*Transactions of the Materials Research Society of Japan* 33[2] 373-376 (2008)

# Material Failure Mechanism with Deflagration And Needful Engineering Study

Hiroshi Kaneko
Tokyo Gas Technology Research Institute
1-7-7, Suehiro-cho,Tsurumi-ku, Yokohama-city, Kanagawa 230-0045,Japan
Fax: 81-045-500-8790, e-mail: hrkaneko@tokyo-gas.co.jp

The accidental explosion of natural gas is almost deflagration from beginning to end. Material failure mechanism with deflagration was studied with the steel vessel of a fragile material on the end. The breakage pressure depends on pressure increasing rate. Rapid pressure increasing causes higher pressure breaking. The tensile tests of different tensile speed showed that the constant strain breakage ruled the material breakage. The rheology model of material breakage with the increasing stress could explain the constant strain breakage mechanism. Voigt model (or Kelvin model) consisted of a spring and a dashpot was suitable for the rheology model. The tensile tests determined the coefficients of the spring and the dashpot of the model. These 2 parameters and the breakage strain (= constant) predict the breakage pressure and time. A case study of tracing paper as the fragile material showed good result of this approach. Further studies of actual constructional material as steel bar, float glass, duralumin plate are needful for next engineering step.

Key words: Deflagration, Natural gas, Explosion, Rheology model, Material failure

## 1. INTRODUCTION

This study is related the accidental gas explosion in buildings. Natural Gas is relatively favorable fossil fuel as its minimum $CO_2$ generation from a viewpoint of global warming. Another favorable point of natural gas is that the accidental explosion is almost always deflagration from beginning to end.

The reason of its placid disposition is that the burning velocity of natural gas based methane is slow and the turbulent flame acceleration effect is weak. Typical deflagration in the natural gas and air mixture in a closed space shows the clear separation between deflagration wave and pressure wave. The velocity of pressure wave is same as sound velocity in the space consist of burned hot gas and unburned cold gas. Deflagration wave velocity is from a few meters per second to several dozen meters per second in the typical residential room. Obstacles in the space accelerate the deflagration wave speed. But it is very difficult to catch up the pressure wave that phenomenon called the deflagration to detonation transition. As a result material consisted room faces same pressure at the same time. If there was a person in room, the person does not get shock before the fragile part as windows or doors breaking.

The explosion pressure of the stoichiometric gas-air mixture in the closed vessel reached nearly 8kg/cm$^2$ or 80tonne/m$^2$ though the explosion stayed in deflagration. If the accidental gas explosion happened in the building without a fragile part, the building should be break down because a common building floor is designed under 400kg/ m$^2$. Fortunately common building has several windows and doors. These fragile material breaks down from a few kg/ m$^2$ to several hundred g/ m$^2$ .The area of these fragile part is large enough, the maximum pressure is the break down pressure of the fragile materials.

The pressure difference between outside atmosphere pressure and internal space pressure applies stress to the constructional materials. The fragile part of the building materials fails when the pressure gets over the withstand pressure. Strong shock wave generates and moves outside the room and rarefaction wave attacks inside the room.

The well known equation of Cubbage and Simmonds for the industrial furnace venting is not good estimation for residential building light materials as windows, doors and wall panels. This study has done to make practical estimation of the damage of building by accidental gas explosion.

## 2. Experiment

Natural gas of the experiment was same composition of city gas 13A which contained methane 88% and other higher hydrocarbons 12%. Old type city gas called 6B that contained 30% methane, 36% hydrogen, 16% carbon dioxide and others was used for comparison.

Figure 1 is a photograph of the experimental apparatus of gas explosion. The apparatus had 30cm diameter and 30cm length steel cylinder with flanges in both end. One side flange had a fragile part. A propeller in the vessel mixed gas-air to homogeneous state. The ignition was in the center of vessel. The pressure sensors are strain gauge type on the wall of the vessel. Interference gas analyzer and the conduction of heat type gas chromatograph analyzed the density and homogeneity.

