Chinese J. Chem. Eng., **11** (1) 90 – 93 (2003)

Experimental Study on Unconfined Vapor Cloud Explosion*

BI Mingshu(毕明树)[a,], DING Xinwei(丁信伟)[a], ZHOU Yihui(周一卉)[a], YU Jianliang(喻建良)[a], WANG Shulan(王淑兰)[a] and ABULITI Abudula[b]**
[a] School of Chemical Engineering, Dalian University of Technology, Dalian 116012, China
[b] Faculty of Science and Technology, Hirosaki University, Japan

Abstract An experimental system was setup to study the pressure field of unconfined vapor cloud explosions. The semi-spherical vapor clouds were formed by slotted 0.02 mm polyethylene film. In the center of the cloud was an ignition electrode that met ISO6164 "Explosion Protection System" and NFPA68 "Guide for Venting of Deflagrations". A data-acquisition system, with dynamic responding time less than 0.001 s with 0.5% accuracy, recorded the pressure-time diagram of acetylene-air mixture explosion with stoichiometrical ratio. The initial cloud diameters varied from 60 cm to 300 cm. Based on the analysis of experimental data, the quantitative relationship is obtained for the cloud explosion pressure, the cloud radius and the distance from ignition point. Present results provide a useful way to evaluate the building damage caused by unconfined vapor cloud explosions and to determine the indispensable explosion grade in the application of multi-energy model.
Keywords unconfined vapor cloud explosion, safety, experiment, deflagration

1 INTRODUCTION

The pressure of unconfined vapor cloud explosion(UVCE) is a very important parameter to risk assessment and safety design. Some experiments were carried out under given conditions[1–3], but it is not enough to draw a quantitative conclusion because of the scatter of experimental conditions and the complex mechanism of UVCE. As an empirical model, TNT equivalency method has been applied to the assessment of industrial accidents. Nevertheless, its applications show that the equivalent efficiency is scattered from 0.02% to 15.9%[4,5]. Self-resemblance theory[6,7] is an over-simplified model in which the flame velocity is assumed as a constant. Multi-energy model[8–10] is considered as the most reasonable one so far, but it is difficult to determine the explosion grade in its practical applications. The scaling method[11] according to 1/3 power of cloud volume is inconsistent with industrial cases. Therefore this paper focuses on the experimental study for a quantitative relationship of the cloud explosion pressure, the cloud radius and the distance from ignition point.

2 EXPERIMENTAL SYSTEM

The experiments were carried out in an open field of 4000 m^2 with safety defences. The experimental system is as follows.

2.1 Pressure transducers

The pressure transducers were used to receive pressure signals. Their measuring range is −5—10 kPa with an accuracy of 0.5%. The voltage supplied for transducers is 24 V(D.C.)

2.2 Data acquisition card

The card used for experimental data acquisition was a 12 bit A/D conversion card with 8 synchronic channels with sampling frequency of 200 kHz per channel.

2.3 Ignition device

The ignition device was made according to ISO6164 "Explosion Protection System" and NFPA68 "Guide for Venting of Deflagrations". The ignition energy is approximate 100 mJ which is higher than that of most industrial ignition sources such as static electricity, sparks and so on. Fig. 1 shows the principle of ignition device.

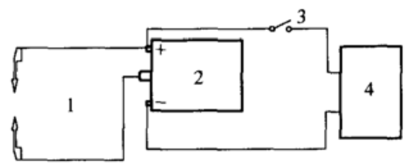

Figure 1 The principle diagram of ignition device
1—ignition electrodes; 2—ignition coil;
3—switch; 4—battery (12V)

2.4 Computer

A computer was used to save and process the data. The card was plugged in the PC socket of the computer and the transducers were connected with data acquisition card by shielded cables. Fig. 2 shows the principle of data acquisition.

2.5 Experimental method

The semi-spherical stoichiometrical acetylene-air mixture clouds were formed by 4 pieces of 0.02 mm

Received 2001-12-18, accepted 2002-08-09.
* Supported by the National Natural Science Foundation of China(No. 50076006).
** To whom correspondence should be addressed.

polyethylene film. Each of them is one-eighth sphere. In the process of inflation, they were connected with each other by adhesive tapes. Just before ignition, the tapes were removed. The ignition electrode was in the center of the sphere. And 16 transducers were arranged around the sphere in different radii and heights.

