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NUMERICAL STUDIES ON ATRIUM SMOKE MOVEMENT INDUCED BY A SHOP FIRE

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ABSTRACT

To reduce the effect to other floors, smoke should be extracted out or controlled out of the atrium in general atrium smoke management system when its adjacent storey catches a fire. While if the compartmentation between the atrium and its adjacent floors is good enough and it is needed to prevent the fire and smoke from spreading to the nearby important or dangerous buildings, atrium with open ceiling can be used as a chimney to vent smoke. Under this flow pattern, air from surroundings flows into the fire floor through its openings to the ambient, all of the smoke enters the atrium and flows out though its top opening. By analyzing the flow pattern in an atrium with fire in an adjacent floor and simulating the fire process with a CFD software package, the condition of this "flooding flow" of smoke in the atrium and fire floor was given, and the relation between the time when flooding flow occurs and the aspect ratio of atrium under different heat release rate (HRR) of fire was discussed.

Keywords: atrium, flooding flow, shop fire, numerical simulation

1. INTRODUCTION

In January 2000, a fire occurred in a building with an atrium which was designed for wholesale market in HeFei, China. The atrium and the fire floor were burnt with nearly nothing inside left, while the shops close to that building were kept in a whole skin. According to the investigation after the fire, smoke was found flowing from the fire floor to the atrium and flowing out through its broken ceiling and air was drawn from the ambient to the fire floor through the vents open to outside.

Nowadays, more and more large space buildings with a central atrium were built. In this kind of buildings, the atria are usually connected to many of the floors of the buildings. Once a fire occurs in an adjacent floor, smoke is easy to spread to the atrium and affect other floors. On general opinions of smoke control, smoke should be controlled out of atrium or extracted to outside as soon as possible. However, if the compartmentation between the atrium and other floors is good enough, or it is not important any longer to let smoke enter the atrium, using atrium with open ceiling to exhaust smoke out will be of great advantage in protecting the buildings near that building with an atrium, especially when the nearby buildings are very close or have much fire goods.

CFD fire "field" models were widely applied in fire research to study smoke movement since the computation ability of computer system was greatly improved in recent decades. In this paper [1], the flow pattern is simply analyzed when a shop fire occurs in an adjacent floor to an atrium and the CFD software Fire Dynamics Simulator (FDS Version 3), developed at National Institute of Standards and Technology (NIST) USA, based on Large Eddy Simulation (LES) [2] is selected for studying air flow induced by a fire in an adjacent floor to an atrium.

2. ANALYSIS ON SMOKE FLOW AFTER ADJACENT FLOOR CATCHING A FIRE

Fig. 1 shows the situation of early stage when a fire occurs in an adjacent floor to an atrium. The fire floor has two vertical vents (W_A and W_B) open to outside and the atrium respectively. The ceiling of the atrium is open, and it is supposed that the isolation between the atrium and the other floors is ideal.

2.1 Flow in the Fire Floor

At the early stage of the fire, smoke moves out to outside and the atrium, and air from outside and the atrium enters the fire floor though the two vents at the same time. The velocity profile at the vents is simply shown in Fig. 1. At the top of the vents, because the smoke in the fire floor is lighter than the air in the atrium and outside, pressure difference between the fire floor and outside (atrium as the same) is larger than at the lower place of the vents. At the bottom of the vents, the pressure difference gets negative to that at the top. So there should be a zero-pressure-difference or zero-velocity plane α and β at the two vents respectively. At the early stage, the pressure, temperature and air density in the atrium (P_a, T_a, ρ_a) are almost the same with those outside (P_0, T_0, ρ_0), so the flow at the two vents does not differ much from each other. Plane α and β are almost at the same vertical position. At vent W_A, along with the smoke flowing into the atrium, smoke with high temperature in the atrium becomes more and more and flows upward to the ceiling of the atrium, the air in the atrium lessens due to the entrainment by the rising plume and supplying to the fire floor, and pressure in the atrium P_a decreases, too. It results that the amount of air entering the fire floor from the atrium is reduced, the amount of smoke entering the atrium increases and the vertical position of plane α drops till it reaches the sill of W_A. At vent W_B, the ambient pressure and temperature (P_0, T_0) will not change much during the fire, so the flow at W_B is mainly decided by the flow at W_A. The amount of air flows into fire floor through W_B will increase if the amount of smoke flows into the atrium through W_A increases because of continuity of flow, and the outflow of smoke at W_B will decrease. The vertical position of β will rise till it reaches the soffit of W_B. When α and β are at the sill and soffit of W_A and W_B respectively, the flow status is: hot smoke rushes into the atrium and flows out though the top opening of the atrium with cold air flowing into the fire floor from surroundings at a fairly large velocity. No smoke flows out though the opening between the fire floor and the environment, and no flow from the atrium to the fire floor, either. The atrium then acts like a large chimney to lead the flow of smoke.

