International Journal of Automotive Technology, Vol. 4, No. 1, pp. 1−8 (2003)

1229−9138/2003/011−01

COMBUSTION CHARACTERISTICS OF WASTE-PYROLYSIS GASES IN AN INTERNAL COMBUSTION ENGINE

T. SHUDO[1)*], T. NAGANO[2)] and M. KOBAYASHI[3)]

[*1)]Musashi Institute of Technology, Tamazutsumi 1-28-1, Setagaya-ward, Tokyo, Japan
[2)]Yamaha Motor Corporation, Japan
[3)]Toshiba Corporation, Japan

(Received 8 May 2002; Revised 11 February 2003)

ABSTRACT−Wastes such as shredder dust of disposed vehicles can be decomposed into low calorific flammable gases by pyrolysis gasification. A stationary electric power generation using an internal combustion engine fuelled with the waste-pyrolysis gas is an effective way to ease both waste management and energy saving issues. The waste-pyrolysis gas mainly consists of H_2, CO, CO_2 and N_2. The composition and heating value of the gas generated depend on the conversion process and the property of the initial waste. This research analyzed the characteristics of the combustion and the exhaust emissions in a premixed charge spark ignition engine fuelled with several kinds of model gases, which were selected to simulate the pyrolysis-gases of automobile shredder dusts. The influences of the heating value and composition of the fuel were analyzed parametrically. Furthermore, optical analyses of the combustion flame were made to study the influence of the fuel's inert gas on the flame propagation.

KEY WORDS : Gas engine, Waste-pyrolysis gas, Hydrogen, Thermal efficiency, Combustion

1. INTRODUCTION

Wastes such as shredder dust of automobiles can be decomposed into flammable gases that contain hydrogen and carbon monoxide. A stationary electric power generation system that can use the waste-pyrolysis gas presents the advantage of addressing the current issues of waste processing and efficient energy utilization. Byproducts of the pyrolysis gasification such as metals and char also can be utilized as materials or fuel in industries. The power source for such electric power generation system should be able to adapt to variations in the composition and heating value of the fuel. From this point of view, the internal combustion engine appears as the most suitable power source because of its high flexibility regarding fuel properties.

Figure 1 shows an example of the waste-pyrolysis system. The gas generated by the waste mainly consists of hydrogen, carbon monoxide, carbon dioxide and nitrogen. The composition and the heating value vary in accordance with the pyrolysis process and the property of the original waste. Changes in the gas properties affect the combustion characteristics in the internal combustion engine. Consequently, it appears very important to investigate their influence in order to achieve a better understanding and an efficient application of the pyrolysis-gas system. The hydrogen present in the pyrolysis-gas has a quite higher burning velocity and wider flammable limits compared to other fuels. Those properties bring unique characteristics in the thermal efficiency of the internal combustion engine fuelled with hydrogen. Thus hydrogen supposedly have strong influences on the combustion characteristics of the pyrolysis gas.

This research investigated the combustion, power output, thermal efficiency and exhaust emissions of an internal combustion engine fuelled with several model fuels that simulated the pyrolysis-gases generated from shredder dusts of automobile. In addition, combustion enhancement by using hydrogen was studied along with optical analyses of the combustion flames.

2. EXPERIMENT

The engine used in this study is a four-stroke single-cylinder spark-ignition engine with a bore of 85 mm, a stroke of 88 mm, and a compression ratio of 13. Fuel gas was continuously supplied to the intake manifold of the engine. The in-cylinder pressure was measured with a piezoelectric type pressure transducer (AVL, GM12D)

**Corresponding author.* e-mail: shudo@herc.musashi-tech.ac.jp

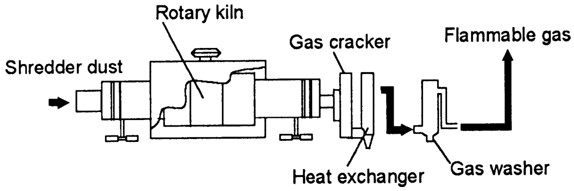


Figure 1. Pyrolysis gasification system.

