수소와 액화석유 가스의 공기혼합기의 폭발 후 화재로 전이 연구

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A Study on the Transition of Hydrogen-Air and LPG-Air Explosion to Fire

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Abstract : Gas explosion characteristics of hydrogen and liquefied petroleum gas(LPG) were measured in 6L cylindrical vessel, and experiment for explosion to fire transition phenomena of the gases were carried out using the 270L vessel. Explosion characteristics were measured using the strain type pressure transducer and explosion to fire transition phenomena was analyzed with the high-speed camera. Base on the experiment, it was found that explosion pressure was most high slightly above the stoichiometric concentration, and explosion pressure rise rate and flame propagation velocity were proportional to the combustion velocity. And we find that those kind of explosion characteristics affect the explosion-to-fire transition, in addition, explosion flame temperature, flame residence time, are important parameters in explosion-to-fire transition.

초록 : 실린더형의 내용적 6리터의 용기를 이용하여 수소와 액화석유 가스(LPG)의 폭발 특성을 측정하였고 270리터의 직육면체 용기를 이용하여 폭발 후 화재로의 전이 현상을 실험하였다. 폭발 특성은 strain type 압력센서를 사용하여 측정하였으며 폭발 후 화재로의 전이 현상은 고속카메라로 촬영하여 분석하였다. 실험 결과 완전 연소 농도 비보다 약간 높은 농도에서 최대 폭발압력을 나타내었다. 폭발압력 상승 속도와 화염 전파속도는 연소속도와 비례함을 알 수 있었으며 이러한 폭발 특성들은 폭발 후 화재로의 전이에 영향을 미침을 알 수 있었다. 또한 폭발 화염온도, 화염의 용기 내 체류시간 등도 폭발 후 화재로의 전이에 중요한 변수가 됨을 알 수 있었다.
Key Words : hydrogen explosion, LPG explosion, explosion to fire transition

1. Introduction

As we know, hydrogen is the smallest and lightest element in earth, and the element exist in the hydrocarbon compound and water mainly. Therefore hydrogen can be made from the cracking of hydrocarbon or the dissociation of water. Hydrogen shows high reactivity with oxygen, and the product of the reaction is water itself without pollutant like the products of hydrocarbon combustion[1]. Hydrogen is usually used as a fuel of rocket and some special field for this reason. Carbon dioxide is a main product of hydrocarbon fuel combustion and recently, the global warming effect caused by the carbon dioxide becomes a big problem for the environment of earth. And the advanced countries make a protocol for regulate the product amount of carbon dioxide. For this reason, many countries speed up to develop a new energy source that could alternate the hydrocarbon fuel. There are many kinds

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of alternative energy such as nuclear energy, solar energy, wind energy, tidal energy and hydrogen energy. Among these alternative energies, hydrogen attracts attention because of its cleanness and efficiency. Fuel cell for electric generation and hydrogen energy automobile were developed during the last century and many countries try to research for practical use of them. There are many kinds of manufacturing and production process of hydrogen such as direct dissociation of natural gas, electric dissociation of water, and photochemistry etc. In spite of many merit of hydrogen, it has some problems for practical use as an energy source. The storage and transportation of hydrogen have many difficulties in contrast to the hydrocarbon because of its difficulty in liquefaction. And it shows great hazards of explosion and fire because of the concentration range of combustion from 4 to 74%, which is much wider than the most of the hydrocarbon gas fuel, and because of its small ignition energy of 10^{-5}J class[1,3]. During the last century, combustion and explosion characteristics of hydrogen were studied in many respects. Research about the explosion-to-fire transition of hydrocarbon gases was carried out by some researchers[3,6], but little were done in the discipline of hydrogen explosion. This paper represents the explosion and combustion characteristics of hydrogen compared with the hydrocarbon gases, and we consider about the explosion to fire transition of hydrogen through the explosion experiment in the 270-litter explosion vessel.[11].

2. Explosion to Fire Transition

In case of fire after gas explosion, a combustible material, which coexists in the space but does not contribute to the explosion, could be ignited by the heat of explosion. So far, the conditions and mechanism of explosion-to-fire transition have not been explained clearly.

But the explosion to fire transition process was considered as follows.

i) combustible gas are generated from the pyrolysis of combustible materials.

ii) combustible gas mixture is formed by mixing the pyrolyzed gas and air.

iii) there are ignition sources to ignite the gas mixture or the temperature of the atmosphere is high enough for igniting the gas mixture.

iv) pyrolyzed solid material is ignited after ignition of gas mixture by the heat. There are many kinds of combustible materials like flammable liquid and gas but we only consider solid fuel in this study.

