

# A Theoretical Estimation Study on the Work Balance of a High Pressure Liquid Hydrogen Pump for a Hydrogen Direct Injection Engine with 1-liter Stroke Volume

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In practical hydrogen fueled engines where hydrogen gas at high pressure is directly injected into the combustion chamber and consequent burns, it is impossible to identify the contribution of the energy of the hydrogen gas pressure to the engine output power. And, it is very important to know theoretically the contribution because the pressure of the hydrogen gas affects the system of the engines. It is also significant to whether the work obtained only by the direct injection into the engine without combustion, namely only by the pressure energy of hydrogen injected into the combustion chamber, can compensate the work needed to pressurize liquid hydrogen in the pump or not. If not, the work of the pump driving is supplied from the engine, decreasing the engine output power and the thermal efficiency.

By varying the direct injection pressure from 5 to 35 MPa and the mixture strength, namely the air-fuel ratio or air excess ratio, a simple theoretical thermodynamic study was carried out to clarify the contribution of the pressure energy of the hydrogen injected, the balance of the work needed for the pump driving and the work obtained by the direct injection. As a result, the followings have been found. The injection pressure studied here is above the critical pressure of hydrogen.

(1) There is the contribution of the energy of the hydrogen gas pressure to the engine output power. The contribution is small, varying from 1.61 % to 1.68 % of the combustion energy when the injection pressure varies from 5 MPa to 35 MPa.

(2) The work obtained by the direct injection can compensate the work needed to drive a liquid hydrogen pump. But it depends on the conversion efficiency of the electric generator.

In addition, the simple estimation study carried out to obtain the results of this paper will be explained.

**Keywords:** Energy Balance, Liquid Hydrogen Pump, Direct Injection, Internal Combustion Engine, Hydrogen Fuel

## 1. Introduction

Hydrogen is a good fuel for automobiles because the exhaust gas contains no carbon dioxide (CO<sub>2</sub>), hydrocarbons (HC) and carbon monoxide (CO). And the output power of hydrogen fueled automobiles with internal mixture formation is about 1.2 times as much as that of gasoline fueled automobiles<sup>(1)</sup>. The thermal efficiency is also much better than that of the gasoline engines.

On the other hand, hydrogen-fueled internal combustion engines with internal mixture formation, namely hydrogen direct injection in the late compression stroke, bring about nitrogen oxides (NO<sub>x</sub>) in the exhaust gas. Recently, a good NO<sub>x</sub> absorption-and-reduction catalysis system can afford to eliminate a large amount of NO<sub>x</sub> in the exhaust gas by using as a small amount of hydrogen on board of the vehicles, taking advantage of the good reducing ability of hydrogen<sup>(2)</sup>.

When using high-pressure hydrogen for the direct injection on board, hydrogen stored at 35 MPa in a light-weight composite cylinder vessel cannot be used up to the end since the direct injection needs more than 10 MPa. As a result, about a third of the hydrogen in the vessel remains unused resulting in a small mileage.

To overcome the problem and obtain good engine performances, liquid hydrogen has been used since 1975 for BMW hydrogen cars and Musashi cars. Especially Musashi cars have been using liquid hydrogen pumps to obtain hydrogen gas at high pressure on board of the vehicles since then. In case of liquid hydrogen storage system with a liquid hydrogen high pressure pump, the pump sucks in the liquid hydrogen at the atmospheric pressure and supplies hydrogen at high pressure more than 10 MPa to the engine. Therefore, the liquid hydrogen in the storage system can be used up to the bottom.

Because of the difficulty in identifying the contribution of the pressure energy of the hydrogen injected into the combustion chamber at high pressure, an attention has been paid to how much the pressure energy of the hydrogen gas contribute to the output power of the engine. And in order to clarify the advantage in using liquid hydrogen as the fuel of the hydrogen fueled engines, it is very interesting to know how much energy the pump needs to pressurize liquid hydrogen to high pressure such as 35 MPa. So the authors calculated the amount of the energy which the pump needed to pressurize the liquid hydrogen to 5, 10, 16, 20, 26, 30 and 35 MPa from the atmospheric pressure respectively.

