REVIEW OF SMOKE MANAGEMENT IN ATRIUM

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Abstract
The scope of the paper is to present an overview of the atrium smoke systems. Atrium is becoming more popular parts of modern buildings. Ensure the safety of people in the building with an atrium in case of fire is very important. The most important is to maintain suitable conditions for escape routes during the evacuation of the people. The paper presents the methods of smoke removing from buildings with the atriums used in other countries. The process of smoke filling the space under the ceiling has been presented. Natural smoke venting is another way to remove smoke from the atrium shown in the article. The last method mechanical smoke exhaust is probably the most common form of smoke management. The attention was also drawn to the phenomena typical for buildings with the atriums, which occurrence could affect the process of the smoke distributing. The computational fluid dynamics (CFD) methods to analyze the spread of smoke in buildings was also presented.

Streszczenie
Artykuł przestawia przegląd metod oddymiania atrium. Atrium staje się coraz bardziej popularnym elementem współczesnych budynków. Zapewnienie bezpieczeństwa ludziom użytkującym tego typu obiekty w czasie pożaru jest bardzo ważne. Oczywiście zapewnienie bezpieczeństwa sprowadza się do utrzymania w czystości dróg ewakuacyjnych tak aby wszyscy ludzie mogli opuścić budynek. Artykuł przedstawia metody oddymiania atrium stosowane w innych krajach. Przedstawiono sposób wypełniania przestrzeni podsufitowej dymem. Drugim zaprezentowanym sposobem jest naturalna wentylacja. Ostatnią metodą jest oddymianie mechaniczne. Zwrócono również uwagę na procesy pojawiające się w czasie oddymiania, które mogą zaburzyć prawidłowy jego przebieg. Wspomniano również o wykorzystaniu metod numerycznej mechaniki płynów do analizowania rozprzestrzeniania się dymu w budynkach.

Keywords: **Atrium; smoke management; smoke filling; smoke venting; mechanical exhaust; computational fluid dynamics.**

1. INTRODUCTION

Economic development causes a brisk increase in investment in construction, particularly commercial buildings such as office buildings, shopping centers or sports arenas. Progress in architecture makes these buildings have got different forms and shapes and they often include the atriums.

The developing fire in a closed environment is a huge threat to human life and health, and often results in huge material damage. Material losses are caused just by the flames, and additionally by the high temperature. Apart of these factors the enormous danger for the men are the smoke and the toxic combustion products, which can be distributed for a long distances in the building. Then the smoke could pose a threat even to the people who are not close to the flames.[1, 2].

There are design guidelines formulated by the Building Research Institute and the Polish Standard in respect of the building that is equipped with a conventional stairway or an elevator shaft, and the corridors and rooms [3, 4]. Thus the smoke ventilation system for a traditional building can be designed using existing materials.

The engineers for years have tried to organize such a ventilation system of smoke exhaust to give people the chance of leaving the danger zone, or the chance for a safe evacuation. They bear the responsibility for creating appropriate conditions for the evacuation and as the result, the designers are increasingly turning to programs designed to enable diagnostics of these systems. The issue of organizing the flow of smoke in buildings with the atriums is widely discussed in foreign publications [5, 6, 7, 8, 9, 10].

The paper presents the methods of smoke removing from buildings with the atriums used in other countries. The attention was also drawn to the phenomena typical for buildings with the atriums, which occurrence could affect the process of the smoke distributing.

2. AN OVERVIEW OF THE ATRIUM SMOKE SYSTEMS

Buildings with atriums are the peculiar challenge for the engineers of smoke ventilation systems. It is very difficult to divide the building which contain large spaces limited by the glass surfaces into possible separate reservoirs of smoke, as is suggested by the Polish standard for fumigation of large volume objects [11]. Providing the security by introducing the sprinkler installations is sometimes impossible, and such facilities, even installed simply do not ensure the safety of the users and the object. This come from the fact that the ceilings of the atriums are often at a height more than 11 to 15 meters. The stream of convection which develops above the source of the fire expands while moving towards top, which results in turn lowering its temperature. The temperatures may fall below the temperature required for activation of the sprinklers [7].

Processes associated with the development of fire are complicated and unstable. Therefore, the tools used to analyze the spread of smoke must meet high demands. The computational fluid dynamics (CFD) is widespread used as a foundation of this kind of programs. The results obtained by a computer program cannot doubt and they must be absolutely certain. Frequently used in such studies is the program FDS (Fire Dynamics Simulator) [12, 13].

