Simulation Analysis of the Pressure and Temperature in the Firing Bus
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Abstract. Fire accident in the running bus is very dangerous for the passengers. The temperature, pressure, and toxic fumes from the fire accident are the main factors of casualties of passenger in the closed bus. It is necessary to research the factors such as the temperature, pressure and smoke of the fire so as to improve the capability of rescuing the passengers and the passengers self-protecting under the emergency fire disaster. In this paper, the software named FDS is used to model and simulate the process of bus-firing, which a simulation describing the bus catching fire. The height of smog layer, distributions of indoor temperature and the carbon monoxide concentration from the firing bus are analyzed. By means of the simulation analysis of the bus fire procedure, the law of smog movement in the carriage is analyzed, and it is helpful for us to response to similar fire accidents.

Introduction
With the fast development of city traffic, people travel more and more convenient. However, the increasing number of vehicles also brought a lot of traffic accidents, bus fire is one of the highlights. Bus fire occurred frequently and has brought a serious threat to the passengers' lives and property.

Domestic and foreign scholars have paid attention to study the fire accident. In 2010, the University of Science and Technology of China Bi Kun[1], Qiu Rong and others use the FDS software on the development of urban bus fire simulation for the numerical simulation of passenger cars. Chen Jie[2], Central South University, took the typical bus as the research object and discussed the defects of the bus structure and the thermal release rate, the internal temperature distribution, the oxygen concentration distribution, the height change of the flue gas and the radiant heat at the time of fire. T.G Ma, J.G Quintiere selected model validation to predict fire temperature distribution and flame height. X.G Zhang, Y.C. Guo, C.K. Chan, W.Y. Lin[4]studied the fire spread and flue gas movement of a large underground car park under different fire scenes, and then investigated the spread of fire and smoke movement in different ventilation conditions.

Above shows that it necessary to make analysis for the bus fire accident, and we have made some active results in theory and application. Consider that the bus fire process is complex, especially the internal temperature, pressure distribution is uneven. In order to improve the emergency level of the bus fires, it is very important to analyze the factors such as the temperature, pressure and smoke with the development of the fire, which makes the emergency personnel rescue the passengers and the passengers self-protection well.

Physical and Chemical Processes of Bus Accidents in Enclosed Spaces

Fire Mechanism in the Closed Space
There are different forms of fire in closed spaces, depending on the geometric nature of the space, the type of fuel, the quantity and the surface area. After the fuel began to burn, the flame slowly increased and spread to the surrounding. In the initial stage, the hot smoke will rise up, and the surrounding cold air will be sucked into the fire plume because of the pressure. When the plumes are in contact with the top of the space, the hot flue gas will spread around the top to the surroundings, which will eventually reach the side walls of the space.
With the increase of the burning rate of fuel, the concentration of oxygen in the space began to change little, declined rapidly after a period of time, and finally maintained at a certain level.

Figure 1. The relation between oxygen and time in closed space fires.

**Chemical Procedure of Bus**

Combustion is a complex process. It’s better to consider the practicality of the model in the actual modeling. The practicality of the combustion model needs to meet two aspects: on the one hand to minimize its complexity; on the other hand to ensure the practicality of the large grid size. So that’s good to use the simplest CO generation and extinguishing mechanism. The reaction is carried out in two steps:

First step: \[ C + O_2 \rightarrow CO + \text{other products} \]  
(1)

The second step: \[ CO + \frac{1}{2} O_2 \rightarrow CO_2 \]  
(2)

The combustion model uses a mixture of percent combustion models that can be used to control the combustible combustion process and the combustion products by setting the percentage of mixture. It is assumed that the combustion process is controlled by the combustible and combustion aid, and that the reaction of the fuel with the combustion aid is completed in a very short time. Percentage of combustible and combustible products can be simplified by using "state relationships", for large-scale, well-ventilated fires, the hybrid model can be a good approximation to real fires \(^9\). The mixed fraction is defined as follows:

\[
Z = \frac{s Y_F - (Y_O - Y_O^\infty)}{s Y'_F + Y_O^\infty}, \quad s = \frac{\nu_0 M_o}{\nu_F M_F}
\]  
(3)

Where \( Y_F \) is the mass fraction of combustion, \( Y'_F \) is the mass fraction of fuel source, \( Y_O \) is the mass fraction of oxygen, \( Y_O^\infty \) is the mass fraction of oxygen in the initial environment, \( M_o \) and \( M_F \) are the relative molecular weights of oxygen and combustion, \( \nu_0 \) and \( \nu_F \) are the calculated coefficients of oxygen and fuel chemical reactions, respectively.

**Create Model Based on Pyrosim Software**

**FDS Simulation Software**

**Introduction to FDS.** FDS is a computational fluid dynamics software developed by the National Institute of Standards and Technology. By solving the Navier-Stokes equation to simulate low-speed, temperature-driven fluid motion, the software has important applications in the field of simulated combustion and flue gas movement and flame propagation during fire. In this paper, the FDS fire simulation software Pyrosim is used to model and analyze the bus fire accident.