These pressures are all above the critical pressure. And in the other hand, the authors also calculated the amount of the energy obtained through the injection into the combustion chamber at high pressure. In practice, the energy obtained from the engine is converted to the electric energy by an electric generator with various conversion efficiencies and is stored in an electric battery to drive the pump. And the conversion efficiency of the electric generator from mechanical energy to electric one varies greatly with the revolution speed of the electric generator. Therefore, the authors would like to know whether the amount of the energy obtained from the engine is enough or not.

To find out whether the energy obtained by expanding the hydrogen gas at high pressure in the engine was enough to drive the pump, the calculation was made theoretically in case of various high pressures and the amount of hydrogen needed to the engine in the operating conditions. The stroke volume  $V_s$  of 1 liter and the compression ratio of 13:1 were used in this study.

**2. Description of System**

To clarify the system, a liquid hydrogen engine system and the energy conversion cycle is described below.

**2.1 Liquid Hydrogen Engine System**

Figure 1 shows the liquid hydrogen engine system employed for a hydrogen-fueled car with internal mixture formation, called Musashi 8; a sport car converted from “Fair Lady” made by Nissan Motor Co. The liquid hydrogen is stored in a double-wall super-insulated container. The liquid hydrogen pump pressurizes the liquid hydrogen to discharge it out of the pump at the injection pressure. The liquid hydrogen is warmed up at a heat exchanger. The warmed hydrogen in gas phase goes to the surge tank. And at last, the hydrogen goes to the hydrogen injector where the injection valve is opened by the working fluid. The

hydrogen injection takes place at the injection pressure. The working fluid is pressurized by a diesel plunger pump at the injection timing of the hydrogen gas. The injected hydrogen gas into the combustion chamber is ignited with a spark plug almost at the same timing of the hydrogen injection one. The injected hydrogen burns heterogeneously in the combustion chamber during and after the injection. The combustion gas acts on the piston. The work of the engine is obtained.

**2.2 Energy Conversion Cycle**

To study theoretically how much the energy obtained by expanding the hydrogen gas at high pressure in the engine was, an energy cycle was established according the liquid hydrogen engine system. In this study, the energy needed for the working fluid was included not in this cycle but in the engine system because, the energy needed to activate the hydrogen gas injector was always included in the engine system. Figure 2 shows the energy conversion cycle with the conversion efficiency of the components used here in this study.

To pressurize the liquid hydrogen with the amount of the liquid hydrogen needed for the 4 strokes of the engine to the injection pressure, the liquid hydrogen pump consumes the energy provided through the engine-to-driving motor. The energy is designated by  $\Delta W_{pump}$  pump work. The liquid hydrogen goes to the heat exchanger where the hydrogen discharged from the pump gains energy from the air or the cooling water at the heat exchanger. As a result, the energy of the hydrogen at the temperature of 20 K rises to the energy at the temperature of 300 K. The hydrogen injection takes place isoenthalpically into the combustion chamber at the injection pressure and 300 K, the hydrogen gas acts on the piston of the engine while expanding in the expansion stroke and the engine obtains the work energy designated by  $\Delta W_{engine}$  without combustion. The mechanical work is converted into electric energy by the electric generator with the conversion efficiency shown in Fig. 2 because the

