Journal of Wind Engineering & Industrial Aerodynamics 170 (2017) 149–161

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Multi-criteria numerical analysis of factors influencing the efficiency of natural smoke venting of atria

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ARTICLE INFO

Keywords:
CFD
Natural venting
Atrium
Smoke management
Taguchi method

ABSTRACT

Smoke management in the atrium with natural smoke venting is influenced by many parameters. The analysis presented considered the impact of atrium height, atrium shape and layout of air inlets, wind direction, wind speed and location of the fire outbreak. Experimental research is here very awkward due to the costs, thus the numerical analysis is a convenient way to examine such a large parameters domain. So wide range of research was feasible thanks to the use of Taguchi method of experiment design. The flow volume through the exhaust vents and the soot mass fraction at the ground floor were chosen as criteria to evaluate the efficiency of the smoke removal system As a result, the relative importance of examined parameters were obtained, and above all the interactions between parameters were revealed. This allows to formulate some hints for designers to make the smoke removal systems robust on the wind influence and other unpredictable factors.

1. Introduction

In modern architecture large spaces such as atriums are becoming increasingly popular. They are often combined with multi-story buildings, and in such cases it seems almost a rule that the balconies of the building overlook the atrium. Creating the relevant conditions for people in such a large space is always a great challenge for engineers. This mainly concerns the proper temperature and indoor air quality but should also ensure the safety in case of fire.

The greatest threat to people in the event of a fire is smoke. It results mainly from its highly toxic properties. However, it should be noted that it is also a serious threat during emergency evacuation because people, moving in the smoke lose their orientation and the speed of their mobility drops significantly (Klote et al., 2012). As a result of the impact of external factors such as wind and temperature, smoke can move in an uncontrolled manner (Mowrer, 2009). Also the structure of the building, its height and the layout of the air inlets influence the smoke movement inside. All of these make large enclosed spaces such as atriums require a well-designed smoke management system.

The above mentioned factors, which disturb the process of smoke removal, become significant especially for buildings with natural smoke venting. This method involves installation of the smoke exhaust vents on the roof of the building (or in the neighborhood, on the outer wall). The inflow of the compensation air is provided by the make-up air inlets, which are located on the ground floor. The driving force of this process is the thermal buoyancy. The efficiency of such natural smoke venting depends on many factors. Some of them are beyond the control of designers and engineers. They include among others the wind speed, the wind direction and the localization of the fire outbreak. There are also factors which can be controlled by the architects and the designers, for instance, the air inlets layout and the shape or the height of the building. It has become common to examine the operation of the smoke removal system at the design stage (Klote et al., 2012).

The computer programs implementing the numerical fluid mechanics (Computational Fluid Dynamics, CFD) are applied here. The program, particularly commonly used in these circumstances is FDS (Fire Dynamics Simulator) (McGrattan et al., 2010). The use of such CFD program always entails the question if it accurately reflects the reality, namely how you can rely on the results of these simulations and apply them to design systems to ensure the safety of people in a building. To reduce or even eliminate the uncertainty of the results obtained, there are many works aimed at the validation and verification of the FDS program (Ayala et al., 2013; Capote et al., 2009; Ray et al., 2014; Rundle et al., 2011; Tilley and Merci, 2009, 2013; Tilley et al., 2011; Xiao, 2012; Yang et al., 2011; Zalok and Hadjisophocleous, 2011). The result is that the calculations using FDS program to analyze the conditions in the event of fire in a

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http://dx.doi.org/10.1016/j.jweia.2017.08.012
Received 10 March 2017; Received in revised form 16 August 2017; Accepted 18 August 2017

building are very popular.

The numerical analysis of a smoke removal system involves testing the influence of the factors which disturb the system's efficiency. The wind influence is considered above all (Wegrzyński and Krajewski, 2017). This effect on smoke removal process of atria have been examined many times. Sinclair claimed that such analyses are necessary and the wind inflow from different directions must be checked (Sinclair and Ratcliff, 2009). Yi i Mowrer pointed out that the pressure caused by the wind can have more powerful influence on smoke flow than the stack effect or thermal buoyancy, especially for fires of low power (Mowrer, 2009; Yi et al., 2013). The pressure on the building wall induced by the wind causes the increase of the compensate air velocity above the recommended value of 1 m/s (NFPA 92B, 2009). There are some opinions stating that the increase of this velocity to 1.25 m/s or even to 1.5 m/s does not disturb the process of forming the convectional plume over the fire source (Hadjisophocleous and Zhou, 2008). However, there are suggestions that the value of velocity of the compensate air inflow is more significant for atria of height below 20 m. Some research on the influence of the inlet diameter on the air inflow velocity has already been done (Gutierrez-Montes et al., 2010). For bigger openings the velocity is lower, but such openings make the inside conditions more dependent on ambient circumstances (such as wind). The small openings increase air inflow velocity which disturbs the stability of the plume over the fire and finally could be harmful for evacuating people. The behavior of the smoke plume under the wind influence has also been examined and the symmetric and asymmetric layout of air inlets has been taken into account (Meroney, 2011). This study, however, has been limited to one wind direction.

