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Experimental study on smoke transportation from a narrow-long hallway to the remote room through doors of different sizes

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Abstract: The reduced scale experimental apparatus was applied to study smoke transportation mechanism. Based on the series of tests conducted on the reduced scale apparatus, smoke transportation from the narrow-long hallway to the remote room was systematically analyzed. The two ends of the hallway were blocked and the smoke could only be exhausted naturally from the remote room. The experimental results show that the size of the opening between the hallway and the remote room has a great effect on the smoke hazard in the remote room. The smoke concentration at the same height sampling point presents an oscillation tendency at a very low level in case of smaller opening size, while it will rise rapidly in a way of multiplication and oscillation decay with the increment of the opening size. Meanwhile, it was found that the smoke concentration at the sampling point in the remote room is higher than in a room close to the fire-origin room in a given period.

Key words: reduced scale; hallway; remote room; smoke; opening size

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不同开口条件下的火灾烟气从狭长走廊向远端非火源房间迁移的实验研究

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摘要:详细介绍了小尺寸烟气迁移实验台,并在此实验台上开展了一系列烟气从狭长走廊向远距离非火源房间迁移的实验研究.狭长走廊的两端封闭,烟气只能从非火源房间出口处排出.研究表明,狭长走廊和非火源房间之间的开口大小对于远端非火源房间中的烟气危害性影响非常大.在非火源房间同一高度设定测点,当开口较小的时候,测点处的烟气浓度处于低水平震荡状态,随着开口尺寸的增大,震荡趋势逐渐衰减,烟气浓度峰值成倍急剧攀升.同时发现,特定时间段中出现靠近走廊远端测出的烟气浓度高于靠近火源房间的烟气浓度的现象.

关键词:小尺度;走廊;非火源房间;烟气;开口尺寸

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0 Introduction

Fire is a combustion phenomenon out of control with a high occurrence frequency among all kinds of disasters. With the rapid development of national economy in recent years, fire safety is becoming increasingly important. Statistically, more than 85% of fatalities in fires are attributed to smoke, as most of the victims transfer from narcosis to death due to the inhalation of smoke dust and poisonous species of smoke[1,2]. The famous Luoyang Dongdu Mansion fire which occurred in China in 2000 causing 309 deaths was attributed to fire smoke, and the Taegu subway fire occurred in Korea in February 2003 causing more than 200 deaths due to the effects of smoke.

It is a common observation that most of the deaths in fires occur in a comparatively remote place from the fire origin and during a post-flashover period[3]. How can the high concentration smoke yields transport to a remote location? Most of the researchers in China focus on the height of the smoke layer while less attention was paid to the smoke toxicity movement.

Currently, smoke toxicity has become a hot topic internationally and the related research institutes have set up all kinds of projects to carry out extensive research on the effect of smoke in fires[4]. Experimental study is one of the most important routes to discover the smoke toxicity hazard. Biological test was the key method adopted previous studies on the smoke hazard[5,6]. The rest of the research focus on combustion and pyrolysis of the polymer aiming at special elements and toxic gas production[7,8]. Little research on the transportation of smoke toxicity has been conducted. The idea of how the smoke toxicity transports to a remote location was brought forward by Brian, Gottuck and Beyler from NIST[9], and some preliminary work has been carried out on smoke transportation in the case of simple fuel and mechanical ventilation. But in reality, most of the fires occur in natural ventilation, and the driving force of smoke transportation depends on the gradient of the concentration and temperature. On the basis of the domestic and the overseas research, more attention was paid to smoke transportation in the case of natural ventilation within a building. Little achievement has been obtained on smoke transportation from the hallway to a remote room of non-fire origin, while in the real fire case, many deaths occur due to unawareness of the smoke transported from the outer to the inner room. In this paper, a series of tests are carried out under this circumstance.

1 Experimental setup

The reduced scale smoke movement experimental apparatus is shown as Fig. 1.

1.1 Main body of the experimental apparatus

The main body of the experimental apparatus includes a combustion room, a narrow-long hallway and a remote room.