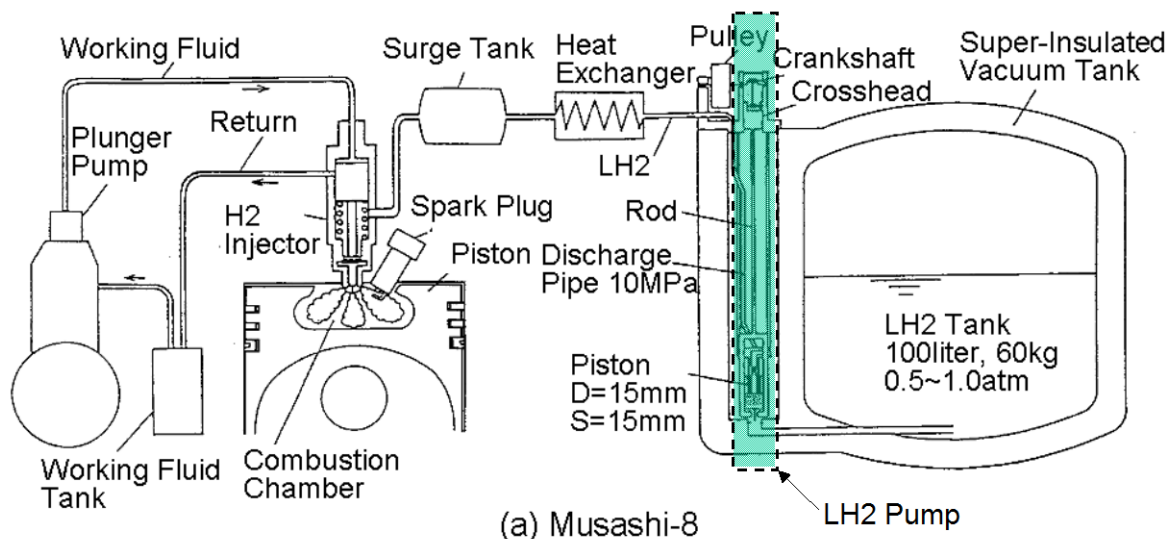


Fig.1 Liquid Hydrogen Engine System

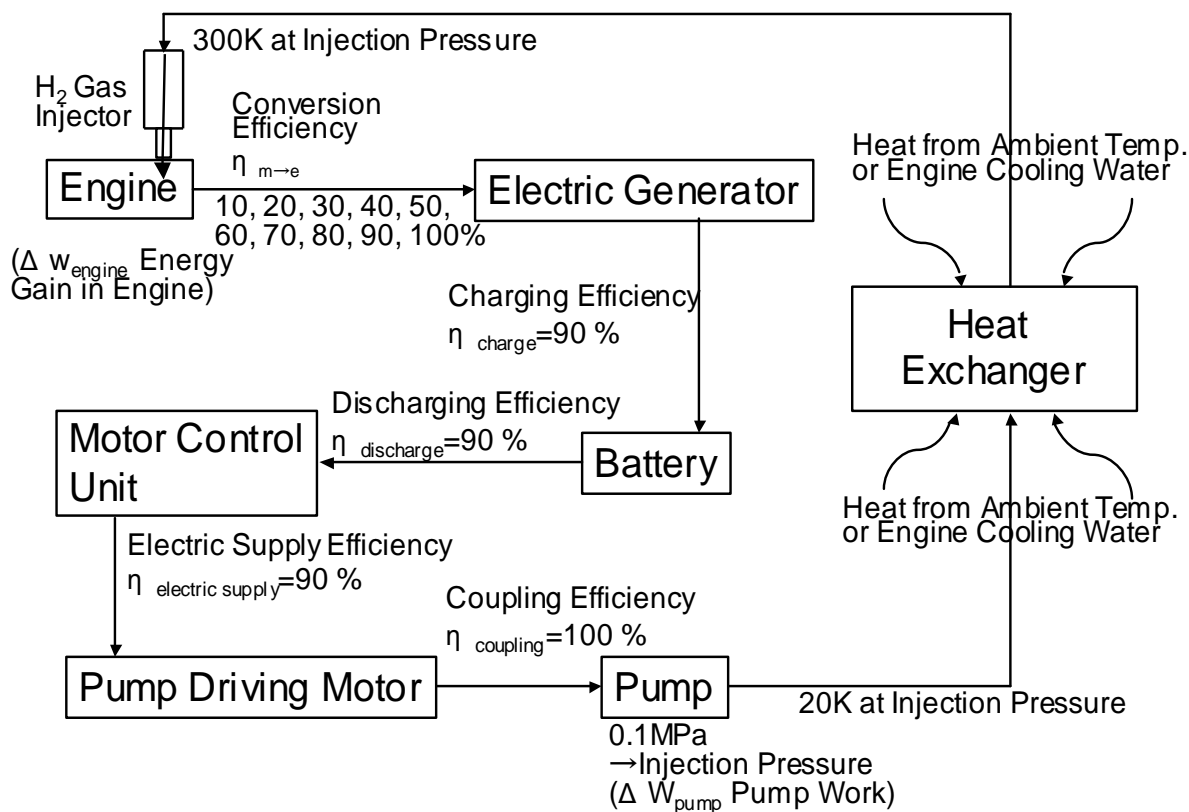


Fig. 2 Energy Conversion Cycle with Conversion Efficiency

conversion efficiency of electric generators changes with the revolution speed. In this study, the conversion efficiency was changed from 10 to 100 % because the conversion efficiency changes in practice while the engine runs. The electric energy is charged to the battery with 90 % charging efficiency and discharged to the motor control unit also with 90 % discharging efficiency. The motor control unit supplies the energy with 90 % electric supply efficiency. And the driving

