Experimental research and numerical modelling of the movement of explosive and deflagrable clouds

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Abstract

In order to achieve a movement rule for contaminative clouds by explosion and deflagration, field experiments were carried out during the summer of 2010 in which the process of the fireball and movement of the clouds were recorded respectively using high speed CCD recorders, video cameras and infrared photography. Based on the assumption that the main effects on the ascending movement of clouds are gravity and buoyancy, we provide a numerical model for the movement of the clouds that considers the meteorological conditions. The modelling results are reasonable compared to the data obtained from the experiment, which can serve as a reference to the related fields.
Keywords: contaminative clouds, explosion, deflagration, field experiments, numerical model.

1   Introduction

Contaminative events, especially a "dirty bomb" or other mephitic vapour explosions, have received a great deal of attention. In order to study the movement of the clouds by explosion and deflagration, experiments and numerical modelling methods have been put forward by a number of scientists. Generally speaking, two kinds of experimental methods are used, one is performed in the laboratory and another is in the field.

After the similar movement theory of the instantaneous heat sources was put forward by Taylor [1], Morton *et al.* [2] performed an experiment on the different densities of liquid in the box gutter to model the movement of the thermal energy in the atmosphere. Zaslavskii and Sconikov [3] designed a method of igniting the

bubbles of He, N_2 and O_2 mixture to produce the buoyancy vortex rings. Zheng [4] used the instantaneous heat sources to study the movement of the buoyant vortex rings by igniting the bubbles of C_2H_4 and O_2 mixture to produce combustion fireballs and smokes in laboratory. Thielen and Schrodl [5] used two cameras to record the movement of the explosive cloud and compared test results with the HOTSPOT health physics codes. The experiment indicated that the approach was reasonable.

On the other hand, the development of numerical calculation have provided the support for the study of the explosive cloud. Makhviladze *et al.* [6] developed a model for simulating the pollution of the explosion. Krispin and Collins [7] and Brown *et al.* [8] used projection method to calculate the development of the low density bubble. They have provided reasonable results of the explosive bubble without considering the meteorological condition and had not given comparison to the experiment data.

In this paper, we performed the experiments in the field and numerical modelling to study the mechanism of the ascending of the explosive and deflagration cloud. The experiments have been performed using two kinds of video recorders, the high speed CCD recorders and the video cameras, to record the process of the fireball and the movement of the cloud respectively. Based on the assumption that the main effects on the clouds ascending movement are gravity and buoyancy, we provided numerical model on the movement of the thermal considering the meteorological condition.

2 Experimental design

The experiments were performed from July 17 to August 4, 2010. We chose a training area as the test site at Beijing northwest suburb. Figure 1 shows the experimental field. Figure 2 shows the experimental devices. The exploders are placed 1.5 meters above the ground. Two high speed CCD recorders of MotionXtra HG–LE are laid from a distant about 100m, which are used to record the change of the explosion fireball. At the same time, two video cameras of SONY are placed in another two different directions about 200m used to record the movement of the explosive cloud.

To consider the influence of meteorological conditions, a meteorological measuring tower is set near the exploder site about 400 meters to provide meteorological observation, which had 12 meters high and could capture 3 levels parameters such as pressure, temperature, density and wind, on 4m, 7.5m and 11m respectively.

2.1 Explosive experiments results

We carried 23 times explosive experiments altogether, the explosive material were RDX and TNT, and the equivalent TNT masses from 0.1kg to 10.0kg. Table 1 contains the matrix of the explosive experiments.
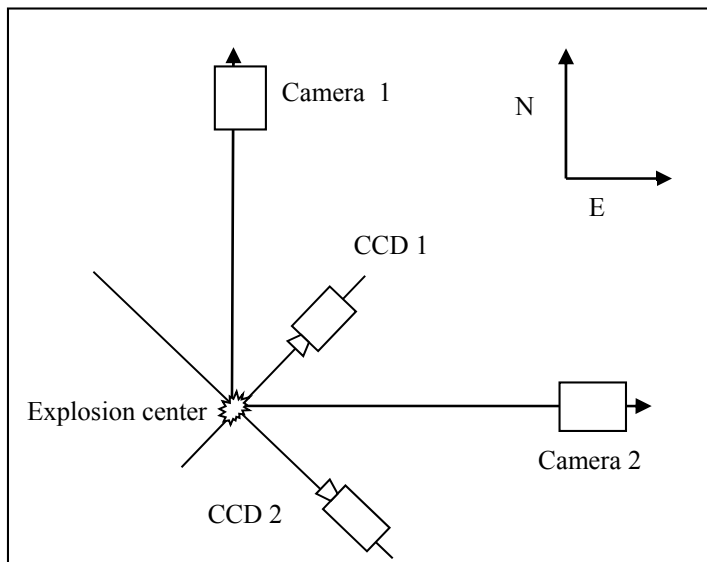
Figure 1: The experimental field.

