124 한국자동차공학회논문집 제 2 권 제 2 호, pp. 124~131, 1994.

〈논 문〉 SAE NO. 943724

A Study on NOx Pollutant Reduction and Combustion Characteristics of Impinging-Jet-Flame Combustion Process(II)

對向噴出焰 燃燒方式에 依한 NOx 生成低減과 燃燒特性 硏究(II)

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ABSTRACT

자동차엔진의 연소과정에 상사하는 밀폐정적연소실을 주연소실과 대향 2개 부연소실로 분할하고 오리피스로 연결하였다. 이때 부연소실로부터 주연소실로 분출하는 대향분출염 연소에 의한 질소산화물 배출저감특성을 연소방식, 연소실형상 그리고 연료종류를 변경한 수종의 실험으로 조사하였다.

질소산화물농도, 연소실 최고압력, 화염전파과정의 고속도슐리렌사진 가시화를 수행한 결과, 대향분출염 연소방식을 도입하면 연소실의 중앙부공간이 상대적으로 넓은 경우에 고부하운전과 동시에 질소산화물의 배출량도 저감할 수 있었다. 그러나 연료의 종류는 질소산화물생성에 매우 영향이 적었다.

주요기술용어 : NOx, Impinging-Jet-Flame(대향분출염), Closed Vessel Burning(밀폐용기연소)

INTRODUCTION

Nitrogen oxides in the atmosphere contribute to photochemical smog, to the formation of acid rain precursors, to the destruction of ozone in the stratosphere and to the global warming. The principal nitrogen oxides present in the atmosphere are nitric oxide(NO) and nitrogen dioxide(NO_2), collectively referred to as NOx, and nitrous oxide(N_20). A significant amount of the increased emissions is attributed to human activities, in particular to increased combustion of biomass and fossil fuels (Bowman(1992))[1].

Automotive engine combustion is one of major sources of NOx emission not only, but also CO_2 productions which also cause global warming. Over the past two decades, increasingly stringent regulations reducing allowable NOx emissions from the automotives have been implemented, and CO_2 regulations are also being discussed, while improvement of fuel economy has been recently required. These requirements may be talked in other words as low NOx, CO_2 formation simultaneously high-load combustion/unit fuel consumption or best fuel economy/unit power output or then minimum NOx, CO_2 formation/unit power output.

But, it has been a general trend that high-load combustion is incompatible with low NOx formation. To some extend, this trends is true for both premixed flames and diffusion flames, whether ho-

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mogeneous mixtures or stratified mixtures, both combustion in closed vessels and flowing systems.

Recently, new combustion systems with various types of prechamber, swirl augumentation or swirl/tumble augumentation, and multi-spark systems, etc. have been developed to improve fuel economy minimizing reduction of power output. In practice, examples of lean burn combustion or EGR reduce a fair amount of NOx formation, but, on the other hand, it may reduce engine output also.

Near stoichiometric burn operation should be favorable, as it can provide high-load operation, better fuel economy and besides low emission of CO and HC, if one can find a way to reduce NOx formation.

Series of demonstration on high-load operation and low NOx formation can be found with the term of the impinging jet/spray/flame(Miura et al(1978)[2], Fujimoto et al(1984)[3], Cho et al(1988)[4], Jeong (1989)[5], and Okajima and Kumagai(1990))[6]. According to Fujimoto et al(1984)[3] and Okajima and Kumagai(1990)[6], an original idea on the impinging-jet-flame proposed by Professor S. Kumagai was that some burnt gas is continously supplied to the unburnt gas just adjacent to the flame front. This idea may be referred to a certain kind of mixing process by intense turbulence of improved better mixing and homogeneous reduced fluctuating rms value.