motor drives the pump with 100 % coupling efficiency. These efficiencies are common values.

### 3. Theoretical Calculation

#### 3.1 Pump Work

The pump work  $\Delta W_{\text{pump}}$  was determined by the product of the volume of the liquid hydrogen  $\Delta V_{\text{LH}_2}$  discharged

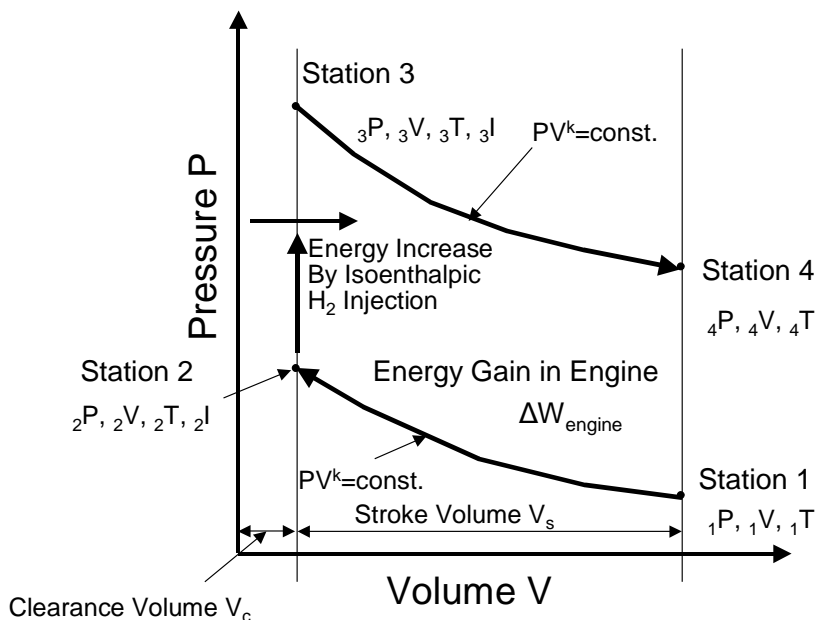


Fig. 3 Energy Gain in Engine

out of the pump for the amount of air introduced in the 4 strokes at the air excess ratio  $\lambda$  and the injection pressure  $P_{inj}$ . Namely the equation is as follows.

