Chinesisch-Deutsches
Zentrum für
Wissenschaftsförderung

中德科学中心

Progress in Fire Science

First Seminar on Fire Science Between China and Germany

Edited by Fan Weicheng
Yang Lizhong

SCIENCE PRESS
www.sciencep.com

Progress in Fire Science

First Seminar on Fire Science Between China and Germany

Edited by Fan Weicheng
Yang Lizhong

SCIENCE PRESS
Beijing

Responsible Editor: Hou Junlin, Wang Jian

图书在版编目(CIP)数据

火灾科学进展 = Progress in Fire Science: 英文/范维澄, 杨立中主编. -北京: 科学出版社, 2007
(中德科学会议文集)
ISBN 978-7-03-019559-3

I. 火… II. ①范…②杨… III. 消防-文集-英文 IV. TU998.1-53

中国版本图书馆 CIP 数据核字 (2007) 第 120754 号

Progress in Fire Science

Published by Science Press
16 Donghuangchenggen North Street
Beijing 100717, China

Printed in Beijing

ISBN 978-7-03-019559-3
RMB 68.00

Preface

The loss caused by fire increases year by year. In the new era of fire safety engineering international exchange and cooperation are essential for fire safety communities, through which resources, experience and research results can be shared upon mutual interest and benefit.

The first joint seminar on fire science and engineering between China and Germany was held in Institute of Fire Department Saxony-Anhalt, Heyrothsberge, Germany, on November 11-18, 2003. 32 scientists and engineers from China and Germany were invited to attend the seminar and 24 papers were chosen to be presented in the seminar. The researchers from China and Germany reported their latest development and experience in fire safety science, engineering and management. All participants, both speakers and audiences, have enjoyed and benefited from the presentation and discussions in the seminar.

This seminar was sponsored by Sino-German Center for Research Promotion of DFG and NSFC. We deeply appreciate their supports.

Fan Weicheng
State Key Laboratory of Fire Science, USTC
Reinhard Grabski
Institute of Fire Department Saxony-Anhalt, D-39175, Heyrothsberge
2004-7-28

Contents

Research on Backdraft in China—A Review

Fan Weicheng , Weng Wenguo
State Key Laboratory of Fire Science, University of Science and Technology of China,
Jinzhai Road 96, Hefei, Anhui, P.R. China, 230026

Abstract Backdraft has the characteristics with abrupt occurrence and powerful destruction, which may cause the death of people in situ and the collapse of building. And so in the past years, researchers in China have further studied backdraft, and in this paper, some fruitful research results including experimental and numerical results are presented. A reduced-scale backdraft experimental apparatus was established, with which, critical condition of backdraft, effect of different opening geometries and mitigation method of water mist for backdraft were studied. Experimental and numerical studies on salt water modeling of gravity current prior to backdraft were conducted. In addition, catastrophe mechanism of backdraft was investigated and nonlinear dynamical model of backdraft was established.

Keywords backdraft, fire, China

1. Introduction

A backdraft can develop from fires of either ordinary combustibles or ignitable liquids that become oxygen starved yet continue to generate a fuel-rich environment in a limited-ventilation building. If the fresh air is allowed to flow into the vitiated space, such as by opening a door or breaking a window, a ***gravity current*** of colder air will flow into the space while the hot fuel-rich gases flow out through the top of the opening. The air and fuel-rich gases will mix along the interface of the two flow streams. Once a localized flammable mixture is formed and in contact with an ignition source, the fuel-rich gases will combust acutely, the temperature will rise rapidly and the initial fire stage will develop into flashover or deflagration. The deflagration will cause the gases to heat and expand within the fire space, thus force unburned gases out of the opening ahead of the flame front. These gases will mix with additional air outside of the fire space. As the flame traverses the building and penetrates the doorway, it ignites the gases outside the space resulting in a fire ball and a blast wave. Apparently, the occurrence of backdraft is a hazard that may cause the death of people in situ and the collapse of building[1]. So to determine the ***critical conditions*** and the ***mitigation methods*** is an important task for fire researchers.

Little research has been done on backdraft worldwide. Fleischmann[2~5] conducted experiments in a half-scale compartment with two opening geometries and methane as fuel. Full-scale experiments have been conducted by Bolliger[6] to determine the effect of scaling the compartment; the results were compared with Fleischmann's work[2]. Gojkovic *et al.*[7] used natural gas as fuel to study backdraft in a compartment (5.2 m×2.2 m×2.2 m). Full-scale backdraft experiments have also been performed[8~10] in two different compartments to improve naval firefighting tactics using Diesel spray as fuel. One compartment was used to produce safe and reliable backdraft scenarios, which could be used as a basis for conducting backdraft experiments onboard a ship. Another compartment with different geometries and ventilation conditions was adjacent to the backdraft compartment. They[8~10] also tried to prevent backdraft using a water spray. However, the knowledge is still not enough to understand backdraft despite of the backdraft researches mentioned above.

