B-14.3.4 Improvement of Energy Regeneration of Heavy Duty Diesel Powered Vehicles

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Abstract

The objective of the study is to clarify regeneration and conversion techniques for abandoned heat energy in exhaust gas from automotive diesel engines during road driving conditions for improving fuel consumption and consequent CO_2 reduction of vehicles. From an estimation based on a conventional turbocharger system equipped on a direct injection diesel engine with the displacement 8000 cm^3, an exhaust turbine generator system which is applicable to a turbo charged diesel engine was developed for trial.

By the experimental result of the component test, 6 kW was obtained as maximum generator out put with this system. Then this was combined with a heavy duty diesel engine and energy regeneration performances under various driving conditions were experimentally studied. As result, it is clarified that the energy regeneration with this method could be effective under high speed and heavy load operating regions of the engine.

Key Words Energy Regeneration, Energy Conversion, Diesel Engine, Turbine Generator

1.Introduction

In the automotive field, many effort has been made to reduce carbon dioxide emission by reducing fuel consumption by combustion improvement of the engine or reducing power train and driving resistance. Especially, improving fuel consumption of heavy duty diesel vehicles which are the most commonly used for freight transportation may be the effective measure for CO_2 reduction in transportation field. However, drastic reduction of fuel consumption of heavy duty diesel vehicles is technically very difficult.

Although further improvement of the fuel consumption seems to be very difficult in case of automotive diesel engines today, only 20 to 30% of fuel energy is used for driving and the remain is abandoned as waste energy. Then, to achieve the epoch-making fuel consumption improvement, it can be an effective measure for CO_2 reduction to recover these wasted energy, such as kinetic energy at deceleration and exhaust gas heat energy etc., and convert (regenerate) to the energy useful for vehicle driving source effectively. Thereby the development for energy regeneration techniques of these wasted energies should be promoted.

By the above back ground, this study deals with exhaust heat energy which is relatively easy to regenerate among these wasted energies and its recovering and regeneration techniques were considered.

2. Method of the study

Today, the system where a part of the wasted energy is regenerated and used as auxiliary power source has been made practicable as pressure storage type hybrid systems and a diesel- electric hybrid system (HIMR Hino Inverter Motor Retarder)[1]. However, these systems regenerates only decelerating energy mechanically or electrically and uses it as auxiliary power source. Therefor, these system can fulfill its function only under driving conditions with high in frequency of accelerating and decelerating driving and may fit urban driving conditions which has relatively low average speed.

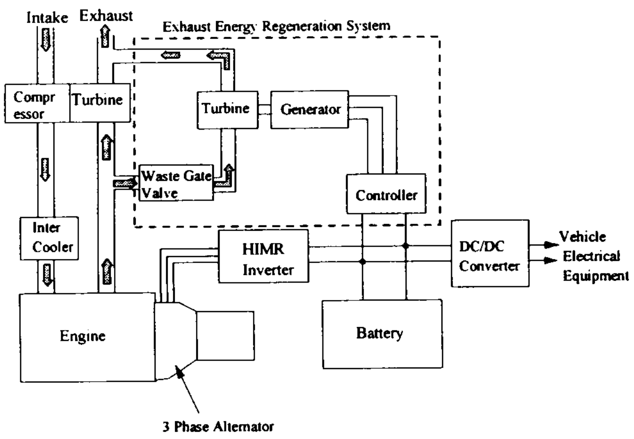

Fig.1 Exhaust Energy Regeneration System

This study aims at the improvement of the total energy regeneration efficiency by regenerating wasted energy mainly at high speed and heavy load engine operating regions such as highway or long uphill driving and adding them to the existing hybrid system. Then, on this study, the method for regenerating exhaust heat energy to electric energy which is the most convenient energy to use and applying them to HIMR system has been considered.

For that, a turbine generator system, in which a generator is driven by a exhaust power turbine was paid attention for the method of exhaust energy regeneration to convert it to electric energy.