Many research centers around the world conduct studies to verify the FDS. Then there are papers that describe the simulations performed using FDS, where the real object, where the fire had occurred was the subject of analysis [14]. The FDS program was used to reproduce the course of fire and the movement of smoke. Using the program in such a way make a perfect verification for it.

There are many studies on the models of small-scale atrium [15, 16, 17, 18].Two centers in the world can boast of the possession in their laboratories full-size objects. In these objects, you can perform the analysis on the operation of the smoke exhaust system and the vertical temperature distribution depending on the size of the source of fire.These tests are then compared with the calculations carried out using the FDS.

One of the models of the atrium in a large scale is located in Murcia, Spain, in the Technological Metal Centre. It is the prismatic shaped with the squared base building, sized 19.5 m × 19.5 m × 20 m made of aluminum, with several vents arranged in its walls and four exhaust fans at the roof. Series of experimental tests have been carried out with the use of several heptane normalized pool-fires, placed at the center of the atrium. The data obtained from these experiments have been later used for a validation study of the two CFD simulations determining the wall temperature, the ambient temperature and the assessment of the exhaust fan. The results show good agreement between the experiment and the numerical predictions and allow concluding that for a fire test of 1.6MW of average heat release power, the exhaust and ventilation system is not enough to extract the hot combustion products. There is an excessive and dangerous accumulation of hot gases at the upper part of the atrium and the exhaust capacity of the roof fans must be increased. The CFD models could give the help in that matter. [19, 20].

The another model of the atrium is located in China. A full-scale burning facility, the PolyU/USTC Atrium, was constructed for studying experimentally the atrium smoke movement. Results would be applied in determining useful design parameters and in evaluating the performance of smoke management systems. This is a 20-year joint project between The Hong Kong Polytechnic University (PolyU) and the University of Science and Technology of China (USTC). The facility is located at the campus of the USTC at Hefei. Its outer dimensions are 27.6 m long, 18.1 m wide and 30.6 m high, and the inner dimension of 22.4 m long, 11.9 m wide and 27 m high. The first phase of the study is of five years duration. The smoke filling, the natural ventilation, the smoke extraction systems, the sprinklers in the high headroom atrium and the fire detection systems will be examined. Note that very few experimental data on atrium smoke movement are available in the literature. Therefore, the results achieved from this testing facility are useful to tune up parameters in design equations, such as the NFPA equation [21] on a smoke filling process; and to validate the fire models for predicting of the fire environment [22, 23].

3. ATRIUM SMOKE EXHAUST SYSTEMS

The smoke which appears in the atrium, may come from a fire developing in the atrium or in the passage directly connected to it. Then a fire in the atrium space may produce an axisymmetric plume, while a fire in a place opened to the atrium may produce so called balcony spill plume (Fig. 1). Depending on the assumptions used, the differences reveal in the design of smoke exhaust system. For example, in the United States the systems of the atrium smoke extraction are designed assuming the source of the fire is in the atrium, while in Australia and Western Europe the source of the fire lies in an adjacent space, opened to the atrium. While carrying out calculations for buildings with smoke exhaust systems in atrium one can rely on standards [21]. In considering the issue of the building with an atrium smoke exhaust can be used different assumption on sand therefore different solutions. We can choose the "filling with smoke" system (smoke filling), the natural ventilation or the mechanical ventilation [7].

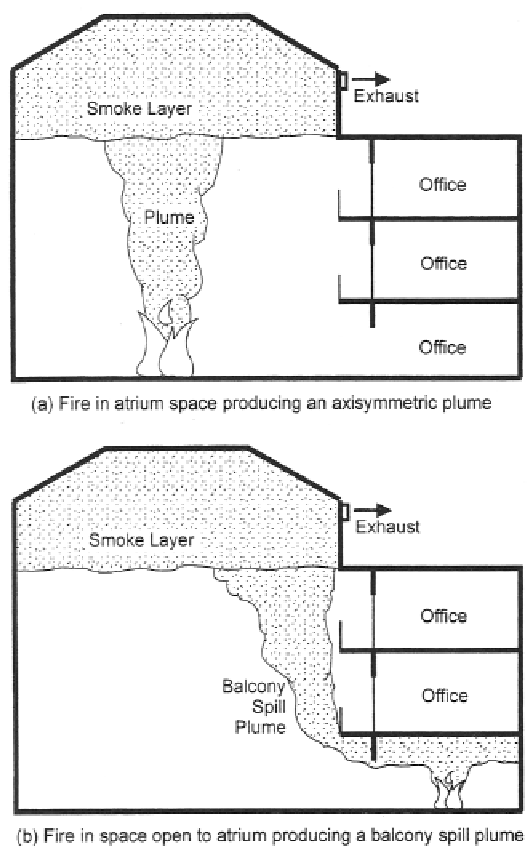

Figure 1.
The kind of plume determined by location of the fire [7]