For the pyrolysis of solid material, certain amount of heat transfer is needed and the heat transfer to raise temperature of the solid exists from the beginning to the end of explosion, and hot gas is vented.

As we know, there are three types of heat transfer process, i.e. conduction, convection, radiation[3].

Conduction and convection depend on the temperature gradient and heat transfer rate of hot gas which contacts on the solid surface.

The amount of heat transfer to the surface of solid material per unit time and unit q_c'' area can be expressed as follows:

$$\dot{q}_c'' = -\left(\lambda_g \frac{\partial T}{\partial y}\right)_\omega \tag{1}$$

λ_g : heat transfer rate of hot gas

$\frac{\partial T}{\partial y}$: temperature gradient

And the radiation heat transfer depends on the temperature of hot gas T_g and emissivity ε like following equation.

$$\dot{q}_r'' = \varepsilon\sigma T_g^4 \tag{2}$$

ε : emissivity

σ : Stefan - Boltzmann constant

T_g : Hot gas temperature

In equation (1) the temperature gradient can be express by using Nusselt number

$$\left(\frac{\partial T}{\partial y}\right)_\omega = -\frac{\Delta T}{\ell} Nu \tag{3}$$

In this equation ΔT is the temperature difference between hot gas and combustible solid, l is the size of combustible material and x is the distance from the tip to heat transferred position in flow direction. If we substitute the equation (3) to equation (1)

$$\dot{q}_c'' = \lambda_{g\omega}\frac{\Delta T}{\ell}Nu \tag{4}$$

And if we consider the combustible solid is smooth plate in horizontal, Nusselt number can be express like following

$$Nu = \frac{C_{fx}}{2}\mathrm{Re} \tag{5}$$

If we substitute the equation (5) to equation (4)

$$\dot{q}_c'' = \frac{C_{fx}\lambda_{g\omega}}{2}\bullet\frac{\Delta T}{\ell}Nu\,\mathrm{Re} \tag{6}$$

In equation (5) C_{fx} is local friction coefficient and Re is Reynold number.

Heat transfer from the gas explosion to solid is implemented in the manner of convection and radiation mainly.

From the above equations, we can find that heat transfer from the explosion flame to solid depends on the temperature of flame and hot gas, and the resident time of flame and hot gas in the space.

Also the explosion to fire transition strongly depends on the thermal property of combustible solid material.

3. Experiment

Two kinds of experiments were carried out. One is for determining the explosion characteristic and another is explosion to fire transition.

A 6L vessel of cylindrical type was used for measuring explosion characteristics of gas mixture. Fig. 2 shows a 270L hexahedral type vessel for the explosion to fire transition experiment. To simulate a living room of 87m^2 apartment, dimension of the vessel was scale down 1/5 in length scale. Vented explosion was carried out in the 270L vessel to simulate the explosion accident, and the vent size was of 27cm×40cm.

Hydrogen-air mixture concentration was varied from 10vol% to 60vol% (in equivalent ratio(φ): 0.27~3.57) and LPG concentration was varied from 2.5vol% to 7vol%(in equivalent ratio(φ): 0.61~1.79).

Table 1 shows a conversion of gas concentration (vol%) to equivalent ratio(φ).

10kV electric spark was used as the ignition source of the gas mixture in the vessel and strain type pressure transducer was used to measure explosion characteristics.

Fig. 1 is a schematic diagram of the experimental setup for measuring the explosion characteristics of hydrogen-air mixture. Gas mixture was injected after the vessel is vacuumed. Explosion to fire transition phenomena was visualized by a high-speed camera, and the experiment was carried out as the concentration was

Table 1. Conversion of gas concentration to equivalent ratio (φ)

H_2	Vol(%)	10	15	20	25	30	35	40	45	50	55	60
	φ	0.27	0.42	0.59	0.79	1.02	1.28	1.59	1.95	2.38	2.91	3.57
LPG	Vol(%)	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	-
	φ	0.61	0.74	0.86	0.99	1.12	1.25	1.39	1.52	1.66	1.79	-

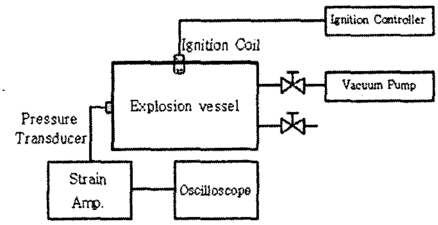

Fig. 1. Schematic diagram of experimental apparatus for explosion characteristics.