Here, we summarized previous experimental results of Fujimoto et al(1984)[4] and Jeong(1989)[5], who burnt propane-air premixed gas in a rectangular combustion vessel, and our present experiment burning propane-air premixed gas in a flat discal combustion vessel. All those equipped with dual opposed prechambers, which can produce a pair of impinging-jet-flame from the prechamber immersed in the main chamber that come into a head-on collision with each other impinging jet at the central zone of the main chamber. And we attempted to draw a possible common explanation on the impinging-jet-flame characteristics.

EXPERIMENT

In order to investigate characteristic behavior of the impinging-jet-flame, a flat discal combustion vessel was constructed, and pressure measurement, NOx measurement, and high-speed schlieren photography were done.

Figure 1 shows a view of the flat discal combustion vessel which consists of a main chamber and dual prechambers. A case when none of prechamber is installed, the case is said to be the case of Laminar Combustion. And a case when only one prechamber is installed, the case is said to be the case of Single-Jet-Flame Combustion. And finally a case when dual opposed prechambers are installed, the case is said to be the case of Impinging-Jet-Flame Combustion.

This vessel of aluminum, 120mm in diameter, 40mm in depth and about 425cc in volume, has two optical glass windows on both sides for high-speed schlieren photography. The main chamber is equipped with a piezoelectric pressure transducer, valves for gas intake/exhaust/sampling, a thermocouple, spark plugs on the cylindrical wall(Compare with the vessel of Fujimoto et al(1984)[3], 116

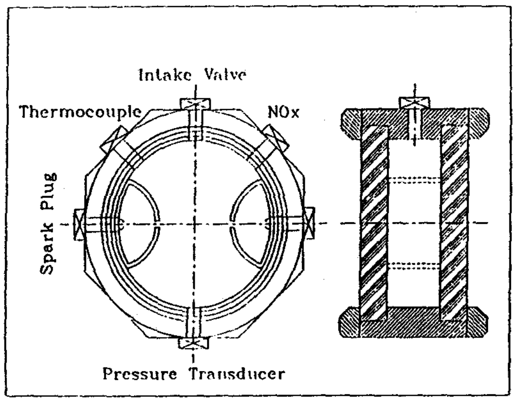

Figure 1. Flat discal combustion vessel

mm in diameter, 38mm in depth, and about 400cc in volume.) Ignition was made coincidently at both prechambers with the home-made CDI sets.

Figure 2 shows a view of the rectangular combustion vessel whose size is 50mm×50mm×150mm for the main chamber with varying volume of dual prechambers. Maximum size of each prechamber is 50mm×50mm×50mm. Maximum total volume of this combustion vessel configuration is 625cc. (Cho et al(1988)[4], Jeong(1989))[5]

Premixed gas used was propane-air premixed gas of 3.8% volumetric mixture ratio of equivalence ratio 0.95.(Notice that Fujimoto et al(1984)[3] used methane-air premixed gas of equivalence ratio 0.95, while Jeong(1989)[5] used propane-air premixed gas of same equivalence ratio.) The equivalence ratio was calculated from their partial pressures. This premixed gas was initially charged into the combustion vessel at atmospheric pressure and room temperature.

An evacuated sampling bottle and a high pressure buffer bottle pressurized by argon gas were used to dilute sample exhaust gas, and diluted sampled gas was introduced to a chemiluminescence analyzer(Yanagimoto ECL-77A, Japan) through the sampling bottle.

Experiments were carried out changing the volumetric ratio of the prechamber to the main chamber and the diameter of the connecting orifice between the main chamber to the prechambers, but the distance from an orifice to the other opposed orifice was kept constant.

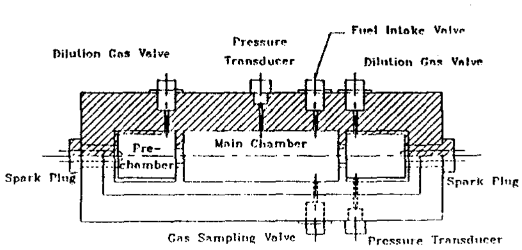

Figure 2. Rectangular combustion vessel

More detailed informations on the experiments can be found from the references(Miura et al (1978)[2], Fujimoto et al(1984)[3], Cho et al(1988)[4] and Jeong(1989))[5].