2.2 Flow in the Atrium

Wall plume forms after smoke enters the atrium through W_A. Cross-sectional area and mass flux of the plume increase by entraining nearby air while rising up. If the cross-sectional area of the atrium (A) is not large and the atrium (H) is tall enough, the rising plume will touch all the walls of the atrium at some height. Above the point where the plume contacts all the walls of the atrium, the cross-section of the atrium is filled with smoke. Below the point, there is some cold air left at first, but the cold air becomes less due to the entrainment by the smoke plume. There will form a hot smoke column in the atrium at last which results that temperature in the whole atrium is higher than the ambient. At the same time, there are two openings at the top and bottom of the hot smoke column respectively (e.g. the vent open to outside of the fire floor and the open ceiling of the atrium). Therefore, "flooding flow" will occur in the atrium: air enters the fire floor through W_B, all the smoke flows into the atrium through W_A and goes out through the top opening of the atrium.

If the cross-sectional area is larger, the plume does not touch all the walls of the atrium when rising up. Outside air will come into the atrium through its top opening and move down because the plume entrains air at lower place of the atrium. Heat is transferred from the rising hot smoke to the descending cold air and from smoke to the walls of the atrium. If the cross-sectional area of the atrium is not too large and the HRR of fire is large enough, a hot smoke column will form and flooding flow will occur in the atrium, too. Otherwise, if the cross-sectional area of the atrium is too large and the HRR of fire is small, hot smoke column will not form in the atrium and flooding flow will not occur to vent smoke effectively.

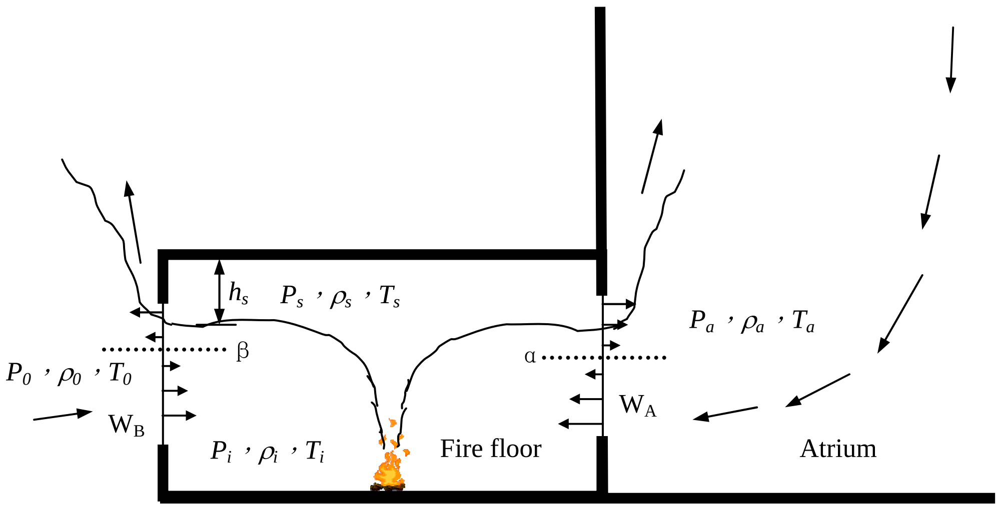


Fig. 1: Flow at the early stage of adjacent floor fire

2.3 The Criterion of Flooding Flow Occurs in an Atrium

Aspect ratio (γ) is commonly used to describe the geometric character of an atrium,

$$\gamma = \frac{A}{H^2} \tag{1}$$

where A is the cross-sectional area of an atrium and H is the height of it. Researchers have made statistics on some atria whose cross-sectional area do not vary with the height in China and classified them by their aspect ratio; atria are labeled as tall with aspect ratio less than 0.4, flat with aspect ratio larger than 2 and cubic for the others [2].