$$\Delta W_{pump} = \Delta V_{LH2} \times P_{inj} \quad (1)$$

### 3.2 Energy gain in Engine

To determine the energy gain in engine  $\Delta W_{engine}$ , the adiabatic compression and expansion process was used theoretically. And the gases used in this study were all ideal ones. Figure 3 shows the process of the theoretical calculation. As an example, the authors would like to determine the energy gain in the engine when the H2 injection pressure was 30 MPa as follows. In Fig. 3, the condition such as the pressure  ${}_1P$ , the volume  ${}_1V$  and the temperature  ${}_1T$  at the station 1 was kept constant at  $({}_1P, {}_1V, {}_1T)=(74924 \text{ (Pa)}, 1.0833 \times 10^{-3} \text{ (m}^3\text{)}, 300 \text{ (K)})$  in this study. The reason that the pressure  ${}_1P$  was below the atmospheric pressure was owing to the volumetric efficiency of the engine is 0.8.

The condition at the station 2 was determined by the adiabatic compression process, resulting in the condition such as  $({}_2P, {}_2V, {}_2T)=(2718373 \text{ (Pa)}, 0.0833 \times 10^{-3} \text{ (m}^3\text{)}, 837 \text{ (K)})$ . The specific heat ratio of 1.4 was used because the all the working gases were diatomic ones. And on the assumption that there was no loss in the enthalpy when the hydrogen was injected into the combustion chamber, the condition at the station 3 was determined by adding the enthalpy of the injected hydrogen at the injection pressure of 30 MPa and the H<sub>2</sub> temperature of 300 K to the condition of the station 2, resulting in the condition such as  $({}_3P, {}_3V, {}_3T)=(3138398 \text{ (Pa)}, 0.0833 \times 10^{-3} \text{ (m}^3\text{)}, 677\text{(K)})$  in case of the H2 injection pressure of 30MPa. And the condition at the station 4 was determined by the adiabatic expansion process, resulting in the condition such as  $({}_4P, {}_4V, {}_4T)=(86489 \text{ (Pa)}, 1.0833 \times 10^{-3} \text{ (m}^3\text{)}, 243\text{(K)})$  in case of the H2 injection pressure of 30MPa. The energy gain in engine  $\Delta W_{engine}$  was finally determined by integrating the work done from the station 1 to 4 to be 56.1 (J).

### 3.3 Engine Work Required

The engine work required  $\Delta W$  was determined by calculating back from the pump work  $\Delta W_{pump}$  obtained in the paragraph 3.1 by using the efficiency shown in Fig. 2.

## 4. Results and Discussions

### 4.1 Pump Work

Figure 4 shows the results. As known from the equation (1), the pump work linearly increases with the injection pressure increase and that the values change with the air excess ratio  $\lambda$ , namely the amount of hydrogen, because the air sucked in is constant. The values are very small. For example, when the engine is operated with the air excess ratio  $\lambda=1$  and the injection pressure is 35 MPa, the pump work  $\Delta W_{pump}$  is 13.62 (J). The amount is only 0.41% of the low heat value of the combustion of the injected hydrogen. To obtain hydrogen gas at high pressure, it is more reasonable to pressurize hydrogen in liquid state in case liquid hydrogen is easily available than to pressurize hydrogen gas to high pressure such as 10, 20 and 35 MPa.

### 4.2 Energy Gain in Engine

Figure 5 shows the results. It is found that the energy gain in engine does not largely change with the increase of the injection pressure. It is found, however, that the energy gain decreases with the increase of the air excess ratio  $\lambda$ , namely the decrease in the amount of hydrogen injected into the engine. The reason is that the enthalpy of the hydrogen at 300 K does not increase greatly with the increase of the injection pressure. In other words, if the air excess ratio  $\lambda$  is same, or the amount of the injected hydrogen is same, the energy gain in engine  $\Delta W_{engine}$  does not change greatly.

Considering the ratio between the energy gain in engine and the low heat value of the combustion, the ratio is around 1.6 %. From this result, it is found that the injection of hydrogen into the combustion chamber does not play a large part in the increase in the engine thermal efficiency.

