Flame Acceleration and Blast Wave Generation in Accidental Gas Explosions

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博士論文（要約）

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（ガス爆発における火炎伝ぱの加速と爆風の発生）

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1. INTRODUCTION

All facilities using combustible gases are subject to accidental gas explosions, and the industrial processing and storage of combustible gases often creates explosion hazards that require precision risk management. To perform effective gas explosion risk management, consequence analysis of the possible damage induced by an accidental gas explosion must be conducted.

In particular, the accelerative motions in flame propagation due to flame front instabilities might cause the considerable damages in accidental large-scale gas explosions, because the onset of the development of cellular structure on the surface of the expanding spherical flames lead to the increase in the flame speed. In order to the appropriate safety management against accidental gas explosions, we need to understand one of the most important mechanisms about the cellular structure and flame acceleration.

In addition, further studies on whether the flame acceleration could be self-similar are merited. In particular, the damage caused by blast wave generation during gas explosions is extremely serious because the blast wave can spread quickly and over a long distance. To evaluate the consequence of the blast wave damage, the intensity of the blast wave in partially unconfined regions needs to investigate.

In view of the above consideration, the present study investigated the development of cellular structure, the self-similar propagation and the blast wave in accidental gas explosions. Especially, the influences of diffusional-thermal as well as hydrodynamic instabilities on the development of cellular structure of the expanding spherical flame have been examined. Additional considerations are the onset of self-acceleration and self-similarity of expanding spherical flames in the accidental gas explosions. Furthermore, the effects of blast wave intensity investigated using the acoustic theory. In this study, theoretical prediction model of flame speed for accidental gas explosions was proposed.

2. EXPERIMENTAL

In the present study, laboratory-scale and large-scale tests were conducted. The present experiments were performed under the initial condition when the gas flow is quiescent and the concentration distribution is uniform.

2.1 Laboratory-Scale Tests

In order to observe the cellular formation on the flame surface in detail, the laboratory-scale experiments carried out using a soap bubble method. The experimental apparatus consisted of the gas supplying system, the ignition system, the high-speed Schlieren photography system and the sound pressure measuring system. A spherical bubble with combustible gas/air mixtures was formed from designed soap bubble apparatus. The flame propagation phenomena of hydrogen/air, methane/air, propane/air, in an unconfined area was imaged with the Schieren photography as well as the Shadow photography and recorded using the high-speed camera.

2.2 Large-Scale Tests

In addition, large-scale experiments conducted to investigate the self-similar characteristics of propagation of the expanding spherical flame. The large-scale experimental apparatus manufactured in the free field. The apparatus is basically same as laboratory-scale apparatus.

In the experiment, a plastic tent consisted of the large frame in the field designed to investigate the self-similar propagation. Procedurally, the large frame was packed by a thin plastic sheet. The combustible gas was injected to the tent directly and the mixtures in the tent were circulated by a circulation pump concurrently. Thereafter, the concentration of the reactant mixture at top and bottom of the tent was measured by a gas concentration measuring instrument. The mixture was ignited at the center of the tent. The Fuel injected at the bottom of the tent and the concentration in the tent measured at top and bottom of the tent. A fan at the bottom of the tent also placed to make the mixture uniform and to stop before the ignition. Designed regular hexahedron frame length is L = 1m, 3m, volume is V = 1 m^3, 27 m^3, respectively. The flame behaviors of hydrogen/air, methane/air, propane/air at various concentrations were captured using an infrared photography and a visible photography.

3. RESULTS AND DISCUSSIONS

3.1 Cellular Structure and Flame Front Instabilities

Crack initiation on the flame surface is created by initial disturbance, which is formed by the spark. Such flame cracking propagates to form cells on the surface. The crack propagation across the surface and the cracks start to develop along regions of high curvature. Such mechanism of cellular flame development persists in localized regimes simultaneously and thereby the cell size on the overall flame surface also decreases. Consequently, the flame surface is fully covered by cells.

As the flame propagates, the flame was wrinkled by intrinsic flame instabilities such as diffusional-thermal instability, which is caused by different diffusion transports of the fuels at non-equidiffusive flames and hydrodynamic instability, which is caused by the expansion across the flame. Cellular structure of the flame during the initial propagation is mainly affected by the intensity of diffusional-thermal instability. The onset of the instability for unimolecular reactions in binary mixtures can be demonstrated as Lewis number, $Le = \alpha/D$, where α is the thermal diffusivity and D is the mass diffusivity. For $Le < 1$, the influence of the mass diffusivity strongly dominated, the thermal diffusivity weakly affected, consequently a cellular shape observed. For $Le > 1$, the influence of the diffusivity oppositely dominated in the propagating process, conversely the flame structure is smooth and stable. Developments of cellular structure on the surface appeared for $Le > 1$ flame, although the $Le < 1$ flame was stable. Lean hydrogen flame was more cellularly unstable than rich propane flame, because of the intensity of the diffusional-thermal instability. Such effect of the intensity of the diffusional-thermal instability on the formation of cellular flame is greater only in small flame radius. As the flame scale becomes larger, the formations of cellular structure are affected intensively by the hydrodynamic instability. The observed cell on the surface indicates the size of cells formed by hydrodynamic instability is greater than that of cells generated by diffusional-thermal instability.

3.2 Self-Acceleration and Self-Similar Propagation

Development of the cellular structure on the flame surface due to the cellular instability might cause the self-acceleration in the accidental gas explosions. Such acceleration can strongly affect the considerable damages, as the explosion scale larger. In this section, the accelerative dynamic of the flame is quantitatively evaluated.