At first, amount of the energy which can be regenerated was theoretically studied for a typical diesel engine and the basic estimation has been done. Then the performance target of a turbine generator system was settled based on the estimation and the system has been designed and made for trial followed by the component test for performance evaluation. The system was then equipped to a commercial heavy duty diesel engine and the evaluation has been implemented for complete engine system by engine dynamometer tests.

Finally, the effectiveness of the system, the energy regeneration effect and the fuel consumption improvement were clarified according to these results.

3. Design and development of the exhaust energy regenerating system

(1) Outline of the exhaust energy regenerating system

Since this system premises not to affect the engine basic performance, the power regeneration method by exhaust gas from the waste-gate valve of a turbo charged engine was chosen as basic system concept. Fig.1 shows the schematic of the energy regeneration system dealt with this study. An exhaust gas flow control valve (waste gate valve) was located between the engine and the turbo charger turbine and the bypassed exhaust gas is introduced to the power turbine of the exhaust energy regeneration system. The power turbine drives the directly connected alternative current generator and the surplus energy is converted to electric energy. The system controller governs the control of generated power

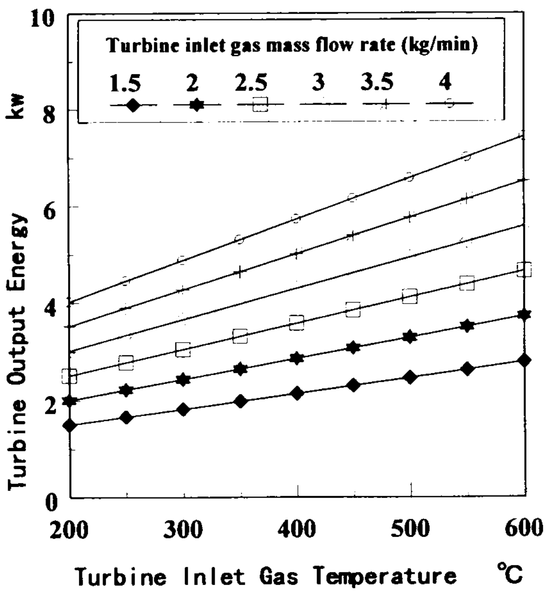

Fig.2 Estimation of Turbine Output Power

and the conversion of AC power to DC and charging batteries.

(2) Estimation of energy regeneration performance

Amount of turbine power generated by combustion gas was estimated as following. The turbine work L is generally indicated as the following equation.

$$L = Gg \cdot Cp \cdot T_{VT} \cdot \left(1 - \frac{1}{\pi_T^{(\kappa-1)/\kappa}}\right) \cdot \eta$$

Where

Cp : specific heat at constant pressure = 0.28

κ : ratio of specific heat = 1.36

T_{VT} : turbine inlet temperature

π_T : expansion ratio

Gg : turbine gas flow rate

η : turbine efficiency

Fig.2 shows the estimation results of turbine inlet temperatures versus power output with supposing turbine efficiency η =65% and expansion ratio π_T=2.0. The figure indicates that about 7 kW could be obtained as maximum turbine output.

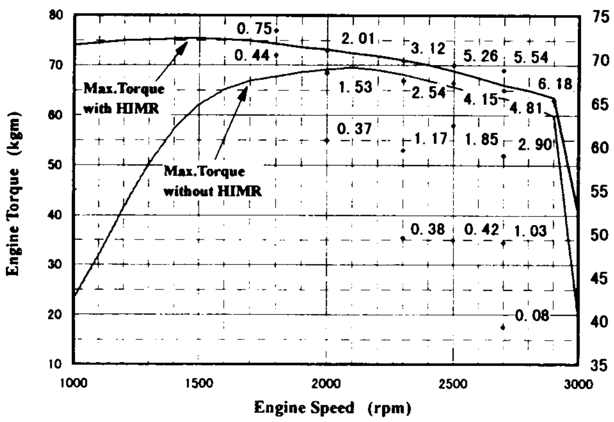

Fig.3 estimated turbine power at different engine operating points

Fig.3 shows the estimated turbine power at different engine operating points of a direct injection diesel engine with 8000 cm^3 swept volume based on measured exhaust temperatures, expansion ratios and gas flow rates from the waste gate. As shown in the figure, regained turbine power is very little at low engine speed regions because of lower gas flow rates and temperature. On the contrary, it goes up rapidly at high speed and heavy load regions. Thereby this energy regeneration system may work effectively at high speed and heavy load regions as the intention of the study.

