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Research Paper

A new technology to overcome the limits of HCCI engine through fuel modification

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HIGHLIGHTS

- Problems of HCCI engine can be overcome by adopting fuel modification.
- Gasoline vapor with HHO gas showed drastic improvement of fuel efficiency.
- Performance of single cylinder engine shows fuel efficiency more than double.

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ABSTRACT

The energy efficiency of internal combustion engine reached to about 30% only recently. To increase the efficiency, homogeneous charge compression ignition (HCCI) has been proposed, however, there is no available commercial engine yet. The main problem lies in the delayed heating rate in spite of fast reaction of homogeneous charged state of HCCI with excess air. To overcome this difficulty, a modification of fuel by vaporization of liquid gasoline with water electrolysis gas and air was adopted in order to warrant the fast and high temperature rise. Experiments were carried out with single cylinder engines supplied from the four different manufacturers. Experimental results show that fuel consumption was decreased by more than 50% compared to the case of supplying liquid fuel. It is believed it was due to the combined effects of the high and fast heating potential of water electrolysis gas together with the efficient turbulence mixing effect of vaporized fuel with excess air. By this method, the drawbacks caused by lean burn in the HCCI engine such as small power range can be overcome.

1. Introduction

The technologies of automobile engine have not been changed much since the invention of the first four stroke engine in 1876 by Nikolaus Otto, possibly due to the inherent nature of complexity involved in two phase turbulent reacting process occurring in practical engine. Thus, today's engine still faces low fuel efficiency only about 30% with at least 50% of the fuel energy supplied wasting into heat losses. Even if a wide range of more efficient direct injection techniques replaces various types of engines equipped with a carburetor or port fuel injection, the improvement of fuel efficiency is still unsatisfactory [1]. These days, the strategy of dilution method with excess air is believed to be one of the best ways to increase engine efficiency. Usually, the efficiency increases with increased excess air until the reduction of temperature rise becomes larger than the heat evolved by more efficient mixing and combustion with excess air. Further, the engines designed for excess air can employ a higher compression ratio and thus provide better performance than conventional engines.

More specifically, the homogeneous charge compression ignition (HCCI) engine is regarded as one of the best lean burn combustion modes of internal combustion engine [2] since it was proposed by Onishi et al. [3]. In HCCI, dilute and pre-mixed fuel–air charging is employed for the volumetric and simultaneous ignition accompanied by high compression ratio. This can provide higher fuel efficiency like in diesel engine together with low emission of NOx and particulates. However, the adoption of the dilution process intended for the homogeneous mixing and efficient burning is exposed to significant problems or disadvantages. Firstly, auto-ignition of the HCCI engine by high compression ratio is difficult to control compared to spark ignition (SI) or compression ignition (CI) engines, which can be regularly controlled by spark plug and fuel injection [4]. Secondly, HCCI engine has a relatively limited operating range, which is constrained by the lean flammability limit at low rpm and by the deficiency of power at high load [5]. For example, in a natural gas, lean burn engine from Cummins, the

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combustion process must be controlled within a narrow excess air range in order to prevent either knocking or misfiring [6]. The rich mixture less than 60% excess air can potentially produce knocking and higher NOx emissions and the leaner mixture more than 80% excess air may not well burn properly due to misfiring.

2. Materials and methods

2.1. Development of a new burning method

There is no doubt that producing a homogeneous mixture of fuel and oxidizer by excess air will lead to faster reaction, which results in high performance of engine operation [7]. In general, there are roughly three steps for the spray combustion such as atomization and vaporization of liquid droplet, turbulent mixing of vaporized fuel and air, and finally the chemical reaction between gasoline molecules and oxygen species. In order to make complete combustion successfully, it is necessary to have the liquid state of gasoline converted into vapor to make the maximum surface area exposed. The next step is to mix efficiently the gasoline vapor and air, for example, by eddy breakup action in turbulent flows. And finally the vapor will collide with oxygen molecules in air for chemical reaction. The overall reaction rate occurring in a series of competitive process can be expressed empirically in a harmonic form such as below.