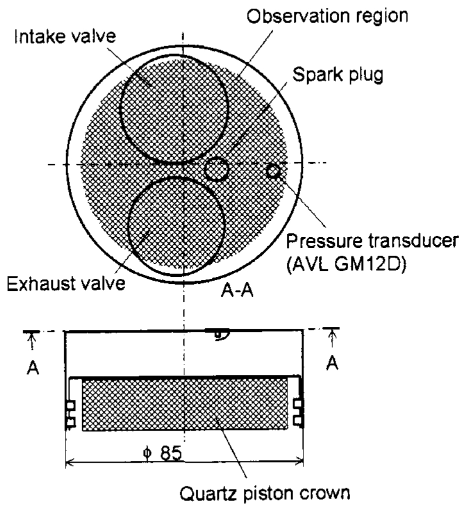


Figure 2. Combustion chamber geometry and observation region.

installed in the cylinder head as shown in Figure 2. For each experimental condition, a set of 100 cycles of pressure data was averaged and used to calculate the indicated thermal efficiency, the indicated mean effective pressure, the rate of heat release, the cycle to cycle combustion variation, and other parameters. This research evaluated the power output by the indicated mean effective pressure and the thermal efficiency by the indicated thermal efficiency. During all the experiments, the engine speed and the volumetric efficiency were fixed at 1000 rpm and 45% including fuel gas. The fuel gas flow was controlled and measured using respectively a needle valve and a mass flow meter (Oval, MASFLO-OVAL F203).

Table 1 shows the compositions and lower heating values of the fuels tested in this research. Those model fuels represented several typical pyrolysis-gases generated from wastes such as automobile shredder dusts. Hydrogen and carbon monoxide, the flammable contents of the fuel were diluted with inert gases such as carbon dioxide or nitrogen.

The concentrations of NOx and CO in the exhaust gas were respectively measured with a CLD type gas analyzer, and an NDIR analyzer. In some experiments,

Table 1. Compositions of tested model gases.

Case	CO/H_2 vol. ratio	Inert gas	Inert gas vol%	LHV MJ/m^3 ($kcal/m^3$)
1	1.0	N_2	58	5.02 (1200)
2	1.0	CO_2	58	5.02 (1200)
3	1.0	CO_2	36	7.54 (1800)
4	1.0	CO_2	24	8.79 (2100)
5	1.3	N_2	58	5.02 (1200)
6	1.3	CO_2	36	7.54 (1800)
7	1.3	CO_2	26	8.79 (2100)
8	1.6	N_2	58	5.02 (1200)
9	1.6	CO_2	37	7.54 (1800)
10	1.6	CO_2	27	8.79 (2100)
11	0.6	CO_2	56	5.02 (1200)

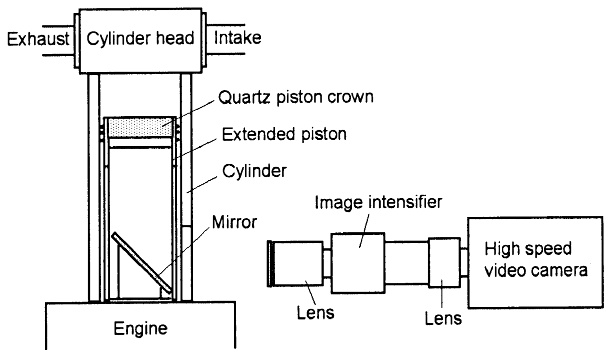


Figure 3. Tested bottom view engine and optical system.

the propagation of the combustion flame was observed through a fused silica piston crown from the bottom as described in Figure 3. The combustion flame images were enhanced with an image intensifier (Hamamatsu Photonics, C4273MOD) and recorded with a memory type high-speed video camera (Photoron, FASTCAM-utlima).

3. RESULTS AND DISCUSSIONS

3.1. Influence of the Heating Value

The effect of fuel's heating value on the combustion and exhaust emissions from the combustion engine was studied under the constant CO/H_2 ratio of 1.0. The heating value was successively set at 5.02, 7.54 and 8.79 MJ/m^3 by varying the fuels' CO_2 content. Figure 4 shows the indicated mean effective pressure IMEP, the indicated thermal efficiency η_i, as well as the CO and NOx exhaust emissions. The excess air ratio λ was set at 1.0 and 1.5. The optimum ignition timing for the indicated mean effective pressure MBT tended to