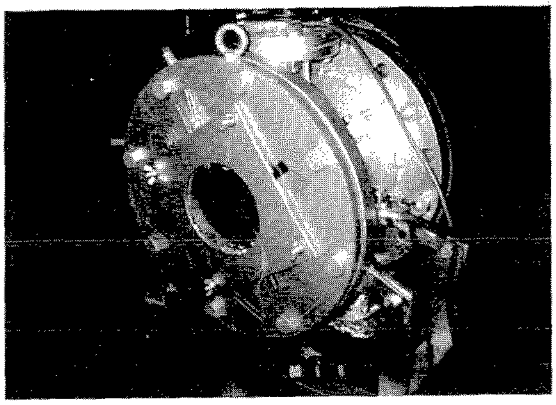

Fig.1 The experimental apparatus of gas explosion

The fragile part fixing is as shown Fig.2. Experimental fragile materials were the tracing paper, plate glass, metal films. The diameter of fragile part is determined by the fixed square metal plate with hole that diameters were 78mm and 45mm. Fig.1 shows after explosion of a plate glass as the fragile material. No glass left at the hole but some cracked glass still fixed between the square metal plate and flange.

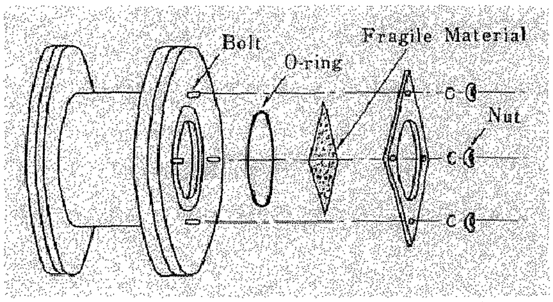

Fig.2 The assembly diagram of the fragile part fixing

Fig.3 is the pressure-time relations of gas explosion. X-axis is a time scale (sec), Y-axis is a pressure in the vessel (kg/cm$^2$), parameter $\phi$ is equivalent ratio of natural gas-air mixture ( $\phi$ =1 is the stoichiometric mixture). The fragile material was a tracing paper of 40g/m$^3$. The diameter of fragile part was 78mm.

The important results of the Fig. 3 are: (1) Breaking pressures of the fragile part are not same pressure. The breaking pressures distributed from 0.14 kg/cm$^2$ to 0.07 kg/cm$^2$. The criterion of the fragile part failure is not constant stress. (2) The breaking pressure depended on pressure increasing speed. Faster pressure increasing showed higher breaking pressure. (3) After the break of the fragile part, pressure increased again. The effect is clear in the case of $\phi$ =0.88 as the second pressure peak appeared. (4) After the break of the fragile part, pressure vibration occurred. (5) Breaking times distributed from 0.04sec (40msec) to 0.24sec (240msec). Considering that the distance from ignition point to the fragile part is only 15cm (150mm), the phenomenon is very slow.

These experimental results are quite different as compared detonation. The detonation with strong shock wave by itself has a distinguished breaking power. The breaking mechanism with detonation is the shock wave problem. We should take the quite different approach to solve the breaking problem with deflagration not in the point of view of detonation. Deflagration generates week and slow pressure increasing. This is the key point to understand the breaking mechanism of deflagration correctly.

