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Development of a Highly Efficient Boiler System Using a Diesel Engine

D. H. Lee† · D. Y. Lee* · M. C. Jo* · H. N. Cho* · Y. S. Kim*

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Abstract : We have developed a highly efficient boiler system using the 2,600cc Diesel engine. In this system, the co-generation concept is utilized in that the electric power is produced by the generator connected to the engine, and waste heat is recovered from both the exhaust gases and the engine itself by the shell-and-tube heat exchangers. The heat exchanger connected to the engine outlet is specially designed such that it not only recovers waste heat effectively from the exhaust gases, but significantly reduces an engine noise. It is found that the total efficiency(thermal efficiency plus electric power generation efficiency) of this system reaches maximum 96.3% which is about 15% higher than the typical Diesel engine boiler system currently being used worldwide.

Key words : Diesel Engine, Co-Generation, Total Efficiency, Waste Heat, Heat Exchanger

1. Introduction

Due to a rapid industrial development, the fossil fuel consumption has been steadily increased. Because of the recent unstable international crude oil supply, there were many researches and economic assessment programs for an efficient energy utilization. And several summary papers on the economic assessment program and the economic analysis for efficient energy utilization have been published by Park and Kim[1], and Kim [2].

Recently, many researches have been conducted in order to improve the thermal efficiency of the boiler system. The existing boiler systems utilize not a waste heat recovered from exhaust gas, but a heat from fuel combustion only. Thus, the typical boiler systems efficiency reaches no more than 40%. Since 1970s the government made an effort on introduction of the co-generation technology to improve the energy utilization. As a result, the co-generation system had been widely used at industrial complex, industrial factories

† Corresponding Author(School of Mechanical and Automotive Engineering, Technology Innovation Center for Automotive Parts Inje University), E-mail : mechdhl@inje.ac.kr, Tel : 055)320-3185
* Inje Univesity.

and power plants. Since 1990s the co-generation system has been applied to not only an industrial boiler system, but also a household boiler system. Lee[3], Lee[4], Yodovard et al.[5], and Shin[6] studied efficient ways of recovering waste heat in the co-generation systems.

On the other hand, in spite of the continuing researches and developments, the total(thermal plus electric power generation) efficiency of the co-generation boiler system using internal combustion engine still remains less than 80%. Besides, the co-generation boiler system using an internal combustion engine is too big to be used for the household boiler system and a small and more efficient boiler system is needed to develop.

Thus, the current research focuses on the development of a small and highly efficient co-generation boiler system using a 2,600cc Diesel engine. This co-generation system utilizes the electric power produced by generator as well as waste heat recovered from both the exhaust gases and the engine itself by the shell and tube type heat exchangers.

2. Experimental apparatus

A schematic diagram for the performance test of the engine boiler system is shown in Fig. 1. The boiler system consists of a 2,600cc Diesel engine, a 22kW electric generator, and three shell and tube heat exchangers with disk & doughnut baffle installed(one for the engine cooling and two for the heat recovery from exhaust gases). In this system, the co-generation concept is utilized in that the electric power is produced by the generator connected to the engine, and waste heat is recovered from both the exhaust gases and the engine itself by the heat exchangers. The electric power output is later used to heat the water which is added to the heated water from the heat exchangers.