3.1. Smoke filling

The solution is to provide time to evacuate people from the atrium or through the atrium till the time as smoke fills the atrium space (Fig. 2). Of course, this method is applicable only for very large objects where the filling time is sufficient to carry out the evacuation. The basis for the design of this system is to determine the time needed to fill the atrium space with the smoke while maintaining a smoke-free space that is necessary to evacuate on the top floor adjacent to the atrium. This time may be determined basing on empirical equations depending on whether the fire is assumed as a steady or unsteady process.

For the steady fire, the time can be expressed as (1):

$$t = \frac{AH^{4/3}}{H^2 Q^{1/3}} \sqrt{\left[\frac{1}{0,28}\left(C_{ef1} - \frac{z}{H}\right)\right]} \tag{1}$$

where:

A – cross-sectional area of the atrium, m^2;

H – ceiling height above the fire, m;

Q – heat release rate from steady fire, kW;

C_{ef1} – 1.11

z – height of the first indication of smoke above the fire surface, m;

And the equation for unsteady filling gives the time (2):

$$t = C_{ef3} t_g^{2/5} H^{4/5} \left(\frac{A}{H^2}\right)^{3/5} \left(\frac{z}{H}\right)^{-0,69} \tag{2}$$

where:

t_g – growth time, s;

C_{ef3} – 0.937

As already stated, evacuation times are often in the range of 15 to 30 minutes. The fire at the end of the evacuation time can be extremely large, what limits the applicability of the equation. The undeniable fact remains that the application of the smoke filling system must be limited to a very large volume space.

This problem is considered in many articles [23, 18].

Currently, to calculate the time of smoke filling the ceiling space are often used the zone fire models such as AZONE or CFAST.

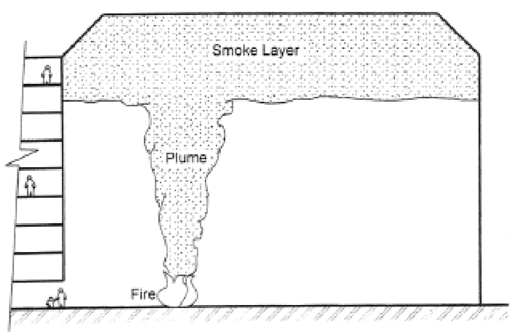

Figure 2.
Atrium smoke filling [7]

3.2. Natural venting

Natural smoke venting is common in many countries in Europe, Australia and New Zealand. Natural venting relies on the buoyancy of hot smoke, what forces it out by open vents on the top or near the top of the atrium (Fig. 3). Because buoyancy of the hot smoke is the driving force of natural venting, the mass flow rate through the vent increases with increasing smoke temperature. As the size of the fire grows, the mass flow rate of the plume into the upper layer increases, and the temperature of the smoke layer becomes higher.

The mass flow rate through the vent for the steady conditions can be expressed:

$$\dot{m}_v = \frac{C A_v \rho_o \left[2 g d_b (T_s - T_o)(T_o / T_s)\right]^{1/2}}{\left[T_s + (A_v / A_i)^2 T_o\right]^{1/2}} \qquad (3)$$

where:

m_v – mass flow rate through the vent, kg/s;

C – discharge coefficient (dimensionless);

A_v – vent area, m^2;

A_i – inlet opening area, m2;

ρ_o – outsider air density, kg/m^3;

g – acceleration of gravity, m/s^2;

d_b – depth of smoke layer below the smoke vent, m;

T_o – temperature of outsider air, K;

T_s – temperature of smoke, K;

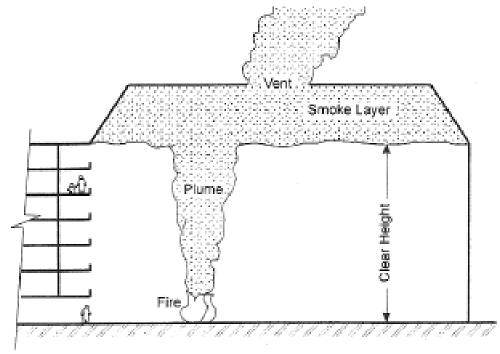

Figure 3.
Natural smoke venting [7]

The use of natural ventilation system for the atrium is a good solution. However, it should be appreciated, that there are possible phenomena, the appearance of which can significantly affect the process of smoke exhaust.