(3) Design of turbine generator system

1) Generator type

Generally speaking, a permanent magnet or Crow pole type is used as high speed generators. Although Crow pole generator is more suitable for very high speed operations, the size and weight may become bigger due to its complicated mechanism. Thereby, permanent magnet type was selected for this system due to its high generating efficiency and potential of smaller

Table 1 Generator Spesification

Generator Type	Three Phase Permanent Magnet Type Synchronous Generator
Rated Power Rated Output Voltage Number of Poles	6 kW (80,000rpm) AC 200 V 4 Poles
Operating Speed Range	50,000 to 80,000 rpm
Over Speed Max.	84,000 rpm (105%)
Bearing	Ball Bearing
Weight	Approximately 10 kg
Size	115mm ϕ × 170mmL

size and weight.

Table 1 shows the estimated specification of the generator. The normal operating speed range was 50,000 to 80,000 rpm and the continuous maximum output was aimed 6 kW with estimation of 90% energy conversion efficiency.

2) Power turbine

A turbo charger turbine for a diesel engine was applied as the power turbine and variable nozzle was added for optimization of the system efficiency. At first prototype, a coupling was used to connect the generator and the turbine shaft. However, increase in vibration due to heat strain was observed at spinning test and the second prototype in which the turbine shaft was integrated with the generator shaft was made. Fig.4 shows both prototypes. The generator part is smaller at the second one.

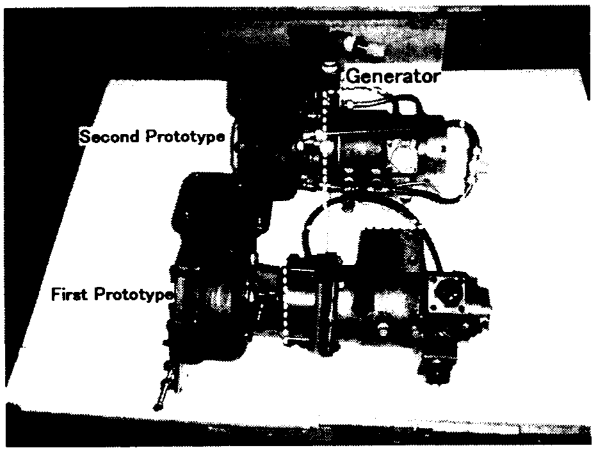

Fig.4 Prototype Turbine Generator System

4. Experimental results and discussion

(1) Component performance test

The component performance test has been conducted to evaluate the steady state performance of the prototype turbine generator system. At the test, compressed air from an high pressure air source was introduced to the power turbine for driving the generator. The generator output was observed according to the turbine speed and the generator current which was controlled by the system controller connected between the generator output line and the resistance load for power absorption. The voltage and current was measured between the generator and the controller and between the controller and the resister to calculate output power and efficiencies.