$$\text{Overall reaction rate} \sim \frac{1}{\frac{1}{RR1}+\frac{1}{RR2}+\frac{1}{RR3}} \tag{1}$$

where RR stands for the reaction rate of the particular process associated with the overall reaction rates. Specifically, RR_1 is the rate of atomization and vaporization process, RR_2 is the rate of turbulence mixing process, and finally RR_3 is the rate of chemical kinetic process. It is generally known that the third term of the reaction rate, RR_3, is much faster compared to those of spray atomization and vaporization rate or turbulent mixing process. As a result, the first two terms in the denominator of Eq. (1) become more critical time consuming step. Therefore, in order to improve the engine efficiency, effective homogeneous mixing of fuel and air is important to reduce the delayed time rate. Considering the fact that more than 50% of fuel is wasted into heat, the lean burn approach to improve the efficiency by producing a homogeneous mixture with excess air looks promising and quite attractive. Conceptually, there is no doubt for the justification of lean burn method in HCCI engine mode.

Actually, HCCI method is quite successful in inducing fast reaction by homogeneous mixing and volumetric ignition with a large amount of excess air. However, it does not have a high heating rate due to the relatively small heating capacity of lean fuel. In other words, even if the burning reaction occurs fast, heat release rate may not be enough to run an engine if too much excess air is employed. This may result in shortage of power at high load or high rpm. The power of internal combustion engine can be analyzed simply by the change of the PV work using an ideal gas equation, PV = nRT, as

$$\frac{d(PV)}{dt}=\frac{d(nRT)}{dt}=\mathrm{n}\mathrm{R}\frac{dT}{dt}+TR\frac{dn}{dt}\fallingdotseq nR\frac{dT}{dt} \tag{2}$$

where the term TR(dn/dt) stands for the mole change of reactants in the combustion process. This term is not significant, especially in excess air condition due to the presence of large amounts of nitrogen in air. For example, the change of mole number, $\triangle n/n$, during the complete oxidation reaction of C_8H_{18} is only $\{(64 - 59.5)\}/59.5 \fallingdotseq 7.6\%$ due to the large amount of nitrogen gas in the air, 47 moles. As a result, the temperature rise (dT/dt) plays a critical role from the aspect of power generation. The excess air may contribute to fast temperature rise through increased reaction rate by the volumetric reaction due to the near complete mixing. However, it does not always warrant enough power generation because of the absolutely deficient amount of energy and retarded chemical kinetics due to lower flame temperature. Specifically, the calorific value of one mole of octane (C_8H_{18}) is 5,116,172 J, as shown in Eq. (3). For the full combustion of one mole of octane, 12.5 moles of oxygen is required. To supply this amount of oxygen from the air, supply of 47 moles of nitrogen is unavoidable. As a result, the total amount of the final products including nitrogen is 64 moles. In this case, the calorific value generated after combustion is about 79,940 J per mole of combustion. This value decreases significantly to about 41,426 J with 100% of excess air since 59.5 moles of oxygen and nitrogen is added further from the excess air.

$$C_8H_{18}+12.5O_2+47N_2 \rightarrow 8CO_2+9H_2O+47N_2+5{,}116{,}172\ \mathrm{J} \tag{3}$$

Considering the shortage of absolute energy and delayed reaction due to reduced flame temperature, it is believed that the simple dilution method employed in the HCCI engine does not look suitable to cover the wide range of performance. Based on the calculation of energy destruction during combustion by Dunbar and Lior [8], the energy efficiency decreases from 77% at stoichiometric condition to 66% at 100% excess air for H_2 combustion. In the case of methane flame, it decreases similarly from 72% to 60% from the same change of excess air ratio. Because of this fact, dilution method requires some remedies for a successful achievement of engine performance.