RESULTS AND DISCUSSIONS

Results on the relation between NOx concentration and final maximum combustion pressure of different combustion features and on the related flame propagation photography are presented. Typical three different combustion features are categorized(Fujimoto et al(1984))[3], i.e., Laminar- and Ordinary Turbulent- Combustion System, Single-Jet-Flame Combustion System, and Impinging-Jet-Flame Combustion System.

Laminar- and Ordinary Turbulent-Combustion System

Figure 3 shows relation between NOx concentration and final maximum combustion pressure for the case of laminar-and ordinary turbulent-combustion system of Fujimoto et al(1984)[3], Cho et al (1988)[4], Jeong(1989)[5], and our present experiment. These results show that usual laminar flame propagation or ordinary turbulent flame propagation give NOx concentration increasing almost linearly wrt combustion pressure, if system combustion pressure is increasing. As the final combustion pressure is related to the burnt gas temperature, which basically governs the NOx concentration. This combustion system continues for a rather relatively long combustion period(usually 50ms ca.), or burnt gas is staying long period under high temperature circumstance. When we recall that thermal NOx formation reaction kinetics is very rate limiting and temperature sensitive, results of Figure 3 is reasonable as far as product gas is exposed to the high temperature circumstance for a long period.

Notice that even different combustion vessel geometry or fuel type do not change basic feature

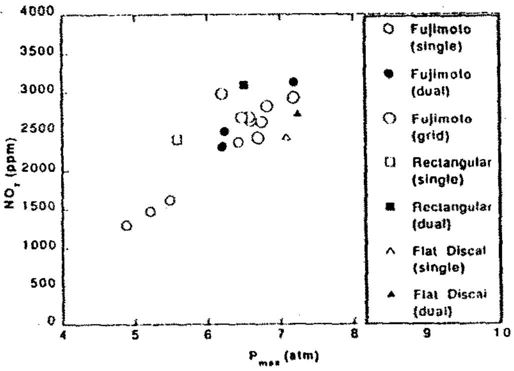

Figure 3. NOx concentration wrt final maximum combustion pressure Pmax for laminar- and ordinary turbulent-combustion system.
Single means laminar flame propagation in a main chamber at single point spark, dual means laminar flame propagation in a main chamber at dual point sparks, and grid means turbulent flame propagation in a main chamber at central spark with grid.

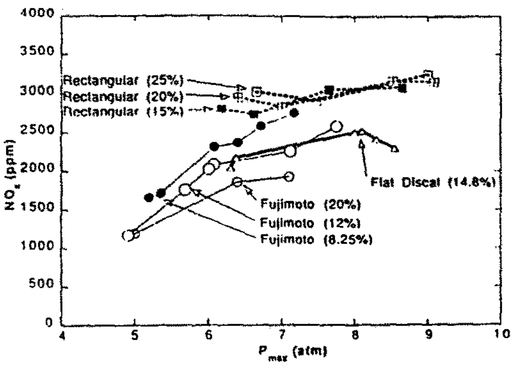

Figure 4. NOx concentration wrt final maximum combustion pressure Pmax for single-jet-flame combustion system.

of this system.