The heat recovery exchangers are

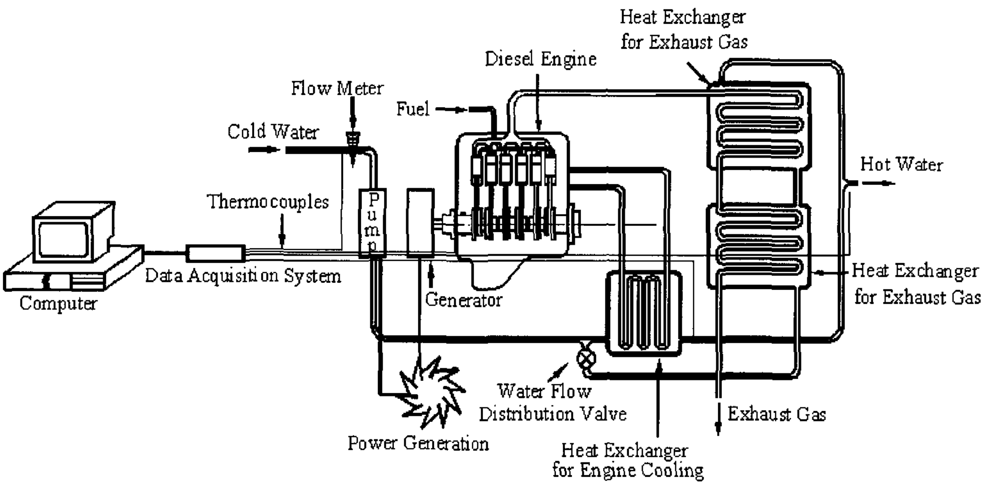


Fig. 1 Schematic diagram for the performance test of the engine boiler system with separated line piping.

specially designed such that not only waste heat from the exhaust gases is effectively recovered, but an engine noise is significantly reduced because the exhaust gases have to pass through the multiple small circular tubes. On the other hand, the same type heat exchanger is used to replace the usual radiator in the Diesel engine and cools the engine cylinder block, cylinder head and others. Measurement of the water supply at the inlet of the boiler system is made by a water flow meter which is located in front of water pump to minimize a fluctuation in the water flow gage. The water pump is operated by utilizing a part of power output from generator and the amount of fuel(Diesel) consumption is accurately measured by the fuel gage.

Six E-type(Chrome-Constantan) thermocouples of 0.25 mm diameter are used to measure the temperatures of inlet and outlet water, exhaust gas and ambient air at various positions in the boiler system. All of thermocouples are calibrated against the Platinum Resistance Thermometer(SDL CO. T25/ 30) to an accuracy of 0.15 C. These thermocouples are then connected to a data acquisition system which consists of 12-bit A/D board(Strawberry Tree/DATA Shuttle) and Pentium computer. A three phase power meter(Yokogawa M&C CO. IM 2433-E) is used to measure the power output from the generator. The Diesel engine boiler system is housed in the well-conditioned testing room with soundproofing material embedded at the walls.

3. Performance test and data reduction

The performance tests are conducted to produce the thermal efficiency, the electric power generation efficiency, and the total efficiency for the developed engine boiler system. These tests are made at the water flow rates of 12, 20, 26 and 30 L/min and at the magnitudes of electric power generation of 6, 9, 12, 14 and 17㎾.

The two different piping arrangements for the cooling water supply to the heat exchanger inlets are tested to establish the better performance in this system. One type is called One line piping system, and the other type is Separated line piping system. The one line piping system is arranged such that the cooling water first enters the engine heat exchanger to remove heat from the engine, and the preheated water then enters the second and third heat exchangers to recover the heat from the exhaust gas, thereby producing the hot water through the same water outlet in the system.

On the other hand, the separated line piping system is arranged with two separated cooling water inlet lines to the heat exchangers. The one inlet line is connected to the engine heat exchanger and the other line is connected to the heat exchanger to recover the waste heat from exhaust gas. Finally, the hot water accumulated from the two different outlets is supplied. The cooling water flow rates to these two heat exchangers are adjusted by the ball valve such that the hot water temperatures at each heat exchanger outlet become nearly the same.

It takes about 30 minutes until the engine boiler system reaches a steady state condition. Thus, the actual data gatherings are made 30 minutes after the system is turned on. The experiments are first made for two different piping systems with the cooling water flow rate ranging from 12 to 30 L/min at one power output of 14㎾ and followed by the tests with power output ranging from 6 to 17㎾ at one cooling water flow rate of 26 L/min. Based on inlet and outlet water temperatures, water flow rates, fuel consumption and electric power generation, the thermal efficiency, the electric power generation efficiency, and the total efficiency for the diesel engine boiler system can be determined.