**Theoretical basis of FDS.**

(1) Basic control equation

The basic theory of aerodynamics is fundamental to the numerical simulation of fire smoke control, that is mass conservation equation, momentum conservation equation and energy conservation equation.

(2) Large Eddy Simulation-LES
FDS provides a variety of numerical simulation methods, under normal circumstances, LES is selected for FDS fire simulation.

The large eddy simulation is to decompose the turbulent transient motion, including pulsation, into a large-scale motion and a small-scale motion by some filtering method. The large scale is calculated directly by numerical solution of the differential equation. The effect of small-scale motion on large-scale motion is simulated by establishing a sub-lattice model. This greatly simplifies the calculation of workload and the need for computer memory.

**Simulation Model**

According to the actual bus size (12 * 2.6 * 3.3) to establish the bus model, the model has 36 seats inside, both sides of the window can open and close.

When use Pyrosim to build a model, we need some simplification, and get model as follows:

![Figure 2. The bus model built with Pyrosim.](image)

This paper mainly consider the bus fire flame spread and flue gas distribution, a total of 17 sets of monitoring points are designed, the specific distribution is as follows:

<table>
<thead>
<tr>
<th>Name</th>
<th>Equipment</th>
<th>Coordinates</th>
<th>Name</th>
<th>Equipment</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>THCP</td>
<td>Thermocouple</td>
<td>(-1.5,2)</td>
<td>GAS03</td>
<td>Concentration meter of CO</td>
<td>(0, -2.2)</td>
</tr>
<tr>
<td>THCP02</td>
<td>Thermocouple</td>
<td>(-1.2,2)</td>
<td>GAS04</td>
<td>Concentration meter of CO</td>
<td>(0, -5.2)</td>
</tr>
<tr>
<td>THCP03</td>
<td>Thermocouple</td>
<td>(-1, -2,2)</td>
<td>GAS05</td>
<td>Concentration meter of CO</td>
<td>(1.2,0,2)</td>
</tr>
<tr>
<td>THCP04</td>
<td>Thermocouple</td>
<td>(-1, -5,2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THCP05</td>
<td>Thermocouple</td>
<td>(1, -5,2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THCP06</td>
<td>Thermocouple</td>
<td>(1, -2,2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THCP07</td>
<td>Thermocouple</td>
<td>(1, 0,2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THCP09</td>
<td>Thermocouple</td>
<td>(1,5,2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GAS</td>
<td>Concentration meter of CO</td>
<td>(0, 2,2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GAS01</td>
<td>Concentration meter of CO</td>
<td>(0, 0,2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GAS02</td>
<td>Concentration meter of CO</td>
<td>(0,0,2)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The main parameters of the bus interior decoration are as follows:

<table>
<thead>
<tr>
<th>Constructs</th>
<th>material</th>
<th>Thickness (mm)</th>
<th>Density (Kg/m³)</th>
<th>Specific heat capacity (KJ/kg·K)</th>
<th>Heat transfer rate (W/m·k)</th>
<th>Heat of combustion (KJ/kg)</th>
<th>Heat release rate (kw/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td>Soft PVC</td>
<td>50</td>
<td>1200</td>
<td>1.1</td>
<td>0.14</td>
<td>1.5×10⁴</td>
<td>168</td>
</tr>
<tr>
<td>Seat</td>
<td>Rigid PVC</td>
<td>10</td>
<td>1380</td>
<td>1.1</td>
<td>0.17</td>
<td>1.9×10⁴</td>
<td>392</td>
</tr>
<tr>
<td>Interior</td>
<td>Rigid PVC</td>
<td>10</td>
<td>941</td>
<td>2.3</td>
<td>0.51</td>
<td>4.6×10⁴</td>
<td>1007</td>
</tr>
<tr>
<td>Seat legs</td>
<td>Steel</td>
<td>10</td>
<td>7850</td>
<td>0.46</td>
<td>45.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carriage</td>
<td>Steel</td>
<td>20</td>
<td>7850</td>
<td>0.46</td>
<td>45.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceiling</td>
<td>Steel</td>
<td>30</td>
<td>7850</td>
<td>0.46</td>
<td>45.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windows</td>
<td>Ceramic fiber</td>
<td>10</td>
<td>1.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Simulation Case Analysis

When the fire begins, set the time as the start of the simulation. The two doors are closed at the beginning. It is assumed that the driver notices the fire and open the doors 30 seconds after the fire starts. At the same time, all the windows, expect the one near the seat of driver, are closed initially. What’s more, the windows on both sides of the bus are set to be open when the simulation time is 100 second. The fire source is located in the front of the bus (XB=-1.0,-0.9,3.9,4.0, 1.35,1.35) while the heat release rate per unit area is set to 20000KW / m², the ignition area is 0.01m² and the fire power is 200KW. In this case, the situation of fire in the front of the bus is simulated.

Spreading Situation about Smoke and Flame

The bus fire accident, the situation of smoke and the flame spreading out are described as follows.