In the present study the critical flame radius associated with the onset of self-acceleration defined from the relationship between the measured flame speed and the flame stretch rate, $K = (2/r)\ (dr/dt)$. Just after the ignition, the flame radius is small and the stretch effect is strong and progressively the effect decreases with the scale increasing. As the stretch effect is further reduced, the flame speed at $r \geq r_c$ increased dramatically into cellular regime. We defined critical flame radius as the transition point to cellular regime. In the present study, Markstein length, L, laminar flame thickness, δ, are calculated by using CHEMKIN. It is found that the critical Peclet number, $Pe_c = r_c/\delta$, for the onset of self-acceleration tends to increase as the value of Markstein number, $Ma = L/\delta$, increases. In other word, the critical Peclet number is correlated with the Markstein number.

The self-acceleration for lower values of Markstein number occurred early when the flame radius was small. Conversely, the onset of self-acceleration for higher values of Markstein number was observed late when the flame radius was larger. Results demonstrate that the onset of accelerative motions of expanding spherical flame depends on the intensity of diffusional-thermal instability as well as hydrodynamic instability.

The measured exponents α are positive values in the propagation process and increased with the flame radius. Consequently, the exponents α is constant, when the acceleration reached the limited point associated with self-turbulization. Our result suggests self-acceleration ($\alpha > 1$) and self-similarity (α = constant) definitely exist for the flame propagation of hydrogen/air mixtures. The mechanism of the self-similar acceleration can be demonstrated as following; the flame in the initial stage of propagation smoothly propagates. As the flame propagates, the onset of the flame front instabilities becomes manifest and progressively the flame surface becomes unstable at critical flame radius lead to the flame acceleration. Subsequently, the self-acceleration might be reached the self-similar regime.

To investigate the effect of hydrodynamic instability on the flame fractal nature, we plotted fractal excess with expansion parameter, $\gamma = (\rho_u - \rho_b)/\rho_u$ at $0<\gamma<1$, where ρ_u is the density of the unburned gas mixture, and ρ_b is the density of the burned gas mixture. This result shows that the fractal dimension depends on the hydrodynamic instability. However, the fractal dimension for real flames exist in range of $D_3 \approx 2.2\text{-}2.35$, since the practical conditions of expansion parameter in accidental gas explosions are $\gamma \approx 0.8\text{-}0.9$. This value is similar to the 2.33 reported in the literature. It is very useful to evaluate the accelerative dynamic of flame in large-scale accidental gas explosions.

3.3 Blast Wave

The effect of flame acceleration on the intensity of blast wave from gas deflagrations was investigated by using the acoustic theory. The results show that the blast wave generated by gas deflagrations was enhanced dramatically by the accelerating propagation of the flames and was induced by diffusional-thermal and hydrodynamic instabilities on the flame surface. In particular, the flame acceleration due to hydrodynamic instability strongly affects the intensity of the blast wave, as the explosion scale become larger.

3.4 Self-Similar Model

Self-similar models for flame acceleration and blast wave in accidental gas explosions were developed by using the fractal and acoustic theories. For self-similar acceleration, the flame speed, V_f, can be written as

$$V_f = \varepsilon S_L \left(\frac{Pe}{Pe_c} \right)^d \tag{1}$$

where d is fractal excess associated with the acceleration exponent. The blast wave can be derived using the acoustic model as follow

$$p = \frac{\rho}{R}(2d+2)\delta\varepsilon^2 S_L^2 \frac{Pe^{3d+1}}{Pe_c^{3d}} \tag{2}$$

where $Pe = \delta^{-1}\left\{ d\left(Pe_c\delta\right)^{1-d} + (1-d)\left(Pe_c\delta\right)^{-d} \varepsilon S_L t \right\}^{1/(1-d)}$.

In this equation, the term of Pe^{3d+1}/Pe_c^{3d} indicates that he flame accelerates with self-similarity and the structure can be attributed to its fractal nature. The evaluated values agree well with the measured data from the experiments. These agreements show that the flame speed as well as overpressure for accidental gas explosions can be quantitatively estimated by the theoretical equations.

4. CONCLUDING REMARKS

In the present study, cellular structure, self-similar propagation of flames and blast wave generation in accidental gas explosions investigated conducting laboratory-scale and large-scale tests. The main conclusions are summarized as follows;

1) The created flame cracking on the surface propagates to form cells and starts to develop along regions of high curvature and consequently the flame surface become fully cellular structure. Such development of cellular structure in the initial propagation is mainly affected by the intensity of diffusional-thermal instability. As the flame scale becomes larger, the formation is largely affected by the hydrodynamic instability.

2) The onset of self-acceleration and self-similar propagation in accidental gas explosions investigated. Results demonstrate that the evaluated critical Peclet number for the onset of flame acceleration is correlated with the calculated Markstein number. Such result demonstrated that the onset of accelerative motions of expanding spherical flame depends on the intensity of diffusional-thermal instability as well as hydrodynamic instability. Additionally, our result suggests self-acceleration ($\alpha > 1$) and self-similarity (α = constant) definitely exist for the flame propagation of hydrogen/air mixtures. Fractal dimension for real flames also evaluated.

3) The cellular flame develops due to the intrinsic instability and thereby the increase of the flame speed. Consequently, the overpressure also increases. The flame acceleration due to the hydrodynamic instability can be strongly affected the blast wave intensity.

4) The flame speed as well as blast wave for gas explosions was predicted by using fractal theory. The evaluated speed showed good agreement with the experimental value. This result illustrates that the flame speed as well as overpressure for accidental gas explosions can be quantitatively estimated by the self-similar concept.