第40卷第4期　　中国科学技术大学学报　　Vol. 40, No. 4
2010年4月　　JOURNAL OF UNIVERSITY OF SCIENCE AND TECHNOLOGY OF CHINA　　Apr. 2010

Article ID: 0253-2778(2010)04-0387-08

Reconstruction of a bus fire based on numerical simulation

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Abstract: Fire scene simulation using fire dynamics simulator (FDS) may provide evidence for fire investigation. Numerical simulation of the bus fire may recur the fire scene, reconstruct fire processes and explain fire development, smoke movement and deaths by describing the fire source, configuration of the bus and property of fuel. Based on the descriptions of evacuees and rescuers, and the combustion evidence of the scene, reconstruction simulation was performed by adopting parallel operation. Multi-parameter measurement, including heat release rate (HRR), temperature field, soot density and species concentration, was accomplished. The simulation results, compared with the fire site reconnaissance results, demonstrated good prediction of fire development and smoke movement and explained the causes of deaths. Furnishing a good foundation for further research into whole fire reconstruction and demonstrate the application of fire simulation to actual fire scene investigation.

Key words: scene reconstruction; numerical simulation; FDS; fire investigation; bus fire

CLC number: TK16　　**Document code**: A　　doi: 10.3969/j.issn.0253-2778.2010.04.010

基于数值模拟的某公交车火灾重构

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摘要：使用 FDS 进行火灾场景模拟可以给火灾调查提供证据支持．对公交车火灾的数值模拟可以重现火灾现场，通过描述火源、公交车的结构以及可燃物的属性，可以重构火灾过程，解释火灾的发展、烟气的运动和人员的死亡．基于逃生人员和营救人员的描述，以及火灾现场的燃烧证据，采用并行运算方法进行了重构模拟．完成了包括热释放速率、温度场、烟气密度以及组分浓度等在内的多参数数据采集．通过比较模拟结果和火灾现场的调查结果，推测了火势的发展和烟气运动，解释了人员死亡的原因．从而为整个火灾重构的进一步研究打下基础，同时指出了火灾模拟在实际火灾场景调查中的应用价值．

关键词：场景重构；数值模拟；FDS；火灾调查；公交车火灾

Received: 2009-09-07; **Revised**: 2009-12-15

Foundation item: Supported by National Natural Science Foundation of China (50876097), Program for New Century Excellent Talents in University of China (NCET-06-0546).

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Nomenclature

v/(m·s^{-1})	burning rate	L_i/m	the fuel height above the floor
V/m^3	volume	κ/(W·m^{-1}·K^{-1})	thermal conductivity
ρ/(kg·m^{-3})	density	L_f/m	the flame height above the fuel surface
Q/(kW·m^{-2})	heat release rate per unit area	C_p/(kJ·kg^{-1}·K^{-1})	constant pressure specific heat
D/m	diameter of the fuel bed	L_r/m	the flame height above the floor
t/s	time	ΔH_c/(MJ·kg^{-1})	heat of combustion

0 Introduction

In the case of air-conditioned bus fires, large quantities of smoke are likely to spread rapidly to the entire carriage due to narrow aisles and confinement of the closure condition. In particular, it can cause fatalities because the fire growth path usually coincides with the evacuation path. Therefore, we must reconstruct the bus fire scene through numerical simulation to analyze the fire process. The investigation results of the fire not only provide a references for adjusting the fire safety policies, but also gives important professional opinions to the judiciary to identify civil and criminal responsibilities[1-2]. With the development of fire science, courts of law are now inclined to use scientific methods in demonstrating the evidence of the fire scene. Therefore, fire simulation has become an important tool for fire investigation[3-4].

1 A bus fire in Chengdu

A bus fire happened in Chengdu City, Sichuan Province at 08:00 AM on June 5, 2009. The air-conditioned bus had 14 windows made of tempered glass, only 5 of which could be opened, but of which 4 could not be got through. The standard load of the bus was 75 persons, but the actual load was 120. The origin of initial the fire was at seat 35 (Fig. 1) where the petrol fumes were first smelt. It was arson, caused by gasoline spilt around the seat. The fire and smoke spread very fast, leading to 25 deaths and 76 injuries on the spot.