Researchers in State Key Laboratory of Fire Science, University of Science and Technology of China have further studied backdraft in the past years, and in this paper, some fruitful research results are presented. In the following section, experimental study on backdraft is described. Section 3 gives the numerical study, followed by concluding remarks and future work.

2. Experimental Study on Backdraft

2.1 Experimental design and procedure

The configuration of the apparatus is given in Fig. 1. The apparatus is made up of a reduced-scale compartment, fuel system, water mist system, ignition system, data acquisition system.

The reduced-scale compartment, limited to 1/4 residential room (1.2m×0.6m×0.6m), was designed and constructed to safely control the dangerous overpressures expected in backdraft. In one of the short walls and ceiling, blot holes were built so that various opening geometries, shown in Fig. 2, could be easily modified by replacing a face plate bolted to the compartment. These end and ceiling opening geometries were covered with a computer activated hatch, which was opened after the fire had been burning for the predetermined time. Every effort was made to seal all construction holes to control leakage. Fuel system includes a methane (99.8% pure) burner, 0.15m square and 0.15m

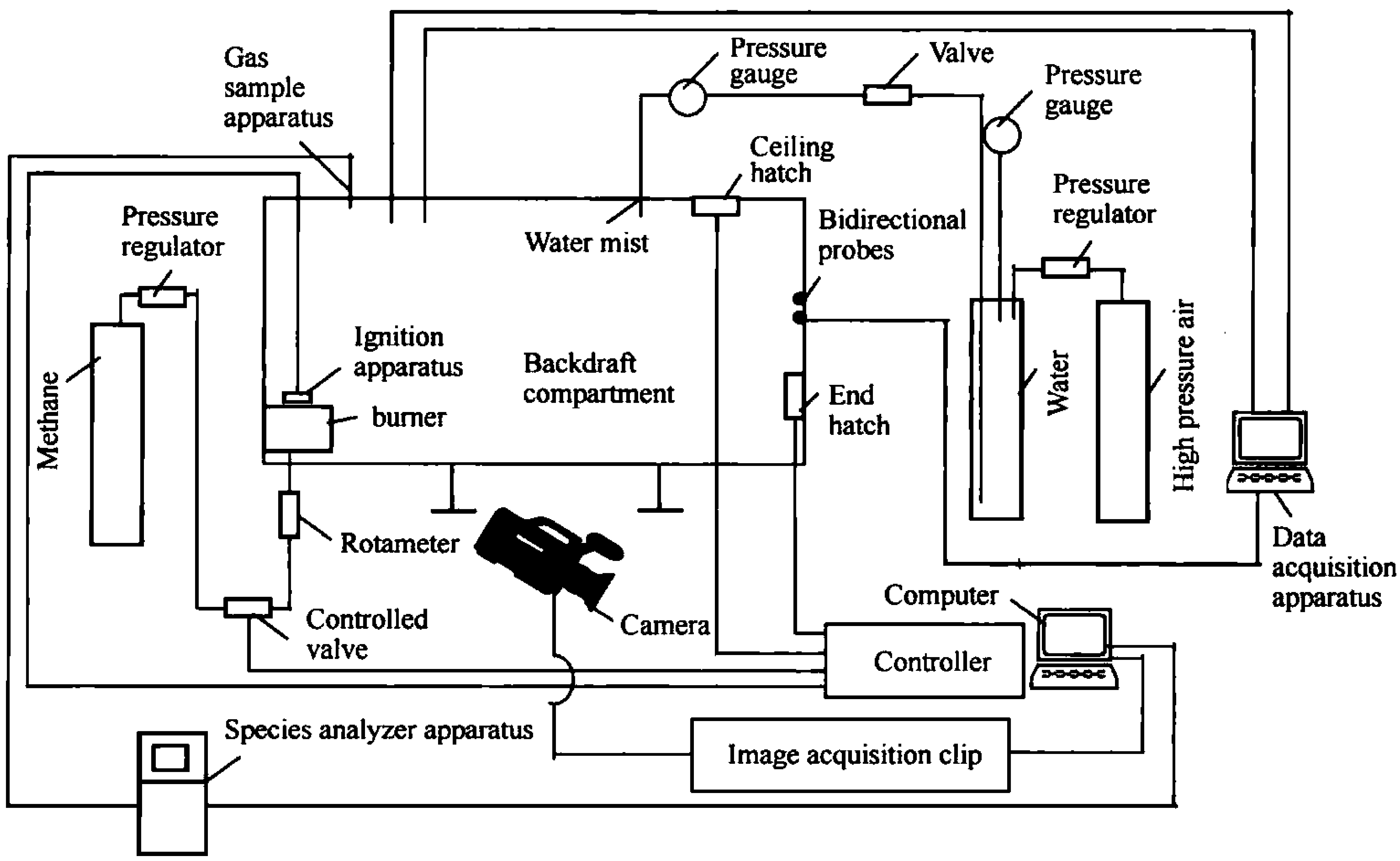

Fig. 1 Schematic of the experimental apparatus

high and placed against the wall opposite the end opening, a rotameter with an effective range of 160 to 1600 L/h, a controlled valve, a pressure regulator and methane tank. Water mist system is made up of a downward-directed pressure nozzle 212.285 (from Lechler GmbH & Co. KG), two pressure gauges, a valve, a pressure regulator, a water tank and a high pressure air tank. The nozzle was positioned 0.3m from the end opening wall, 0.078m from the ceiling, and 0.3m from the side wall with the observation window. Ignition system is an electrically heated metal wire with 1200W power. The wire was 0.6m long and circled around a 0.05m diameter ceramic cylinder, which was horizontally fastened on the burner.