Figure 2: Sketch of the explosion experiment.

Table 1: Explosive experiments matrix.

Test	Explosive Material	Equivalent TNT mass /kg	Recording altitude /m	Recording time /s
BZ1	RDX	0.1	33.6	35
BZ2	RDX	0.1	21.7	15
BZ3	RDX	0.1	17.9	40
BZ4	RDX	0.1	11.8	17
BZ5	TNT	0.1		
BZ6	TNT	0.1	30.9	54
BZ7	TNT	0.1	33.9	60
BZ8	TNT	0.1	19.2	27
BZ9	TNT	0.1	14.8	8
BZ10	TNT	0.1	11.9	8
BZ11	RDX	0.5	26.9	71
BZ12	TNT	0.5	27.37	21
BZ13	RDX	1.0	25.4	34
BZ14	TNT	1.0	23.2	45
BZ15	TNT	1.0	30.7	14
BZ16	TNT	1.0	30.89	16
BZ17	TNT	1.0	29.02	21
BZ18	TNT	1.0	48.3	30
BZ19	TNT	1.0	46.7	34
BZ20	RDX	5.0	40.5	33
BZ21	RDX	5.0	38.4	34
BZ22	RDX	5.0	34.8	35
BZ23	RDX	10.0	61.3	35

"Recording altitude" and "Recording time" represent the maximal recording top altitude and the maximal recording time of the cloud respectively.

Figure 3 shows a picture of explosion clouds from two observed directions at different times of test BZ7.

(a) From the direction of camera 1 (t = 20s)

(b) From the direction of camera 2 (t = 20s)

(c) From the direction of camera 1 (t = 35s)

(d) From the direction of camera 2 (t = 35s)

Figure 3:   Explosion clouds from two observed directions at different times of test BZ7.

2.2 Deflagrable experiment results

Several deflagrable experiments have been carried out through during the same time. The recording method was the same as the explosive experiment. The difference between explosion and deflagration tests is in the producing of the cloud. Deflagration clouds are created by burning of the fuel using the equipment of the deflagrator but no chemical explosion taking place. When the detonator is ignited, the liquid fuel can be jetted into the air and ignited instantly. At the same time, we adopt the infrared photography of DALI DM60 to obtain the temperature of the fireball during the deflagrable experiments. Table 2 contains the matrix of the deflagrable experiments.

Table 2: Deflagrable experiments matrix.

Test	Fuel	Volume	Recording radius /m	Recording altitude /m
BR1	gasoline	4L		
BR2	gasoline	4L	9.4	13.04
BR3	gasoline	4L		
BR4	gasoline	4L	17.7	38
BR5	gasoline	4L	19.6	40.9
BR6	gasoline	4L	9.9	32.9
BR7	gasoline	4L	15.4	33.2

"Volume" represents the volume of the fuel, "Recording radius" and "Recording altitude" represent the maximal recording radius and altitude of the cloud respectively during the recording time.

Figure 4 shows the states of the fireball at different times from high speed CCD recorder of BR2 test, the frequency of the CCD recording was 1000 frame/s.

(a) t = 100ms   (b) t = 300ms   (c) t = 500ms
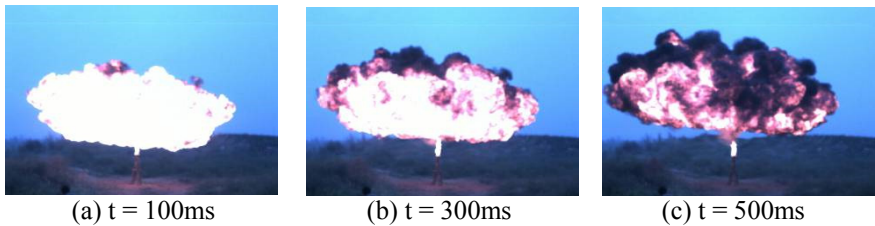
Figure 4: Fireballs at different times of deflagrable test BR2.