The thermal efficiency of the diesel engine boiler system is calculated from

$$Q_{H_2O} = \dot{m}\, C_P (T_{out} - T_{in}) \quad (1)$$

$$\eta_{th} = \frac{Q_{H_2O}}{Q_{diesel}} \times 100\% \quad (2)$$

And, the electric power generation efficiency is calculated from

$$\eta_{elect} = \frac{Q_{elect}}{Q_{diesel}} \times 100\% \quad (3)$$

Finally, the total efficiency of the system, which is a sum of the thermal efficiency and the electric power generation efficiency, is calculated from

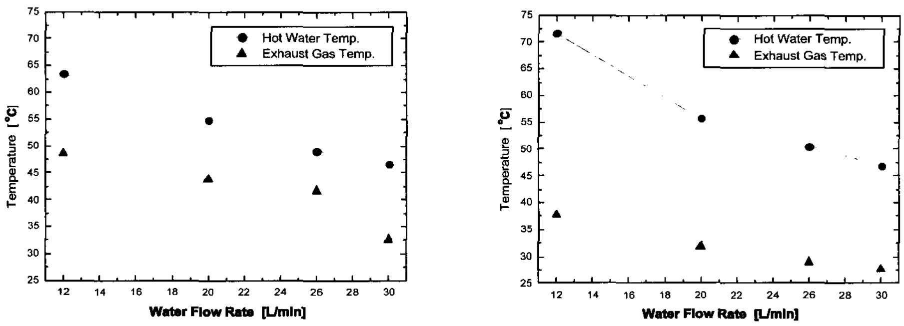
$$\eta_{total} = \frac{Q_{H_2O} + Q_{elect}}{Q_{diesel}} \times 100\% \quad (4)$$

Where, Q_{H_2O} is the electric energy recovered by the water from both the exhaust gases and the engine, Q_{diesel} is the energy produced by fuel combustion, Q_{elect} is the electric energy produced by the generator, $\dot{m}$ is the mass flow rate of the cooling water, C_p is the specific heat of the cooling water, T_{out} is the mass flow rate of the colling water. C_p is the specific heat of the Cooling water, T_{out} is the outlet hot water temperature and T_{in} is the inlet cooling water temperature.

4. Discussion of results

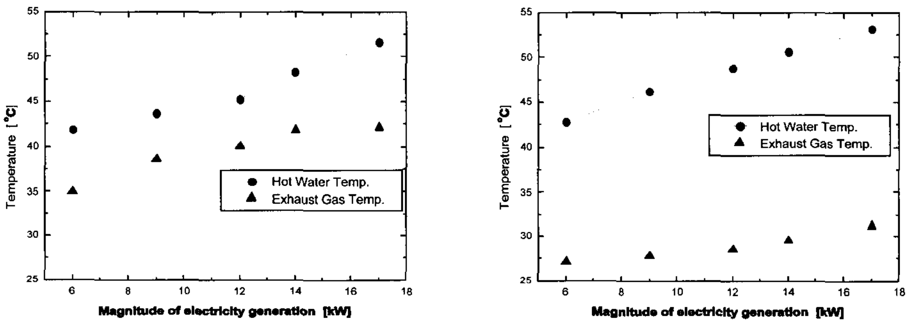
Variations of the outlet hot water and exhaust gas temperatures for both one line and separated line piping systems with the inlet cooling water flow rate at one power generation output of 14㎾ and with the power generation output at one inlet cooling water flow rate of 26 L/min are shown in Fig. 2 and Fig. 3, respectively. As can be seen in Fig. 2, that for both one line and separated line piping systems the outlet hot water temperature is decreased linearly as the cooling water flow rate is increased. Fig. 3 also shows that the outlet hot water temperature is increased linearly with an increasing power generation output. In order to generate more electric power, more fuel is consumed, resulting in more available heat energy and more waste heat that must be recovered by the heat exchanger, which in turn produces a higher hot water temperature.

Both Fig. 2 and Fig. 3 clearly indicate that a gap between the outlet water temperature and exhaust gas temperature for the separated line piping



(a) One line piping system (b) Separated line piping system

Fig. 2 Variation of output water and exhaust gas temperatures with water flow rate at a power output of 14kW.