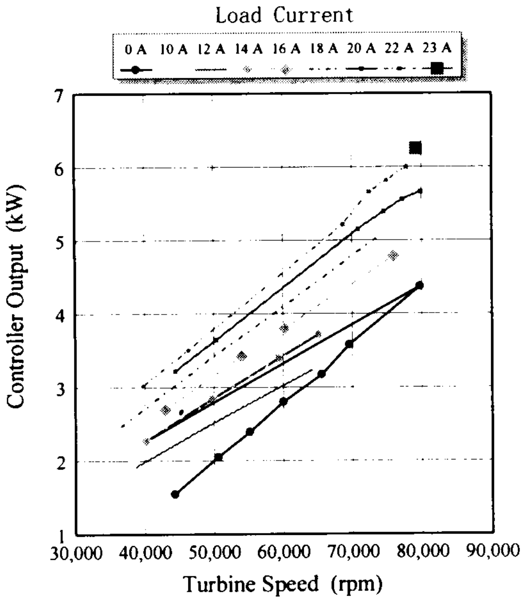

Fig.5 controller output power versus turbine speeds

Fig.5 shows measured results of the controller output power versus turbine speeds. The maximum output was about 6 kW at 80,000 rpm and this is close to the estimated value. The efficiency of the generator itself varied with load currents and turbine speeds though, it was 70% or higher at lowest as shown in Fig.6. The measured over all system efficiency was shown in Fig.7. As shown in the figure, about 50% of the turbine input energy

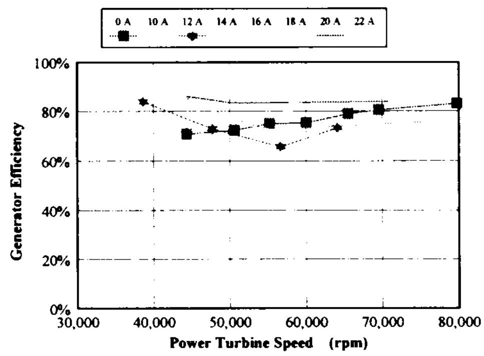

Fig.6 Generator efficiency versus turbine speed

can be converted to electric energy.

Based on these results, 5 to 10% of energy consumption improvement may be expected from calculations of energy regeneration effects under various driving patterns and vehicle specifications with assumption that average exhaust energy regeneration electric power is 3 kW.

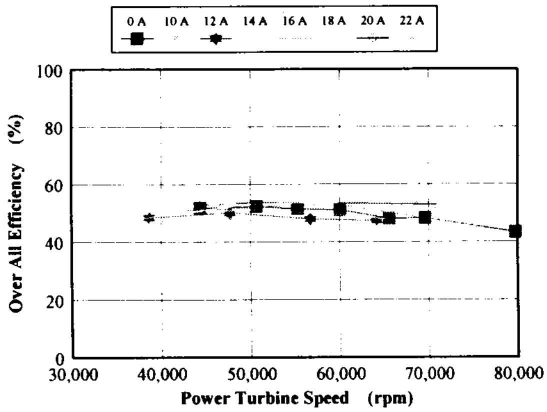

Fig.7 Overall system efficiency

(2) Energy regeneration effect at the engine dynamometer test

Fig.8 shows the schematic of the engine test. The test engine was a turbo charged direct injection diesel engine with 8,000 cm^3 in displacement. The prototype turbine generator system was located separately from the engine and drove the generator by introducing exhaust gases from the waste gate through a flexible pipe. The generated power was absorbed by resistance load. Fig.9 shows the turbine generator and the test engine.