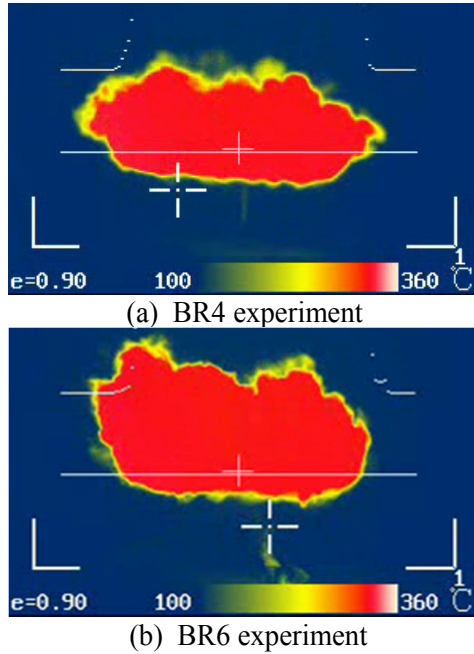Figure 5 shows the picture of the temperature increment of fireball during the deflagrable test BR4 and BR6.

(a) BR4 experiment

(b) BR6 experiment

Figure 5: Temperature increment of the deflagrable experiment.

3 Numerical model

Suppose that the main mechanism of the explosive bubble rising is the buoyancy. Since the top altitude of the cloud is about 50 meters from the experiments, we assume that the calculated domain (60m × 60m × 60m) fill with incompressible gas, a spherical thermal with radius of R fill with higher temperature air and locate at 1.5m above the domain bottom. The equation can be written as the following:

$$\frac{\partial u'}{\partial t} + \mathbf{U} \bullet \nabla u' = -\frac{1}{\rho}\frac{\partial p'}{\partial x} \tag{1}$$

$$\frac{\partial v'}{\partial t} + \mathbf{U} \bullet \nabla v' = -\frac{1}{\rho}\frac{\partial p'}{\partial y} \tag{2}$$

$$\frac{\partial w'}{\partial t} + \mathbf{U} \bullet \nabla w' = -\frac{1}{\rho}\frac{\partial p'}{\partial z} + g\frac{\theta'}{\overline{\theta}} \tag{3}$$

$$\frac{\partial \theta'}{\partial t} + \mathbf{U} \bullet \nabla \theta' + \frac{N^2 \overline{\theta}}{g} w = 0 \tag{4}$$

$$\frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} + \frac{\partial w'}{\partial z} = 0 \tag{5}$$

where u', v', w', θ', p' represent the disturbance of three directions velocity, potential temperature and pressure. U, $\bar{\rho}$, $\bar{\theta}$ represent the mean velocity, mean density and mean potential temperature. N represents the Brunt–Vaisala frequency.

3.1 Potential temperature increment of the explosive experiment

The potential temperature increment can be calculated by the equation of the following:

$$Q = C_v \bar{\rho} V_0 \Delta\theta \tag{6}$$

where Q is the energy of the explosion, and we assume that about 1/3 of the explosive energy were transformed to the heat. C_v is the specific heat and the value is 718J/(kg·K). At the same time we assume that all the heat energy were used to increase the potential temperature increment. $\bar{\rho}$ is mean atmospheric density. V_0 presents the volume of the initial cloud and $\Delta\theta$ presents the potential temperature increment of the explosive fireball. Table 3 shows the calculated condition of the explosive tests.

Table 3: Calculated condition of the explosive experiments.

Test	Mean temperature /°C	Mean velocity /(m·s^{-1})	Brunt–Vaisala frequency /s^{-2}	Potential temperature increment /K	Initial cloud radius /m
BZ4	24.906	1.5264	1.648×10^{-3}	47.02	0.711
BZ6	26.756	0.7861	2.136×10^{-3}	46.89	1.11
BZ8	29.266	2.8195	-1.36×10^{-4}	46.749	2.06
BZ12	28.482	1.5631	7.17×10^{-4}	47.063	2.465
BZ18	25.403	0.964	2.23×10^{-3}	47.308	3.75
BZ19	25.403	0.9638	1.65×10^{-3}	47.296	2.297

The "Mean temperature", "Mean velocity" and "Brunt-Vaisala frequency" represent the mean temperature, mean velocity and the Brunt–Vaisala frequency of the atmospheric environment respectively during the tests. "Potential temperature increment" represents the value of the potential temperature increment calculated from equation (6). "Initial cloud radius" represents the radius of the cloud measuring from CCD camera when the fireball crush out.

3.2 Potential temperature increment of deflagrable experiment

Due to the character of the deflagrable test, the deflagrable energy cannot be exacted since we cannot make sure how much fuel is joined to the deflagration. We adopt the infrared photography to determinate the temperature of the fireball. We can obtain the potential temperature increment from the temperature increment. The calculated parameters are shown in Table 4.

Table 4: Calculated condition of deflagrable experiment.