Data acquisition system is made up of data acquisition units (including a HP E1413 and a Panasonic DS28 camera), and various instruments to measure temperature, compartment pressure, species concentration and opening flow mass. A vertical thermocouple tree, made from 0.2 mm type K thermocouple wire with a stainless steel overbraid, was placed in the middle of the ceiling. The average bead diameter was 1mm. The ten thermocouples were located at 0.05 m intervals, with the highest thermocouple at 0.075m below the ceiling. The compartment pressure history was recorded using an electronic pressure transducer whose calibrated range was −150 to 300 Pa. The pressure pot was placed 0.3m from the end opening wall and mounted in the wall opposite the observation window at floor level. Gas concentrations measured were oxygen, carbon dioxide and carbon monoxide. Continuous gas samples were taken with stainless steel probes. The probes were located 0.9m from the end opening wall, 0.1m from the ceiling, and 0.1m from the side wall with the observation window. Analyzers consisted of SIEMENS ULTRAMAT 23 for carbon dioxide (25% mass full-scale range), oxygen (25% mass full-scale range) and SIEMENS ULTRAMAT 22 for carbon monoxide (3% mass full-scale range). These data were collected at rate of once per second. Fuel mass (CH_4) could be calculated based on a chemical reaction equation. The flow in and out of the compartment after the hatch was opened was recorded using bidirectional probes, 15mm in diameter, in the opening. The probes were located in the horizontal center of the opening and 37.5 mm apart for all of the opening geometries except the vertical middle-slot end opening, where the probes were 75 mm apart, and the top and bottom probes were 37.5 mm from the soffit and sill, respectively. The pressure difference of the probe was measured using a differential pressure transducer which had a calibrated range of ±300 Pa. The total mass flow was calculated by integrating the velocity and density profiles over the height of the opening as[2].

