Safety Science 55 (2013) 17–25

Contents lists available at SciVerse ScienceDirect

Safety Science

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

An experiment and simulation of smoke confinement and exhaust efficiency utilizing a modified Opposite Double-Jet Air Curtain

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ARTICLE INFO

Article history:
Received 8 August 2012
Received in revised form 17 October 2012
Accepted 7 December 2012
Available online 31 January 2013

Keywords:
High-rise building fires
Opposite Double-Jet Air Curtain
Smoke
Confinement
Exhaust

ABSTRACT

Fires in high-rise buildings often result in tremendous property losses and heavy casualties. Smoke has been reported to be the main cause of these casualties. A modified Opposite Double-Jet Air Curtain (ODAC) is introduced in order to confine smoke movement and to exhaust smoke during a high-rise building fire. Here, a study including an experiment and a numerical simulation, was performed to determine the efficacy of a modified ODAC. The experiment was conducted on a 1:12 scale model of a high-rise building. A complementary Fire Dynamics Simulator (FDS) simulation was conducted on a full scale building. The influences of the air curtain discharge velocity and heat release rates (HRRs) were examined.

The results of this study show that given the same supply air volume and HRR, the carbon monoxide (CO) concentration with the ODAC is clearly lower than the levels found with a traditional air curtain in a high rise building fire. The gas temperatures in the hallway increased significantly with the increase of HRR, and when the HRR reached 1.5 MW or more, a significant increase in the temperature of the smoke in the stairwell entrance was observed. When HRR reaches 2 MW, and the velocity has increased to 9 m/s, the CO concentration in the entrance of stairwell just meets the minimum Safety and Health standards.

1. Introduction

Huge numbers of people rushing into metropolitan areas result in enormous demands for floor space (Ma et al., 2012), causing an ever-increasing demand for residential space in high-rise buildings. These building have some prominent characteristics, such as larger residential capacity and few exits to the outside. In the past few years, fires have caused tremendous loss of life and property, and have occurred very frequently (Zhong et al., 2004). In 1996, for example, fire broke out in Hong Kong's Garley Building, resulting in the deaths of forty people, and an additional 81 injuries in the fire. On February 9, 2009, CCTV North Side Building, in Beijing, experienced a fire which lasted 6 h, resulted in one death, seven injuries and several billion Yuan in damages (Hou et al., 2011). According to fire statistics, about 60% of accidental fires occur in buildings, especially in high-rise buildings. Over a period of 3 years, there were 41 accidental fires in 115 buildings in America. Smoke is a major cause of fire-related deaths, and is the most fatal factor in a fire (Cox and Kumar, 1992; Besserre and Delort, 1997). Statistical data shows that 85% of the people killed in building fires are killed by toxic smoke (Hietaniemi et al., 1999; Hu et al., 2008). Once a fire is detected in a typical high-rise building, elevators are closed and the stairways become one of the most important emergency accesses during the emergency. The evacuation performance of a stairwell is thus extremely important for the safety and lives of the building occupants in an emergency (Fang et al., 2012). At the same time, the stairwell is often one of the main conduits for the spread of smoke. Smoke released during the fire can migrate along the roof and then buoyancy forces can drive it into the upper floor. Once smoke spreads into the stairwell, it decreases visibility, which is also very bad in an emergency. Thus, it is critical to prevent toxic smoke from spreading into stairwells.

Many studies have been conducted to investigate high-rise building fires. Miller and Beasley (2009) studied the stack effect and pressurization systems for stairwells designed to prevent smoke from spreading into the stairwell. A thirty story building model was researched utilizing CONTAM simulation software. Stairwell pressurization was found to be completely feasible, and the impact of different locations, louvers and vents was examined to achieve optimal pressurization. Tamura (1989) analyzed stair pressurization systems for smoke control. Their test was conducted in a 10 story experimental fire tower. Unfortunately, during their research, they simplified the models and some of the simplified conditions are unrealistic. Furthermore, the volume of the supplied air was not specified. If the system becomes over-pressured, it can be disastrous for the occupant's safe evacuation.