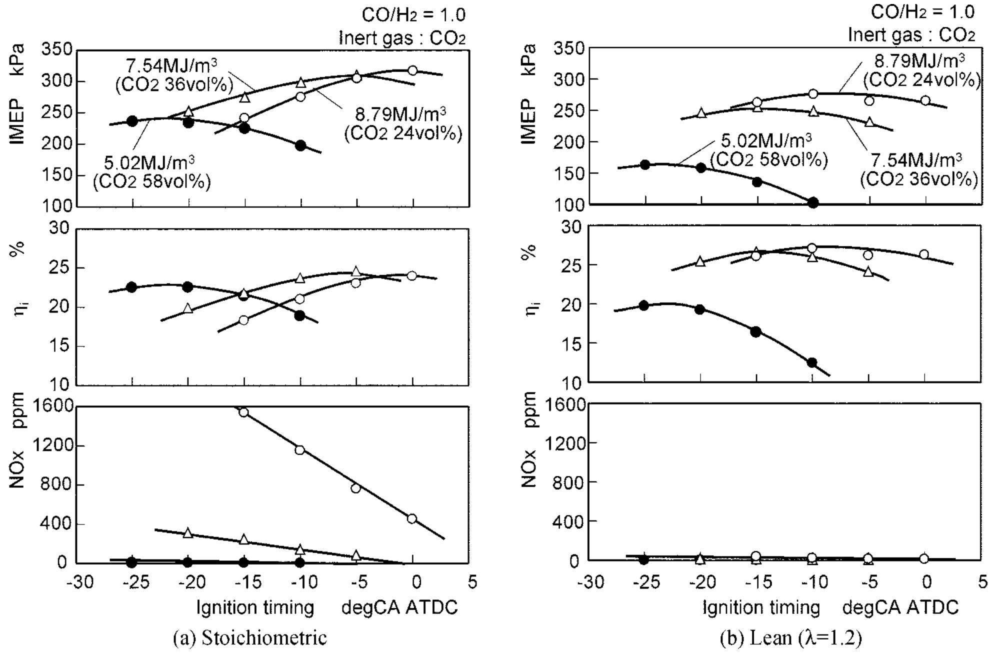


Figure 4. Influence of heating value on combustion and emissions.

advance with a decrease in the heating value of the fuel. The highest indicated thermal efficiency increased with the heating value. However, the difference in the thermal efficiency between the fuel with a heating value of 7.54 MJ/m^3 and that of 8.79 MJ/m^3 is quite small. Though the advanced ignition timing induced a higher NOx emission, the decrease in the heating value greatly reduced that emission. The fuels with 58 vol% CO_2 emitted almost no NOx even under stoichiometric mixture conditions. All the fuels tested in this research generated quite low NOx emissions under the lean combustion conditions with an excess air ratio of 1.5. On the other hand, though the fuel with the maximum heating value had the highest power output, there was no significant difference in the highest power output between the fuel with a heating value of 7.54 MJ/m^3 and that of 8.79 MJ/m^3.

3.2. Influence of the CO/H_2 Ratio

Because hydrogen and carbon monoxide have largely different combustion characteristics, their fractions in the fuel were supposed to influence combustion even at a fixed heating value. Figure 5 shows the influence of the CO/H_2 ratio on the power output, thermal efficiency and NOx emission. The CO/H_2 ratio was set at 1.0, 1.3 and 1.6, and the heating value of the three fuels was fixed at 7.54 MJ/m^3. Carbon dioxide was the inert gas content in the fuels. The excess air ratio was set at 1.0 and 1.5. In both cases of mixing ratios, the decreased burning velocity due to increased CO/H_2 ratio advanced the MBT. With the same inert gas and heating value, minor influences of the CO/H_2 ratio on the maximum power output were observed. NOx emission in the stoichiometric combustion tended to increase with the decrease in CO/H_2 ratio, because the faster combustion due to the increased hydrogen fraction increases maximum pressure and maximum temperature of in-cylinder gas. The higher adiabatic flame temperature of hydrogen than that of carbon monoxide might also a reason for the larger NOx emission. On the other hand, NOx emission in the lean combustion was very low.

Figure 6 illustrates influence of hydrogen amount on combustion of the fuels with a low heating value of 5.02 MJ/m^3. The heating value was controlled by varying the amount of CO_2. The CO/H_2 ratio was set at 1.0 and 0.6. Increasing hydrogen fraction as well as decreasing the CO/H_2 ratio in the fuel effectively improved thermal efficiency and power output especially in the lean mixture condition. It is also important to note that NOx emission was near zero even for the highly promoted combustion.