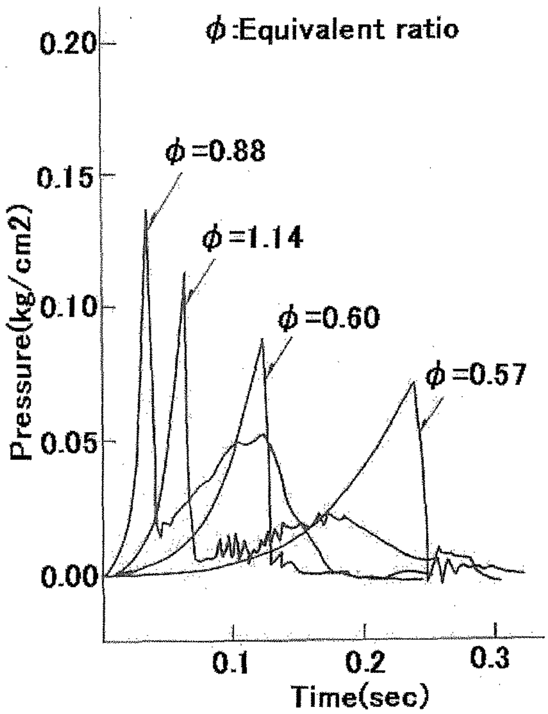

Fig.3 Pressure-time relation of gas explosion

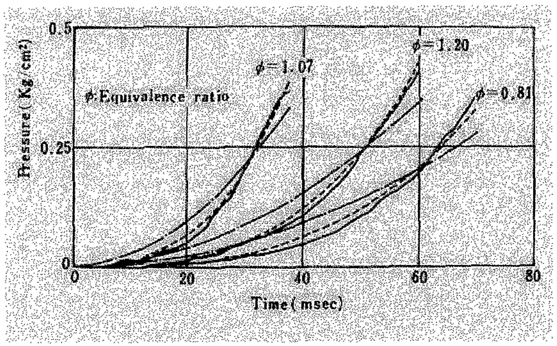

Fig.4 The functional approximation of pressure-time curves of gas explosion

Fig.4 shows curve fitting to the pressure increasing in the case of 45mm diameter tracing paper. The solid line is experimental data, the broken line is the $t^3$ approximated function, and the chain line is the $t^2$ approximated function. The $t^3$ approximated function seems to be good enough. Then we got the equation (1).

$$P = At^3 \qquad \text{..........} (1)$$

This approximation has a physical reason why the flame shape of gas-air mixture is spherical form. A is a constant that could be determined by the volume of the vessel, burning velocity and flame temperature.

## 3. Theory

### 3.1 Voigt (or Kelvin) model

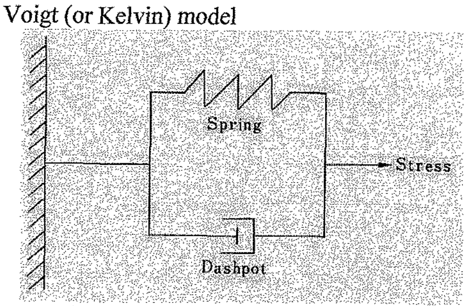

Fig.5 The fragile part breaking model as Voigt model or Kelvin model

Paper is a composite material of plant fiber. The stress-strain relation of paper could be described as the Voigt (or Kelvin) Model of visco-elastic body. The element of the weight could be ignored because the paper is light enough.

Voigt model follows the equation (2) with viscous modulus C, elastic modulus E, strain $\varepsilon$, stress $\sigma$, time t,

$$C\frac{d\varepsilon}{dt} + E\varepsilon = \sigma \quad \text{......................} \quad (2)$$

The failure criteria of the Voigt model are the dashpot breaking ($\varepsilon = \hat{\varepsilon}$). This is the constant strain breaking condition. The tensile test tried to verify the model.

### 3.2 Tensile Test of the fragile material

Tensile test of the tracing paper in various tensile velocities has been tried. The speed of tensile loading was very slow compared gas explosion because tensile testing machine offered commercially used.. Test pieces were 800, 600, 400, 350, 320mm length and 10mm width.

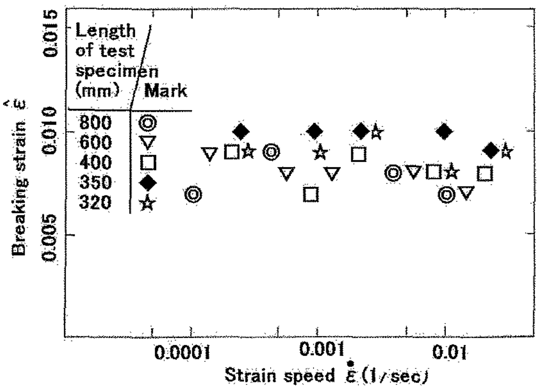

Fig.6 The strain speed $\dot{\varepsilon}$ (1/sec) and Breaking Strain $\hat{\varepsilon}$ of tensile test

Fig.6 shows the results of the test. In the area of the strain speed from 0.0001 (1/sec) to nearly 0.05(1/sec), the breaking strains were constant from 0.007 to 0.010. The tracing paper breaking is a constant strain breaking as the results. The Voigt model could use as the breaking criteria of the tracing paper.