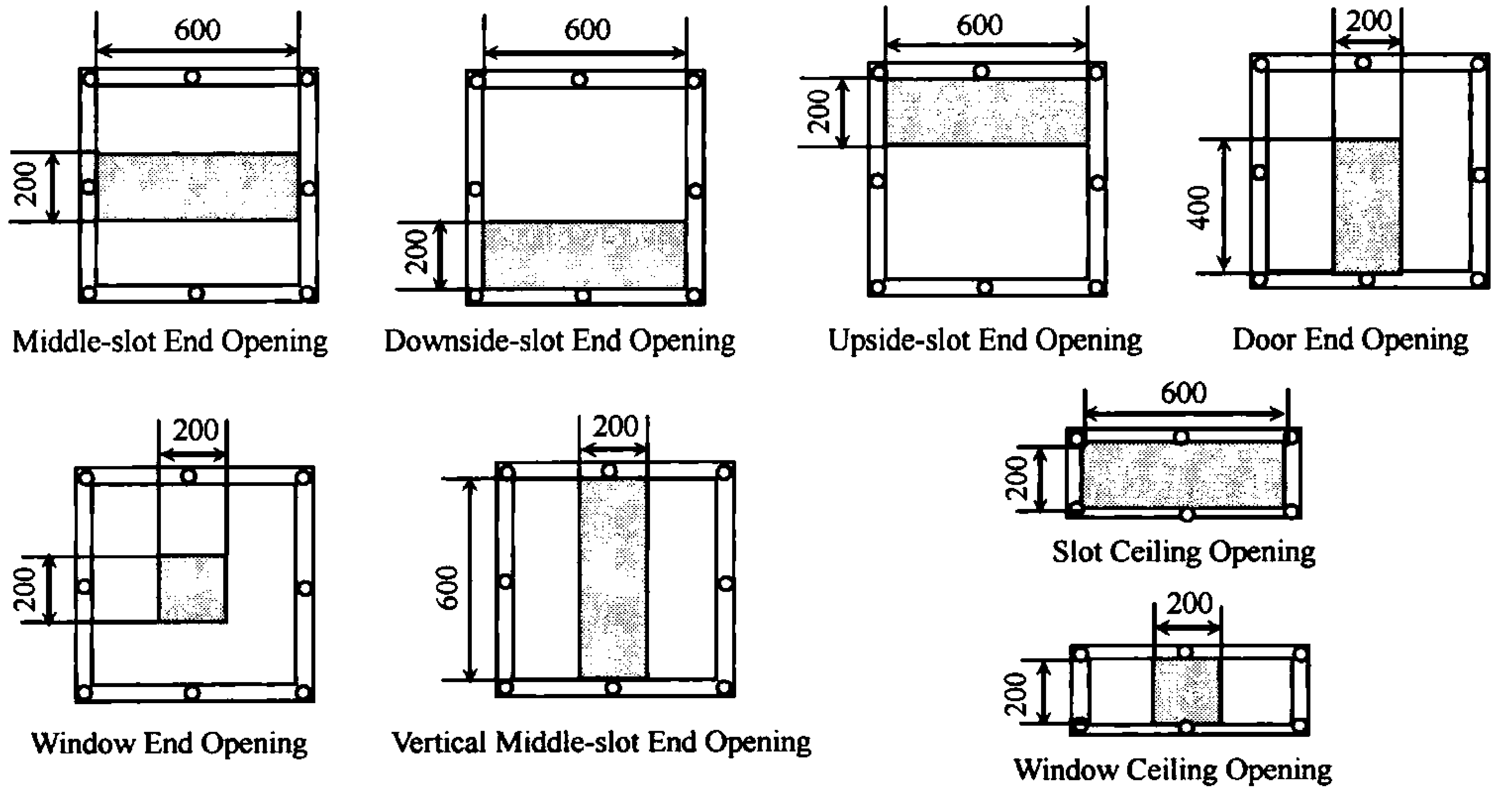

Fig. 2 Sketch of eight opening geometries for the reduced-scale compartment

Before each experiment, a 60 s base line was taken to record the initial conditions. The burner was left on and the flame was ignited using the electrically heated metal wire before the start of the experiment. At 0 s, the hatch was closed. After a predetermined time

Table 1 Summary of the backdraft experiments in the reduced-scale compartment with vertical middle-slot end opening

Run Number	T_a /K	Fuel Flow Rate /(10^{-3} kg/s)	Burner Flow Time /s	Species Concentration /%				Compartment Temperature /K and Layer Height (m)			P_{max} /P	Opening Flow Mass /kg				Fire Ball /m	
				Y_{O_2}	Y_{CO_2}	Y_{CO}	Y_F	Y_U	Y_L	h_L		$m_{in}^{t=t_i}$	$m_{out}^{t=t_i}$	$m_{in}^{t=t_{fo}}$	$m_{out}^{t=t_{fo}}$	Length	Height
The end opening geometries																	
Middle-slot opening																	
1	295	0.2340	140	14.6	0.5	0.32	5.73	375	326	0.28	0.66	0.233	0.077	0.243	0.285	nonoccurrence	
2	296	0.2385	160	13.5	0.2	0.40	6.72	388	344	0.27	0.97	0.107	0.046	0.107	0.122	nonoccurrence	
3	297	0.1553	260	14.5	0.3	0.25	7.15	394	352	0.26	1.01	0.137	0.049	0.137	0.170	nonoccurrence	
4	296	0.2399	180	13.6	1.0	0.38	7.29	378	335	0.27	1.26	0.231	0.191	0.239	0.258	nonoccurrence	
5	297	0.1606	320	14.3	0.7	0.23	8.86	389	349	0.30	1.46	0.039	0.009	0.039	0.251	nonoccurrence	
6	296	0.1589	360	14.4	0.4	0.45	9.76	402	353	0.28	2.74	0.025	0.025	0.025	0.253	nonoccurrence	
7	296	0.2389	240	14.5	0.2	0.30	9.94	386	347	0.26	4.31	0.074	0.068	0.074	0.324	0.62	0.88
8	297	0.1583	480	14.6	2.1	0.12	12.2	376	340	0.28	7.79	0.149	0.070	0.149	0.173	0.93	0.90

period (the flow time of the fuel), the gas flow to the burner was terminated immediately when the hatch was opened. During this time period, if water mist was used to mitigate backdraft, a known amount of water mist was injected into the compartment and allowed to vaporize and mix with the gases. And then the fire would be from combustion to extinction due to insufficient oxygen. After the hatch was opened, the metal wire would ignite the combustible mixture in the compartment if ignition was reached. At the end of the experiments, the metal wire was taken off.

2.2 Critical condition of backdraft

In order to study the critical condition of backdraft, a series of experiments were conducted[11]. Table 1 is a summary of the 8 backdraft experiments in the reduced-scale compartment with vertical middle-slot end opening. From Table 1, it is the first view that the relationship between the mass fractions of O_2, CO_2 and CO, upper temperature, lower temperature and layer height, opening flow mass and the occurrence of backdraft are fuzzy. So these parameters are not the key parameters determining the occurrence of backdraft. Table 1 and Fig. 3 indicate that the fuel mass fraction is the key parameter determining the occurrence of backdraft. Fig. 3 shows the fuel mass fraction, in which the solid symbol means the nonoccurrence of backdraft and the hollow means the occurrence of backdraft, and the dash line is the estimated critical value (i.e. 9.8) of fuel mass fraction determining the occurrence of backdraft. When the mass fraction of fuel at opening exceeds the critical value, backdraft will take place. Further more, the peak pressure and size of the fire ball increase with the fuel mass fraction from Table 1. So the more fuel mass fraction, the more intensity of backdraft.