1.1 Basic information of the bus

The fire began at the back of the bus. the layout of this bus is shown in Fig. 1 and Fig 2. The bus wreckage is shown in Fig 3. The background details of the bus can be seen in Tab 1. The burned materials are shown in Tab 2.

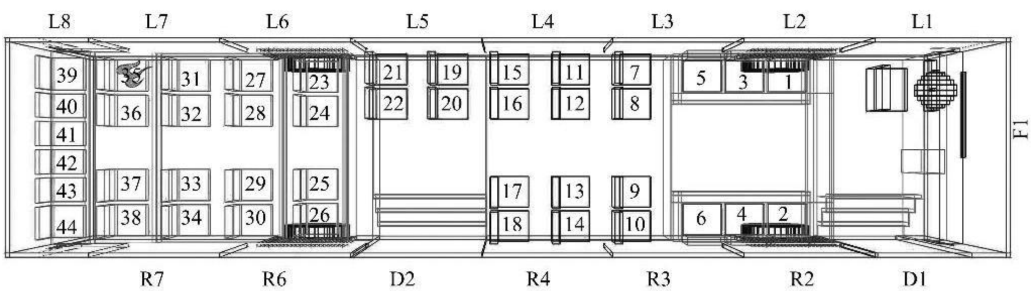


Fig. 1 Layout of the bus

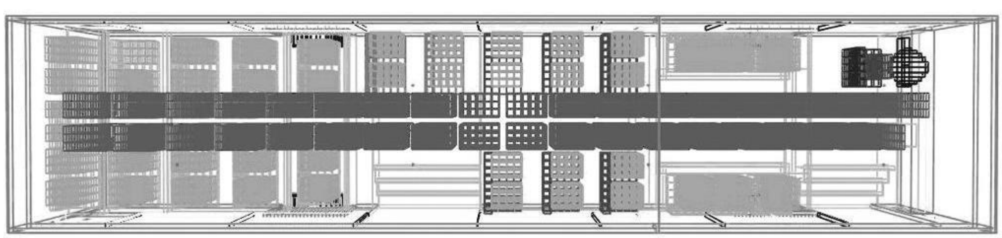


Fig. 2 Layout of the passengers

Fig. 3　Bus wreckage (pictures from website)

Tab. 1　Background details of the bus (data from Chengdu Fire Corps)

space dimension	15 m × 3 m × 5 m
bus dimension	11. 73 m × 2. 55 m × 3. 5 m
effective space height	2. 2 m
initial temperature	18 ℃
bus shell material	exterior shell: sheet steel interior shell: upholstery (0. 102 m thickness)
ventilation	windows closed

Tab. 2　List of burned materials (data from website)

item	combustible material	size/ number
bus interior shell	upholstery, plastic board	thickness 10 mm
seat	cushion, seatback	cushion: (0. 4 m × 0. 4 m × 0. 1 m) × 45 seatback: (0. 4 m × 0. 1 m × 0. 5 m) × 45
passenger	clothes, shoes	passenger: (0. 5 m × 0. 3 m × 1. 7 m) × 120
bus attachment	front counter, window bands	counter: (2. 5 m × 0. 3 m × 0. 6 m) × 1 bands: (0. 05 m × 0. 05 m × 1. 5 m) × 14
bus tyres	rubber	(0. 8 m × 0. 8 m × 0. 2 m) × 4
accelerant	gasoline	$(0.3 \times 0.3) m^2$

【Note】 Humidity: 40% ~ 50%.

1.2　Passengers' and passers' behavior in the fire

Tab. 3 and Fig 4 are produced based on the survey with some onsite rescuers and evacuees. The information can be used to depict the fire development[5].

2　Fire numerical simulation

2.1　FDS description

Fire dynamics simulator (FDS), which has been publicly released by NIST since 2000, is a computational fluid dynamics (CFD) model of fire-driven fluid flow. It numerically solves a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow on smoke and heat transport from fires. FDS aims at solving practical fire problems in fire protection engineering, while at the same time providing a tool to study fundamental fire dynamics and combustion. The core algorithm is an explicit predictor-corrector scheme that is second order accurate in space and time. Turbulence is treated by means of the smagorinsky form of large eddy simulation (LES). It also can be used for introducing large eddy transport coefficients to describe the unresolved fluxes of mass, momentum and energy[6]. Now, FDS is widely used in the research of fire dynamics. It will also become a useful tool in fire investigation and fire scene reconstruction[7].

