test numerical simulations in three different ventilation systems (natural ventilation, pressurization and dilution) under three cases (closed, semi-open and open).

Based on the simulation model, and according to the results clearly show that the dilution system is a possible solution and has better performance than other systems, both to issues of visibility in the stairwell as well as the difference pressure. So we believe that it is worth applying the dilution system in projects based on performance. However, regarding the amount of exchange ideal air into the system, need an even more comprehensive and thorough investigation.

Future Work

Centered in the methodology of projects based on performance, the future work will further validate the model by comparing these experimental data and the calculated results with simulation models of the evacuation zones of higher flow of occupants (FDS+Evac *vs* Pathfinder) according to the structure of the building under the fire in the study.

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