The external dimension of the combustion room is 0.8 m×0.8 m×1.2 m, approximately 1/3 scale of the ISO 9705 Standard Room. A 0.4 m×0.4 m glass inspection window is installed on one side of the combustion room, and a 0.5 m×0.5 m maintenance door is installed on the opposite side of the combustion room. There is a vent with maximum diameter of 0.13 m connected to the combustion room on one side with a series of adjustable plates to achieve different ventilation volumes, and an adjustable opening template is installed on the opposite side of the combustion room to set the opening size between the combustion room and the hallway. An isolation gate is also installed on the outlet of the combustion room, which can separate the combustion room and the hallway completely and can start to open at anytime designed for the test.

The external dimension of the narrow-long hallway is 0.4 m×0.8 m×4.0 m. The two ends of the hallway can be closed or opened, and the opening size can be set from 0 to 0.8 m in height.

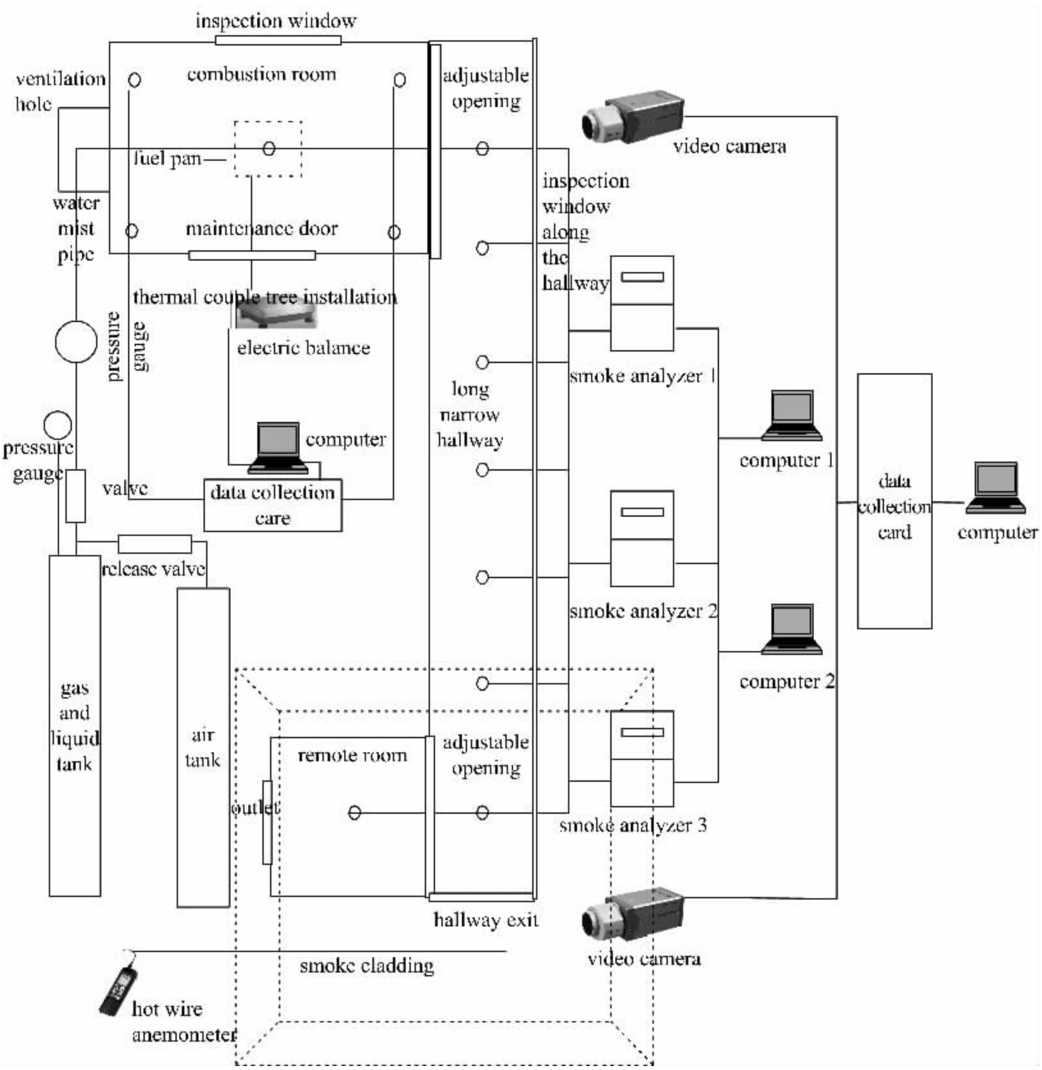

Fig. 1　Reduced scale smoke movement experimental apparatus

There are sliding flanges connecting the hallway to the combustion room and the remote room. The glass inspection wall is installed on the hallway on one side. There are many sampling points on the top of the hallway to install smoke analyzers, thermocouple trees, etc.