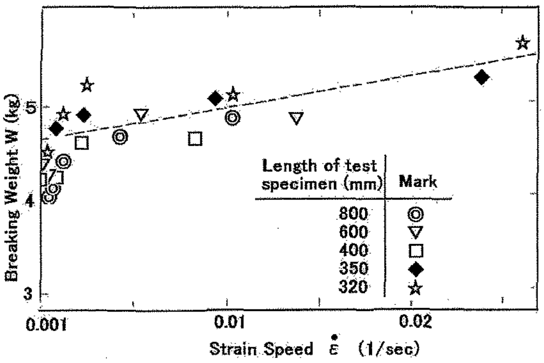

Fig.7 The strain speed $\dot{\varepsilon}$ (1/sec) and breaking weight W (kg) of tensile test

Fig.7 shows the relation between the strain speed and breaking weight of the same tensile test of Fig.6. The breaking weight increased as strain speed increasing. Voigt model shows stress-strain relation under constant strain speed as equation (3).

$$C\dot{\varepsilon} + E\dot{\varepsilon}t = \sigma \quad \text{......................} \quad (3)$$

We define that the breaking time is $\hat{t}$, the breaking stress is $\hat{\sigma}$, the breaking strain is $\hat{\varepsilon}$. The relation between the constant strain speed $\dot{\varepsilon}$, the breaking time $\hat{t}$ and the breaking strain $\hat{\varepsilon}$ shown as the equation (4).

$$\dot{\varepsilon}\hat{t} = \hat{\varepsilon}\ (\neq 0) \quad \text{......................} \quad (4)$$

If the strain speed $\dot{\varepsilon}$ approached to zero, breaking stress $\hat{\sigma}$ approximated $E\hat{\varepsilon}$ as equation (5).

$$\lim_{\dot{\varepsilon}\to 0}\hat{\sigma} = E\hat{\varepsilon} \quad \text{......................} \quad (5)$$

In Fig.7, as Y-axis could be converted to stress, the intersection point between asymptotic line (broken line) and the Y-axis gives $E\hat{\varepsilon}$ (the breaking stress $\hat{\sigma} = 1.3 \times 10^8$ (N/m$^2$)). As $\hat{\varepsilon}$ is known data of the tensile test, elastic modulus E is determined. In this case, elastic modulus E is $0.2 \times 10^{10}$ (N/m$^2$). The gradient of the asymptotic line gives the viscous modulus C. In this case C is $6.7 \times 10^7$ (N· sec/m$^2$).

### 3.3 Deformation of the fragile part and pressure to stress conversion

The shape of the fragile part is a circular membrane. The thickness of the membrane is h, the radius is a. The membrane is clamped at circular. The following analysis is limiting in relatively small deformation and in elastic region. The analysis is on the circular cylindrical coordinate of the direction of central axis Z, its displacement W, radial direction r, angular direction $\theta$. Fig.8 shows that the pressure and stress balanced on the small square area of the membrane. The balance equation on Z-axis is as following,

$$2\pi(r + dr)\left(\sigma_r + \frac{d\sigma_r}{dr}dr\right)h\left|\frac{dw}{dr}\right| - 2\pi r\sigma_r h\left|\frac{dw}{dr}\right| = 2\pi r dr P \quad \text{..........} \quad (6)$$

By omitted second order small term, the equation is simplified as,

$$\left(\frac{d\sigma_r}{dr}+\frac{\sigma_r}{r}\right)\left|\frac{dw}{dr}\right|=\frac{P}{h} \quad \cdots\cdots\cdots (7)$$

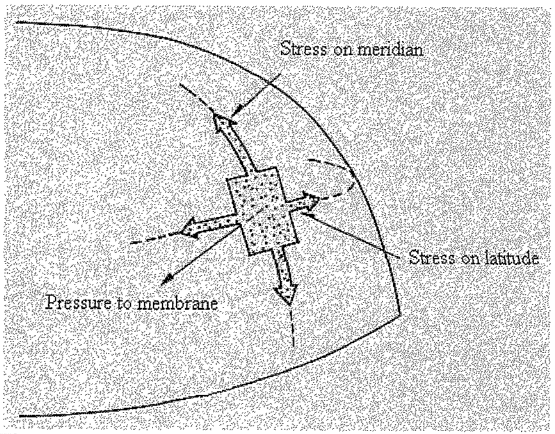

Fig. 8 Pressure and stress balance on the small square area

Next the stress balance of r-direction is following equation,

$$\left\{\sigma_r hr\varphi-\left(\sigma_r+\frac{d\sigma_r}{dr}dr\right)h(r+dr)\varphi\right\}$$
$$+\sigma_\theta h\varphi dr=P_r\varphi dr\left|\frac{dw}{dr}\right| \quad \cdots\cdots\cdots (8)$$