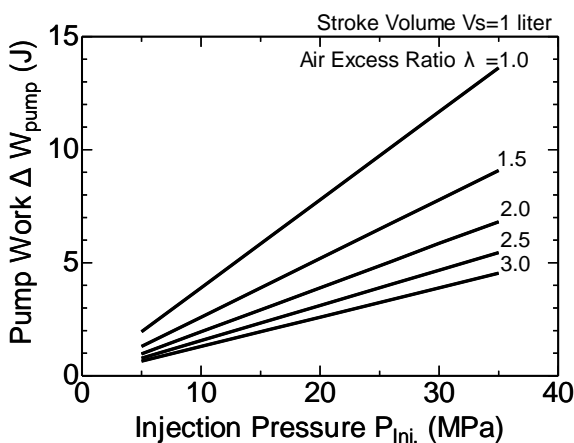


Fig. 4 Pump Work

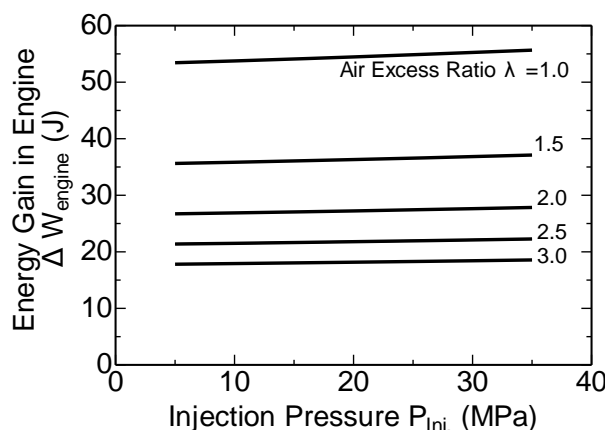
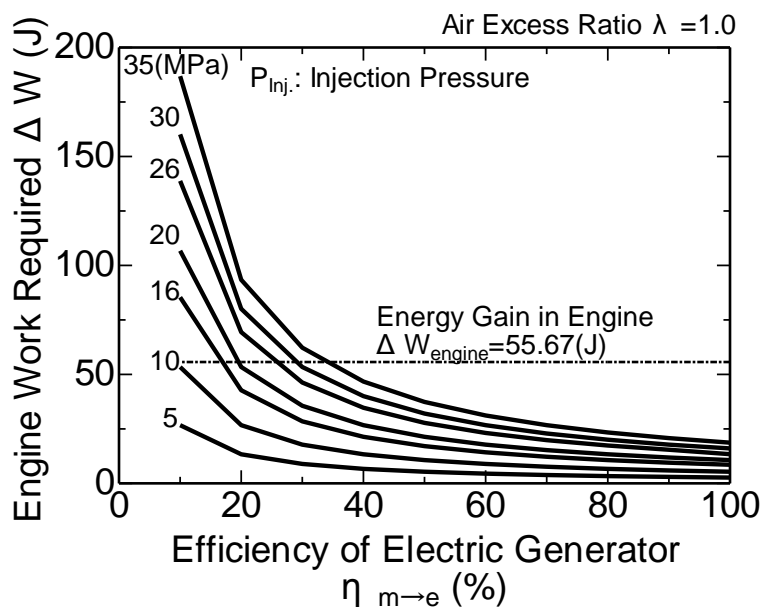