The external dimension of the non-fire-origin remote room is 0.6 m×0.6 m×0.8 m. There is an adjustable opening template installed between the hallway and the remote room. On the opposite side of the remote room is a 0.2 m×0.3 m exit, which can be closed or opened.

1.2 The auxiliary system of the experimental apparatus

The auxiliary system mainly includes a water mist restraining system, a fuel ignition system, a mass loss rate measuring system, a thermal couple tree temperature measuring system, a velocity measuring system, a smoke analysis system, a data and photo collection system and a smoke exhaustion system.

1.2.1 The water mist restraining system

The water mist restraining system is applied to conduct the research on the effect of smoke toxicity release and transportation with water mist involved. It includes an air tank, a gas-liquid tank, a pressure relief valve, a pressure gauge and a ball valve.

1.2.2 The fuel ignition and mass loss rate measuring system

The fuel is ignited with a sparkle igniter through the combustion room maintenance door.

The fuel is loaded on the fuel pan, and the elevation of the load cell can be adjusted according to the requirement of the experiment. The fuel pan is supported on the electronic scaleSL8000. The weight range of the electric scale is 8 kg and the resolution is 0.1 g. The data collected is transferred to the computer timely.

1.2.3 The thermocouple tree temperature measuring system

The thermocouple trees are located in one corner of the combustion room and the opening area between the combustion room and the hallway. The combined data is used for the inlet and outlet mass volume calculation, which can be used for GER (fuel and air equivalence ratio) calculation. GER is a very important parameter for the description of the combustion situation in the combustion room, which can be correlated to the smoke production in the hallway. There are also thermocouple trees located along the hallway and in the remote room for the temperature file measurement.

1.2.4 The velocity measuring system

There are two locations where the smoke velocity needs to be studied. One is at the exit of the hallway end, and the other is at the opening between the combustion room and the hallway. But it is very difficult to measure the smoke velocity here at the opening. The velocity can be calculated based on the temperature file. The smoke velocity at the end exit is measured by the hot wire anemometer TSL.

1.2.5 The smoke production analysis system

It mainly includes smoke analyzers installed at different locations according to the experimental requirement. There are smoke analyzers of ENCEL M9000, M900 and M900H, which can measure smoke temperature, the concentration of the O_2, CO, SO_2, NO, NO_2 and the pressure differential Δp, and calculate the concentration of CO_2, NO_x and CO and combustion efficiency η at the air over coefficient $\alpha=1$. The communication terminal RS232 can be used to connect with the computer, which can turn multi-points measurement into reality.

1.2.6 The image collection system

Images are acquired by the video cameras, which are located at the hallway end exit and the side of glass inspection window of the hallway. The location can also be adjusted according to the experimental design. The images are obtained by an image collection card.

1.2.7 The smoke exhaustion system

The smoke cladding, the duct and the air fan are located at the elevation of 1m at the end exit of the hallway.

1.3 The experimental setup

The test modes are as follows:

Sampling points. There are six sampling points selected for measurement in the experiment, which are sampling points No.1, No.2, No.3, No.4, No.5 and No.6. Sampling point No.1 mainly reflects the combustion room, sampling point No.2 is located at the end of the hallway close to the combustion room, sampling point No.3 is located on the center line of the opening between the combustion room and the hallway, No.4 is located in the middle of the hallway, sampling point No.5 is located at the end of the hallway close to the remote room, and sampling point No.6 is located at the remote room. The sampling height is 100 mm under the roof of the structure. In this paper, we mainly study the concentration variation at the sampling point No.6 with respect to the changing positions of the sliding gate.