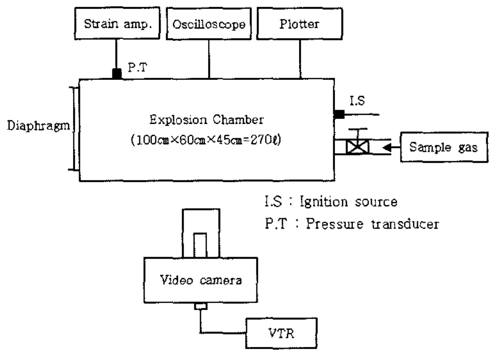

Fig. 2. Schematic diagram of experimental apparatus.

varied from 10% to 50%. A piece of newspaper was used as the combustible solid material. Fig. 2 shows the schematic diagram of this experiment.

4. Results and Discussions

Fig. 3 and Fig. 4 show the explosion characteristics of hydrogen-air mixture and LPG-air mixture in 6L vessel.

Fig. 3 shows the maximum explosion pressure according to the concentration of gas-air mixture. From the Fig. 3 explosion pressure of LPG-air mixture is slightly higher than the hydrogen-air mixture, but the difference is not so great. Flammable range of hydrogen was more wide than the LPG and explosion pressure was still high to the near the upper flammable limit.

It means that hydrogen-air mixture has more dangerously than LPG-air mixture.

Fig. 4 shows the average explosion pressure rising rate (APR). As we know, APR is represent a pressure divided by the time of explosion($\Delta P/\Delta t$). Maximum combustion velocity of hydrogen-air mixture is about 7 times faster than LPG-air mixture. Similarly, APR of hydrogen-air mixture in Fig. 4 is about 5 times higher than that of LPG-air mixture.

This means that the time for pyrolysis of solid combustibles is shorter in hydrogen explosion in contrast to the LPG explosion. Radiation heat transfer fraction of explosion of hydrogen-air mixture is 17~25% and LPG-air mixture is 20~35%. We can predict that the probability of gas explosion to fire transition will be higher in LPG explosion than in hydrogen explosion. But hydrogen explosion flame temperature is higher than that of LPG explosion flame. Therefore it is difficult to predict the probability of explosion to fire transition with this data.

Fig. 5 shows the explosion flame propagation velocity in 270L vessel.

Explosion flame propagation velocity of hydrogen-air mixture is about 5 times faster than that of LPG-air mixture. Therefore contact time between explosion flame and combustible material in the explosion vessel will be shorter, and the possibility of explosion to fire transition will be lower compare with the LPG-air explosion.

Explosion flame residence time in 270L vessel was analyzed according to the high-speed photograph and the Fig. 6 shows the experimental result. Explosion flame residence time of LPG-air mixture was longer than that of the hydrogen-air mixture. With the increase of gas concentration more than the stoichiometric, the explosion flame residence time become longer. Especially flame residence time of LPG-air mixture was increased much more than that of the hydrogen-air mixture.

In case of hydrogen-air mixture explosion, flame residence time was short because of high flame propagation velocity and high explosion pressure rising rate.

From the analysis of high speed photograph, ignition of combustible solid was began after incoming a fresh air from outside of vessel after vented the explosion gas. And a time to ignition of combustible solid in vessel of hydrogen-air mixture was 160ms and it was about one fifth of the LPG-air mixture.

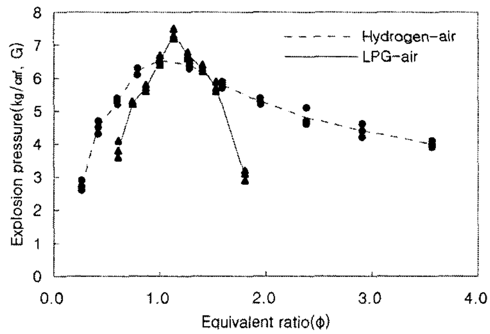

Fig. 3. Explosion pressure of gas-air mixture in 6L vessel.