3.3. Influence of the Inert Gas Present in the Fuel

The sort of inert gas in the pyrolysis-gas depends on the pyrolysis system. Figure 7 shows the influence of two inert gases present in two fuels with the same heating value of 5.02 MJ/m^3. The inert gas content in the fuels was CO_2 or N_2. The combustion of the N_2 containing fuel generated higher power output, thermal efficiency and NOx emission compared to the fuel with CO_2. The

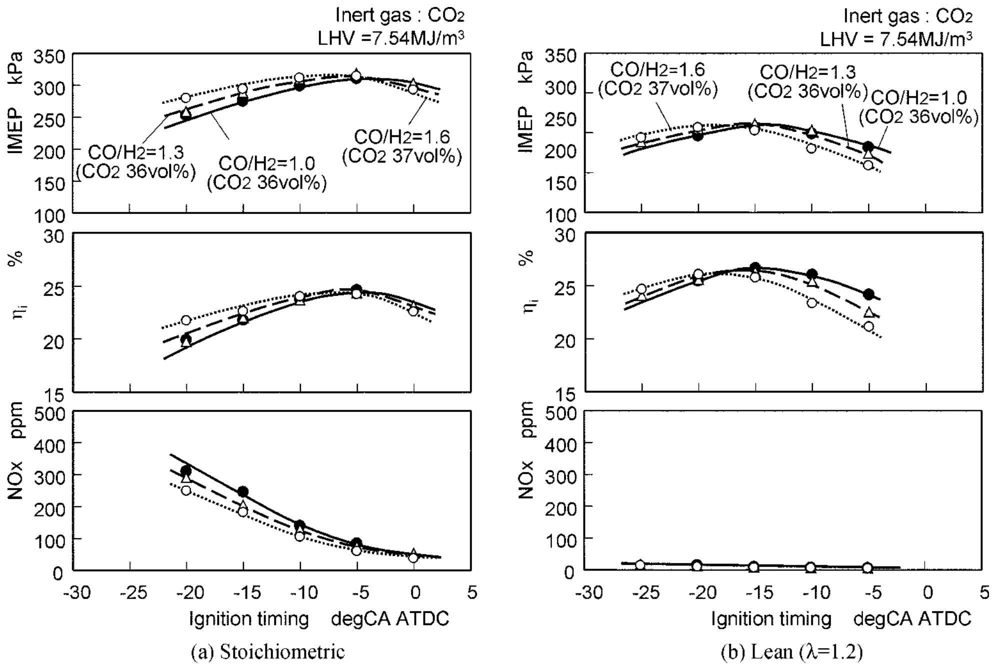


Figure 5. Influence of CO/H_2 ratio on combustion and emissions.