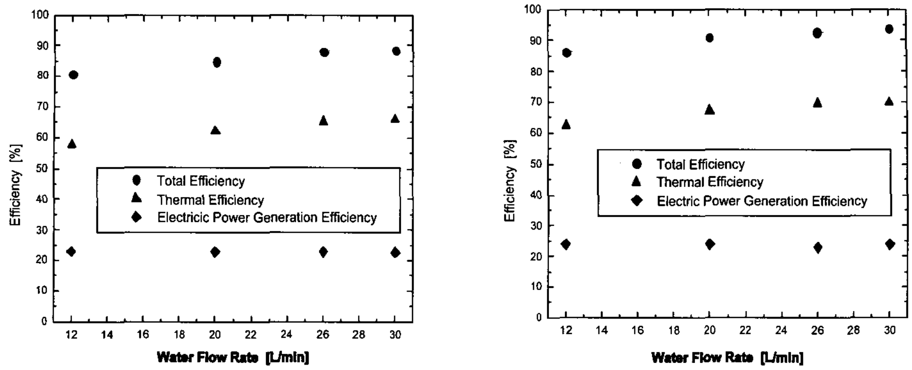
(a) One line piping system (b) Separated line piping system

Fig. 3 Variation of output water and exhaust gas temperatures with power output at a water flow rate of 26 L/min

system is much bigger than for the one line system. In other words, the separated line piping system produces the higher outlet water temperature and lower exhaust gas temperature than the one line piping system, suggesting a better heat transfer arrangement and resulting in a higher total efficiency of the engine boiler system. This behavior is consistent with the systems efficiency curves which will be shown later in Fig. 4 and Fig. 5.

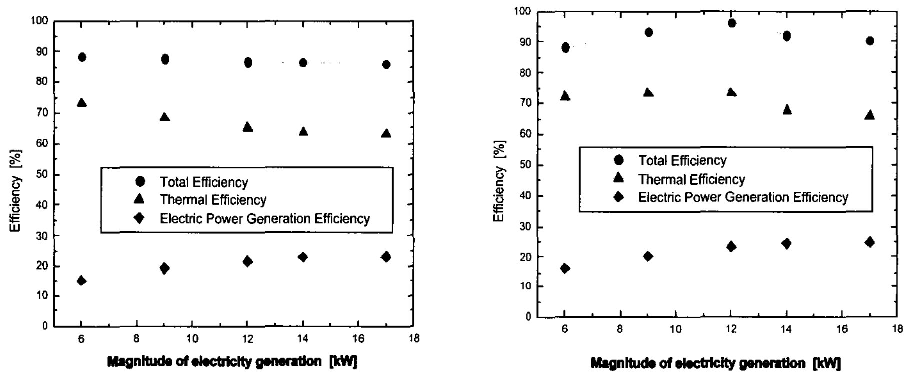
As previously described, the separated line piping system is arranged with two separated cooling water inlet lines to the heat exchangers. The one inlet line is connected to the heat exchanger for the engine cooling and the other line is connected to the heat exchanger to recover the waste heat from exhaust gas, resulting in the lower exhaust gas temperature, the higher hot water temperature, and the higher total efficiency of the engine boiler system.

To be more specific, at the same cooling water flow rate, the average hot water temperature for the separated line system is 2.7℃ higher than for the one line system and the average exhaust gas temperature is 5.4℃ lower. On the other



(a) One line piping system (b) Separated line piping system

Fig. 4 Variation of the engine boiler system efficiency with water flow rate at a power output of 14 ㎾



(a) One line piping system (b) Separated line piping system

Fig. 5 Variation of the engine boiler system efficiency with power output at a water flow rate of 26 L/min

hand, for the separated line system at the same power generation output, the average hot water temperature is 2.1℃ higher and the average exhaust gas temperature is 7℃ lower. Under the same condition, the hot water temperature for the separated line piping system is maximum 10.3℃ higher for the one line piping system and the exhaust gas temperature is maximum 14.6℃ lower.

Fig. 4 and Fig. 5 show variations of the thermal, power generation and total (thermal plus power generation) efficiencies for both one line and separated line piping systems with the inlet water flow rate at one power generation output of 14㎾ and with the power generation output at one inlet water flow rate of 26 L/min, respectively. Fig. 4 shows that at a fixed power output of 14㎾, the thermal efficiency is increased from 57.7% to 66.0% for the one line piping system and from 62.4% to 70.1% for the separated line piping system as the inlet cooling water flow rate is changed from 12 L/min to 30 L/min. Under the same conditions, the total efficiency is increased from 80.7% to 88.5% for the one line piping system and from 86.2% to 93.7% for the separated line piping system. This behavior clearly demonstrates again that the separated line piping system in the present boiler system produces by 5.0% in maximum higher heat transfer rate than the one line piping system for the reasons previously described.