Air curtains have now become the main approach used to prevent smoke from spreading during fires. They are easily installed and useful when it is desirable to separate two contiguous areas,

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http://dx.doi.org/10.1016/j.ssci.2012.12.002

Nomenclature

D_i	diffusion coefficient of each of the elements
H	height of the model
f	external force
g	acceleration of free fall
L	length of the model
m_i	generation mass of one of the elements
P	pressure
t_A	the highest smoke temperature of the 13 points in the thermocouple tree, in position *A*
t_B	the highest smoke temperature of the 13 points in the thermocouple tree, in position *B*
t_C	the highest smoke temperature of the 13 points in the thermocouple tree, in position *C*
t_{en}	the highest smoke temperature of the 39 points in the entrance of the stairwell
$\vec{u}$	velocity of the air
V	discharging velocity
W	width of the model
Y_i	mass fraction of one of the elements
Greek letters	
α	physical dimension between the model and the actual design
ρ	air density
τ	time
Δ	Laplace operator
$\vec{\tau}$	viscous force
Abbreviations	
CO	carbon monoxide
Fr	Froude number
HRR	heat release rate (kW)
ODAC	a modified Opposite Double-Jet Air Curtain
Re	Reynolds number

while permitting occupants to move (Loubiere and Pavageau, 2008; Lecaros et al., 2010a). Hu et al. (2007, 2008) studied the confinement of fire-induced smoke and carbon monoxide movement with an air curtain in a channel. During their research, bench scale experiments were carried out in a 3.6 m model channel, along with complementary numerical simulation of an 88 m, full scale channel, utilizing a Fire Dynamics Simulator (FDS). The results showed that smoke released by the fire was well confined, remaining largely in the region of the channel near the fire, at one side of the air curtain. Elicer-Cortes et al. (2009) and Lecaros et al. (2010b) studied heat confinement in a tunnel between two double – stream twin – jet air curtains. Fluid dynamics simulations and experiments were conducted and the results of the 2D and 3D simulations were compared. Goncalves et al. (2012) researched aerodynamic sealing through the use of vertical and horizontal air curtains. They conducted a 3D numerical study that compared the sealing efficiency of doorways connecting two rooms that were at different temperatures. Their research showed that the air curtain was useful in sealing heat flow. Unfortunately, the scenarios tested did not include a stairwell in a high-rise building fire. Due to the specificity of a stairwell, the efficacy of an air curtain, when installed in a stairwell, remained unclear.

Based on the above analyses, we know that air curtains are useful for smoke isolation. Based upon the characteristics of a traditional air curtain system for a high-rise building, a modified Opposite Double-Jet Air Curtain (ODAC) was proposed. Experiments and numerical simulations were performed in this study to determine whether ODAC is useful in confining smoke movement, in order to keep stairwells free of smoke and exhaust during a high-rise building fire. The experiment was carried out on a 1:12 scale model high-rise building, with photographs taken to observe and record the spread of the smoke. Comparisons were made of the highest smoke temperatures, as measured by thermocouple trees, with the ODAC set-up, and without the air curtain set-up. Complementary fluid dynamics simulations were carried out with a Fire Dynamics Simulator (FDS) on a full scale building, in order to check the experimental accuracy and to further examine the effects of different discharge velocities and heat release rates (HRRs).

2. Experiment

2.1. Experiment similarity theory

Usually, experimental models are smaller than the actual designs, and the laboratory or experimental results are not necessarily found to be reliable. Once similitude is achieved, then the experimental results are known to be applicable to the actual design (Li et al., 2010). Similitude means that these three requirements have been met:

- Geometric similarity – the model and the real design have the same shape, angle and ratio of geometrical scale for each part.
- Kinematic similarity – the velocities of points in the model and the corresponding points in the real design have the same directions and the ratio of the velocities is the same.
- Dynamic similarity – the ratio of the dynamic parameters of the points in the model and the corresponding points in the real design are constant.

In reality it is quite difficult to achieve strict similitude during an experimental model. In practice, then, we often neglect some aspects of similitude, and focus on the most important parameters (Li and Lei, 1999). In this experiment, the two numbers Re and Fr, are very important in the simulation of fire-induced transportation of smoke. Re and Fr should be the same for both the model and the actual design during the experiment, which is very difficult to achieve. According to previous research, when the Re number was large enough to keep fluid moving in the area of self (Markatos, 1986; Heskestad, 1972), it was not important that the Re number was the same for both the model and the actual design. So when the fluid moving is in the area of self, the Fr number is more important. The geometrical scale α is the ratio between the model's dimensions and the actual dimensions. Based on similarity theory and consideration of the bench and previous studies, we determined that the ratio of the model to the actual size should be 1–12. According to similarity theory, the other parameter ratios between the model and actual design are shown in Table 1.

2.2. Experiment model

Our research purpose is to check the efficacy of the ODAC and observe if there is smoke in the stairwell once one floor is on fire, so there is no need to study an entire high-rise building, when one part of a floor is enough for our research, as presented in Fig. 1. The stairwell model was made of transparent plexiglas, to facilitate clear observation of any movement of the smoke. The model was a reduced-scale approximate replica of an actual building. The model consisted of two main sections, the stairwell and the hallway. The stairwell had a two-way stairs, with dimensions of: