Fire and Explosion Hazard Prediction Base on Virtual Reality in Tank Farm

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***Abstract*—Many fires and explosions happen in tank farm. A fire and explosion simulation method based on VR is used. Tank fire and explosion special effect is realized by classical particle system. The real-time fire growth model, fireball growth model, fireball heat radiation model are created. The shock wave model of BLEVE also is created. The models and results of FDS (Fire Dynamic Simulator) are built in virtual reality system. It can show the process of fire and explosion development and calculate the hazard of fire and explosion. The virtual reality system can predict and provide a method to control the fire and explosion hazard**

***Index Terms*—fire, explosion, particle system, hazard prediction, real-time, prediction**

I. INTRODUCTION

The hazardous chemicals have been concerned, when some major and extraordinarily serious accidents happen. On December 11th, 2005, fire and explosion happened in Buncefield oil depot. It caused 43 persons wound, and the direct economic loss is 2.5 billion pounds. On October 29th, 2009, the fire and explosion happened in a large oil tank farm at rajasthan state of India. It caused thirteen persons were killed and one hundred fifty persons injured. November 13th, 2005, China Petroleum Jilin Petro-chemical Company pairs of benzene plant explosion triggered 8 persons dead, and 60 persons wound. It also induced a major Songhua River water pollution accident. January 7th, 2010, China Petroleum Lanzhou Petro-chemical Company hydrocarbon explosion made 6 persons dead, 6 persons wound. Virtual reality will be applied to simulate and predict the accidents of hazardous chemicals, which can provide a new method on rescue and controls.

The fire simulator of CFAST was built in virtual reality visualization system of building fire by Bukowski. The FDS use large eddy simulation to simulate the development process of tank fire[1-3].Liu Kun et al developed a virtual training system for fire using some algorithms of real time rendering, AI and PR, combining with hazards model fire. They advanced a method, which used virtual reality method, to implement a software system of fire hazard and training. They combined OpenGL with DirectX to realize C-S based virtual training system for fire in Windows [4-7].Li Jianwei modified the particle system, and which could not only get the area of fire suffering, the direction of fire spreading and size of fire, but also provide realistic simulation to observers[8].Lin Kaihui et al studied a fire fighting simulation system of forest simulation base on the High Level Architecture in order to meet the requirements of performing simulation tests on multiple scenarios[9].Based on Vega, the feasibility of developing fire fighting and rescuing simulation training system is analyzed by Jin Xusheng et al. Some key technologies concerning how to realize the system are introduced, including the flow of data processing, 3D modeling, the development of application software [10].Chen Chi, et al investigated the application of virtual reality technology to building fire simulation, and presented the methods for simulating a fire in an interactive virtual environment. The spreading of flame and smoke in the virtual fire scene is based on the simulation results of fire simulation software FDS[11-16].

II. REALIZATION OF FIRE SPECIAL EFFECT

A. Realization of Flame Special Effect

According to the classical theory of particle systems, each particle should be considered a little light in the flame simulation, the value of each pixel on screen brightness are calculated based on light model. However, because lighting calculations are very time-consuming, it is difficult to meet real-time requirements if classical particle theory is used to simulate the flame. Therefore, the flame particles are simplified. Each particles of flame is looked as a point in the OSG, and use its color changes to achieve the approximate effect of the flame. In the drawing of a specific frame, it draws the point in the current movement position or line which behalf the movement of particles in the adjacent two frames.

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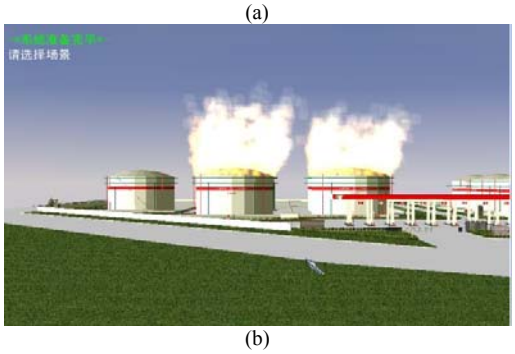
A circle, parallel with coordinate system, is looked as flame particles emitter. The center of circle and its radius are (o_x, o_y, o_z) and r. So the coordinates of new particle is $x = o_x + rand() \times r$, $y = o_y$ $z = o_z + rand() \times r$. The life cycle of particle can be calculated, and it equals to the ratio of flame height and mean velocity of particle movement. The flame height can be calculated by equation (1).

$$H/D = 42(m''/\rho_a\sqrt{gD})^{0.61} \quad (1)$$

In order to improve the authenticity of the flame, textures are pasted on pool fire and jet fire. The particle density lies on the scope of 200-400. The special effect is shown in Fig.1.