If the analyzed atrium is equipped with air-conditioning system, it can cause the temperature of the combustion gases fall below the projected level and smoke extraction will be much less effective than expected. Another piece of equipment that could disrupt the process of natural smoke exhaust is the sprinklers system. Its job is to just lower the temperature of fire gases in order to facilitate people to evacuate. Unfortunately, it remains in contradiction with the main assumption of natural ventilation. Gas temperature can be reduced to a level such that the gases do not reach the exhaust opening.

When designing of a natural ventilation system for the atrium should also pay attention to the surroundings of the building. Natural ventilation is a system which is greatly influenced by the wind. For an atrium attached to a tall building or very near a tall building located in open terrain, wind can produce positive pressures at the top of the atrium (Fig.4). Such positive pressures can interfere with natural venting, then natural venting is not recommended for atrium with such wind conditions.

Despite the attention it should be noted that natural ventilation is the most popular way of smoke exhaust the atrium objects. Not without significance is the fact that the cost of this solution are small compared with the installation of mechanical ventilation and this solution is often in accordance with the architectural

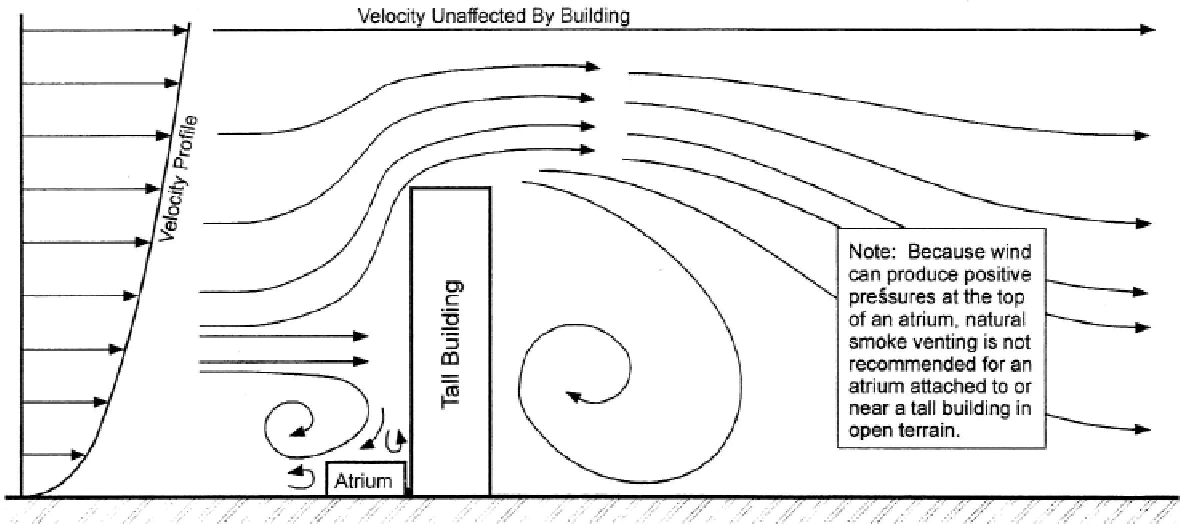

Figure 4.
Windflow pattern of producing a positive pressure on the top of an atrium due to the presence of a tall building nearby [7]

vision of the object. The particular attention has to be taken on the settings of temperature sensors, which activation is necessary for the functioning of the system. It is important that the drop of the gas temperature do not prevent the excitation of the sensor.

3.3. Mechanical exhaust

Mechanical smoke exhaust is probably the most common form of smoke management. This is the usual way of smoke management in the United States. It consists on the placement of the exhaust fans in the upper part of the atrium, so that they were within the smoke layer (Fig. 5).