Each opening size. The vent of the combustion room is closed. The opening between the combustion room and the hallway is 0.4 m×0.2 m. The end exit of the hallway is closed. The opening between the remote room and the hallway can be adjusted in height, and the width is 0.183 m. There are three heights established in this experiment, which is 0.2 m, 0.4 m, 0.6 m respectively. The exit from the remote room to the outside is open. The detail of sampling points and

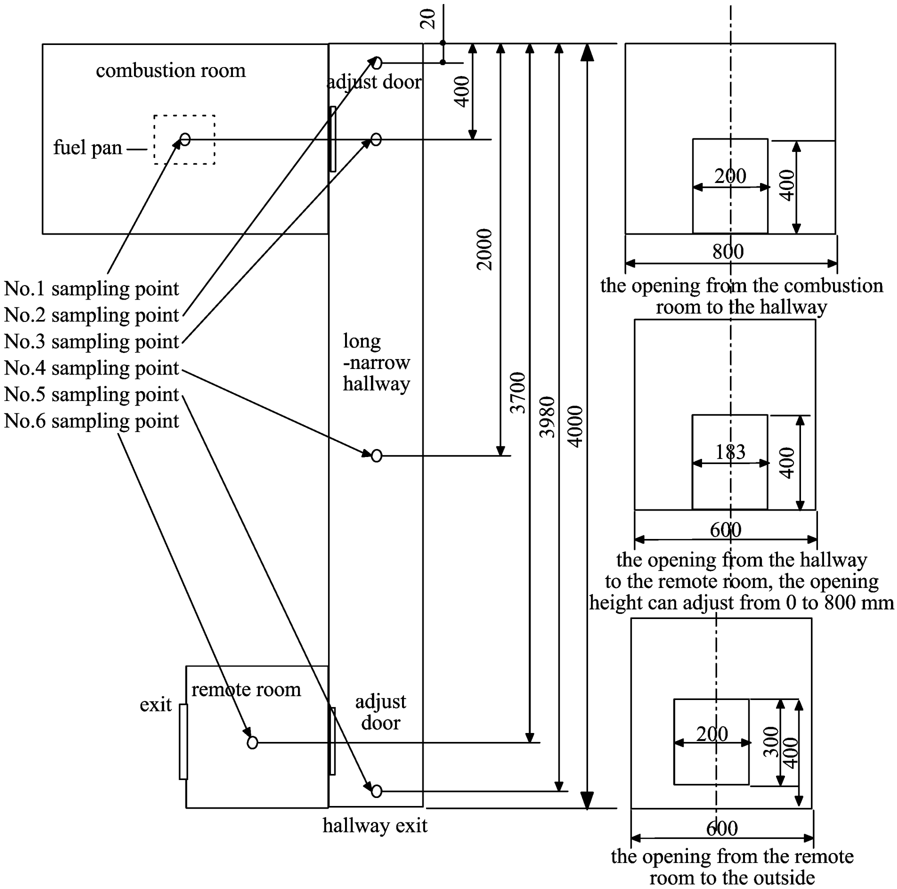

Fig. 2　The sampling points layout and the opening size

the opening displacement is shown in Fig. 2.

Fuel. 40 g paper and 10 g gasoline are used in this experiment. The paper is made into strips. The method of placement is the consistent for each test to ensure similar combustion. The gasoline is added to achieve stable combustion.

2　Experimental results

Six experiments are carried out in the paper. The mass loss rate curves are similar due to the same ventilation status. In these experiments, the only variation is the opening size between the remote room and the hallway, and the opening is remote from the combustion room with less effect on the combustion behavior in the combustion room, so the repeatability is excellent. Fig. 3 shows the mass loss of the sample. It can be expressed as the following equation:

$$y = A_1 \times \exp(-x/t_1) + A_2 \times \exp(-x/t_2) + A_3 \times \exp(-x/t_3) + y_0. \quad (1)$$