Based on a number of discussions made above, one viable method would be increasing the heating rate of fuel with excess amount of air. This can be achieved by supplying an auxiliary fuel, which has high calorific value to make up the power deficiency caused by excess air. For this purpose, two methods are employed in this study; the first one is to use water electrolysis gas (WEG) as an auxiliary fuel to enhance the heating potential of the mixture employing excess air. The other one is to employ vaporized gasoline for rapid homogeneous mixing and burning by skipping the evaporation process in the cylinder.

As shown in Eq. (4) of the reaction of WEG, there is only one mole of combustion product in the reaction of WEG. As a result, the calorific value of WEG per mole of combustion product, 241,827 J, is about three times than that of gasoline, 79,940 J. Additionally, it increases further to about 5.8 times when excess 100% air is employed.

$$H_2+\frac{1}{2}O_2 \rightarrow H_2O+241{,}827\ \mathrm{J} \tag{4}$$

Besides this fact, a couple of advantages should be noted in the use of the WEG. First of all, since the water electrolysis gas can be fed with well premixed state in a stoichiometric condition, it is not necessary to waste time for gaseous turbulent mixing process between hydrogen and oxygen. In addition to this, the high diffusion and flame speed of hydrogen and high auto ignition temperature are helpful to increase the engine power and reliable engine operation [9]. And the presence of hydrogen in WEG has a wider flammability limit than that of gasoline, which ensures smooth engine operation under diluent condition such as low speed operation. These features of WEG will be greatly favorable for the power generation by the rapid rise of temperature as shown in Eq. (3), $d(PV)/dt \fallingdotseq n\,R\,(dT/dt)$.

The laminar flame burning velocity of H_2-air is at least five times faster than that of octane-air and this ratio becomes more significant when the amount of oxygen fraction increases in oxidizer stream [10]. As was noted previously, the calorific value of WEG is about three times compared to that of octane at stoichiometric condition. The overall energy release rate of WEG is assumed by multiplying the two factors, approximately more than 15 times faster than that of octane in the air. As a result, the engine performance with reduced fuel by mixing WEG is still expected to generate the same magnitude of engine power using liquid gasoline. In detail, for example, if the total combined heating potential of WEG is more than n times than that of gasoline, then only one nth of the WEG is enough to substitute gasoline in energy ratio. If the x mole fraction of gasoline is substituted with WEG, then the combustion equation for a WEG mixed fuel with stoichiometric condition will be expressed as in Eq. (5), where n stands for the fuel reduction coefficient of replaced fuel considering the overall heating potential of WEG compared to gasoline fuel. In this study the value of n is considered to be about 20. And the coefficient 21 in Eq. (5) comes from the ratio of the heating value of gasoline to WEG, that is 5,116,172 J/241,827 J ~ 21.

$$(1-x)C_8H_{18}+(1-x)(12.5O_2+47N_2)+\frac{21x}{n}\left(H_2+\frac{1}{2}O_2\right)$$
$$\rightarrow(1-x)(8CO_2+9H_2O)+47(1-x)N_2+\frac{21x}{n}H_2O \quad (5)$$

Since it is desirable to run the engine by lean burn condition, excess air is put into the cylinder with gasoline vapor with WEG and air. In this case, the combustion equation will be as in Eq. (6).

$$(1-x)C_8H_{18}+12.5O_2+47N_2+\frac{21x}{n}\left(H_2+\frac{1}{2}O_2\right)$$
$$\rightarrow(1-x)(8CO_2+9H_2O)+xO_2+47N_2+\frac{21x}{n}H_2O \quad (6)$$

Considering the fact that vaporized gasoline reacts faster than the atomized fuel, it is natural to use gasoline vapor rather than liquid fuel in order to achieve more homogeneous mixing between fuel and oxidizer and faster reaction. There are two methods reported in literature to generate gasoline vapor; one is directly heating liquid gasoline to generate vapor [11] and the other one is to use the conventional bubbling method [12]. However, two methods are not quite successful in practical application. In heating method, especially in the case of octane considered in this study, it makes the situation difficult since the boiling temperature of octane is very close to the pre-ignition temperature of octane [13]. In this study, therefore, a modified bubbling method is employed to generate the mixture of gasoline vapor with air and WEG by passing them through the gasoline vessel. By mixing the gasoline vapor with WEG, the low energy density encountered in the use of gasoline vapor only can be successfully overcome.