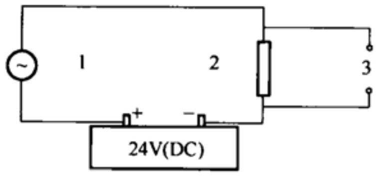

Figure 2 The principle diagram of data collection
1—pressure transducer; 2—sampling resistance;
3—signal output

3 EXPERIMENTAL RESULTS

The experiments were carried out for acetylene-air clouds with initial radius of 30 cm, 50 cm, 100 cm and 150 cm, respectively. Fig. 3 is an instantaneous record of flame. Fig. 4 is a typical pressure-time curve measured during explosion of a 100 cm hemisphere with the time counted from the ignition. Fig. 5 is the experimental results and their fitting curves. Fig. 6 is the comprehensive results and their fitting curve.

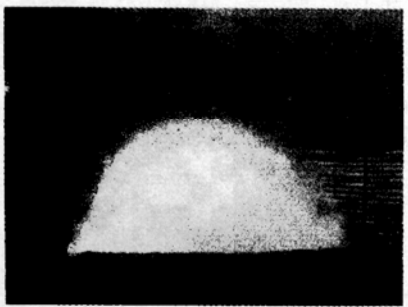

Figure 3 An instantaneous record of flame

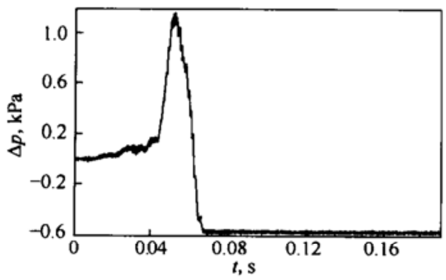

Figure 4 Measured explosion pressure-time diagram
($R_0 = 100$ cm)

During explosion, the cloud volume increases with the propagation of flame. When the flammable gas mixture burns up, the combustion ends and the pressures reach their peaks. Of all the peaks, the maximum pressure was detected at the final radius of cloud.

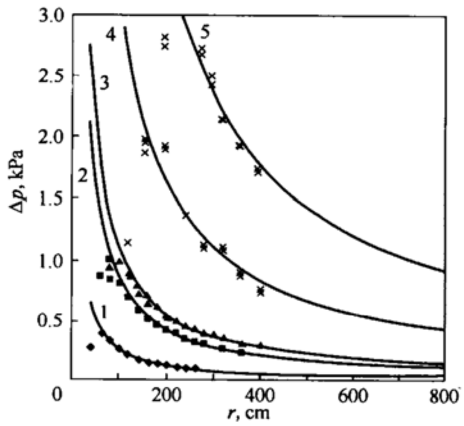

Figure 5 Experimental results and their fitting curves
1—$\Delta p = 0.264/r$, $R_0 = 30$ cm;
2—$\Delta p = 0.847/r$, $R_0 = 50$ cm;
3—$\Delta p = 1.101/r$, $R_0 = 60$ cm;
4—$\Delta p = 3.275/r$, $R_0 = 100$ cm;
5—$\Delta P = 7.117/r$, $R_0 = 150$ cm;
◆, ■, ▲, ×, ∗ experimental data;
—— fitting curve

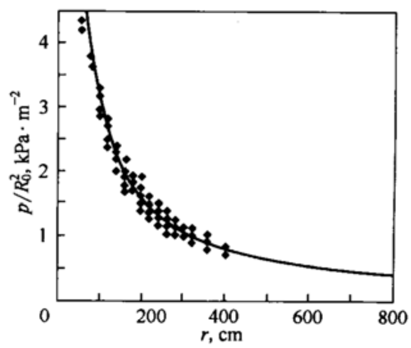

Figure 6 The comprehensive result and its fitting curve
◆ experimental data; —— fitting curve

For acetylene-air mixture, it is clear from Fig. 5 that the maximum pressure occurs at the place 1.7 times of initial cloud radius from ignition point.

For $r > 1.7R_0$, the fitting equation of the experimental data shown in Fig. 6 is

$$\Delta p = 3R_0^2/r \tag{1}$$

The equation is effective under the confidence level of 0.99 based on the result of square deviation analysis listed in Table 1.