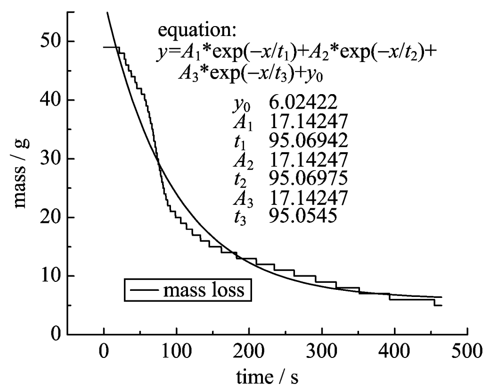

Fig. 3　Mass loss of the sample

Where $y_0 = 6.024\ 22$, $A_1 = 17.142\ 47$, $t_1 = 95.069\ 42$, $A_2 = 17.142\ 47$, $t_2 = 95.069\ 75$, $A_3 = 17.142\ 47$, $t_3 = 95.054\ 5$.

The key point in this paper is to study CO transportation from the hallway to the remote room. Some conclusions can be drawn from Fig. 4, Fig. 5 and Fig. 6:

(Ⅰ) The variation of opening size has a great impact on the smoke concentration in the remote

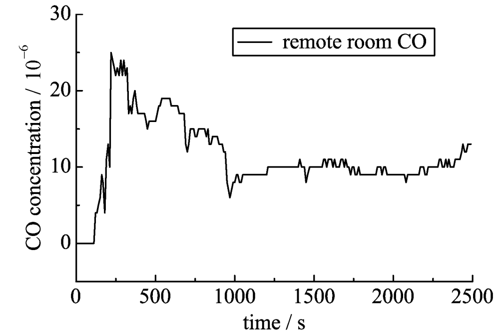

Fig. 4 CO concentration with opening size of 200 mm in height

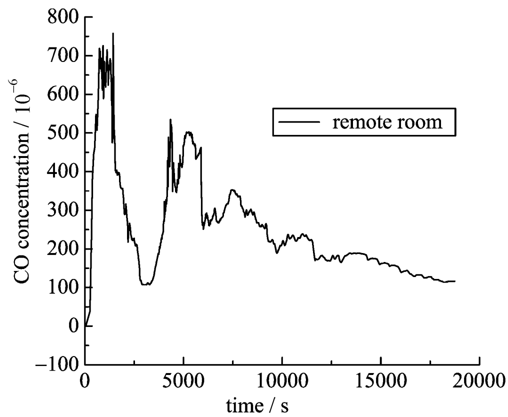

Fig. 5 CO concentration with opening size of 400 mm in height

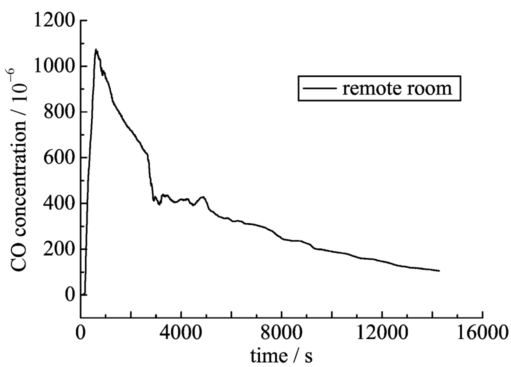

Fig. 6 CO concentration with opening size of 600 mm in height

room, and the CO concentration is very low when the opening size is very small at the same elevation sampling point. In this experiment, if the opening size is only 200mm in height, the concentration (volume fraction) of CO obtained at the sampling point can only achieve the maximum value of around 20×10^{-6}, which is a very low concentration. It means that a smaller and lower opening size between the remote room and the hallway will lead to less smoke hazard and higher human safety index. However, when the height of the opening size increases to 400 mm, the concentration of CO rapidly rises to around 800×10^{-6}. The peak value is around 40 times higher than the value when the height is 200 mm. It is very dangerous in this case, especially, when the opening height increases to 600 mm, the peak of the CO concentration can reach $1\,100 \times 10^{-6}$. The concentration peak value will increase gradually with the variation of opening height. Especially, when the opening height increases to the medium size opening height, the concentration will rise rapidly. This means that in a typical building structure such as the hallway with a lot of rooms on both sides, when fire occurs in one room as far as the rooms along the hallway are concerned, it does not mean that the room closer to the fire origin will have much more hazard. The hazard degree has much dependence on the opening size and location between the hallway and the room. This phenomenon has been demonstrated in the HILLHEAVEN nursing house fire in Pennsylvania, where many people died remote from the fire origin.