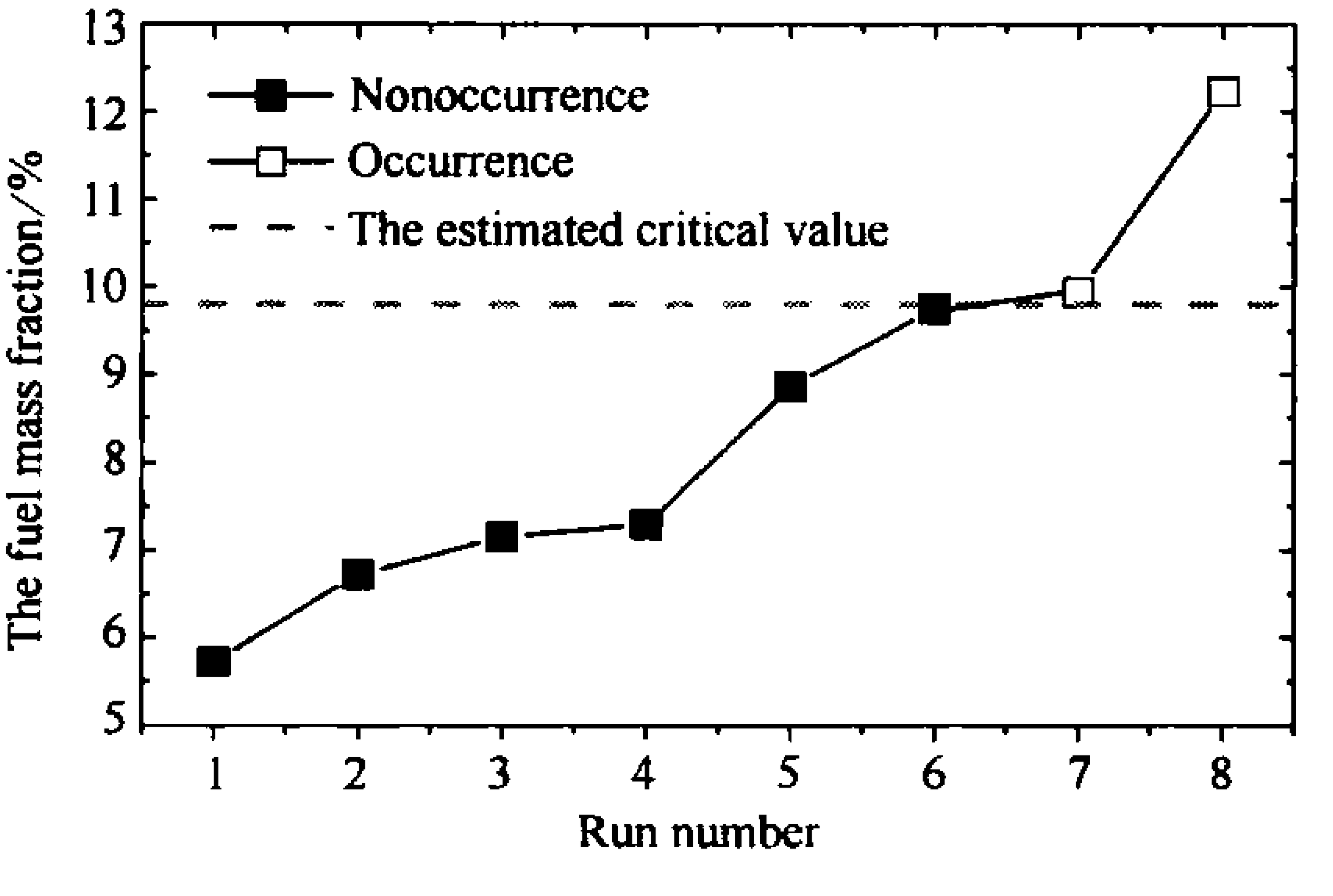

Fig. 3 Figure of the fuel mass fraction. The solid symbol means the nonoccurrence of backdraft and the hollow means the occurrence of backdraft. The dash line is the estimated critical value of fuel mass fraction determining the occurrence of backdraft

2.3 Effect of different opening geometries

Comparing the different opening geometries, the critical values of the fuel mass fraction are different[12]. Table 2 gives the corresponding estimated critical values for the occurrence of backdraft. These differences for eight opening geometries are the area of the opening and its location. From Table 2, the first impression is that the critical values of the ceiling openings are lower than for the end openings. Among the middle-slot end opening, the downside-slot end opening, the upside-slot end opening and the slot ceiling opening, whose open area are the same, but locations are different, the critical value for the slot ceiling opening is the lowest and that of the downside-slot end opening is the highest. The higher the location of the center of the openings, the same location of its center, the critical value of the fuel mass fraction is lower. The same conclusion is also drawn from comparing the slot ceiling opening and the window ceiling opening. But the critical values for the window end opening and the vertical middle-slot end opening, whose location centers have the same location, are approximately the same, in spite of the different open areas. The critical value for door end wall is lower than that for the window and the vertical middle-slot end opening.