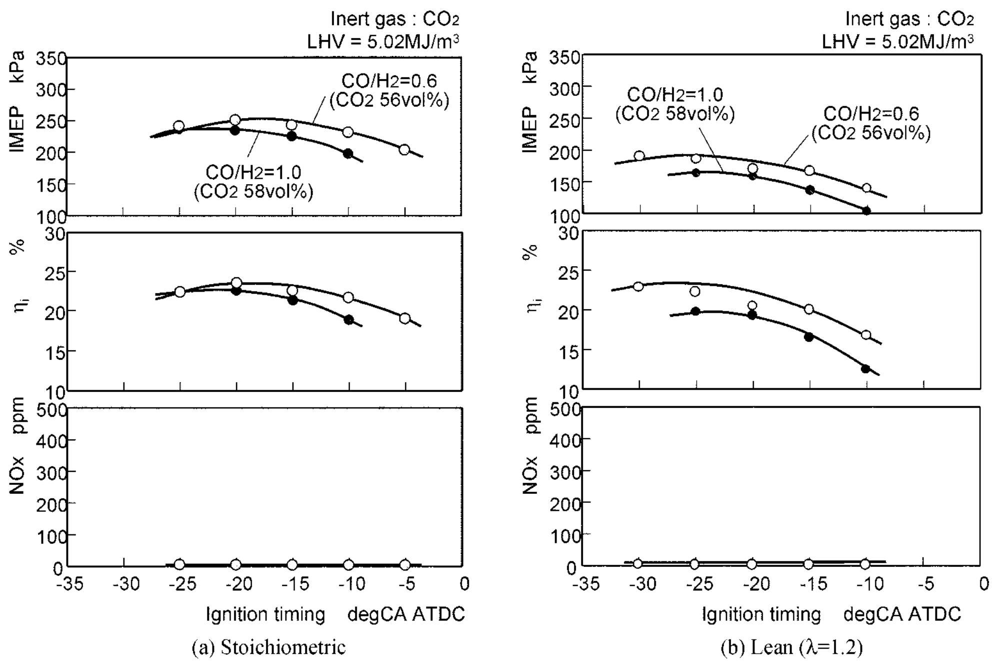


Figure 6. Influence of CO/H_2 ratio on combustion and emissions.

increases in power output and thermal efficiency were very large. The fuel with N_2 had a MBT in retarded timing than the fuel with CO_2. The retarded MBT can be attributed to the increased burning velocity due to the smaller heat capacity of the N_2 containing mixture.

In order to further analyze the thermal efficiency, the experimental data were used to calculate the degree of constant volume η_{glh}, the initial combustion period $\theta_{10\text{-}30}$ and the maximum rate of heat release $dQ/d\theta_{max}$. The degree of constant volume was calculated using the

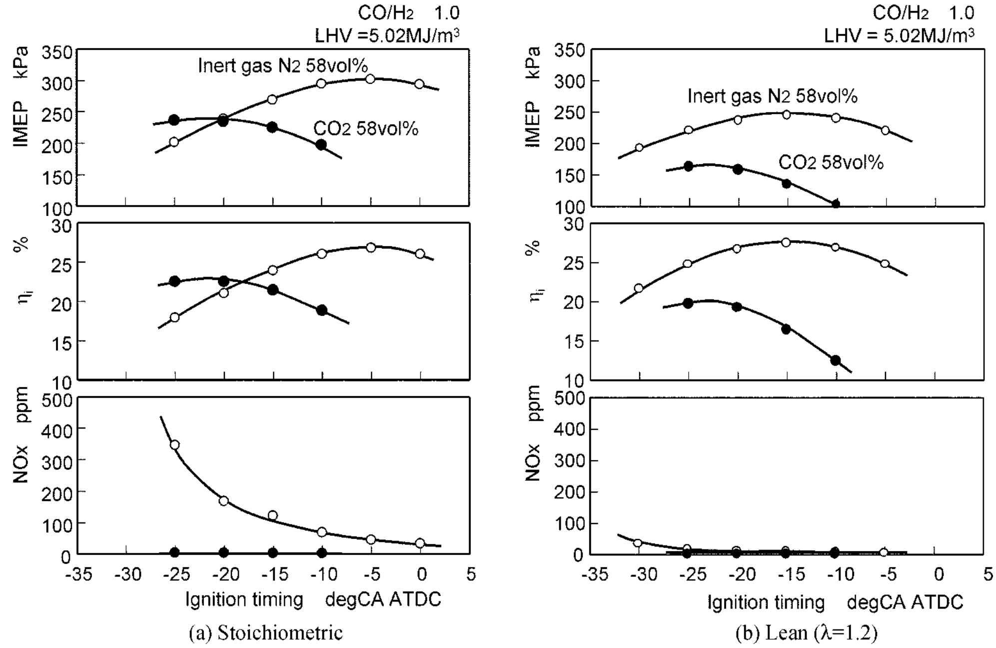


Figure 7. Influence of inert gas on combustion and emissions.

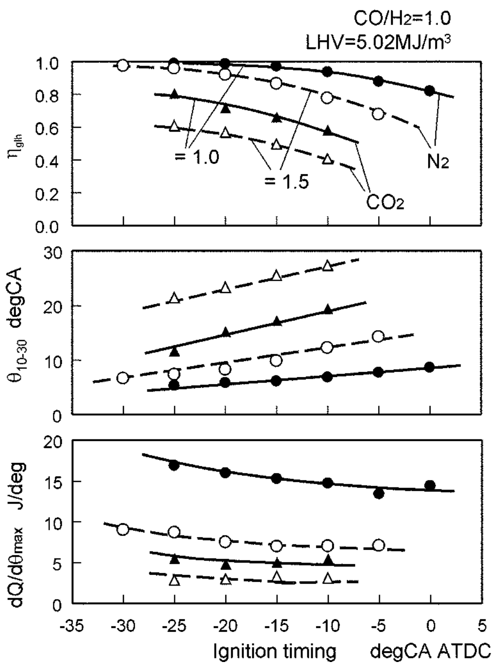


Figure 8. Influence of inert gas on combustion characteristics.