Suppose the base of a fire is at the same level with the atrium floor, and the cross-sectional area of the atrium does not change along with its height. Analysis can be made on the formation criterion of hot smoke column in an atrium when one of its adjacent floors catches a fire.

Case 1: The rising plume touches all the walls before it rises to the top of the atrium. As shown in Fig. 2.

NFPA 92B [3] has characterized axisymmetric plume and window plume in simple expressions. For example, the diameter of axisymmetric plume can be estimated as

$$d = 0.5 \cdot z \tag{2}$$

where d is the plume diameter at height z above the fire source. If the plume is close to a wall, according to Mirror Model [4], it can be considered as half of an axisymmetric plume with double HRR of fire. So the cross-sectional radius can be estimated as

$$r = 0.25 \cdot z \tag{3}$$

where r is the radius of the wall plume at height z.

Window plume with free space above the window is considered as an axisymmetric plume, the distance from its virtual source to the suffit of the window (a) can be calculated using:

$$a = 2.4 A_w^{2/5} H_w^{1/5} - 2.1 H_w \tag{4}$$

where A_w and H_w is the area and height of the window, respectively. For approximatively square window, $a \approx 0.3 H_w$ and $a << H$. Therefore, the plume that flows out from a window and rises along a wall can be nearly considered as half of an axisymmetric plume with the source at the center of the window. For atrium with a square cross-section, the vent between the atrium and the fire floor is located at the middle part of one side of the atrium, the criterion of plume touching all the walls before it reaches the top of the atrium is

$$r^2 = [0.25(H - Z_w)]^2 \geq L^2 + (L/2)^2 = (1.12L)^2$$

$$H - Z_w \geq 4.5L \tag{5}$$

where Z_w is the vertical distance from the centre of the vent to the atrium floor. If Z_w is much smaller than the height of the atrium H (e.g. fire occurs on ground floor and atrium is tall), the above inequation can be rewritten as:

$$\gamma = \frac{A}{H^2} = \frac{L^2}{H^2} \approx \frac{L^2}{(H - Z_w)^2} \leq 0.049 \tag{6}$$

If the cross-section of the atrium is not a square and the vent between the atrium and the fire floor is not located at the middle part of a side of the atrium, two new variables are introduced, L_r and H_f, which indicate the maximum horizontal distance from the atrium walls to the center of the vent open to the atrium and the vertical distance from the centre of the vent of the lowest fire floor to the ceiling of the atrium, $H_f = H - Z_w$. Redefining the aspect ratio of the atrium under fire,

$$\gamma_f = \frac{A}{H_f^2} \tag{7}$$

Therefore, the criterion of plume touching all the walls before it reaches the top of the atrium can be written as:

$$\gamma_f = \frac{A}{H_f^2} \leq \frac{A}{(4L_r)^2} = \frac{A}{16 L_r^2} \tag{8}$$

The above inequation is a sufficient condition of the formation of hot smoke column, namely, if the aspect ratio of a top-open atrium under adjacent floor fire γ_f meets the above formula and there are vents of fire floor open to atrium and outside, flooding flow will occur in the atrium when smoke moves.

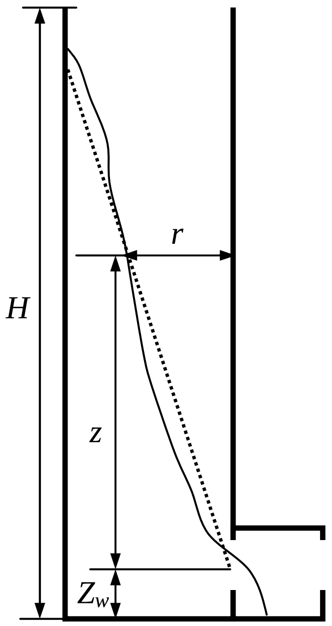
Case 2: The window plume does not touch all the walls before it rises to the top of the atrium. Under this condition, whether hot smoke column will be formed depends on the heat transfer between the window plume and cold air in the atrium. Because the involved mass flow and heat transfer in the process of smoke rising and air descending in restricted space is complex, there is no available quantificational study on it. The criterion of occurrence of flooding flow to vent smoke efficiently can be acquired by numerical and experimental means.