Table 2 The estimated critical values of the fuel mass fraction determining the occurrence of backdraft for eight different opening geometries

Openings	Critical values /%
Middle-slot end opening	8.5
Downside-slot end opening	9.0
Upside-slot end opening	7.1
Door end opening	8.8
Window end opening	9.8
Vertical middle-slot end opening	9.8
Slot ceiling opening	7.0
Window ceiling opening	7.7

2.4 Mitigation method for backdraft

In order to study the mitigation method of backdraft, a series of experiments using water mist were conducted[13~14]. Table 3 is a summary of experiments with and without water mist in the reduced-scale compartment with the door end opening geometry. Column 5 and 6 describe water mist parameters, i.e. injection time and mass. In column 5, "30～50" means water mist was injected from 30s to 50s, and blank means no water mist was injected.

Table 3 Summary of experiments with and without water mist in the reduced-scale compartment with the door end opening geometry

Run	T_a / K	Fuel flow rate / (10^{-3} kg/s)	Burner time /s	Water mist		Species concentration at the time hatch opened /%				Compartment temperature /K and layer height /m			P_{max} /P	Fire ball /m	
				Time /s	Mass /(10^{-3} kg)	Y_{O_2}	Y_{CO_2}	Y_{CO}	Y_F	Y_U	Y_L	h_L		length	height
1	295	0.1981	300	20~40	54.2	10.5	2.8	0.52	8.29	391	333	0.27	0.66	nonoccurrence	
2	293	0.1995	300	30~50	54.0	12.2	3.0	0.32	8.39	371	327	0.25	1.04	nonoccurrence	
3	295	0.1991	300	20~30	39.7	14.4	2.1	0.14	9.04	385	343	0.31	1.94	0.60	0.72
4	294	0.1985	300	30~40	34.0	14.2	2.1	0.12	9.11	371	327	0.25	2.02	0.60	0.77
5	296	0.1991	300	30~40	30.8	14.0	2.1	0.10	9.20	370	333	0.29	2.17	0.62	0.83
6	297	0.1989	300			11.6	3.1	0.22	9.31	375	337	0.28	2.28	0.70	0.92