following equation;

$$\eta_{glh}=1/(\eta_{th}Q)(1-((V_h+V_c)/V(\theta))^{1-\gamma})dQ/d\theta d\theta$$

Figure 8 shows the result. The fuel with N_2 had a shorter combustion period and a higher degree of constant volume. The fuel with N_2 also featured higher maximum rates of heat release. These results imply that the replacement of CO_2 by N_2 enhanced combustion and caused for the higher thermal efficiency of the fuel with N_2 illustrated in Figure 7. The combustion flame in the combustion chamber was optically observed through a transparent piston crown from the bottom, to analyze the influence of the inert gas on flame propagation. Figure 9 shows the flame propagation of the two fuels in stoichiometric combustion. The ignition timing was set at 20 degree BTDC. The combustion of the fuel with CO_2 had a slower flame propagation and weaker flame emission compared to the combustion of the N_2 containing fuel. These were supposedly caused by lower flame temperature

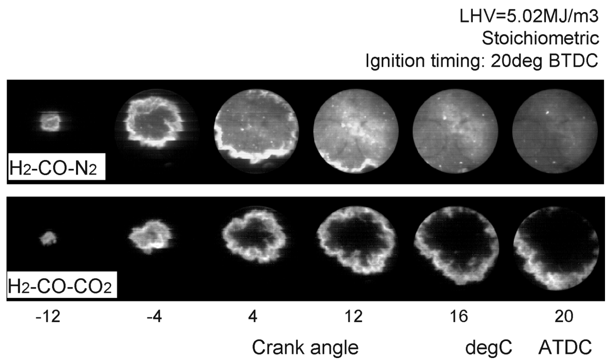
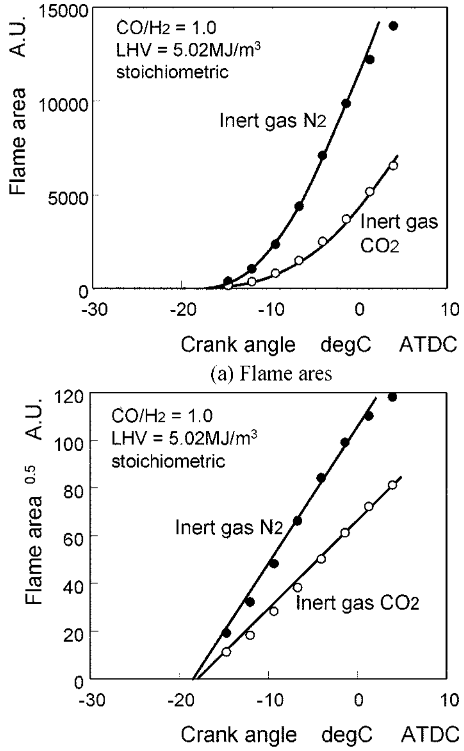


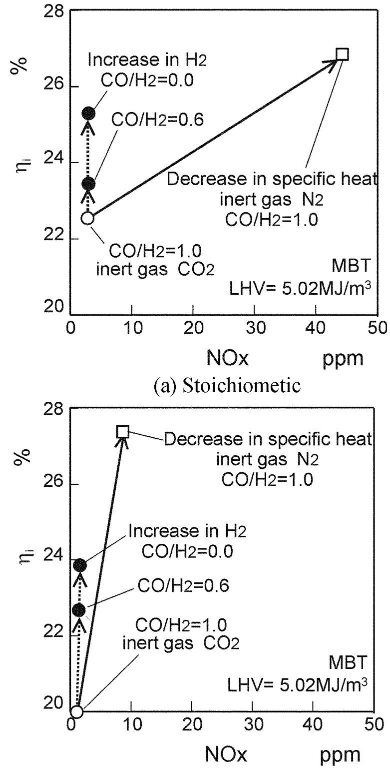
Figure 9. Influence of inert gas on flame propagation.