If the ceiling of an atrium is closed at the beginning of a fire in adjacent floor and broken after some time (for example, the glass breaks due to heated by smoke), because a hot smoke column has formed in the atrium, the unclosing of the ceiling will cause flooding flow, too.

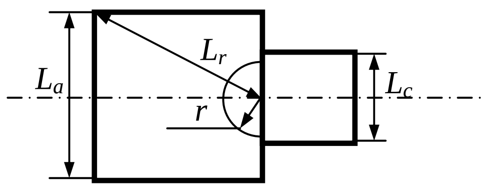
It should be pointed out that the atrium is connected to each floor with windows and doors which are usually open. Windows and doors will not only increase the effective area of cross-section of an atrium, but also bring negative impact to corresponding floors with smoke in the atrium. Therefore, the precondition to use flooding flow in atrium to extract smoke out is the effective isolation between the atrium and its adjacent floors that does not catch a fire.

3. NUMERICAL SIMULATIONS AND DISCUSSION OF THE RESULTS

32 simulations were carried out using a "field" model, FDS (Fire Dynamics Simulator, Version 3). The size of the atrium and HRR of steady fire are listed in Table 1. In all the simulations, the size of the fire room was set at 3 m × 3 m × 3 m, the fire was located at the center of the floor of the fire room, the height of atrium was 27 m. The vents in the fire floor were both 2 m × 1.5 m with sill at 1 m above the floor. The ambient temperature is 20 ^{o}C. By watching the dynamic display of calculation results, whether and when flooding flow occurs can be obtained. Among the series of simulations, flooding flow did not occur till the end time of simulation (at 800 s) in the atria with size 11 m ×11 m × 27 m and 12 m × 12 m × 27 m. In the range of designed HRR of fire (100 kW to 2000 kW), HRR of fire almost had no attribution to whether flooding flow occurs or not, but affected the time when it became significant.



a) Side view



b) Plan

Fig. 2: Window plume in an atrium

Table 1: Conditions of each simulation

Size of atrium (m)	HRR of fire (kW)	Size of atrium (m)	HRR of fire (kW)
3 × 3 × 27	2000/1000/500/100	7.2 × 7.2 × 27	2000/1000/500/100
4.5 × 4.5 × 27	2000/1000/500/100	9 × 9 × 27	2000/1000/500/100
4.5 × 6 × 27	2000/1000/500/100	10 × 10 × 27	1000
6 × 6 × 27	2000/1000/500/100	11 × 1 × 27	1000
7.2 × 6 × 27	2000/1000/500/100	12 × 12 × 27	2000/1000

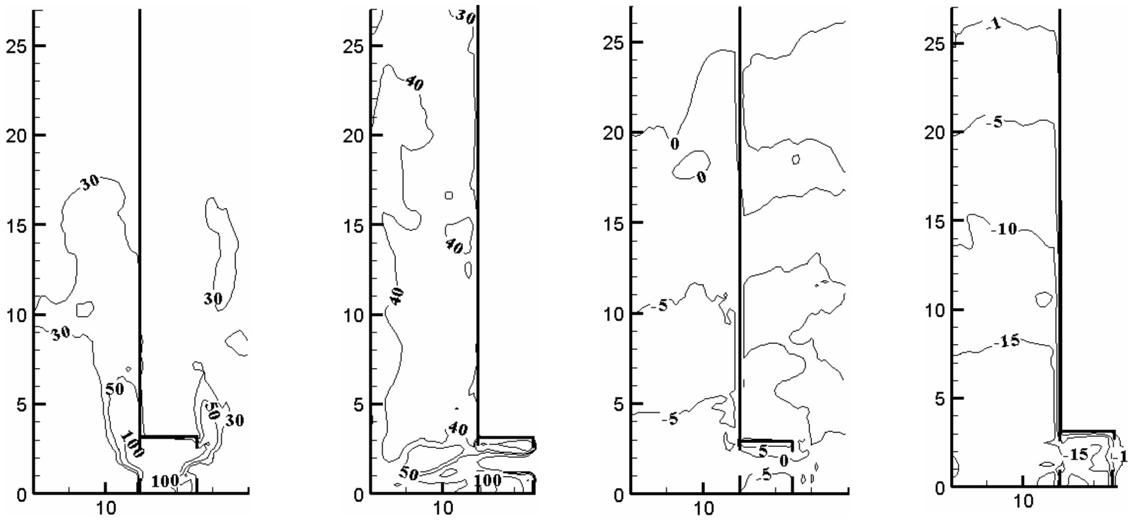
3.1 The Case that Flooding Flow Occurred