(a)



(b)

Figure 1. Flame special effect.

B. Realization of Smoke Special Effect

Because of the complexity of smoke movement, the smoke movement is simplified base on mechanical properties. The main purpose is improving system performance to achieve the real-time effect. The model is shown as flowing.

$$\frac{\partial \rho}{\partial t} + \nabla \rho u = 0 \quad (2)$$

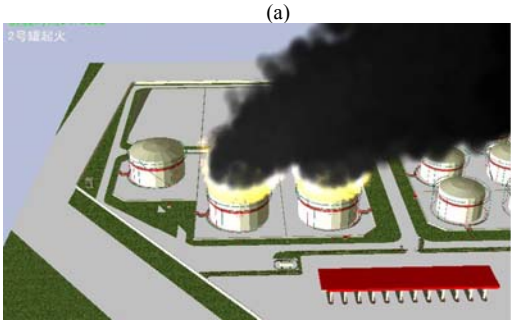
$$\rho\left(\frac{\partial u}{\partial t} + (u\nabla)u\right) + \nabla p - \rho g = \nabla \sigma \quad (3)$$

$$\rho c_P\left(\frac{\partial T}{\partial t} + u\nabla T\right) + \frac{dp}{dt} = q + \nabla k \nabla T \quad (4)$$

In order to improve the realistic results of drawing, the texture mapping technology is used in the process of smoke drawing. The main method is put an image map on polygonal surface chip.

Two layer particles are used in realization of fire special effect. In order to reduce the speed, the flame and smoke is tighter. Ring flame is applied in fire, and smoke generated from the root of a certain position the flame. Smoke special effect is shown in Fig.2.

(a)



(b)

Figure 2. Flame and smoke special effect.

III. Fire and Explosion Accident Hazard Prediction

A. Fire Hazard Accident Prediction

The fire growth equation is gotten as each kind of diameter tank fire is simulated by FDS (Fig.3 is one case of simulation). Flame growth equation is $H=0.0469t^2$

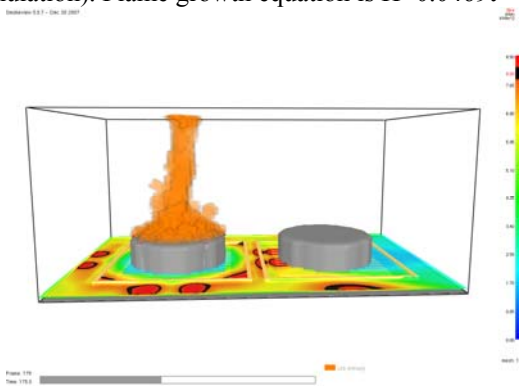


Figure 3. Tank fire simulated by FDS.

There is no deflection on flame and smoke, when you select no-wind mode on virtual reality system. It is shown in Fig.4.The flame height can be calculated by equation (5) on wind condition.

$$H/D = 55(m''/\rho_a\sqrt{gD})^{0.61}(u^*)^{-0.21} \quad (5)$$

$$u^* = u_w \Big/ \left(\frac{gm''D}{\rho_a}\right)^{\frac{1}{3}}$$

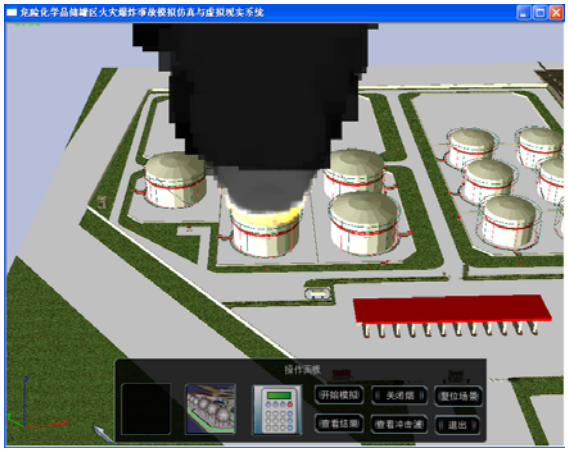


Figure 4. Tank fire on condition of no-wind.

When the wind speed is 5m / s, flames and smoke simulation results are shown in Fig.5. It can be found the deflection of flame and smoke because of wind. The deflection angle β can be calculated. $\beta = \frac{0.55\mu_w^2}{D} \times 57.32$. In addition, the smoke concentration and the color fade as the impact of the wind.