Single-Jet-Flame Combustion System

Figure 4 shows relation between NOx concentration and final maximum combustion pressure for the case of single-jet-flame combustion system. Even though slope of NOx concentration wrt final

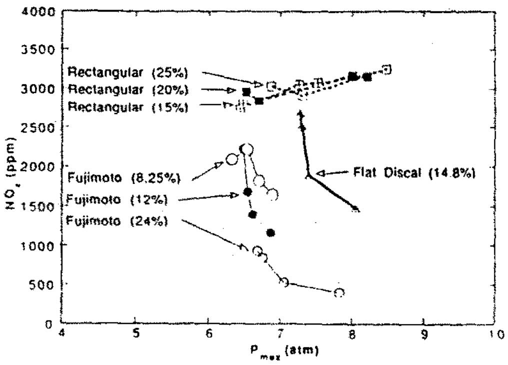

Figure 5. NOx concentration wrt final maximum combustion pressure Pmax for impinging-jet-flame combustion system.
Numbers in parethesis denote volumetric ratio of prechamber to main chamber.

maximum combustion pressure for this case is slightly lower than that of the case in Figure 3, we still can see that NOx concentration is increasing according to the increase of the final maximum combustion pressure. Slight reduction of NOx concentration may be understood with the fact that single-jet-flame combustion system reduces total burning time(ca. 25ms, by half to the case of laminar- and ordinary turbulent-combustion system), or burning velocity increases with turbulence intensity, and then mixing process of the hot burnt gas into the cold unburnt gas becomes a better improved mixing process resulting reduced peak fluctuating temperature.

This imagination can be noticable for the result of present experiment that NOx concentration is reversely decreasing at the higher final maximum pressure region. In this region, it resembles the behavior of impinging-jet-flame combustion system explaining next.

Impinging-Jet-Flame Combustion System

Results of impinging-jet-flame combustion system are summarized in Figure 5. Notice that result

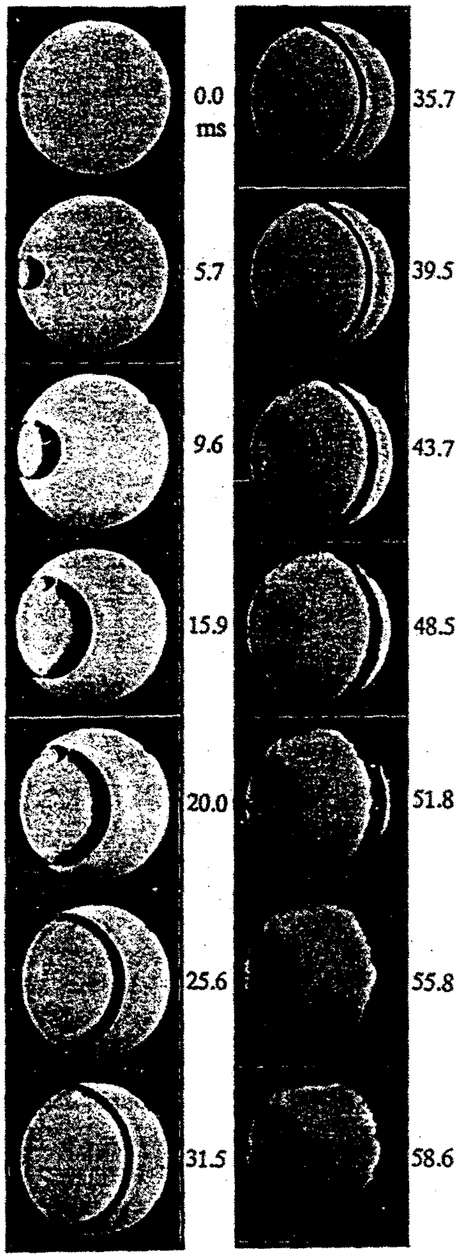

Figure 6. Flame propagations of laminar combustion sparked at one side of the main chamber.