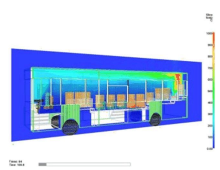
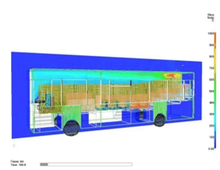
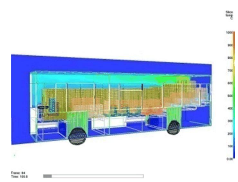
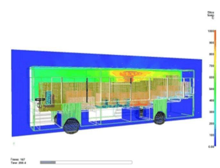
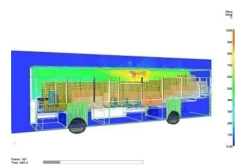
2.2　The design of fire origin

The bus fire is an incendiary event caused by the dumpage and ignition of gasoline under the seat. After a particular fire scene investigation on

Tab. 3 Actions of rescuers and successful evacuees in the fire

passenger	position	time analysis
A	passenger in seat 43, the first one to discover the fire	Smelled gasoline and saw the white smoke from seat 35, shouted to the driver to stop and then found that the smoke spread quickly and flames appeared, jumped out the bus from R8 (about 30 s passed).
B C D	passengers in seats 44, 42 and 41	Immediately escaped from R8 following A. Before D passed R8, the fire had reached his left arm and burned it (about 25 s passed).
E F	driver, passenger in seat 2	E immediately jumped out of the bus from L1, meanwhile, F opened R2 and cried for help. F was pulled out by a passerby quickly (about 35 s passed).
G	passengers near the front door D1	Escaped from a hole in D1 smashed by a taxi driver using a fire extinguisher (about 30 s passed).
H	passengers in front of seat 1	Smelled gasoline and saw the black smoke diffusing (about 25 s passed), asked the driver about the situation and held their breath; after L2 was broken (about 60 s passed), one of them threw out his niece and jumped out of the bus, his wife who escaped after him was burned (about 30 s passed).
I	passengers around seat 34	Escaped from R7 smashed by another bus driver using a crowbar (about 20 s passed). All were burned seriously.

Tab. 4 Temperature profiles

time/ s	$y=0.7$ m	$y=1.5$ m	$y=2.3$ m
100			
200			
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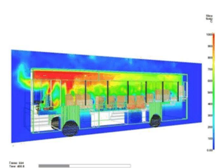
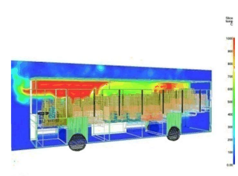
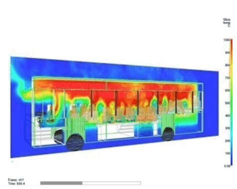
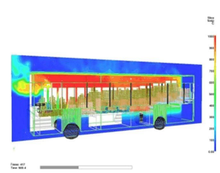
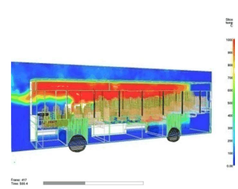
400			
500			

the burned area, the quantity of the combustible liquid on the spot could be reasonably deduced.

(Ⅰ) The volume of gasoline

The burned area is $0.3\ \text{m}\times 0.3\ \text{m}=0.09\ \text{m}^2$, the thickness of gasoline is 0.009～0.011 m, the volume is almost 0.8 ～ 1 L. The density of gasoline is 0.74 kg/L.

(Ⅱ) The heat release rate (HRR) of gasoline

$$Q=0.036\ \text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\times 46\ \text{MJ}\cdot\text{kg}^{-1}=1\ 656\ \text{kW}\cdot\text{m}^{-2}.$$

The amount of gasoline causing the initial fire was almost 1 L, judging from the descriptions of witnesses about the size of the box carried by the culprit.

