Smoke Movement and Evacuation Time in the Arcade of a Traditional Market using Numerical Simulation

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Abstract

This study proposes to analyze the smoke exhausting performance and evacuation time in an arcade of a Korean traditional market. The effect of three types of ventilation opening on smoke exhausting performance was analyzed using the CFD (Computational Fluid Dynamics) method. The ventilation opening delayed the spread of smoke efficiently, and is an important design factor to control smoke movement in arcades. Also the evacuation time was analyzed according to the height of the building and increased significantly with the increase in the number of floors. Given the conditions of the study, the arcade building had to be less than three-stories considering the spread of smoke.

Keywords: traditional market; arcade; smoke movement; evacuation; CFD

1. Introduction

Since the Korean government started the campaign for improvement of cities in 2002, Korean traditional markets were renovated with arched roofs or streamlined surroundings as shown in Fig.1. The big changes in market appearance are intended to create a clean and more convenient marketplace regardless of weather conditions resulting in an improved image of traditional markets in Korea. The completed renovation of traditional markets however, proved ineffective in terms of air quality, thermal control and fire safety. Many traditional markets in Korea still lack emergency facilities and are hazardous when it comes to ensuring safety. These problems could result in a catastrophe if fire breaks out. To make matters worse, some markets block ventilation openings to maximize the greenhouse effect and to make the indoor area warm during the winter. Also, the risk of a bottleneck arises where shops are lined up on both sides of the road with a single exit facing the road. (Kim et al., 2003)

In the study, the authors concentrated on the ventilation openings in the arcade, giving attention to both a better indoor environment as well as fire safety. For thermal conditions and indoor air quality in the arcade buildings, Kaynakli et al. (2005) and Edmonds et al. (1997) asserted that thermal stress from the roof is a major factor causing indoor temperature to rise, and making it difficult to control. Tsujihara et al. (2004) reported that the amount of reflected sunlight induced a rise in indoor temperature in traditional markets in Japan. They also stressed that indoor temperature can be controlled by making the ventilation openings more effective. The ventilation openings in the arcades are also expected to exhaust smoke efficiently and to reduce smoke concentration in the event of fire. Ding et al. (2004) investigated the natural ventilation system for smoke control through experiments and CFD simulation. Qin et al. (2006) studied the performance of different smoke exhaust methods in a gymnasium, and found that the natural exhaust system was an effective method to control the spread of smoke. All these studies however, concentrated on evaluating the smoke diffusion time, and were not connected with the evacuation time from the buildings.

This study evaluated the smoke control performance of ventilation openings in the event of fire in arcade-type traditional markets. Also, smoke diffusion and evacuation times were analyzed with numerical

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The computational fluid dynamics (CFD) method was used to analyze the distribution of smoke caused by fire and the diffusion speed of smoke with time.

Secondly, evacuation times were estimated for occupants in buildings having three different floors by using the evacuation simulation program. These results could be used to provide effective design guidelines for ventilation openings in arcade-type markets.

2. Basic Market Model

Arcade-type markets differ according to the shapes of the roofs, width of the roads, height of the buildings, etc. in Korea. The most common arcade-type market was built to analyze the smoke movement and the evacuation time as shown in Figs. 2 and 3. The model was optimized based on the typical or average conditions of 10 traditional markets (Kim et al., 2003). The width and height of the model is 8m and 4.5m, respectively. A vault-type roof was installed at the center with a ventilation opening. There are four two-story buildings with widths of 10m, length 25m and height 5.5m around the central arcade. In the simulation, ventilation is achieved through the ventilation opening and the entrance to the central arcade. According to a survey of 10 traditional markets in Seoul, Korea, two-story buildings and three-story buildings constituted 31.2% and 36.5% of the total buildings respectively. Single story buildings and four-storied buildings made up 22.9% and 9.5%, respectively. The basic simulation model is designed using a two-story building. But evacuation simulation was conducted in three-story and four-story buildings as well. CFD simulations of smoke movement were conducted using the two-story building model only, because three floors or more would have no significant impact on the assessment of smoke ventilation produced by the ventilation openings considering the height of the building.