Flame heat radiation is the main hazard of tank fire. The heat radiation can be calculated the following equations.

$$E = \frac{Q}{\pi D^2} \tag{6}$$

$$Q = m''\Delta H(1 - e^{-k\beta D})\frac{\pi D^2}{4} \tag{7}$$

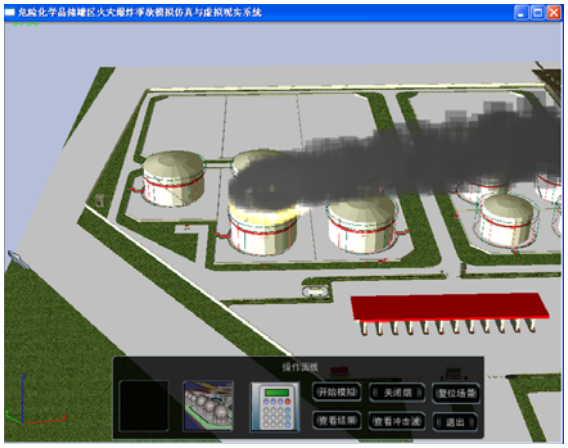


Figure 5. Tank fire flame and smoke on 5m/s wind speed

The heat radiation on different distance from the flame can be calculated in equation (7).

$$I = \alpha\tau \frac{Q}{4\pi(L^2 + (\frac{H}{2} + H_1)^2)} \tag{8}$$

According to heat radiation hazard index (as shown in Tab.1) and the FDS simulation results, the gasoline tank fire hazard zone such as death, serious wound and mild wound areas is calculated. The results are shown in Fig.6, and the red, blue and green round means the death, serious burns and mild burns area.

TABLE I. HEAT RADIATION HAZARD INDEX

Hazard grade	Mild burns	Serious burns	Death(death rate is 100 % in a minute)
Heat radiation intensity(kW/m^2)	4.0	12.5	25

Figure 6. Hazard zone of gasoline tank fire

B. Explosion Hazard Prediction

LPG and LNG tanks easy cause the boiling liquid expanding vapor explosion (BLEVE) in fire condition. The main hazard of BLEVE is fireball and shock wave. The fireball is developing on the process of rise. The equation (9) can calculate the radius of fireball in rise.

$$\mathrm{R}(t) = \begin{cases} 4.332(cW)^{\frac{1}{4}} t^{\frac{1}{3}} & 0 \le t \le \frac{1}{3}t_d \\ 2.9(cW)^{\frac{1}{3}} & \frac{1}{3}t_d < t \le t_d \end{cases} \tag{9}$$

$$t_d = 1.26(cW)^{0.224}$$

If he heat radiation energy on fireball surface is uniformly spread. The heat radiation on fireball surface is calculated by equation (10).

$$\mathrm{E}(t) = \begin{cases} 0.0036(1.21P_v)^{0.32}\Delta H_c(cW)^{\frac{1}{12}} & 0 \le t \le \frac{1}{3}t_d \\ 400[\frac{3}{2}(1 - \frac{t}{t_d})] & \frac{1}{3}t_d < t \le t_d \end{cases} \tag{10}$$

The heat radiation of each time in the process of rise can be calculated by equation (11) and (12).

$$I = \begin{cases} \frac{0.0036\alpha\tau(1.21P_v)^{0.32}\Delta H_c(cW)^{\frac{1}{12}}R^2(t)}{4(L^2 + H^2(t))} & 0 \le t \le \frac{1}{3}t_d \\ \frac{400\alpha\tau[\frac{3}{2}(1 - \frac{t}{t_d})]R^2(t)}{4(L^2 + H^2(t))} & \frac{1}{3}t_d < t \le t_d \end{cases} \tag{11}$$

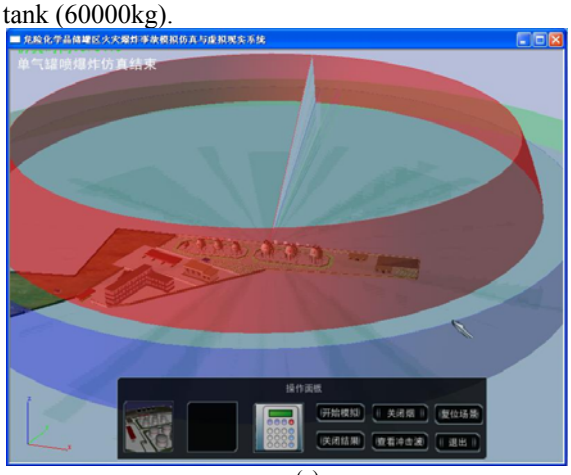
$$\mathrm{H}(t) = \begin{cases} 4.332(cW)^{\frac{1}{4}} t^{\frac{1}{3}} & 0 \le t \le \frac{1}{3}t_d \\ 6.9(cW)^{0.109} t & \frac{1}{3}t_d < t \le t_d \end{cases} \tag{12}$$

Another main hazard is shock wave of BLEVE, which can be calculated by equation(13).