(Ⅲ) Burning time

$$T = \text{gasoline weight/burning rate} = V\times\rho/v = 1\ \text{L}\times 0.74\ \text{kg}\cdot\text{L}^{-1}/(0.3\ \text{m}\times 0.3\ \text{m}\times 0.036\ \text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) = 228\ \text{s}.$$

Taking 230 s, if we assume a burning efficiency of 0.8, the total burning time is about 290 s. The burning time agrees with rescuer presentations[9].

2.3 Simulation setup

After the grid independence test is conducted[10], all meshes are cut into 10 cm×10 cm×10 cm grids, suitable for the case. There are altogether 0.225 million grids in the computational area. All grids are distributed into 6 node computers to execute parallel processing and a control server is used to collect the data from each node. Each node has 2 XEON5 5335 CPUs and 8 G memory. The simulation models are shown in Fig. 5. It takes 55 h to complete the simulation, and the final simulation result of HRR is shown in Fig. 6.

3 Result and discussion

3.1 Temperature of the simulation

The temperature in the simulation (1 000 ℃) is almost the same as the actual burning temperature of gasoline (1 026 ℃). The temperature profiles of the bus fire are calculated and presented in Tab. 4, based on the rescue time of the passers-by. The stripes on the right side of

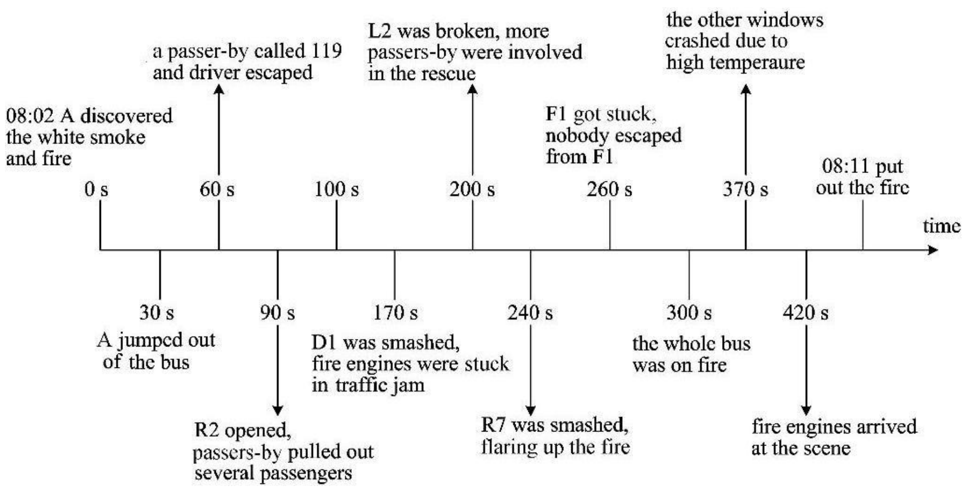


Fig. 4 Timeline based on rescuers' and evacuees' descriptions

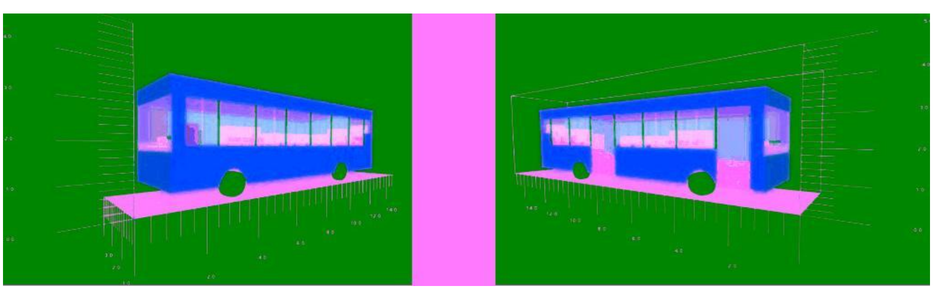


Fig. 5 Scene designed figure

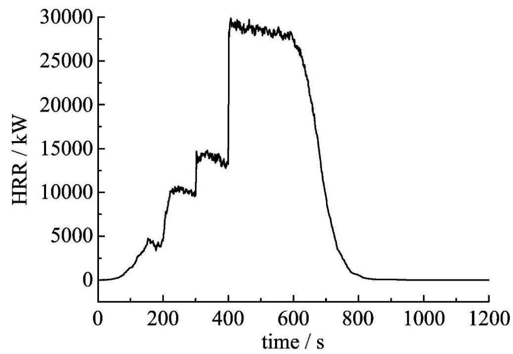


Fig. 6 HRR curve

the figure represent a summary of the visual observations[11].