It can be inferred from above results that the pressure of UVCE is proportional to the square of cloud initial radius and inversely proportional to the distance from ignition point. Thus Eq. (2) can be proposed for any cloud explosions.

$$\Delta p = AR_0^2/r \tag{2}$$

where A is a constant depending on the cloud mixture.

Table 1 Mean square deviation analysis on fitting equation

S_1	S_2	$F=\dfrac{s_1/1}{S_2/(n-2)}$	$F_{0.01}(1,n-2)$
305524	248	3692	34.10

4 DISCUSSION

4.1 Damage of UVCE

The experimental results show that the maximum pressure occurs at the final radius of cloud, and for acetylene-air mixture, the maximum pressure occurs at the place 1.7 times of initial cloud radius from ignition point. Substituting $r = 1.7R_0$ into Eq. (1), the calculated cloud initial radii causing building-damage are obtained and listed in Table 2.

Table 2 The building-damaging pressure[12] and calculated gas cloud radius

Damaging part	p_d, kPa	R_0, m
glass window	12.0	6.8
removing roof	24	13.6
damaging brick wall	37	21.0
damaging concrete wall	76	43.1

4.2 Scaling rule

An alternative to the TNT equivalence method is to scale experimental results[11]. If a pressure-distance curve is given based on the experimental data of explosions for $1000\,m^3$, for a cloud explosion with a volume V, the blast wave pressure can be found from the curve simply by scaling the actual distance from the explosion center r to an equivalent distance r_{eq}.

$$r_{eq} = r\left(\frac{1000}{V}\right)^{1/3} \tag{3}$$

It is clear that the pressure varies only with the equivalent distance r_{eq} and is irrelevant to the cloud volume. However, the experimental results of present study show that the explosion pressure increases with the 2/3 power of cloud volume. Other experimental results[1] have also confirmed that the explosion pressure increases with the cloud volume.

4.3 Comparison to multi-energy model

The converted experimental results according to the coordinates of multi-energy model are shown in Fig. 7. It is obvious that our results agree well with those of multi-energy model in dimensionless over pressure-dimensionless distance relationship. The explosion grade increases with the radius of flammable gas cloud. For example, the explosion grade is lower than 1 for a cloud with a radius of 50 cm and reaches 4 for a cloud with a radius of 500 cm. Thus Eq. (2) can be used to determine the explosion grade required in the application of multi-energy model.

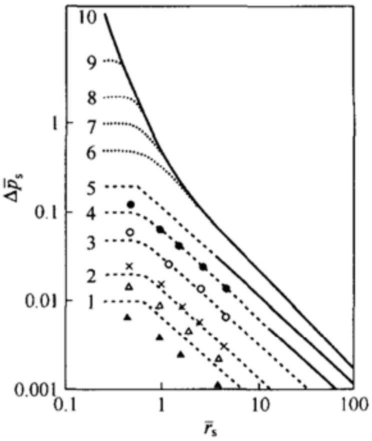

Figure 7 The comparison of present results with muli-energy model

R_0, cm: ● 500; ○ 300; × 150; △ 100; ▲50

4.4 Comparison to TNT equivalency method

The converted experimental results according to the coordinates of TNT equivalency method are shown in Fig. 8. It is evident that the explosion pressures from TNT equivalency method are much higher than those of the present study because of the essential distinction between TNT explosion and cloud explosion. First, TNT explosion can be considered as point explosion and the volume of explosive can be ignored, but cloud volume should be considered because it increases with the propagation of flame. Second, the energy releases instantaneously in TNT explosion, while it releases step by step in cloud explosion. Third, TNT explosion causes strong shock wave, but cloud explosion usually causes weak pressure wave.