And therefore, the Analysis of Flame and Flue Gas Spreading out are necessary. As we know, when the fire begins to burn, doors and windows are closed. When it comes to 200 seconds, the fire has spread to the central part of the vehicle. When it is 400 seconds, the cab after the baffle also begins to burn and it is hard to identify objects resulting from the smoke.

Temperature and CO Concentration Distribution

(1) left side temperature (2) right side temperature (1) CO concentration in whole bus (2) CO concentration near doors

Analysis of Temperature Distribution

Human tolerance temperature is about 70 degrees to 90 degrees. If the temperature is more than tolerance temperature, human life will be seriously threatened. From the whole Z = 2 temperature cut plane, the distribution of the car temperature changes with the spread of the flame. The initial fire is small, and the temperature rise is relatively slow. At 100s, only a small area around the front of the car near the fire source location exceeds the critical temperature, and the temperature at the fire source is more than 600 degrees. The overall temperature is low at this time, so people have more possibility to escape; 200s, the flame has spread to the seat at the other side of the front bus. The temperature on the front of the car seat position has reached the critical value, and the highest temperature is above 900 degrees Celsius. The situation has been more dangerous at this time, and the temperature of the back door and the front door has been relatively high; 300s, the front of the bus and a small part of the central area have reached the critical temperature; 400s, the middle of the compartment and the front area of the bus have exceeded the critical temperature.

According to the observation of the temperature sensor, THCP, THCP08 and THCP09 at the initial distance reach the critical temperature quickly, and the temperature of the other observation points is not obviously changed at the beginning. After 100s, with the spread of the fire, the temperature of THCP01 rises very quickly; 200s, the temperature of THCP02 and THCP07 also rises quickly, and in comparison, the temperature of THCP02 has a faster rate and a higher temperature because of more combustibles; After 400s, except THCP09, THCP04 and THCP05, other observations have exceeded the critical temperature.
Analysis of CO Concentration Distribution

CO is a colorless, tasteless toxic gas. CO is able to combine with hemoglobin in the blood in human body, forming a carbon oxygen hemoglobin (HbCO), which is more than 200 times more approachable than oxygen and hemoglobin. When the level of HbCO in the blood reached 5 percent, the body began to feel uncomfortable. When the concentration reaches 30%, the victim will be giddy, blurred, and lose the ability to be free. With the concentrations runs up to 60% to 70%, people will die quickly. When the bus fire happens, fuel cannot be fully burned due to bad ventilation situation, to produce a large number of toxic gases CO. Its higher concentration at the early fire will make people suffocation coma. It is difficult to escape, then people will be burned to death because of the spread of flame.

From the figure about the CO concentration variation in the bus, we can see that the CO concentration in GAS01 and GAS observation point which is nearest the early fire location is higher than that the rest of the observation point. This is due to the early bus is approximately all closed, and O\textsubscript{2} is limited. The bus has a good sealing ability and air flow is poor, so CO diffusion is slow. Only the observation point concentration near the fire is higher. At the GAS02 observation point in the middle of the carriage, as the fire spread, the CO concentration began to rise rapidly around 200s. At 400s, the GAS03 observation point also began to rise rapidly; The GAS observation points in car department, whose initial concentration of CO is low. In the 200 s - 700 s, their CO concentration is much higher than GAS03, GAS04 observation point. But due to the ventilation and the front of the fuel combustion status, their concentration begin to decline in late stage, and the final concentration is lower than the rear. To the observation point at the front and back of bus, as a result of ventilation, the overall front door concentration is less than the back door, and the back door grows faster than the front door. Front and back door observation point is close to the doors, and ventilation is good, so compared with the CO concentration inside, their concentration kept a lower level. The fuel at the back door is more abundant, then CO concentration is higher.

Conclusions

Based on the study of the theory of closed space fire, this paper introduces the overall process of combustion and explains the various phenomena in the process of fire. Finally, the flue gas spread, the commonly used fire formula and the effective fire combustion model. The model of the simulated bus was established by using the fire dynamics software FDS. The heat release rate, the internal temperature distribution, the CO concentration distribution and the propagation condition of the bus were simulated. The following conclusions can be drawn from the simulation analysis:

1. The beginning of the fire, due to more combustibles, the flame will grow rapidly. Passengers open doors and windows to escape which makes a lot of fresh air into the bus, accelerating the fire spread process. Passengers need to flee the bus as soon as the temperature rises rapidly.

2. The main cause of casualties is high temperature and CO and other toxic gases. Pre-fire is small, the toxic flue gas has been rapidly spread throughout the car. After the doors and windows open, CO concentration rise rate decreased, but still remain at a high level, so that the car suffocating people difficult to escape.

3. According to the simulation results, it can be found that within 200 seconds before the fire development, CO and other toxic gas concentrations are at a low level. Flame spread and high temperature areas are also concentrated in the distance from the fire near the location, this time should be the golden age of escape, passengers should remain calm, do not crowded, it is also conducive to rescue workers rescue.

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