The temperature profiles of the calculation agree closely with the description of evacuees and rescuers, based on the comparison at different rescue times. The HRR curve conforms to the timeline of fire scene investigation of the evacuees. The detailed temperature profile of a critical section is shown in Fig 8.

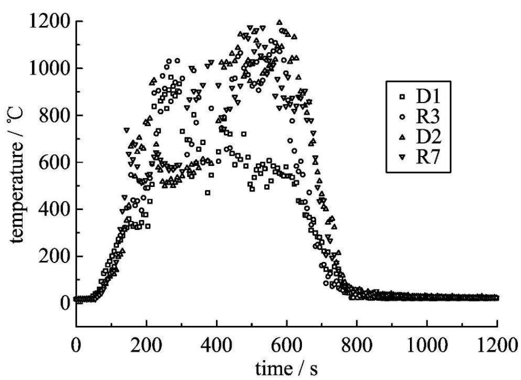


Fig. 7 Temperature curves of detectors

Fig. 7 presents the temperature curves of detectors at the front door, window R3, back door and window R7, respectively. It is apparent that the tendency of temperature change is in accordance with the HRR curve. The temperature of detector D1 is relatively low and a little more than 600 ℃. But the temperatures of other detectors are very close and at a higher level. It might be concluded that a great deal of smoke with high temperature flew out of the front door under the action of natural convection resulting from the breaking of D1, which led to a large amount of heat loss. It was such an advantageous circumstance that some valuable time was gained to help several passengers near D1 to escape the plight.

Fig. 8 Temperature contour with $t = 240$ s

3.2 Smoke and fire propagation analysis

The smoke and fire propagation profiles of the fire scene are also assessed in accordance with the rescue times (30 s, 100 s, 200 s, 300 s, 400 s) of witnesses on the spot, as demonstrated in Fig. 9.

The smoke and fire diffusion simulation shows that if the narrow, closed carriage of the bus ignited with the accelerating agent, heavy smoke would spread along the roof rapidly and obstruct the escape paths. The smoke layer would also become lower to the floor level within 100 s. Everywhere in the bus would be filled with thick smoke in 200 s. This scenario conforms to the investigation into the escape of the evacuees.

The temperature around the seats at the fire source reached 600 ℃ at 40 s from the initial period. In that situation, passengers would be trapped in the closed carriage unless doors or windows could be opened quickly and easily. The crowded carriage was shrouded in heavy smoke immediately in the initial stages of the fire. It was impossible to move along the aisle at 100 s. Smoke then grew increasingly thicker. The area near the driver, although far from the fire's origin, also had heavy smoke accumulation because of the sealed environment. At 200 s, with the breaking of D1, cold air came into the bus under the action of natural convection. The fire around D1 grew bigger because of the supplement of fresh air. Both soot density and temperature increased rapidly, as can be seen in Fig 7 and Fig. 10. It can be concluded that the fire growth path usually