Mixing gasoline vapor with WEG as auxiliary fuel has often been criticized even as pseudoscience since the employment of WEG as a fuel or fuel additive has been considered meaningless from the aspect of the 1st law of thermodynamics. The most common and decisive counterargument against employing WEG as an auxiliary fuel is that more energy is needed to split water molecules than that obtained by burning the WEG [14]. The situation becomes worse considering the combined efficiency associated with the generation of electricity and WEG. For example, if we assume the efficiency of electric power generation to be about 40% and the efficiency of WEG generation is about 70–80%, then the overall efficiency will be about 30%. To adopt the WEG it should be proved that it is beneficial despite of the fact that the overall efficiency of WEG generation is only 30% range. Since it does not look highly plausible, the use of WEG has been seriously criticized and not recommended. However, as has been discussed in this study, the use of WEG as an auxiliary fuel shows a dramatic increase of engine performance more than 20 times than that of the replaced fuel in energy ratio. Power, which is related to engine performance, is the rate at which work is done or energy is transmitted. Therefore, it is not fair to blame the use of WEG simply on the basis of the first law of thermodynamics without considering the potential of this gas in generating power.

2.2. Experimental methods

In order to evaluate the basic idea of a new burning method described above, a series of experiments have been made using a number of one-cylinder engines. The detailed layout for this experiment is shown in Fig. 1, which consists of the water electrolysis device, bubbler, centrifugal mixer, engine, and control/gauge panels. The electrolysis device used in this experiment is a high efficiency electrolyte cell in which distilled water mixed with KOH is dissociated into hydrogen and oxygen molecules in stoichiometric ratio. A homogeneous mixture of gasoline vapor with water electrolysis gas is prepared by bubbling of air and electrolysis gas passing through the liquid gasoline vessel. The premixed gaseous mixture is supplied directly into the nearest point of the engine intake valve with the supply of additional air by adjusting the throttle valve. The amount of WEG generated is controlled by the power supplied to the electrolyte cell. Comparison of engine performance between this mixture and liquid gasoline has been made by measuring the fuel consumption rate at a fixed rotational speed. In this experiment, only fuel consumption rate for an hour has been simply compared for two different types of fuels without any load applied. The amount of fuel consumed in normal operation using liquid gasoline was found to be very close to the calculated amount of gasoline obtained from the stoichiometric condition for oxygen in the air supplied to the engine as shown in Table 1. The calculated air supply ratio in the case of gasoline vapor and WEG mixture is summarized in Table 2 in terms of equivalence ratio and excess air. Note that the excess air ratio reaches to the level as high as 178%. This implies that complete oxidation in short time is possible and the temperature of the cylinder would be lower, as was confirmed by the measurement of exhaust gas temperature.

3. Results and discussions

In Table 3, results of fuel consumption rate measurement using the mixture of WEG and gasoline vapor are compared to the case of using liquid gasoline. This experiment was carried out using a Mitsubishi air cooled, single-cylinder engine (4.2 HP, 3 kW) with a displacement of 126 cc. The rotational speed was set at 1400 RPM and the amount of fuel consumption was measured after 1 hour of operation. The amount of fuel consumed in the case of liquid gasoline was 432 cc, that is, 2.84 moles, while in the case of a mixture of WEG and gasoline vapor it was 150 cc of liquid gasoline with 144 liters of WEG. The fuel energy of WEG may be obtained for two different cases; the first case is simply to calculate the heating value of 6.4 moles of WEG($H2 + 1/2\ O_2$), 1.03 MJ, and the other case is to count for the electric energy consumed in the production of WEG in an hour, 400 watt, i.e., 1.44 MJ. In this case, the total energy of the fuel mixture, including the electricity used for WEG generation, is about 45% compared to that of liquid gasoline.