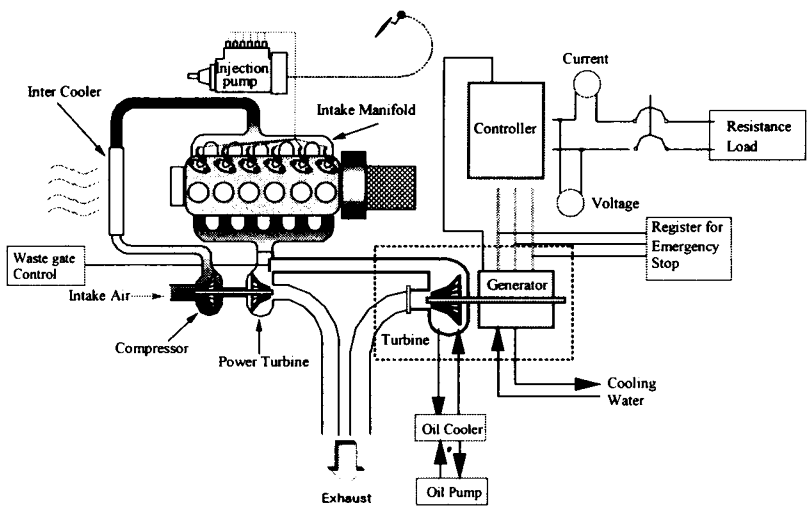

Fig.8 Schematic of engine test

1) Steady state test results

Fig.10 shows results of regenerated electric power measurements under steady state engine operations at various engine operating points. The maximum output was gained at a point of engine full load with 2900 rpm in engine speed and was about 5.3 kW. This value was about 85% of the estimation as shown in Fig.3 and other measured values were also lower than the estimation in most of operating points. This may be caused by lowered exhaust temperature due to the distance from the waste gate to the turbine inlet. As shown in the figure, 1 kW or higher output was regenerated at the regions of over 2000 rpm in engine speed and 1/2 or higher in engine load. Thereby, it was also supported from the experiments that this system may be effective under driving conditions where relatively heavy load engine operating regions are mainly used.

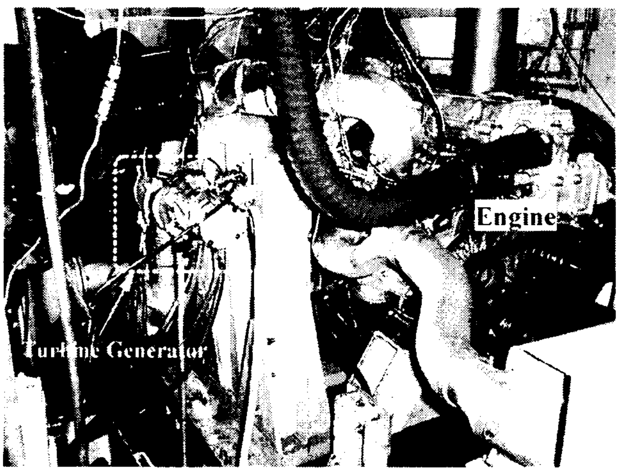

Fig.9 Turbine Generator and test engine

On the contrary, energy regeneration effect can be expected little because most of the exhaust energy was consumed by the turbo charger.

2) Transient engine test results

To evaluate exhaust energy regeneration effects under actual driving conditions, transient engine test was conducted under 4 different engine transient operating patterns based on vehicle driving patens with different average vehicle speed.

Table 2 shows the characteristics of each engine operating patterns. Among thes

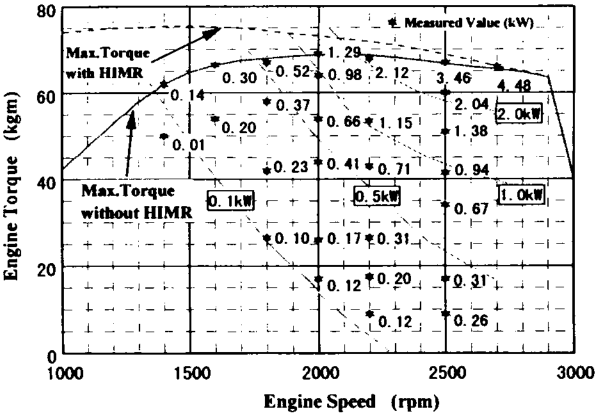

Fig.10 Steady state engine test result

Table 2 Characteristics of engine operating pettern

Name of Pattern	Operating Time (Sec)	Driving Distance (km)	Average Speed (km/h)	Ratio of 4 mode (time %)				Total Work (kWh)
				Idling	Acceleration	Cruising	Deceleration	
F20	789	4,726	21.56	34.7	24.9	17.7	22.7	5.79
F40	806	8,870	39.52	13	25.6	38.4	23	8.68
HW1	766	15,290	71.86	2.7	7.8	82	7.5	14.93
HW2	725	Max. Engine Speed 2500rpm	Max. Engine Torque 65kgm	0	0	100	0	19.92

※ HW2 is high speed and heavy load operating pattern for durability test and not including acceleration and deceleration.

patterns, F20 and F40 are constructed from actual vehicle driving patterns with average speed of 20 and 40 km/h respectively and represents urban driving engine operating conditions. HW1 represents the engine conditions under highway driving conditions and HW2 is a combined operating pattern with highway and long distance uphill driving and the total engine work is the highest among these four patterns.