(a) Flame ares

(b) Root of flame area

Figure 10. Flame area for different inert gases.



(a) Stoichiometic

(b) Lean (λ=1.5)

Figure 11. Influence of CO/H_2 ratio and inert gas on thermal efficiency and NOx emission.

due to the large heat capacity of CO_2. Figure 10 indicates flame area and square root of flame area for the two fuels. Here, the root of the flame area roughly corresponds to the flame propagation velocity. It is clear that the fuel with CO_2 had a lower burning velocity than the one with N_2. Since CO_2 had a larger heat capacity than N_2, it seems reasonable to suppose that the heat capacity influences the result.

Figure 11 describes the relationships between thermal efficiencies and NOx emissions in the combustion of fuels of different compositions but with the same heating value of 5.02 MJ/m^3. The result with a fuel of CO/H_2=0.0, which means a mixture of just H_2 and CO_2, is also shown for a reference. The replacement of the inert gas CO_2 by N_2 brought higher thermal efficiency and a slightly higher NOx emission. On the other hand, the increase in hydrogen improved the thermal efficiency even for fuels with CO_2. However the effect of the increase in thermal efficiency was lower than the decreased heat capacity of mixture by the replacing inert gas. It is important to note that fuels with such a large amount of CO_2 hardly emitted NOx. Even in stoichiometric combustion of the fuel with the lowest CO/H_2 ratio of 0.0, NOx emission was quite low. This was attributed to the decreased flame temperature because of the large heat capacity of mixture containing large amount of CO_2. It may also be due to a slower NOx formation reaction by a lower molecule fraction of N_2 in the burning gas.

3.4. Comparison of all the Tested Fuels

Figure 12 indicates a comparison of all the fuels tested in this research. The ignition timing was set at MBT in each case. The figure describes IMEP, η_i, as well as the NOx and CO emissions and the cycle by cycle variation of IMEP as a function of the CO/H_2 ratio of the fuels. As expected, power output and thermal efficiency were higher in fuels with higher heating values. When the heating value was constant, N_2 containing fuel generated higher power output, thermal efficiency and combustion stability than fuel with CO_2. NOx exhaust emission during the pyrolysis gas combustion tended to increase with the fuel's hydrogen fraction. Pyrolysis gases of shredder dust with large amount of inert gases emitted quite low NOx in lean mixture combustion with excess air ratio of 1.5. Since low NOx emission in the lean combustion could be achieved without retarding ignition timing, a high thermal efficiency was also obtained. All the tested fuels emitted relatively high CO. That suggests that the