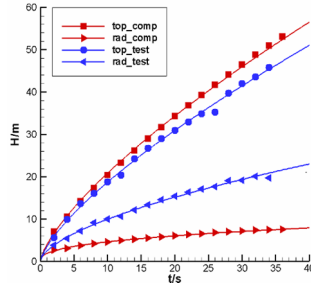| Test	Mean temperature /°C	Mean velocity/ m·s^{-1}	Brunt–Vaisala frequency/s^{-2}	Potential temperature increment /K	Initial cloud radius /m
BR1	25.928	1.461	1.406×10^{-3}		
BR2	26.303	1.523	1.394×10^{-3}	324.4	4.594
BR3	26.526	1.111	1.484×10^{-3}		
BR4	26.655	1.294	1.396×10^{-3}	324.2	4.336
BR5	27.034	1.395	1.189×10^{-3}	324.1	4.116
BR6	27.034	1.395	1.189×10^{-3}	323.6	2.857
BR7	26.665	2.473	1.755×10^{-3}	324.0	2.735

The "Potential temperature increment" represents the value of the potential temperature increment resulting from temperature increment of the fireball. "Initial cloud radius" represents the radius of the cloud measuring from CCD camera when the fireball crush out. Other parameters are the same as mentioned above.

4   Results and discussion

We use the uniform grid of 0.4m and suppose the underside of the thermal were placed above the bottom 1.5m. The bottom of the calculated space is rigid wall, and the other sides are freedom .Figure 6 shows the comparison of the cloud top altitudes and radius of the explosive experiment and calculated results. Figure 7 represents the comparison of the cloud top altitudes and radius of the deflagrable experiment and calculated results. Where the "top_comp" and the "rad_comp" represent the calculated results of the cloud top altitude and radius respectively; and the "top_experiment" and the "rad_experiment" indicate the observed results of the top altitude and radius respectively.
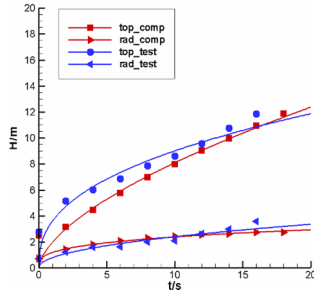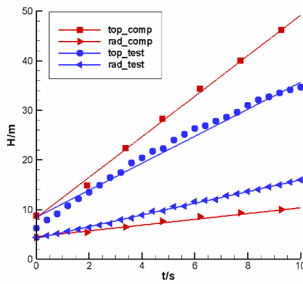
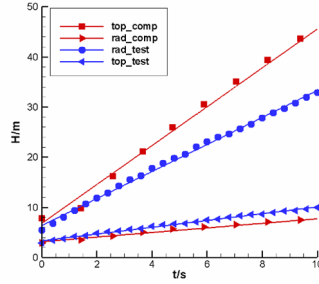(a) Explosive experiment of BZ4   (b) Explosive experiment of BZ19

Figure 6:   Comparison of the explosive test and calculated results of top altitudes and radii.

(a) Deflagrable experiment of BR4   (b) Deflagrable experiment of BR6

Figure 7:   Comparison of the deflagrable test and calculated results of top altitudes and radii.

From the results, we can see that the tendency of the calculated curve closed to the results of the experiments. And the variation rates of the top altitude of the cloud are greater than the variation rate of the radius to both the numerical calculated results and the experiment results. But some differences are existing:

    a.   Top altitudes of numerical results are larger than that of experiments. At the same time, radii of the numerical results are smaller than experiments.

    b.   Top altitudes and radii of the explosive clouds become slow with time while deflagrable clouds appear to be linear with time.

We give some explanations:

To the first difference, we use a package containing carbonic powder placed on an explosive stuff, which make us difficult to determine the radius of the initial cloud. And the difference of the initial value can result different simulated value. Besides, more and more circumambient matter is involved into the clouds with the rise of the cloud. The effect of the atmospheric turbulence can also decrease the altitude of the explosive cloud and increase the radius of the cloud. At last, the fireball of the deflagrable experiment looks more like an ellipsoid thermal. The transverse radius is greater than the lengthwise radius of the fireball. We use

the maximal fireball radius as the spherical thermal in the calculation. This reason can also decrease the top altitude of the cloud and increase the radius of the cloud.

To the second difference, the value of the potential temperature increment is decreased and which result in reducing of the buoyancy with the movement of the cloud. The top altitude and the radius of the explosive cloud become slow with time. To the deflagrable experiment, results seem linear with time because short record time owing to large radius of cloud and small pantoscopic of camera.

5   Conclusions

We present an experimental approach to study the movement of the explosive and deflagrable cloud. We measure both the fireball and the cloud at the same time rather than the cloud as the former. Based on the measured fireball parameter and the assumption that the main effect on the cloud rising is gravity and buoyancy, we provide a numerical model on the movement of the thermal considering the meteorological condition and have a comparison to data of field experiments. The experimental method and the numerical model are reasonable and can be studied further.

Acknowledgements

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