Fig. 5 Energy Gain in Engine

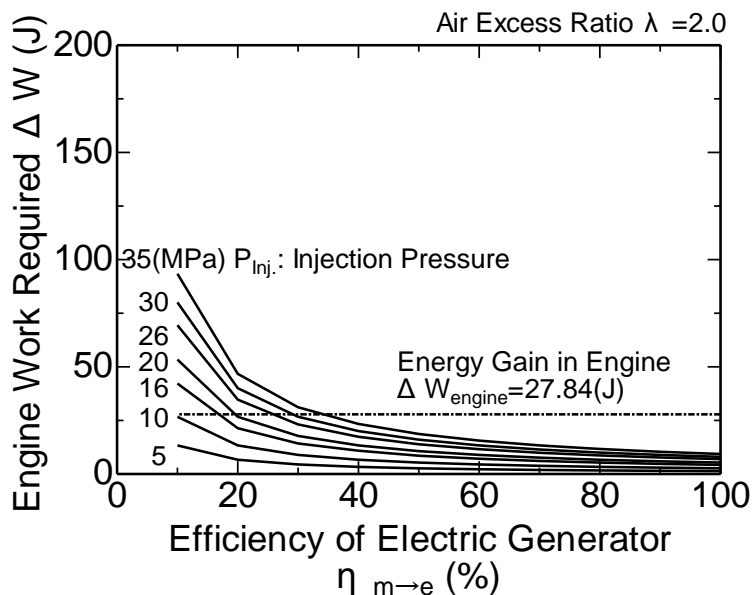
### 4.3 Engine Work Required

As mentioned above, the mechanical-to-electrical conversion efficiency  $\eta_{m \rightarrow e}$  is largely dependent on the revolution speed of the electric generator of the engine. The engine work required  $\Delta W$  was calculated with the conversion efficiency such as 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 %. The results are shown in Fig. 6 in case of the air excess ratio  $\lambda=1.0$  and 2.0 for comparison. It is found that the more the injection pressure becomes, the more the engine work required  $\Delta W$  increases. The engine work required  $\Delta W$  in case of the air excess ratio  $\lambda=1.0$  is twice as much as that in case of the air excess ratio  $\lambda=2.0$ . This is because the amount of hydrogen in

case of the air excess ratio  $\lambda=1.0$  is twice as much as that in case of the air excess ratio  $\lambda=2.0$ . Namely, the engine work required  $\Delta W$  is proportional to the amount of hydrogen pressurized by the pump. In the calculation, once the air excess ratio  $\lambda$  is fixed at a certain injection pressure, the amount of the injected hydrogen is automatically determined. In the figures, the energy gains in engine  $\Delta W_{engine}$  obtained by calculation in case of the air excess ratios  $\lambda=1.0$  and 2.0 is also plotted on the figures in Fig. 6. In either case, the left side of the crossing points where the energy gain in engine  $\Delta W_{engine}$  crosses the lines is the conversion efficiency of electric generators where the energy gain in engine  $\Delta W_{engine}$  is lacking in driving the pump. It is found that



(a) Air Excess Ratio  $\lambda = 1.0$



(b) Air Excess Ratio  $\lambda = 2.0$

Fig. 6 Engine Work Required

the conversion efficiency of electric generators limits the injection pressure applicable to the system if the pump is to be driven only by the energy gain in engine  $\Delta W_{\text{engine}}$ , or if users would not like to make a sacrifice of the thermal efficiency of the engine. For an example, in case of the injection pressure of 35 MPa, the conversion efficiency of the electric generator smaller than 34 % cannot compensate the pump work at all.

In practice, the conversion efficiency of conventional Landel-type electric generators is above 50 % at any revolution speed. Therefore, the energy gain in engine  $\Delta W_{\text{engine}}$  is always enough to drive the pump.

## 5. Conclusions

The theoretical study on the work balance of high-pressure liquid hydrogen pump for a hydrogen direct injection engine with 1-liter stroke volume has shown as follows:

- (1) The contribution of the energy of the hydrogen gas pressure to the engine output power is as small as only 1.6% of the low heat value of the combustion of the injected hydrogen. As a result, the work obtained by the direct injection plays a little part in the thermal efficiency of the engine.
- (2) The work obtained by the direct injection can compensate the work needed to drive a liquid hydrogen pump. But it depends on the conversion efficiency of the electric generator. In practice, the conversion efficiency of the conventional Landel-type electric generator is above 50 %, therefore the energy gain in engine  $\Delta W_{\text{engine}}$  is always enough to drive the high-pressure liquid hydrogen pump.

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