Extensive numerical studies have also been carried out by Tilley (Tilley and Merci, 2013). They have examined the influence of the exhaust air volume and the fire power on the extent of a smoke-free zone. The height of the smoke-free zone is a fundamental design criterion for smoke removal systems in atria. Additionally, different geometric parameters of the atrium such as the height and width have been taken into account in the calculations. The research has also been expanded on the mechanical ventilation. The comprehensive summary of their numerical studies includes a number of comments, such as among others, recommendations as to the volume of the smoke exhaust flow, dimensions of the atrium and the size of the air supply vents.

There are some works on the influence of other factors on the smoke removal process. Doheim has analyzed the influence of an atrium shape on the natural smoke venting of a building (Doheim et al., 2014). The paper takes into consideration three types of shape: square, rectangular and triangular. It indicates, that the rectangle is the most convenient shape considering smoke removal process. The studies on the placement of inlet vents and different wind directions have also been conducted (Król, 2016).

Due to obvious reasons the multi-criteria experimental research are hardly to conduct. An attempt of combining experimental research with comprehensive numerical analysis was done by Ayala et al. (2017). They used the experimental data to validate numerical models, next they designed a fractional series of numerical simulations. The obtained results were the inputs to the linear regression, which allowed to extend the data on other scenarios, beyond the examined ones. This advanced approach resulted among others in reliable prediction of smoke layer height, temperature distribution. They took into account many factors influencing the fire development, but they did not examine the influence of the wind at all. They also did not take into account the mutual influence of the analyzed parameters on themselves.

Many scientists are conducting intensive researches on the effects of the various confounding or adversely acting factors to the process of the smoke removal. They are mostly numerical analysis because of experimental studies of development of fire and smoke extraction process are extremely difficult and expensive. Accurate numerical studies, in turn, require a lot of practice, and are often very time-consuming. As it has been shown above, a large number of recent publications demonstrate that the issue is of great importance. It seems absolutely vital to identify clearly the factors influencing effectiveness of natural and the mechanical smoke extraction for buildings with large spaces. Apparently, identification of the factors having the greatest impact on the smoke removal efficiency should take priority over others. This would allow researchers in future to focus on the most important parameters and to examine them as thoroughly as possible, paying less attention to many other variables.

Examining the interaction between these parameters is another difficult problem to solve. When influence of some factors is tested, the mutual dependencies should be checked too. Having in mind huge computational complexity of a single calculation, the whole series seems to be extremely time consuming.

The paper presents the study on the following factors influencing the efficiency of a smoke removal system: the height of the atrium, its shape, the air inlets layout, the wind speed, the wind direction and the location of the fire development. If each parameter took only two typical values, the full factorial analysis would require 64 numerical calculations. So, to cover the same domain of parameters values the Taguchi method of experiment design was applied. It allowed to diminish the number of calculations to 16. None of discussed above pure numerical analysis was so comprehensive. The same applies to the results of the mentioned experimental works, which in principle were limited to the examined structures.

2. Taguchi method of experiment design

Taguchi method of experiment design originates from his works on making the industry processes robust to the outer noise and ensuring the highest product quality. Taguchi approach aims to achieve the most appropriate value of the given product features and to provide high repeatability of these features (Roy, 1990).

The results of any process are influenced by many parameters, which can take different values. In such case examining all the possible parameter combinations seems impossible due to its costs or required time. In such situations, instead of the full factorial analysis, Taguchi proposed fractional factorial analysis – only the chosen parameter sets would be examined without meaningful loss of reliability. The experiment includes a number of series, which are designed according to the appropriate orthogonal array. An orthogonal array is an abstract entity – a table, in which entries are arranged in such way, that each row is different and each value appears the same number of times in each column. Each row of the array describes values assigned to the process parameters. The result of each series is recorded and then the analysis of such collection of results allows to determine the optimal parameter set. The selection of the orthogonal array depends on the parameters number and on the number of value levels which the parameters take. So called array selector – an additional table is used here to select appropriate orthogonal array.

This idea can be illustrated by the following example: let us assume a process is controlled by 5 parameters and each of them can take 2 values. It gives $2^5 = 32$ possible parameters combination. Meanwhile, the relevant orthogonal array is L8 (Table 1), so only 8 series are actually enough to investigate desirable parameter values. As it can be additionally seen, the L8 array describes the experiments with up to 7 binary (two levels)

Table 1
The L8 orthogonal array.

Series	P1	P2	P3	P4	P5	P6	P7
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2