3. CFD Based Analysis of Smoke Movement

1) Overview of simulation

The spread of smoke inside the arcade was simulated and analyzed using the CFD method. It is important to use a proper CFD model in accordance with flow characteristics and conditions.

The incompressible turbulence model (e.g. the standard k-ε model) is commonly used in the architectural field to demonstrate air circulation and temperature distribution because spatial temperature...
distribution is not huge. The incompressible turbulence models are inappropriate to analyze the movement of smoke because of the big buoyancy effects.

Ding et al. (2004) and Qin et al. (2006) showed the reliability of CFD simulation when compared with the experimental methods. Many kinds of turbulence models could be used for fire simulation. LES (Large Eddy Simulation) became prevalent with the development of computer performance (Qin et al., 2006; McGranttan et al., 1998). The k-ε model also was considered proper for fire simulation. Chow and Yin (2004) compared the results between the k-ε model and other turbulence models and concluded that the former was still practical for simulating smoke movement in a short time. The results of the k-ε model and the experimental methods were compared by Ding et al. (2004), Chow and Yin (2004).

In the study, the compressible k-ε model was used to analyze air movement caused by fire.

2) Input conditions

① Boundary conditions

The area extending as far as 30m above the arcade building in Fig.2. was defined as the calculation area for the CFD simulation. All surfaces of the domain excluding the ground were defined as the pressure boundary conditions. Air temperature and smoke concentration in the inflow air at the pressure boundary surface were 20°C and 0ppm, respectively. Considering the small impact on air flow and smoke movement compared to the heat from the fire, solar heat gains and internal heat gains from occupants and equipment were not considered in the simulation.

Since no wind condition is used in the simulation, air movement is derived by buoyant force only. It was assumed that fire broke out in the central floor region of a shop next to the entrance of the arcade as indicated in Fig.3. Air movement was produced by the buoyancy of the fire only, because the wind condition was not considered. The size of the fire source was 2m × 2m. The simulation domain was divided into about 60,000 cells. Unsteady-state simulation was carried out for five minutes with a time step of 0.05 seconds after the fire broke out (total 6,000 steps).

② Heat and combustion gas conditions

Amounts of heat and combustion gas depend on the type of fuel and surrounding conditions (Kumar and Rao, 1995). Since a fire can erupt for different reasons in markets, it is difficult to estimate the amount of heat and combustion gas in advance. Since the study aims to provide design guidelines for arcades, the speed of smoke spread and the relationship between smoke diffusion time and evacuation time, the growth of a fire is simply modeled here. The t²-type of heat growth model for the fire simulation was used (NFPA, 2005).

As shown in the two equations above, complete and incomplete combustion occur in the ratio of 8:2. Under the assumptions that H₂O and CO₂ are released as a product of complete combustion and that high concentration of CO₂ is dangerous, both complete and incomplete combustion gas were included in the simulation. It was assumed that the amount of heat remained steady after it continuously increased as time

\[ q = at^2 \]

\[ q: \text{Rate of heat release [kW]} \]
\[ a: \text{Constant governing the growth speed (0.04689) [-]} \]
\[ t: \text{Time [sec]} \]

\[ Q_G = 0.721m + 1.127n + a(3.98m + 2.04n) \]

\[ Q_G: \text{Amount of combustion gas [m}^3/\text{kg]} \]
\[ m: \text{Complete combustion efficiency (=0.8) [-]} \]
\[ n: \text{Incomplete combustion efficiency (=0.2) [-]} \]
\[ a: \text{Excess air ratio (=2.0) [-]} \]
Fig. 5. Temperature Distribution with Time (Section of Arcade)

(a) Case 1 (0% of Ventilation Opening)

(b) Case 2 (50% of Ventilation Opening)

(c) Case 3 (100% of Ventilation Opening)
Fig. 6. Concentration of Smoke Distribution with Time
(The parts without color are the spaces under the smoke concentration of 10,000ppm)
Three minutes from outbreak of the fire, the smoke spread were not different in Cases 1, 2 and near the shop where fire broke out. Until the first 2 minutes, compared to those in Cases of smoke diffusion was faster in Case 1 which had with no color; spaces under a smoke concentration of 80% of Case 1, the high concentration area was very narrow. If the occupants could escape within 3 minutes, the ventilation opening could be an effective design element to reduce casualties during fire outbreaks in the arcade. Thus the ventilation openings can eliminate smoke and effectively reduce smoke diffusion.