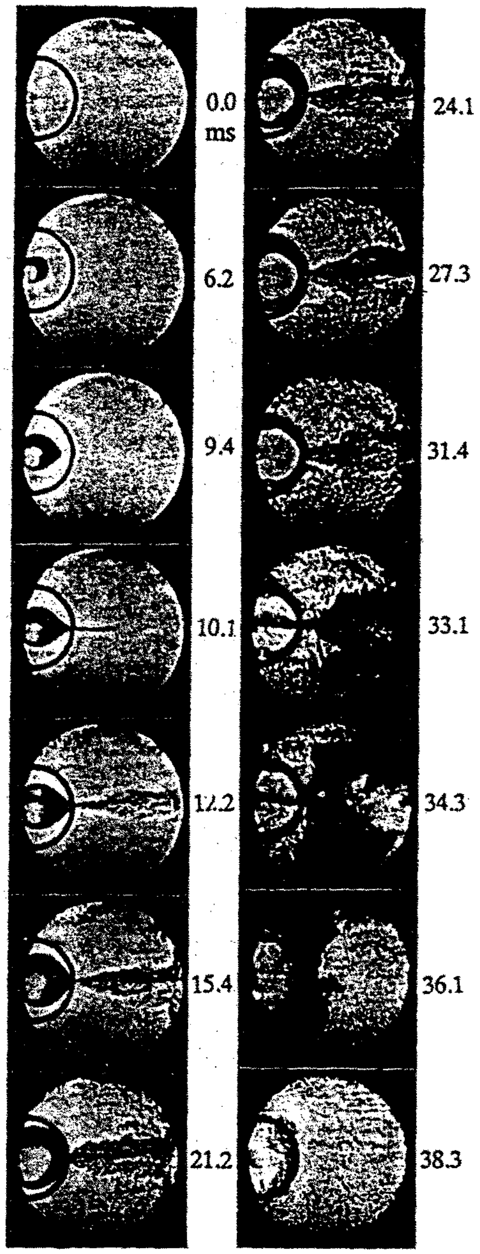

Figure 7. Flame propagations of turbulent combustion of single-jet-flame combustion.
Volumetric ratio of prechamber to main chamber is 14.8%, and orifice diameter is 5mm.

of present experiment and Fujimoto et al(1984)[3] are very alike, both burning in a flat discal combustion vessel with different premixed gases. Both results show that NOx concentration is drastically decreasing with increase of final combustion pressure. But, result of Cho et al(1988)[4] and Jeong (1989)[5] which burnt propane-air premixed gas in a rectangular combustion vessel does not show the reduction of NOx concentration with increase of final combustion pressure, rather show the very similar trend as in the case of single-jet-flame combustion. The fastest burning can be attained by this combustion system.(Total burning time is ca. 20ms.)

Four different flame propagation processes can be seen from Figure 6 to Figure 9. Figure 6 shows a very typical laminar flame propagation process. Figure 7 shows one typical example of turbulent flame propagation of single-jet-flame combustion. This schlieren picture shows that spouting jet immersed into the main chamber would not become a violent active flame until very late period, but this jet would disturb the unburnt gas in the main chamber, which can promote the unburnt gas turbulence intensity in the main chamber. Combustion in the main chamber is starting from the opposite wall where spouting jet collides on and speed of spouting jet becomes slower. When combustion starts to be a vigorous flame, shape of this flame is very similar to a band of wrinkled distorted, but connected flames. This flame proceeds to the main chamber side, but does not show the strong exchange or mixing of burnt gas with unburnt gas, as the established flame is a connected flame band that only the limited front surfaces exposed to the unburnt gas can exchange the hot burnt gas with the cold unburnt gas and keeps hot burnt gas behind the reacting flame front. Two typically different combustion progresses of impinging-jet-flame can be seen from the different flame propagations shown in Figure 8 for the burning in a rectangular combustion vessel which has such narrower space at the central zone of the main chamber where a head-on collision is occurred by a pair of impi-