The atrium with size of 6 m × 6 m × 27 m and fire HRR at 1000 kW is selected. In this case, flooding flow occurred at 32 s after the ignition of fire. The temperature and pressure profiles at 20 s and 50 s are shown in Fig. 3, which present the distribution before and after flooding flow occurred in the atrium respectively.

30^{o}C isotherms were used to compare the temperature distribution before and after flooding flow occurred. Before flooding flow occurred, the place where temperature was higher than 30 ^{o}C was nearly half a turbination close to the wall between the atrium and the fire room. After flooding flow occurred in the atrium, almost all the atrium was filled with hot smoke with temperature greater than 40 ^{o}C, the 30 ^{o}C isotherm only appeared at the top opening of the atrium. Also, the pressure difference between the outside and the atrium increased significantly after 32 s.

3.2 The Case Flooding Flow Did Not Occur

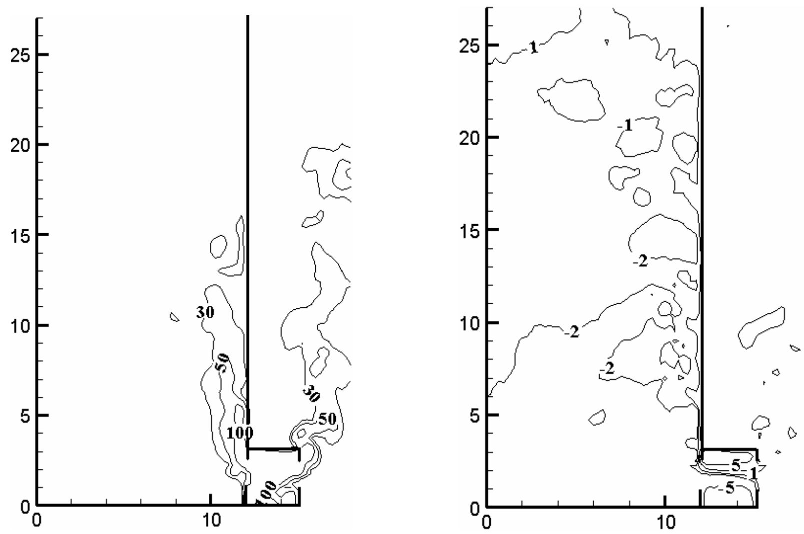
The atrium with size of 12 m × 12 m × 27 m and fire HRR of 1000 kW is selected. The temperature and pressure profiles did not change much after 200 s. Fig. 4 shows the temperature and pressure distribution at 500 s. It can be observed that the place surrounded by 30 ^{o}C isotherm only appeared above the vent and close to the wall and the pressure difference between outside and atrium is very small.



a) Temperature distribution at 20 s | b) Temperature distribution at 50 s | c) Pressure distribution at 20 s | d) Pressure distribution at 50 s

* The minimum value of x-coordinate in Figure a-d is 6

Fig. 3: Part of the simulation results (atrium of 6 m × 6 m × 27 m with HRR of 1000 kW)



a) Temperature distribution at 500 s | b) Pressure distribution at 500 s

Fig. 4: Part of the simulation results (atrium of 12 m × 12 m × 27 m with HRR of 1000 kW)

Fig. 5 shows the relation between the time when flooding flow occurred and aspect ratio of the atrium (γ_f) under different HRR of the fire. It can be observed that flooding flow occurred in atria with γ_f less than 0.157. In addition, there is a turn in each curve at γ_f near 0.06. The curves became steeper on the right side of the point. According to the analysis in section 2.3, when $\gamma_f \leq 0.049$, the smoke plume contacts all the walls of the atrium before it reaches the ceiling, resulting in forming hot smoke column and flooding flow occurring in the atrium. When $\gamma_f > 0.049$, the smoke plume does not contact all the walls of the atrium before it reaches the ceiling, the formation of hot smoke column needs additional time for heating the air in the atrium. So the time when flooding flow occurs will be postponed significantly when $\gamma_f > 0.049$. The difference between the turning point at $\gamma_f = 0.049$ from analysis and at $\gamma_f = 0.06$ from simulations may be attributed to the following two aspects: plume models used in the analysis are just semi-physical models; and numerical simulation is only a prediction on reality. Both will bring some error and need be validated in further study by experimental means.