The volumetric flow of exhaust gases for the steady conditions can be expressed as:

$$\dot{V} = C_{vf} \frac{\dot{m}}{\rho_p} \tag{4}$$

where:

V – volumetric flow of Exhaust gases, m3/s;

m – mass flow of exhaust air, kg/s;

ρ_p – den sity of exhaust gases, kg/m3;

C_{vf} – 60;

So the mass flow can be calculated:

$$\dot{m} = C_{a1} Q_c^{1/3} z^{5/3} + C_{a9} Q_c \tag{5}$$

where:

Q_c – convective heat release rate of fire, kW;

z – height of the smoke layer interface above the fuel, m;

C_{a1} – 0.071

C_{a9} – 0.0018

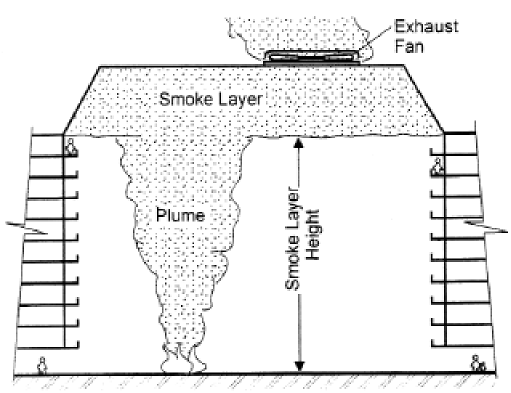

Figure 5.
Mechanical smoke exhaust [7]

Designs of the mechanical ventilation system should be based not only on calculating of the rate of exhaust fans, but also on determining of their numbers. It may, indeed prove, that the use of only the one fan would force it to work with very high efficiency, which may lead to the phenomenon of plugholing (Fig.6). Therefore, it seems necessary to verify the maximum mass flow rate, which can be pulled by a single fan without the occurrence of the clear air intake phenomenon.

The maximum mass flow rate that can be efficiently extracted using a single exhaust inlet is given as:

$$m_{\max} = C_{ph1}\beta d^{5/2}\left(\frac{T_s - T_o}{T_s}\right)^{1/2}\left(\frac{T_o}{T_s}\right)^{1/2} \qquad (6)$$

where:

d – depth of smoke layer below bottom of exhaust inlet, m;

β – exhaust location factor (dimensionless);

C_{ph1} – 3.13

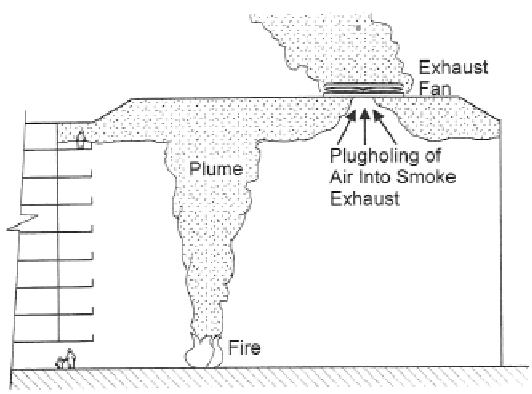

Figure 6.
Plugholing of air into smoke Exhaust inlets [7]

When considering systems, where the exhaust fan or a smoke exhaust damper located on the roof of the atrium are activated by the temperature sensor placed near the ceiling should be remembered that the operation of these sensors can be affected by the characteristic stratification of air in the atrium (Fig. 7). This is connected with the phenomenon of holding a hot layer of the air near the atrium ceiling, which do not allow the smoke to reach the fire sensors. This problem is solved by the special localization of the sensors and the appropriate distribution of the beams.

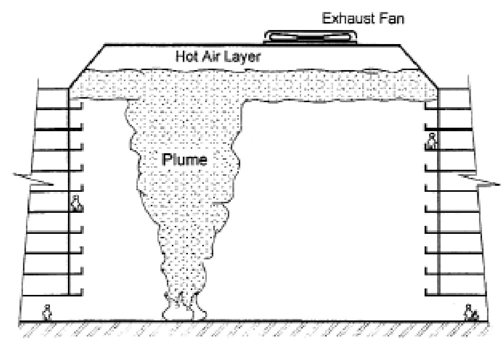

Figure 7.
Smoke stratification under a layer of hot air [7]

4. SUMMARY

The extremely complex mechanism of smoke movement in the atriums in combination with the often complex geometry of these objects forces the designers to look for tools that reflect this complexity. This results in increasingly common use of numerical methods for fluid flow modeling of smoke in buildings with an atrium. Further verifications of the most popular tools used at the numerical modeling have given increasing confidence of use of these tools. At the same time, however, need to be aware of the problems that are specific to buildings with atrium and the particular phenomena that should be properly modeled to reflect the true image of the fire in the atrium.

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