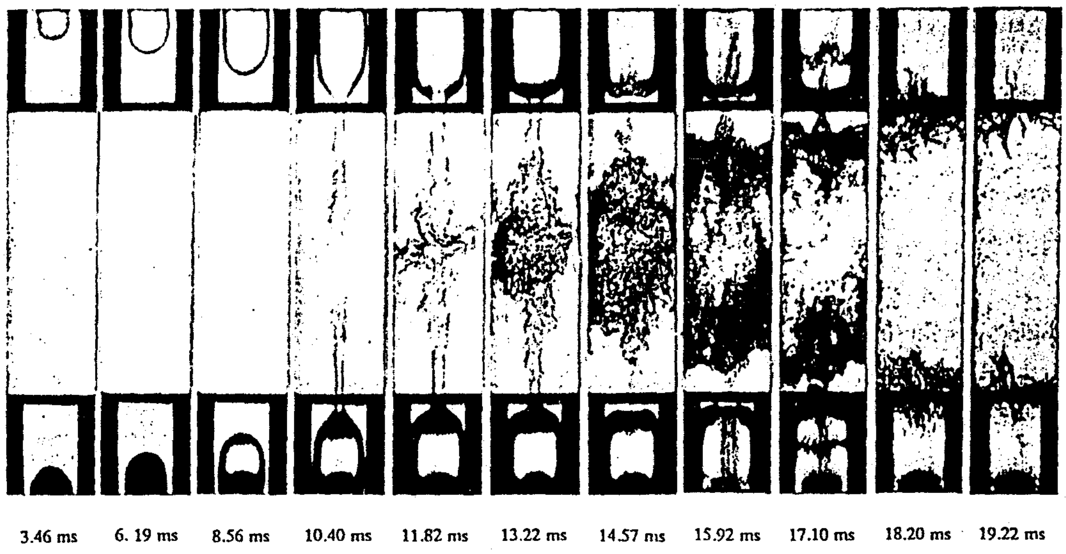

Figure 8. Flame propagation of turbulent combustion in a rectangular combustion vessel. Volumetric ratio of prechamber to main chamber is 20%, and orifice diameter is 10mm.

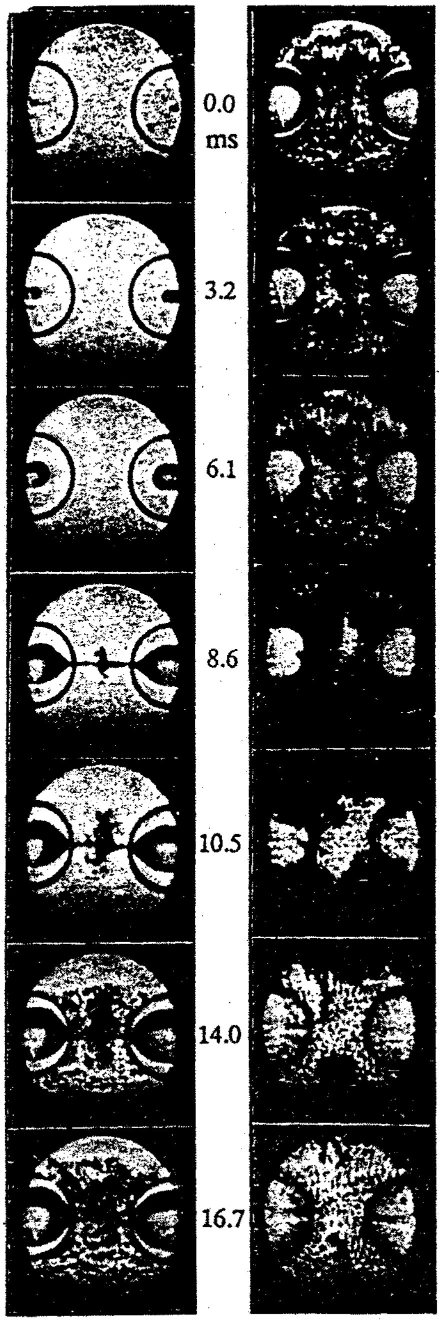

Figure 9. Flame propagation of turbulent combustion in a flat discal combustion vessel.
Volumetric ratio of prechamber to main chamber is 14.8%, and orifice diameter is 5mm.

nging jet flame spouting into the main chamber and in Figure 9 for the burning in a flat discal combustion vessel which has rather wider space at the central zone of the main chamber not much confining the turbulent mixing process as in a relatively confining mixing process of impinging-jet-flame with the unburnt gas due to the geometry of a rectangular combustion vessel. Flames in the rectangular combustion chamber(Figiure 8) are also formed two connected flame shapes similar to the single-jet-flame in the flat discal combustion chamber, and consequently shows same trend as in the case of the single-jet-flame combustion.