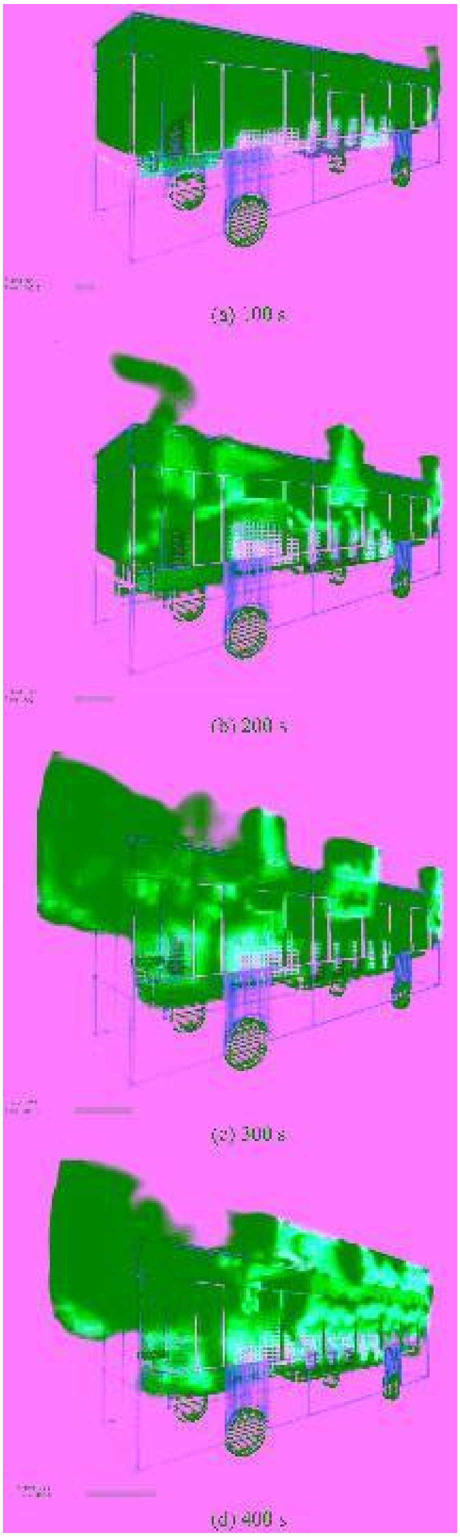


Fig. 9　Smoke and fire development figures

coincides with the evacuation path.

3.3　Species concentration

Fig. 11 and Fig. 12 present the concentration curves of CO and O_2. The product volume fraction of CO is in accordance with the HRR-varying tendency. However, the mass fraction of O_2 is right to the contrary. The peak volume fraction of CO is 10%. Because of the breaking of the front door D1, the CO volume fraction and the O_2 mass fraction of D1 are apparently different from those of other detectors, which is in favor of passengers' escape. The optimal escape stage is the fire growing phase from the beginning to 150 s. In this stage the volume fraction of CO is no more than 0.5%, which is the safety concentration of CO. The following stage is the fire spread phase from 150 s to 300 s. In this stage the content of CO is growing quickly and even reaches 10% partially,

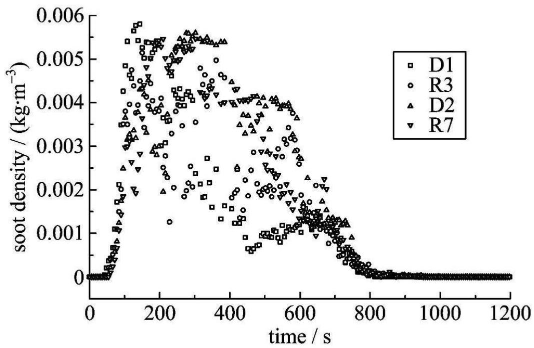


Fig. 10　Soot density curves of detectors

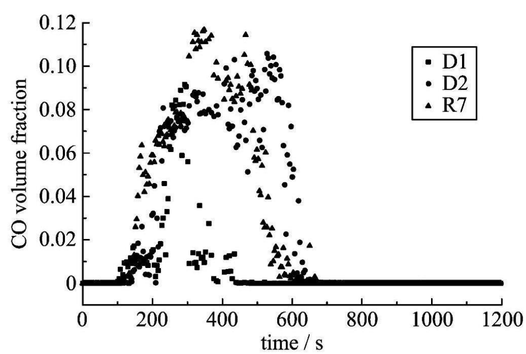


Fig. 11　CO concentration curves of detectors

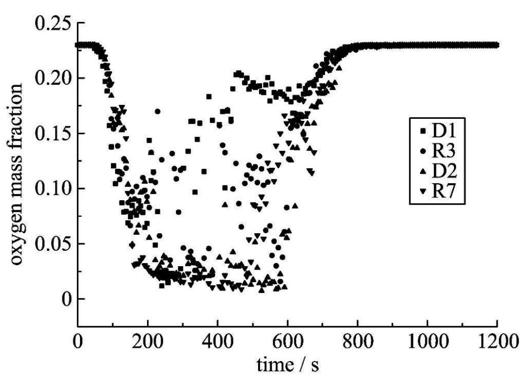


Fig. 12　O_2 concentration curves of detectors which is severely poisonous and makes passengers unable to move freely. Fig 13 and Fig 14 show the CO concentration at bow height and CO isogram of critical section, respectively.