By omitted second order small term, the equation is simplified as,

$$-\left(\frac{d\sigma_r}{dr}+\frac{\sigma_r}{r}\right)+\frac{\sigma_\theta}{r}=\frac{P}{h}\left|\frac{dw}{dr}\right| \quad \cdots\cdots\cdots (9)$$

Neglected the displacement effect by deformation of r direction, we got the following equation,

$$\varepsilon=\sqrt{1+\left(\frac{dw}{dr}\right)^2}-1 \quad \cdots\cdots\cdots (10)$$

As $\frac{dw}{dr} \ll 1$, equation (10) is more simplified,

$$\varepsilon \cong \frac{1}{2}\left(\frac{dw}{dr}\right)^2 \quad \cdots\cdots\cdots (11)$$

The stress-strain relation of

$$\sigma_r=\frac{E}{1-\nu^2}(\varepsilon_r+\nu\,\varepsilon_\theta) \quad \cdots\cdots\cdots (12)$$

and

$$\sigma_\theta=\frac{E}{1-\nu^2}(\varepsilon_\theta+\nu\,\varepsilon_r). \quad \cdots\cdots\cdots (13)$$

Equation (12) and (13) are simplified as

$$\sigma_\theta=\nu\,\sigma_r. \quad \cdots\cdots\cdots (14)$$

Equation (7), (9) and (11) give

$$\sigma_r=\frac{E^{\frac{1}{3}}}{\left(1-\nu^2\right)^{\frac{1}{3}}}\left(\frac{2rP}{h\nu}\right)^{\frac{2}{3}} \quad \cdots\cdots\cdots (15)$$

Equation (1) and (15) give the strain-time relation of the circular membrane as follows,

$$\varepsilon=\frac{Q}{E}\{t^2-2\left(\frac{C}{E}\right)t+2\left(\frac{C}{E}\right)^2\}-\frac{2Q}{C}\left(\frac{C}{E}\right)^3 e^{-\frac{Et}{C}} \quad \cdots\cdots\cdots (16)$$

$$Q=\frac{E^{1/3}}{\left(1-\nu^2\right)^{1/3}}\left(\frac{2a}{h\nu}\right)^{2/3}A^{2/3} \quad . \cdots\cdots\cdots (17)$$

## 4. Results and Discussion

By solving the equation (16) about time, we could compare the theoretical breaking time and the experimental breaking time as shown Fig.9.

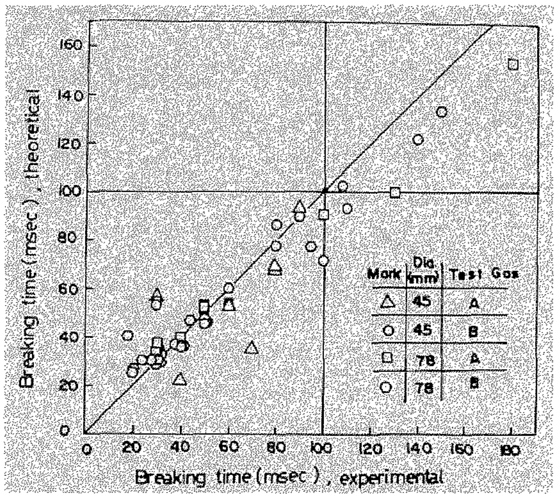

Fig.9 Comparison between the theoretical breaking time and the experimental breaking time

The experimental data contains not only natural gas (A) but also city gas (B). The diameters of the fragile part are 45mm and 78mm.

The results show the good agreement below 100msec region. Because Voigt model fits the small deformation, does not fit the large deformation.

## 4. Conclusion and future work

Rheology model of the fragile part breaking with the gas explosion explained well the experimental data.

But this is only the point of start. The only tracing paper study is not enough to expand this method to actual accidental gas explosion. Also there is no study about different scale and different shape vessel.

Further studies of actual constructional material as steel bar, float glass, duralumin plate are needful for next engineering step.

## References:

[1]H.Kaneko, T.Hirano, The Proceeding of combustion symposium, 100(1978), (Japanese)

[2]H.Kaneko, T.Nishio, The Proceeding of safety engineering symposium, 110 (1979), (Japanese)

(Recieved October 23, 2007 ; Accepted November 16, 2007)