(Ⅱ) When the opening size is very small, at the No. 6 sampling point in the remote room the measured CO concentration is only around 10×10^{-6}, and oscillates frequently, which means the inlet and outlet of the remote room are kept in a comparatively balanced dynamic situation, and it is very difficult for the smoke to accumulate to the elevation of 100 mm under the roof of the remote room. With the opening height increasing, the oscillation tendency begins to reduce. When the height increases to 600 mm, the oscillation tendency almost diminishes. When the smoke diffuses from the hallway to the remote room under the condition of a big opening, it will accumulate in the remote room to achieve a high concentration due to the lower position of the exit in the remote room, and the peak value will reduce gradually after the smoke flows out of the remote room gradually. When the opening height is 400 mm, which is between the big opening and the small opening, the oscillation phenomenon still remains, but the degree of vibration reduces rapidly with an obvious diminishing tendency.

It is also indicated from Fig. 7 that, after about 400 seconds, CO at the point No. 3 in the front of the hallway has lower concentration than at the sampling point No. 5 at the end of the hallway, which is very strange since the point No. 5 is farther from the fire origin room compared with the sampling point No. 3. This is mainly because of the building structure. The sampling point elevation is 100 mm below the roof of the hallway, while the soffit of the opening between the combustion room and the hallway is still 200 mm below the roof of the hallway, so the smoke concentration sampled at the point No. 5 has a quicker response than the sampling point No. 3 during the smoke movement. Another reason is that the sampling point No. 5 is at the end of the hallway, and the opening between the hallway and the remote room is in a lower position, so there is some time for the accumulation of smoke in the area of the sampling point No. 5.

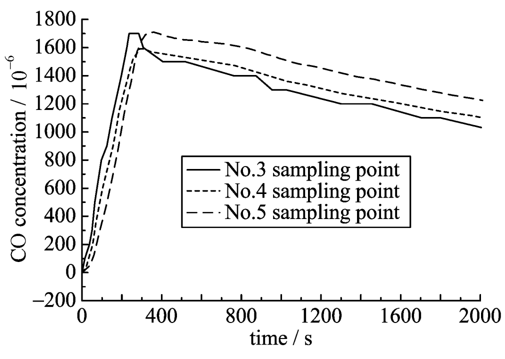

Fig. 7 CO concentration at points No. 3, No. 4 and No. 5

As is shown in Fig. 7, before 400 seconds, the sampling point No. 3 in the front of the hallway achieves higher concentration than the sampling point No. 5 at the end of the hallway, but after the 400th second it exhibits an opposite tendency, which means that at the end smoke accumulation contributes a lot to the higher smoke concentration. The result is also testified to some extent by the fact that there were many fatalities found in the remote location.

As mentioned above, differences in structure and ventilation can lead to the accumulation of smoke in the remote location, so the remote location really has higher CO concentration. Because people in the remote room have less awareness of the fire signal, so they may be invaded by the smoke without knowing it.

3 Conclusion

Reduced scale experiment plays a very important role in fire research. In order to study the very complicated movement of the toxic fire smoke, great attention is paid to the CO transportation under the natural ventilation condition, based on the reduced scale experiment in the Hallway-Room building. The result obtained is very interesting and helpful with investigation of some fire phenomena.

(Ⅰ) The opening size between the hallway and the remote room plays a very important role as far as the hazard in the remote room is considered. It is observed that the CO concentration rises rapidly from tens to hundreds of ppm with the opening size increasing.

(Ⅱ) In a certain period of time there is higher CO concentration in the remote area than the area closer to the fire origin, which presents some explanation of fatalities in the remote location.

References

[1] Fan Weicheng, Wang Qingan, Jiang Fenghui, et al. Fire concise tutorial [M]. Hefei: Publishing company of USTC, 1995.

[2] Quintiere J G. Scaling applications in fire research[J]. Fire Safety Journal, 1989, 15: 3-29.

[3] Lattimer B Y, vandsburger U, Richard R J. The Transport of High Concentrations of Carbon Monoxide to Locations Remote From the Burning Compartment [R]//NIST-GCR-97-713. Gaithersburg: National Institute of standards and Tecnology, 1997: 1-315.