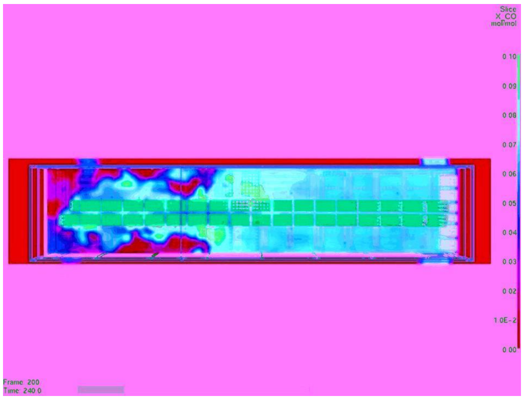


Fig. 13 CO concentration at bow height ($t=240$ s)

Fig. 14 CO isograms of critical section ($t=240$ s)

4 Conclusion

(Ⅰ) It is very obvious that the origin of this bus fire is the ignition of the accelerating agent. The simulation results indicate that the fire growing so quickly is owing to the sufficient heat release rate of the fire source in igniting the attachments on passengers and the supplement of fresh air through broken doors and windows. If the fire spread had not been so fast as was caused by the accelerating agent, the production of heat and smoke would not have been abundant enough to cram the whole carriage in a short time.

(Ⅱ) It can be concluded that the main reason for the death is the high temperature and overload of the bus. The combustion generates lots of toxic gases and soot, but both of them decrease quickly due to the breaking of the doors and windows. It is the sustained high temperature around the evacuation path that renders crowed passengers unable to escape.

(Ⅲ) Fire simulation can provide information on fire growth and spread, and smoke production and movement, which are all necessary to fire investigation, both in causes and protection of life and property. A fire scene reconstruction supported by numerical simulation can also offer important information to fire administrations to find an optimal way to reduce fire damage.

References

[1] Daéid N N. Fire Investigation[M]. London: CRC Press, 2004.

[2] National Fire Protection Association. NFPA 921: Guide for Fire and Explosion investigations[S]. 2003 ed. Orlando: National Fire Protection Association, 2003.

[3] Icove D, DeHaan J. Forensic Fire Scene Reconstruction [M]. New Jersey: Pearson Prentice Hall, 2004.

[4] Schroeder R A. Fire Investigation and Fire Engineer [M]// Fire Protection Engineering. Bethesda, MD: Society of Fire Protection Engineers, 2004.

[5] Wilmot R T D. Information Bulletin of the World Fire Statistics[M]. Geneva: The Geneva association, 2002.

[6] McGrattan K, Forney G. Fire Dynamics Simulator (Version 5. 03)-User's Guide[S]. Maryland: National Institute of Standards and Technology, 2008.

[7] Nam S. Numerical simulation of smoke movement in clean room environments[J]. Fire Safety Journal, 2000, 34: 169-189.

[8] Heskestad G H. Peak gas velocities and flame heights of buoyancy controlled turbulent diffusion flames[J]. Symposium (International) on Combustion, 1981, 18: 951-960.

[9] Evans D D. Use of fire simulation in fire safety engineering and fire investigation[C]// Proceedings of the 15th Meeting of the UJNR Panel on Fire Research and Safety. San Antonio, TX: US/Japan Government Cooperative Program on Natural Resources (UJNR), 2000: 441-448.

[10] Petterson N M. Assessing the Feasibility of Reducing the Grid Resolution in FDS Field Modeling[R]. New Zealand: University of Canterbury, 2002.

[11] McGrattan K B, Baum H R, Rehm R G. Large Eddy simulations of smoke movement[J]. Fire Safety Journal, 1998, 30(2): 161-178.