4. CONCLUSIONS

On the use of atrium in smoke management in a fire, using simplified analysis and numerical simulation, some conclusions can be drawn:

- Under certain conditions, atrium (or parvis) can be used as a stack to extract smoke when its adjacent floor catches fire. Atrium is a large shaft; it can lead smoke to flow out by flooding flow, which is helpful to prevent smoke from spreading to the adjacent building.
- Whether flooding flow will occur in an atrium when its adjacent floor catches fire depends on the aspect ratio of an atrium under fire (γ_f). From the results of simulations, when $\gamma_f \leq 0.157$, and there is open vents between the fire floor and the atrium, the fire floor and outside, and the ceiling of the atrium is open, flooding flow will occur in the atrium after a period of time. The HRR of fire does not determine whether flooding flow will occur or not, but affects the time when it becomes strong. Flooding flow occurs at an earlier time with the increasing HRR of fire. There is a turning point in the relation curve between the time when flooding flow occurs and aspect ratio of atrium (γ_f) which corresponds to the atrium aspect ratio where smoke plume touches all the walls at the top of the atrium exactly.
- Extracting smoke out by smoke management system in the fire floor is the direct way to control smoke. Using atrium to extract smoke out is an optional means especially in the case that there are buildings need strict fire protection on the opposite side of the vents through which smoke will flow out. Fire and smoke compartmentation should be seriously considered while considering extracting smoke by such means.

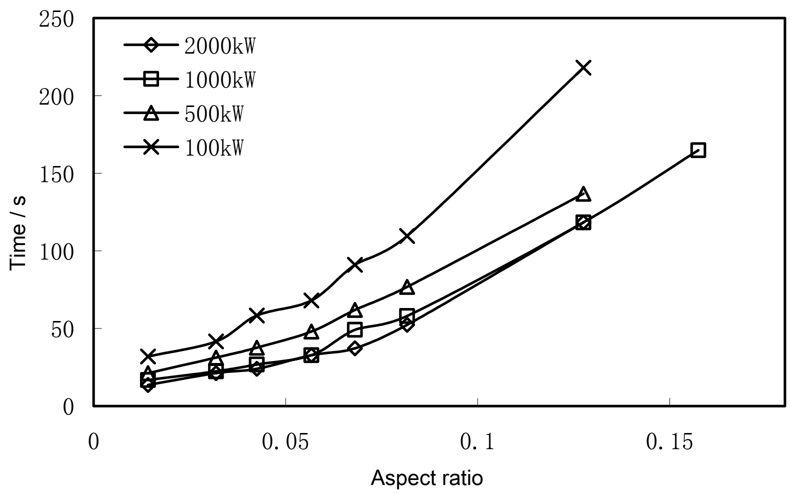


Fig. 5: Relation between the time when flooding flow occurred and γ_f of the atrium under different HRR of fire

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NOMENCLATURE

γ aspect ratio of an atrium, $\gamma = \frac{A}{H^2}$

γ_f aspect ratio of an atrium under fire, $\gamma_f = \frac{A}{H_f^{\ 2}}$

ρ density

a distance from the virtual source of a window plume to the suffit of the window, $a = 2.4A_w^{2/5}H_w^{1/5} - 2.1H_w$

A cross-sectional area of an atrium

A_w area of window

d plume diameter

h_s height of smoke layer in fire floor

H height of an atrium

H_f vertical distance from the centre of window of the lowest fire floor to the ceiling of atrium

H_w height of window

L_r maximum horizontal distance from atrium walls to the center of the vent open to atrium

P pressure

r plume radius

T temperature

z plume height

Z_w vertical distance from the centre of the vent to atrium floor

Subscripts

0 ambient

a atrium

I clear place if fire floor

S smoke in fire floor

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