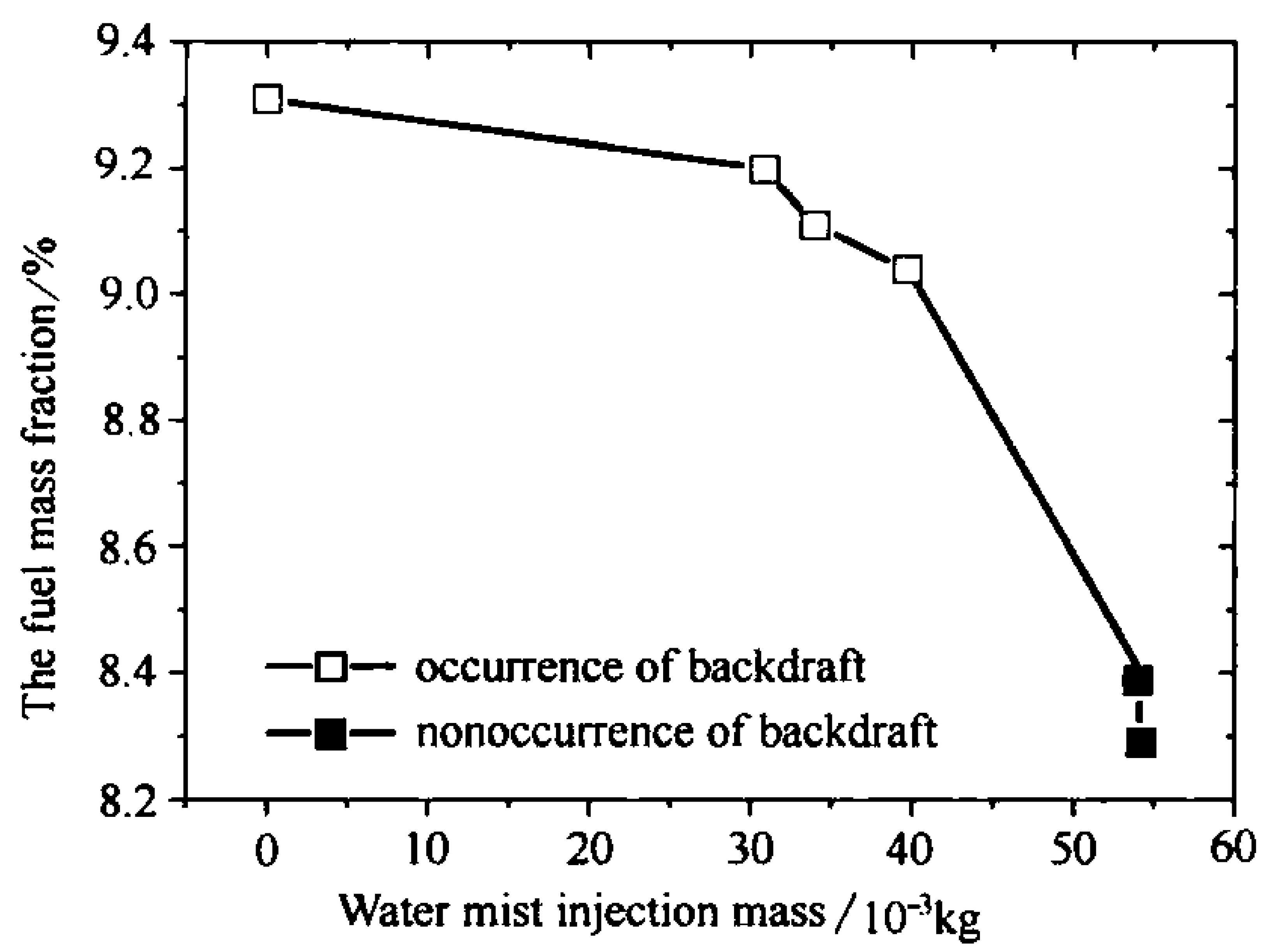

Fig. 4 Figure of the relationship between fuel mass fraction and water mist injection mass with the door end opening. The solid symbol means occurrence of backdraft, and that of hollow means non-occurrence of backdraft

From Table 3, it is also indicated that the peak pressure and size of the fire ball decrease with water mist injection mass. So the more water mist injection mass, the lower the intensity of backdraft. Therefore, water mist is an effective mitigating tactic that is able to suppress backdraft. This is also indicated in Fig. 4, which shows the relationship between fuel mass fraction and water mist injection mass with the door end opening. From Fig. 4, the fuel mass fractions in the experiment without water mist is the maximum value in all of the experiments. The greater the water mist injection mass, the less the fuel mass fraction, and the less the intensity of backdraft. More water mist injection mass make backdraft be from occurrence to nonoccurrence. Therefore, the mitigation mechanism of water mist is by means of reducing fuel mass fraction.

2.5 Salt water modeling of gravity current prior to backdraft

A gravity current is the current that moves as a result of a density difference between the current and the ambient fluid under the influence of gravity. This density difference may be due to a dissolved chemical or a difference in the temperature between the two fluids. In order to investigate the speed and clarity the extent of the mixed region of gravity current prior to backdraft, a series of scaled salt water experiments using flow visualization and DPIV (Digital Particle Image Velocimetry) were conducted[15]. The scaled compartment (0.4 m×0.1 m×0.1 m), shown in Fig. 5, was fitted with a variety of end and ceiling opening geometries, respectively: full, middle-slot, upside-slot, downside-slot, door and window. Salt water experiments were conducted by placing an organic glass compartment within a larger organic glass tank. The large tank, 0.6m long, 0.2 m wide and 0.3 m deep, contained a dense salt water fluid. In flow visualization experiments, a small amount of phenolphthalein was added to the compartment fluid. When phenolphthalein mixed with the base, in this case sodium hydroxide crystals that were added to the tank, the product of the reaction was red, which was strongly visible even in dilute concentrations. To conduct three-dimensional experiments, a mirror was placed above the compartment at a 45° angel to show the plan view of the gravity currents in the same place as the elevation view for video recordings. In 2D-DPIV experiments, the seeding particles, here hollow glass sphere with 8～12 μm diameter and 1.05×10^3 kg/m^3 ～ 1.15×10^3 kg/m^3 density, were added to the compartment and tank at a seeding density of 10～20 particles in an interrogation window. The interrogation method was based on an improved cross-correlation method, described in Ref.[16~17]. Illumination was provided by a 5W continuous wave Argon-ion laser whose beam spread to a 1mm thick sheet using a cylindrical lens. Once the two kinds of fluid were prepared, density difference, temperature and PH were recorded. The compartment was then lowered into the tank and the partition on the compartment was removed within 90s to avoid leakage effects. The partition was completely cleared out of the opening within 0.1s. In flow visualization experiments, the gravity currents were recorded using GR-DV1 (JVC) at 25 frames/s. In 2D-DPIV experiments, the gravity currents were recorded by CCD WAT-902H and sampled at 8 bits per pixel by digitizer and processor DT3155.