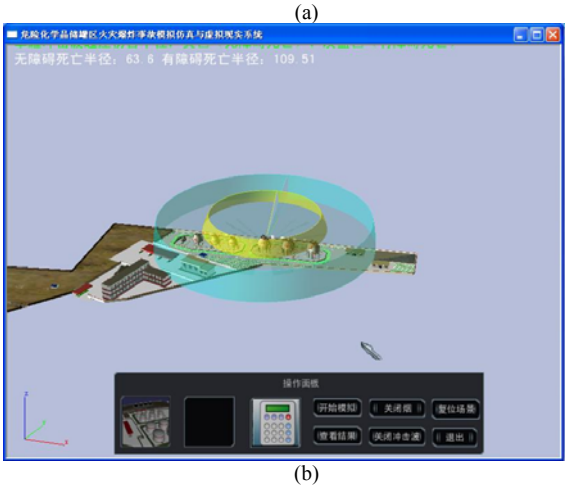
$$S = 0.274W_{TNT}^{\ 0.493} \tag{13}$$

$$W_{TNT} = \frac{c\alpha_e W\Delta H_c}{H_{TNT}}$$

According to the above equation, the Fig.7 shows the fireball hazard and shock wave hazard zone of LPG tank (60000kg).



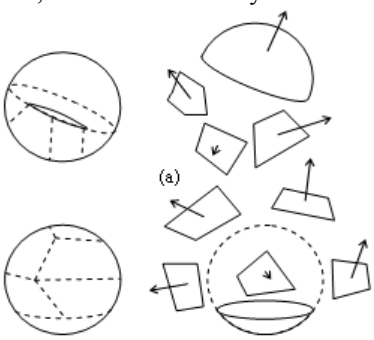
(a)



(b)

Figure 7. Fireball and shock wave hazard zone of LPG tank explosion

Fragments are another main hazard of explosion. The Fig.8 is fragment model of spherical tank explosion. The fragments movement is stochastic and difficult to prediction. Monte-Carlo method is used to calculate the projectile trajectory of fragments.Fig.9 is the spatial distribution of fragments of tank wall. The volume of fuel in tank is main factor of fragments movement,When the volume is 80% of full, the fragments may be projected to about 1200 m away. When the volume is 50% of full, the debris can reach about 820m, and when the volume is only 10% of full, the debris flew only about 200 m away.



(a)

(b)

Figure 8. Fragment model of spherical tank

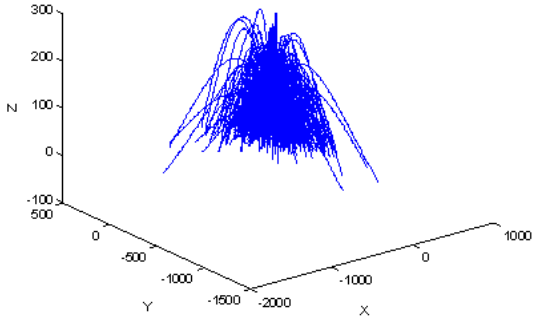


Figure 9. Spatial distribution of fragments

IV. Conclusions

Tank fire and explosion effect is realized by particle system. Fire and explosion real-time model is created. The models and results of FDS are built in virtual reality system. It can show and predict the process of fire and explosion development and calculate the hazard area of fire and explosion.

Appendix A Nomenclature

ρ density, kg/m^3
u velocity vector, m/s
p pressure, Pa,
c_p constant-pressure specific heat, J/(kg. K)
T temperature, K
k coefficient of heat conduction, W/(m^2. K)
t time, s
q heat release rate of per volume, W/m^3
R gas constant
σ standard stresses tensor compressible fluid, Pa
H flame height,m
D tank diameter, m
m'' mass loss rate, kg/m^2.s
ρ_a fule density, kg/m^3
g acceleration of gravity, m/s^2
μ_w wind speed,m/s
β deflection angle
kβ experience coefficient
ΔH combustion heat
L distance from flame,m
H_1 tank height, m
α absorption rate
τ atmospheric transmissivity
R(t) fireball radius, m
c proportion of material involved in the reaction, %
W fuel mass, kg
t_d fireball existence time, s
P_v open-pressure of pressure relief valve, MPa

H(t) the height of fireball, m
W_{TNT} TNT equivalent weight, kg
α_e coefficient of TNT equivalent weigh, α_e=0.04

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