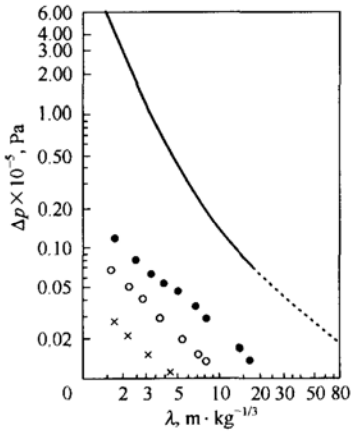

Figure 8 Comparison of present results with TNT equivalency method

R_0, cm: ● 500; ○ 300; × 150;

—— TNT equivalency curve

5 CONCLUSIONS

An experimental study on unconfined vapor cloud explosions was conducted with semi-spherical acetylene-air clouds. The quantitative relationship is obtained for explosion pressure, the cloud radius and the distance from ignition point by fitting the experimental data, that is

$$\Delta p = A\frac{R_0^2}{r}$$

The results agree well with those of multi-energy model in dimensionless pressure-dimensionless distance relationship. The explosion grade increases with the radius of flammable gas cloud. Present results provide a useful way to evaluate the building damage caused by unconfined vapor cloud explosions and to determine the indispensable explosion grade in the application of multi-energy model.

The pressures from TNT equivalency method are far higher than the experimental ones, especially in near field, so it would give over-conservative results in gas cloud explosion accident assessments.

NOMENCLATURE

A	constant depending on cloud mixture, $kPa \cdot m^{-1}$
E_c	combustion energy of clouds in unit volume, $kJ \cdot m^{-3}$
F	F value in square deviation analysis
$F_{0.01}(1, n-2)$	the value under the confidence level of 99% in F test
p_0	initial pressure of clouds, kPa
p_d	building damaging pressure, kPa
Δp	over-pressure of UVCE, kPa
$\Delta \overline{p}_s$	dimensionless over-pressure $\left(\Delta \overline{p}_s = \frac{\Delta p}{p_0}\right)$
R_0	initial radius of gas cloud, m
r	distance from ignition point, m
r_{eq}	equivalent distance
$\overline{r}_s$	dimensionless distance $\left[\overline{r}_s = \frac{r}{(E_C/P_0)^{1/3}}\right]$
S_1	sum of fitting square deviation
S_2	sum of surplus square deviation
t	time, s
V	cloud volume, m^3
W_{TNT}	TNT equivalent mass, kg
λ	equivalent distance $\left(\lambda = \frac{r}{\sqrt[3]{W_{TNT}}}\right)$, $m \cdot kg^{-1/3}$

REFERENCES

1 David, C.B., "Review of large-scale explosion experiments", *Plant/Operations Progress*, **11** (1), 33—40 (1991).

2 Kwon, O.C. , Faeth, G.M., "Flame/stretch interactions of premixed hydrogen-fueled flames", *Combust. Flame*, **124**, 590—610 (2001).

3 Ding, X.W., Li, Z.Y., Li, Y.B., "Flammable gas explosion experiments", *J. Chem. Ind. Eng. (China)*, **50** (4), 558—561 (1999). (in Chinese)

4 Tang, M.J., Baker, Q.A., "Comparison of blast curves from vapor cloud explosions", *J. Loss Prev. Proc. Industries*, **13**, 433—438 (2000).

5 Van den Berg, A.C., "Evaluation of consequence models for gas explosions and blast propagation", The 8th Inter. Symp. on Loss Prev. and Safety Promotion in the Proc. Industries, Antwerp, Belgium(1995).

6 Roger, A. Strehlow, "Blast waves generated by constant velocity flames: A simplified approach", *Combustion and Flame*, **24**, 257—261 (1975).

7 Xu, S.L., Tang, M.J., Mi, Z.C., "Pressure waves generated by steady flames at low velocity", *J. Nanjing Univ. Tech.*, **19** (1), 6—12 (1995). (in Chinese)

8 Van den Berg, A.C., Eggen, J.B.M.M., "Guidance for the application of the multi-energy method", The 2nd Inter. Specialist Meeting on Fuel-Air Explosions, Bergen, Norway(1996).

9 Mercx, W.M., van den Berg, A.C., Hayhurst, C.J., "Developments in vapor cloud explosion blast modeling", *J. Hazardous Mater.*, **71**, 301—319 (2000).

10 Bradley, D., Cresswell, T.M., Puttock, J.S., "Flame acceleration due to flame-induced instabilities in large-scale explosions", *Combust. Flame*, **124**, 551—559 (2001).

11 Dag, B., Jan, R.B., Kees, V.W., "Gas explosion handbook", *J. Harzardous Mater.*, **52**, 72—81 (1997).

12 Li, Y.Q., Ma, S.Z., Mechanics for explosion, *Science Press*, Beijing, 299—301 (1992). (in Chinese)