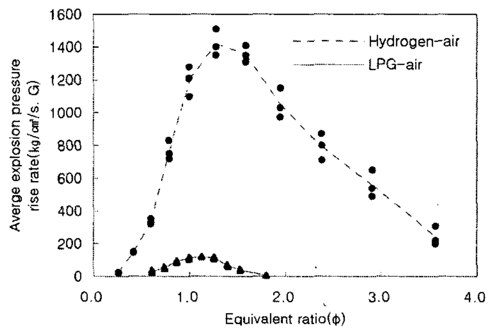

Fig. 4. Average explosion pressure rise rate of gas-air mixture in 6L vessel.

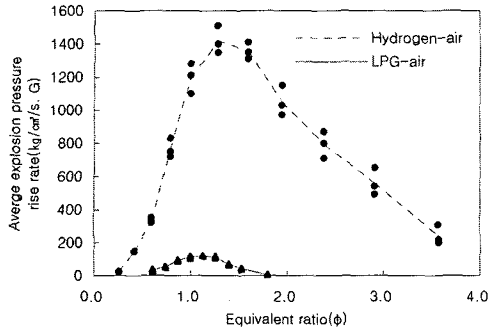

Fig. 5. Explosion flame propagation velocity of gas-air mixture in 270L vessel.

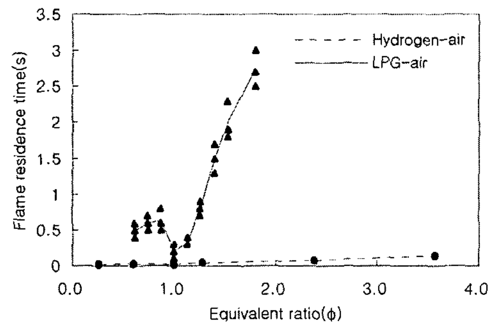

Fig. 6. Explosion flame residence time of gas-air mixture in 270L vessel.

5. Conclusion

Based on the explosion of hydrogen-air and LPG-air mixture and explosion to fire transition experiment, we can get the following conclusions.

· As fast the explosion flame velocity, the flame residence time become short and the probability of explosion to fire transition will be decrease.

· As high the flame temperature, heat transfer rate will be increase and the possibility of explosion to fire transition will be increase also.

· Explosion to fire transition phenomena is affected by the explosion characteristics.

· To occur the explosion to fire transition, additional fresh air should be supplied after explosion.

· Therefore, the oxygen concentration should be reduced by inerting the atmosphere after explosion to prevent the explosion to fire transition and cool down the atmosphere to reduce the heat transfer rate.

References

1. “Safety Guide for Hydrogen”, Hydrogen Safety Committee, NRCC27406 NRC, Canada, 1987.
2. K. H. Oh, “A study on the explosion characteristics and leakage of gas at indoor”, Report KGS 99-007, Korea Gas Safety Corporation, 1999.
3. T. Hirano, “Gas explosion prevention technology”, Kaibumdo, 1984.
4. S. B. Dorofeev. A. S. Kochurko, A.A. Efimonko, B.B. Charvanov, “Evaluation of the hydrogen explosion hazard”, Nuclear Eng. and Design, Vol. 148, p. 305~316, 1994.
5. K. H. Oh, “A study on the damage. estimation of indoor gas explosion”, Report KGS 98-006, Korea Gas Safety Cooperation, 1998.
6. J. G. Moon, K. H. Oh, “Development of protection and prevention technology for hydrogen explosion hazards”, Report. UDC 629, Korea Institute of Machinery and Metals, 1990.
7. K. H. Oh, “A study on the LPG explosion characteristics of non-uniform concentration”, J. of Korean Institute of Fire Sci. & Eng., Vol. 17, No. 4, pp. 111~116, 2003.
8. K. H. Oh, C. H. Lee, “A study on the explosion to fire transition phenomena of liquefied petroleum gas”, J. of Korean Institute of Industrial Safety, Vol. 8, No. 4. pp. 107~113, 1993.
9. S. E. Lee, “A Study on the explosion to fire transition and fire prevention”, Hoseo Univ., Master thesis, 2000.
10. John. H. Lee, R. Knystantas, A, Freiman, “High-Speed turblent deflagrations and transition to detonation in H_2-air mixtures”, Combustion and Flame, Vol. 56, p. 227~239, 1984.
11. K. H. Oh., S. E. Lee, “A Study on the Transition of Explosion to Fire to Fire of LPG and Its' Prevention”, J. of Korean Institute of Fire Sci. & Eng., Vol. 18, No. 2, pp. 20~26, 2004.