4. Evacuation Time Analysis

1) Evacuation simulation

There are many numerical simulation methods to evaluate evacuation time (Gwynne et al., 2001; Pires, 2005; Lo et al., 2004). The SIMULX was one of the most successful programs (Tompson and Marchant, 1995). The program holds the advantage of real-time monitoring of the evacuation process by the position, direction and walking speed of people for every 0.1 second. It is therefore used widely in the field of fire safety engineering and crowd management. In the study, the SIMULX program was used to analyze the evacuation process in the arcade.

2) Input conditions

The floor model used for evacuation simulation is shown in Fig.3.(b). The population density was assumed to be 0.25 person/m² to demonstrate a crowded state. Although walking speed varies with gender, age and health status, a speed of only 1.4m/s was used to eliminate any differences that might be caused by these conditions. A typical walking speed ranges from 0.75m/s to 1.2m/s. This study used a rather faster walking speed than general speed considering the special circumstances. In the building, occupants had to use the stairs for the escape. The final escape path was the road of the arcade. During the evacuation process, occupants tried to choose the nearest escape path. Evacuation time was simulated on the two-story, three-story and four-story buildings under the same conditions described above.

3) Results of evacuation simulation

An occupant evacuation profile in the two-story building is presented in Fig.7. As fire broke out, occupants began to evacuate through the nearest exit. It took 1 minute and 24 seconds on average for evacuation of the two-story building, and 2 minutes and 39 seconds, and 5 minutes 40 seconds in the case of the three-story and four-story buildings respectively. (Fig.8.) Evacuation time significantly increased as the number of floors increased. Those from the four-story building required twice as much time to escape as those from the three-story building, because many people tried to escape using the narrow stairs simultaneously. The four-story building in the arcade had a high risk of damage in the fire. The delay in evacuation time could
become more serious in the case of a higher number of people. A proper evacuation plan for taller buildings is therefore required.

5. Relationship Between Smoke Diffusion Time and Evacuation Time

The big fire disasters, including the 1999 fire accident in the Mont Blanc tunnel in France, the fire in a mountain tunnel in Austria in 2000, the 1997 fire in the Daeyeongak Hotel and the 2003 fire in the Daegu Subway in Korea, were characterized by a large number of deaths caused by toxic gas. The arcade buildings should be designed to preempt and minimize gas casualties during evacuation.

It was found in the analysis of the distribution of smoke that ventilation openings could significantly delay the spread of smoke. With ventilation openings measuring 50% and 100%, smoke could be effectively removed and wide spread smoke prevented.

Without ventilation openings, smoke can spread over a wide area 3 minutes after the outbreak of a fire. Evacuation could take time in tall buildings; more than 5 minutes from the four-story building in the case studied above. The risk of gas casualties is therefore higher in taller buildings. Under the conditions of the study, ventilation openings were necessary in the arcade. Also the arcade building had to be less than three-stories. This study emphasizes the installation of ventilation openings and a proper evacuation plan in traditional markets.

6. Conclusion

This study aimed at providing effective design information for ventilation openings in arcade-type markets by evaluating the smoke control performance of ventilation openings and analyzed safety by comparing smoke diffusion time with evacuation time from three buildings having different heights. The following conclusions were provided based on the analysis of simulations demonstrating smoke diffusion and evacuation in the event of fire in arcade-type traditional markets:

(1) Traditional markets that were remodeled into arcades are considered semi-open marketplaces but have a high risk of high smoke concentration in the event of fire, due to ineffective ventilation openings.

(2) The ventilation opening was highly effective in delaying the spread of smoke caused by fire. Without a ventilation opening, smoke spread over a wide area 3 minutes after the outbreak of fire. Smoke control performance of ventilation openings was therefore crucial to fire safety in those markets.

(3) This study found that evacuation time increased significantly in tall buildings. Evacuation took 1 minute and 24 seconds from the two-story building, 2 minutes 39 seconds from the three-story building and 5 minutes and 40 seconds from the four-story building.

(4) Given the conditions of the study, ventilation openings were deemed necessary for arcades, which had to be less than three-stories.
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