According to this result, only 35% (150 cc/432 cc = 0.35) of gasoline was consumed in the mixture fuel compared to the case of liquid gasoline. Considering the reduced amount of gasoline, 65%, it can be said that 10.1 MJ of energy is substituted by the WEG with 1.03 MJ of energy, which means only 10% of WEG energy is necessary to make up the reduced amount of liquid gasoline. This reflects that the addition of WEG plays an important role to generate strong enough power and efficient operation by the combined effects of high heating potential and fast burning velocity. Further, other reliable combustion features of WEG such as wide flammability limit, high ignition temperature, low ignition energy and pre-mixed state of $H_2 + 1/2\ O_2$ mixture can be considered as auxiliary important

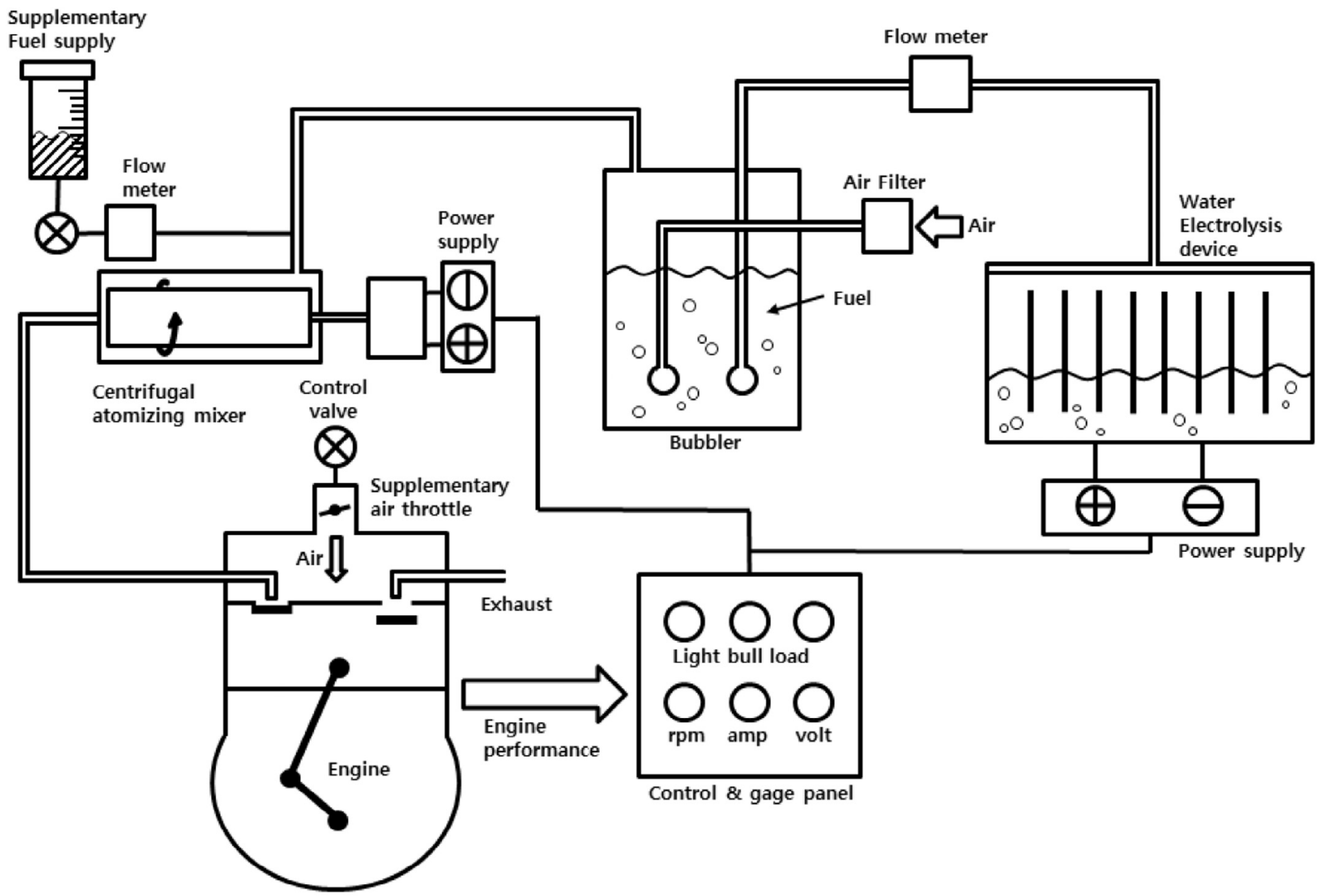

Fig. 1. Experimental layout for the generation of vaporized gasoline and WEG mixture fuel and a burning system with a single cylinder engine.

features to enhance the engine performance. Other similar experiments using 3 different engines such as Honda GX 160, 270 and Chinese Honda B33 showed similar or better engine performance. Even if we have not made any extensive investigation with important variables such as rpm and applied load, it is worth to note that this high efficiency of fuel consumption was achieved consistently employing fuel modification only without complicating modification of the engine.

The net energy addition by WEG is approximately in the range of 5%–15% compared to that of the reduced amount of liquid gasoline

Table 1
Comparison of liquid gasoline consumed with a calculated amount of gasoline required based on the stoichiometric condition for oxygen in the air supplied to the engine.