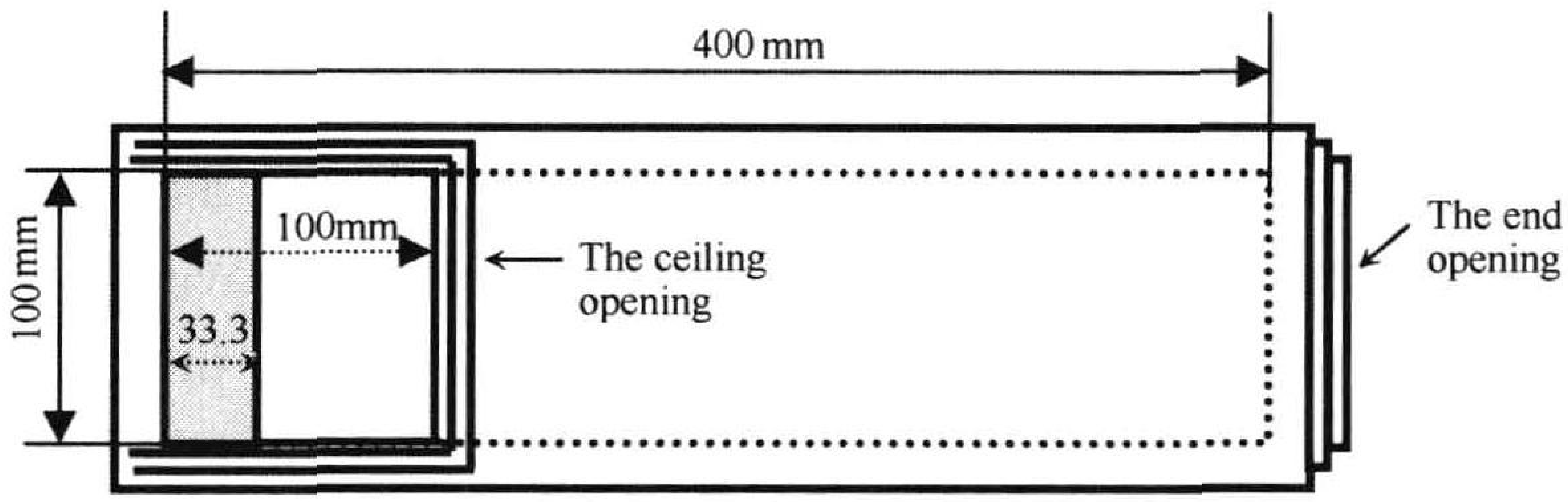

Fig. 5 Plan view of the salt water compartment with upside-slot ceiling opening geometry

As can be seen from Table 4, the nondimensional gravity current velocity v^* values is constant for different β (the density difference), and depends only on opening geometry. The values v (the gravity current velocity) and v^* of the exiting currents are approximately equal to that of the entering currents. For a 3m compartment fire, which is a candidate for a backdraft, the expected range would be $5\times10^3<\mathrm{Re}<5\times10^4$.The independence suggested in this paper, and shown in table 3 for $10^3<\mathrm{Re}<10^4$ indicates that the salt water results are directly applicable to typical fire compartments. Therefore, these scale velocity and geometry results are expected to apply directly to actual and modeled backdraft. For example, a velocity of 0.122 m/s at a β=0.063 for a salt water current with a door end opening geometry gives v^*=0.491, which would correspond to 0.72m/s at β=1.2 in a 2.4m high building. The average values of v^* and h^*, are given in Table 5. From Table 5, the result that the values v^* in the compartment with the end opening geometries are higher than that in the compartment with the ceiling opening geometries. The reason is that the ceiling opening geometries have more remarkable three-dimensional effect which causes more mixing and transient flow.

Table 4 Summary of the salt water modeling results for the entering and exiting current

	Entering Current				Exiting Current		
$\beta = \frac{(\rho_0 - \rho_1)}{\rho_1}$	t_{in} /s	v_{in} /(m/s)	$v_{in}^* = \frac{v_{in}}{\sqrt{\beta g h_1}}$ m/s	$Re = \frac{\rho_0 v_{in} h_0}{\mu}$	t_{out} /s	v_{out} /(m/s)	$v_{out}^* = \frac{v_{out}}{\sqrt{\beta g h_1}}$
The Door End Opening Geometry							
0.003	15.02	0.027	0.50	1098	31.96	0.027	0.50
0.023	5.43	0.074	0.49	2922	11.66	0.074	0.49
0.043	3.98	0.101	0.49	3923	8.53	0.102	0.50
0.063	3.29	0.122	0.49	4576	7.05	0.123	0.50
0.083	2.87	0.139	0.49	5042	6.20	0.140	0.49
0.103	2.59	0.154	0.49	5309	5.57	0.156	0.49

Table 5 Average values for v* and h*

	Full Opening	Door Opening	Middle-slot Opening	Downside-slot Opening	Upside-slot Opening	Window Opening
The End Opening Geometries						
$\overline{v}^*$	0.50	0.49	0.45	0.48	0.40	0.38
$\overline{h}^*$	0.49	0.42	0.44	0.43	0.48	0.41
The Ceiling Opening Geometries						
$\overline{v}^*$	0.39	0.30	0.33	0.31	0.34	0.24
$\overline{h}^*$	0.50	0.44	0.41	0.40	0.40	0.35