Relations between the total required engine work and total regenerated electric energy under the driving of each patterns are shown in Fig.11. Regenerated electric energy goes up almost exponentially according to the increase in required engine work. The percentage for engine work shows the same tendency also. The highest regeneration energy was gained at HW2 pattern and they were 0.125 kWh in total and 0.6% of required engine work.

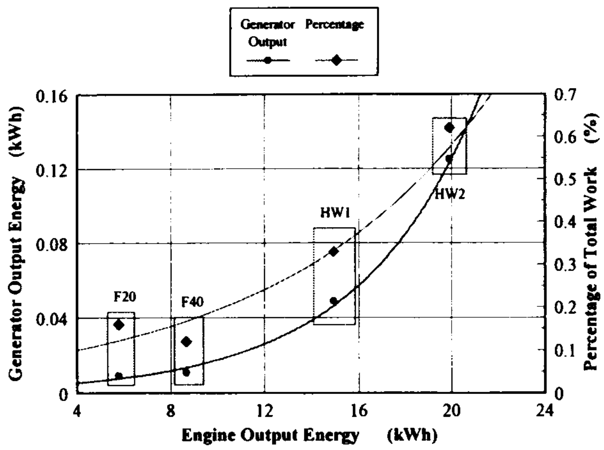

Fig.11 Regenerated energy at transient test

At F20 and F40, the engine was operated mostly low engine speed region and the amount of the regeneration energy was very small because sufficient regeneration could not be expected at these regions as clarified by the steady state test.

In the case of HW1, the engine was mostly operated in the vicinity of 1800 rpm where regenerating power starts to go up and thereby the energy regeneration effect went up from F20 or F40. At HW2, the engine operating regions were limited to heavy load regions of over 1900 rpm and then it is considered that the increase in the regenerated energy at HW2 was due to this reason.

Then, based on these result, as the higher the frequency of high speed and heavy load engine operations, the higher regenerating effect of the turbine generator system can be obtained and therefore it is also experimentally clarified that the exhaust heat energy regeneration will be suited for highway or long distance uphill driving etc.

5. Evaluation of the exhaust heat energy regeneration

A technical possibility for regenerating exhaust heat to electric energy was assured by this study. However, in spite of the 50% in overall efficiency obtained by the component test, exhaust energy regeneration efficiency of the engine test under transient conditions was much lower than expected. For this reason, it can be pointed out that the matching with the engine was not so good such as little regeneration effect at low speed and light load regions etc. If the generating efficiency at lower engine speed regions were improved by controlling the exhaust gas flow introducing into the turbine correctly, the total regeneration efficiency could increase remarkably. As mentioned before, the overall efficiency of the turbine generator itself is 50% or higher and then, by optimizing the matching with the engine particularly at low engine speed regions, 5 to 10% reduction of energy consumption could be possible by exhaust energy regeneration.

6. Conclusion

A vehicle energy regeneration system was considered by recovering exhaust energy and converting it to electric energy. Then a turbine generator system was designed and developed for trial.

By the experimental result of the component test, 6 kW was obtained as maximum generator out put with this system.

At the engine test combined with a heavy duty diesel engine, the energy regeneration efficiency under various transient driving conditions was much lower than the component test results. However, the improvement of the total system efficiency could be possible if the generating efficiency at lower engine speed regions were improved by controlling the exhaust gas flow introducing into the turbine correctly.

As the possibility of regenerating exhaust energy was verified with this system,, the prospect is obtained for improving fuel consumption and consequent CO_2 reduction from heavy duty diesel vehicles by adding the regenerated electric energy to the diesel - electric hybrid system for utilizing waste energy.

Reference

1) Yamamoto, Sekiya, Suzuki: Application of hybrid inverter controlled motor & retarder system to dust gathering vehicles EVS-11 Florence SYMPOSIUM PROCEEDINGS