Experiment No.	Liquid gasoline consumed (A) (moles)	The calculated amount of gasoline for a stoichiometric condition of oxygen supplied (B) (moles)	Deviation, (B – A)/B, (%)
1	2.84	2.88	+1.4
2	5.43	5.47	+0.7
3	15.79	16.1	+1.9
4	5.64	5.40	–4.4

Table 2
Equivalence ratio (φ = (F/A)a/(F/A)s) employed in this experiment.

Experiment No.	Liquid gasoline (excess air, %)	Mixture of gasoline vapor and WEG (excess air, %)
1	0.99 (1.9%)	0.29 (178%)
2	0.99 (0.7%)	0.41 (146%)
3	0.98 (2.0%)	0.40 (153%)
4	1.04 (–4.0%)	0.42 (140%)

Table 3
Experimental results obtained from the comparison of fuel consumption rate by Mitsubishi Engine GB 130 model with 126 cc displacement using liquid gasoline and the mixture of gasoline vapor and WEG.

Item	Fuel type	
	Liquid gasoline (A)	Mixture of gasoline vapor with WEG (B)
Engine operation condition (rpm)	1400	1400
Electric power used for electrolysis of water for 1 hour (calorific value)	None	400 W (1.44 MJ)
WEG generated and calorific value of WEG	None	144 liter/hr (6.4 moles/hr) and 1.03 MJ
Efficiency of water electrolysis	None	1.03/1.44 = 0.715
Gasoline consumed in an hour of operation and its calorific value	432 cc/hr (2.84 moles/hr) 14.54 MJ/hr	150 cc/hr (0.99 moles/hr) 5.06 MJ/hr
Total energy used	14.54 MJ/hr	6.50 MJ/hr*
Ratio of total energy consumption (B/A = 0.45)	1	0.45**

* 5.06 + 1.44 = 6.50 MJ.
** 6.50/14.54 = 0.45.

Table 4
Comparison of energy consumption rate of the fuel mixture compared to liquid gasoline, which were obtained from the four kinds of different engines produced by different manufacturers. The WEG energy was compared to the reduced amount of liquid gasoline.