[4] Gann R G, Averill J D, Butler K M, et al.

International Study of the Sublethal Effects of Fire Smoke on Survivability and Health (SEFS): Phase I Final Report [R]//NIST Technical Note 1439. Gaithersburg: National Institute of standards and Tecnology,2001.
[5] Pauluhn J, Kimmerle G, Märtins T, et al. Toxicity of the combustion gases from plastics: Relevance and limitations of results obtained in animal experiments [J]. Journal of Fire Sciences, 1994,12: 63-64.
[6] Kaplan H L, Switzer W G, Hindered R K, et al. A study on the acute and long-term effects of hydrogen chloride on respiratory response and pulmonary function and morphology in the baboon[J]. Journal of Fire Sciences, 1993,11: 459-484.
[7] Yeh J T, Hsieh S H, Cheng Y C, et al. Combustion and smoke emission properties of poly (ethylene terephthalate) filled with phosphorous and metallic oxides[J]. Polymer Degradation and Stability, 1998, 61:399-407.
[8] Irvine D J, McCluskey J A. Robinson I M. Fire hazards and some common polymers [J]. Polymer Degradation and Stability, 2000,67:383-396.
[9] Vandsburger U, Roby R J. Dynamics, Transport and Chemical Kinetics of Compartment Fire Exhaust Gases [R]// NIST-GCR-96-688. National Institute of standards and Tecnology,1996.

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[4] 柴立和,彭晓峰,张志军,等. 微重力下双组分池内核态沸腾的微楔形模型[J]. 水动力学研究与进展:A辑, 1999,14(2):225-231.
[5] 蔡勇,马东军,孙德军,等. 二维不可压缩流体界面的数值模拟 [J]. 中国科学技术大学学报,2006,36(6):641-645.
[6] Ma Dong-jun, Cai Yong, Sun De-jun, et al. Numerical study of interfacial methods for compressible multi-fluids [J]. Journal of China University of Science and Technology, 2002, 32(2): 186-193.
马东军,蔡勇,孙德军,等. 两种多介质流体可压缩流动界面捕捉方法的数值研究[J]. 中国科学技术大学学报,2002,32(2): 186-193.
[7] 孙小波,范学军,陆夕云. 可压缩双组分混合层的直接数值模拟研究[J]. 中国科学技术大学学报, 2007,37(10):1 273-1 279.
[8] 柯道友,彭楠,孟勐,等. 固定汽泡周围的温度场分布[J]. 清华大学学报(自然科学版), 2006, 46 (2): 218-221.
[9] Lee D J. Bubble departure radius under microgravity [J]. Chemical Engineering Communications, 1992, 117(1): 175-189.
[10] Zhao J F, Liu G, Wan S X, et al. Bubble dynamics in nucleate pool boiling on thin wires in microgravity[J]. Microgravity Science and Technology, 2008, 20(2): 81-89.
[11] 赵建福,万士昕,刘刚. 过冷池沸腾落塔短时微重力实验研究[J]. 工程热物理学报,2007, 28(1):98-100.
[12] Bhunia A, Kamotani Y. Flow around a bubble on a heated wall in a cross-flowing liquid under microgravity condition[J]. International Journal of Heat and Mass Transfer, 2001, 44: 3 895-3 905.
[13] Siegel R, Keshock E G. Effects of reduced gravity on nucleate boiling bubble dynamics in saturated water [J]. AIChE Journal, 1963, 10 (4): 509-517.
[14] Iguchi M, Terauchi Y. Microgravity effects on the rising velocity of bubbles and slugs in vertical pipes of good and poor wettability[J]. International Journal of Multiphase Flow, 2001, 27: 2 189-2 198.
[15] 葛新石,王义方,郭宽良. 传热的基本原理[M]. 合肥: 中国科学技术大学出版社,1985.
[16] Hoffman R L. Study of the advancing interface, Part I: Interface shape in liquid-gas systems [J]. Journal of Colloid and Interface Science, 1975, 50: 228-241.
[17] Milne-Thomson L M. Theoretical hydrodynamics[M]. 3rd ed. London: MacMillan, 1955.