Different from the proceeding 3 cases, last case showing the impinging-jet-flame in the flat discal combustion chamber(Figure 9) gives a different situation, that we can see the very distributed small flame pockets surrounded by the unburnt cold gas pockets, around the time of 20 msec marked as the moment of reignition, from the other 3 cases. This situation suggests us the original idea on the impinging-jet-flame that some burnt gas is continuously supplied to the unburnt gas just adjacent to the flame front. Clearly, we can see this progress from the time of 14.0 msec in Figure 9 when combustion imitiated in the main chamber till the time of 24.0 msec when vigorous combustion is almost finishing. This strong mixing processes are always seen from all the cases, which correspond to the maximum prechamber volume to the minimum prechamber volume.

These results suggest better improved mixing probably due to the pair of impinging-jet-flame introducing much flow of unburnt gas into the burnt gas and homogeneous reduced fluctuating rms value possibly due to the head-on collision of a pair of impinging-jet-flame may cause fast burning, reduced fluctuating temperature peak but rather homogeneous temperature distribution, and then much reduced NOx concentration.

CONCLUDING REMARKS

Impinging-jet-flame combustion system in a closed combustion vessel simulating combustion at the top-dead-center-period of actual automotive engine combustion can give a fair amount of NOx concentration reduction still maintaining the final combustion pressure at highest level near stoichiometric mixture burning. Present results are coincident with the previous results of Fujimoto et al (1984)[3].

It seems that fuel type used should not be even a minor influential factor on the characteristics of impinging-jet-flame, but geometry of combustion vessel may be a possible influential factor.

Here, influence of the combustion vessel geometry suggest in a sense indirectly, that better improved mixing with homogeneous reduced fluctuating rms value may introduce fast burning resulting a highest pressure level, reduced fluctuating temperature peak, and then reduced NOx concentration.

ACKNOWLEDGEMENT

Authors wish to acknowledge that experimental efforts of Dr. K. S. Jeong, Mr. H. B. Park, and Mr. N. K. Cho are contributed in many ways.

REFERENCES

1. Bowman, C.T. ; Control of combustion-generated nitrogen oxide emissions ; Technology driven by regulation. Twenty-fourth Symposium (International)on Combustion, The Combustion Institute, pp.859−878, (1992).
2. Miura, S., Tsukamoto, T., Kawagoe, M., Nakaoji, S., and Kaneko, Y. ; NOx formation with various combustion processes of premixed gas. Mitsubishi Heavy Industries Technical Review, Vol.15, No.5, pp.1−11, (1978).
3. Fujimoto, S., Kaneko, Y., and Tsuruno, S. ; Possibility of low-NOx and high-load combustion in pre-mixed gases. Twentieth Symposium(International) on Combustion, The Combustion Institute. pp.61−66, (1984).
4. Cho, K. K., Jeung, I. S. and Jeong, K. S. ; A Study on Pollutant Reduction and Combustion Characteristics of Opposed-Jet-Flame Combustion Process(I). Journal of KSAE, Vol.10, No.1, pp.53−62, (1988).
5. Jeong, K. S ; A study on the combustion characteristics of premixed gases in a closed combustion chamber with/without prechambers. Ph. D. thesis, Seoul National University(in Korean), (1989).
6. Okajima, S., and Kumagai, S. ; Experimental investigation of soot and NOx reduction by impinging spray combustion in a closed vessel. Twenty-third Symposium(International) on Combustion, The Combustion Institute, pp.275−279, (1990).