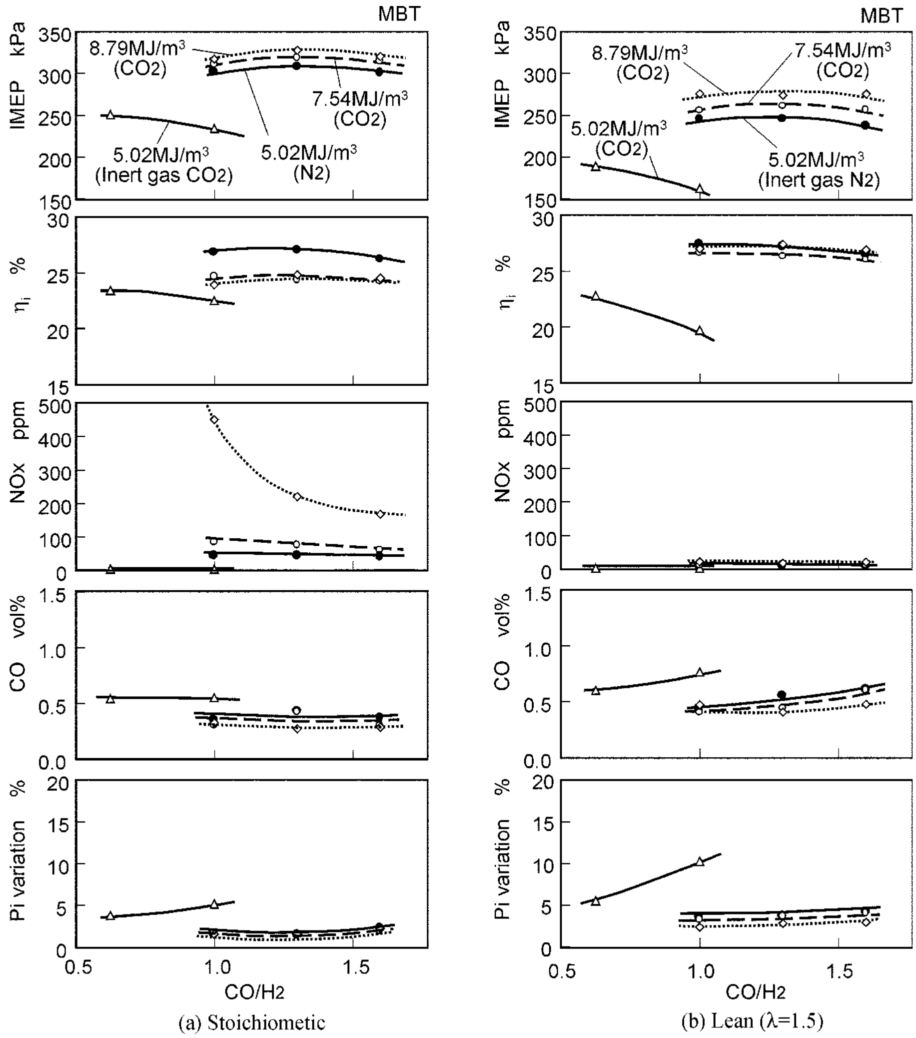


Figure 12. Comparison of all the tested fuels at MBT.

oxidation catalyst should be put in practice for power generation systems using internal combustion engines fuelled with the pyrolysis gases of wastes such as automobile shredder dust.

4. CONCLUSIONS

The results of this research are summarized below.

(1) Fuels with heating values as low as 5.02 MJ/m^3 such as shredder dust pyrolysis-gases were successfully proved to be used as fuels for internal combustion engines.

(2) The heat capacity of the mixture strongly affected the combustion. Fuels with N_2 dilution had highly promoted combustion in contrast to those with CO_2 because of the difference in heat capacity of the two compounds.

(3) The waste-pyrolysis gases containing large amount of inert gas emitted low NOx in lean combustion with excess air ratio of 1.5.

(4) Low NOx emission in lean condition was achieved without retarding ignition timing, and it made possible to obtain both low NOx emission and high thermal efficiency.

(5) All the fuels tested in this research emitted relatively high CO, which suggest that the oxidation catalyst should be used for practical purposes. One of such application can be in electric power generation systems equipped with internal combustion engines fuelled with waste-pyrolysis gases.

ACKNOWLEDGEMENT–The authors wish to express their gratitude to Mr. Y. Ono, a student of Musashi Institute of Technology, for his assistance.

REFERENCES

Lewis, B. and Elbe, G. (1961). *Combustion, Flames and Explosion of Gases*. John Wily & Sons. New York.

Shudo, T. (2002). Combustion analysis with indicator diagram in a hydrogen-fuelled engine. Proc. *FISITA, F02V048*, 1–15.

Shudo, T., Nabetani, S. and Nakajima, Y. (2001). Analysis of degree of constant volume and cooling loss in an SI engine fuelled with hydrogen. *Int. J. Engine Research* **2, 1,** 81–92.

Shudo, T., Nabetani, S. and Nakajima, Y. (2001). Influence of specific heat on indicator analysis in a hydrogen combustion engine, *Elsevier JSAE Review*, **22, 2,** 224–226.

Shudo, T., Nakajima, Y. and Futakuchi, T. (2000). Thermal efficiency analysis in a hydrogen premixed combustion engine, *Elsevier JSAE Review*, **21, 2,** 177–182.

Shudo, T., Nakajima, Y. and Tsuga, K. (2001). Combustion characteristics of H_2-CO-CO_2 mixture in an IC engine. *SAE Trans. J. Engines* **110, 3,** 199–206.

Shudo, T., Shimamura, K. and Nakajima, Y. (2000). Combustion and emissions in a methane DI engine with hydrogen premixing. *Elsevier JSAE Review* **21, 1,** 3–7.

Shudo, T., Tsuga, K. and Nakajima, Y. (2001). Analysis of direct injection SI stratified combustion in hydrogen lean mixture, *Int. J. Automotive Technology*, **2, 3,** 85–92.