Engine No.	The amount of gasoline consumed in an hour of operation, B/A*	Ratio of gasoline consumption, B/A (%)	Ratio of total energy consumption, B/A (%)	The ratio of the energy of the added WEG to the energy corresponding to the reduced amount of gasoline (%)	
				Ratio 1**	Ratio 2**
1	150 cc/432 cc	34.7	45	15.2	10.9
2	330 cc/825 cc	40.0	45	8.6	6.2
3	950 cc/2400 cc	39.6	43	5.9	4.2
4	333 cc/857 cc	38.9	44	8.2	5.8

* A, liquid gasoline; B, gasoline vapor with WEG.
** Ratio 1 = Energy of the added WEG/Energy corresponding to the reduced amount of gasoline.
Ratio 2 = (Energy of the added WEG + Energy used for the electrolysis of water)/(Energy corresponding to the reduced amount of gasoline).

as shown in Table 4. From this result, it may be estimated that the power potential of WEG is 10–20 times larger than the liquid gasoline fuel. The new burning method proposed in this study with a significantly reduced amount of gasoline and an addition of small amounts of WEG in excess air condition exhibits surprisingly the same performance compared to the normal operation using liquid gasoline.

Actually, rough measurement of exhaust gas temperature of tail pipe showed that it is lower for the mixture fuel mode about 100 °C compared to the gasoline only mode. Because the peak temperatures are significantly lower than in a typical spark ignition engine, NOx level and particulate are almost negligible and it does not produce soot. In addition to this, the reduced amount of gasoline, about 35%–40%, implies directly that much of CO_2 has been reduced also.

It is clear from these results that the mixture of gasoline vapor and WEG with excess air has an advantage because of the fast reaction with a high heating rate. This fact results in higher efficiency even though it has only 45% of energy compared to the 100% gasoline. In summary, this study shows that the problems of the HCCI engine adopting a simple dilution method may be resolved simply by the novel method to increase the heating potential using the mixture of gasoline vapor and WEG.

Actually, modification of fuels by blending to extend the operating range has been studied for the manipulation of the onset of ignition and the heat release rate of HCCI engine. This was carried out by blending multiple fuels such as gasoline and diesel fuels, natural gas or ethanol [15–17]. However, as far as the gasoline or diesel is supplied in liquid form, this problem cannot be overcome due to the fundamental restriction as explained above, i.e., time consumption in vaporization of liquid fuel. The heat release rate of liquid flame is low and this is not effective in increasing the power where quick expansion of pressure is desirable.

4. Conclusions

In this new burning method, the homogenized mixture of gasoline vapor and water electrolysis gas is burned in spark ignition engine having a single cylinder under lean-burn condition of more than 100% excess air. By this method, it was possible to reduce the fuel consumption less than 50% compared to the normal operation employing liquid gasoline. More specifically, the actual gasoline consumption rate has been decreased by one third, and if we consider the energy supplied from the WEG, it can be concluded that the total energy consumption rate has been decreased by one half. This experiment was carried out for four different kinds of engines produced by different manufacturers and all of them showed the same tendency. This result indicates that the power efficiency of converting the heating energy of fuel into a dynamic power has been improved drastically. From this result, rather than simply adopting the diluting method of HCCI (homogeneous charge compression ignition) mode, it is expected that the addition of WEG ($H2 + 1/2\ O_2$) as an auxiliary fuel into vaporized gasoline will show more excellent engine performance even though the amount of total energy consumed has been decreased significantly. The high engine performance could be explained by the combined effects of the high heating potential of WEG, the reduced time of reaction by vaporized gasoline and finally lean burn application with the excess air. In other words, the faster reaction rate with high heating potential by WEG and gasoline vapor works successfully to overcome the drawbacks caused by lean burn method adopted in an HCCI operation mode such as absolute power deficiency and unreliable burning feature.

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