It is worthy to note that for both piping systems, the thermal efficiencies beyond the water flow rate of 26 L/min remain nearly unchanged, yet the exhaust gas temperatures for one line and separated line systems are still about 17℃ and 6℃ higher than the ambient temperature, respectively, indicating that the heat exchangers reached the limit of the heat transferring capability at the flow rate of 26 L/min and there will be a room for the further increase of the thermal efficiency if the heat exchanger size is enlarged.

In the mean time, the total efficiencies of the present boiler system, regardless of the piping arrangement, are higher by 15% in maximum than those any other engine boiler systems currently being used worldwide. It is mainly attributed to a unique design of the current engine boiler system that utilizes both the power produced by the Diesel engine and the energy recovered most effectively from the heat sources that would have been lost to the surroundings, otherwise.

Fig. 5a shows the increasing power generation efficiency and the decreasing thermal efficiency for the one line piping system, resulting in a slight decrease of the total efficiency of the engine boiler system as the power generation output is increased. On the other hand, Fig. 5b shows that for the separated line arrangement, the thermal and total efficiencies are increased from 71.9% to 73.1% and from 88.2% to 96.3% (the maximum total efficiency obtained among all of the experiments), respectively, until the power generation output reaches 12㎾. Beyond 12㎾ point, the thermal and total efficiencies drop down to 65.7% and 93.7 at a power generation output of 17 ㎾.

5. Practical application of the diesel engine boiler system

The present Diesel engine boiler system has been being installed at the Bonghwang bath house(26-4 Bonghwang-dong, Kimhae City, Kyongnam Province, Korea) for the practical application. A picture of the actual operation of the system is shown in Fig. 6. In order to satisfy the requirements of water supply to the bath house, the outlet hot water temperature has to be over 70℃. Therefore, the electric power output of 19 ㎾ has to be produced by using 5 heaters connected to the generator. These heaters are then immersed in the water chamber where the heated water from the heat recovery exchangers enters and is mixed. The heating process of the water is first the water recovered from the waste heat at the engine part and the exhaust gas secondly the water flows into the heating

Table 1 Cost saving by substituting the current system with the Diesel engine boiler system.

(Unit : Won)

Boiler Type	Bunker-C Oil Fired Boiler System	Diesel Engine Boiler System
Fuel Cost (Per Liter)	370	750
Monthly Fuel Cost	2,900,000	1,764,000
Monthly Substitution Effect	0	1,136,000
Annual Substitution Effect	0	13,632,000
Boiler System Cost	10,000,000	35,000,000
Payback Period for the Installation Cost		31 Months

chamber and at the inside of the chamber the water is heated by heaters. It turns out that when a cooling water flow rate 20 L/min is used with an electric power of 19kW, the final outlet water temperature coming out from the heating chamber becomes about 72℃.

Fig. 6 Practical application of the Diesel engine boiler system at the bath house

Table 1 shows a cost comparison between the Bunker-C oil fired boiler system and the Diesel engine boiler system. It follows that the Bonghwang bath house is able to save much the fuel cost if their current bunker-C oil fired system is replaced by the Diesel engine boiler system whose total efficiency is as high as 91% under the given conditions.

As result of savings of the fuel cost, Bonghwang bath house saves 1,136,000 won for one month and expects that the payback period for the installation cost will be about 31 months.

6. Conclusions

A highly efficient boiler system using the 2,600cc Diesel engine has been successfully developed. The several conclusions are summarized as follows.

(1) The co-generation concept is utilized in this system in that the electric power is produced by the generator connected to the engine, and waste heat is recovered from both the exhaust gases and the engine parts by the shell and tube heat exchangers.

(2) It is found that the total efficiency(thermal efficiency plus electric power generation efficiency) of this system reaches maximum 96.3% which is about 15% higher than the typical Diesel engine boiler system currently being used worldwide.

(3) The high efficiency of the system is attributed to its unique design that utilizes both the power produced by the Diesel engine and the energy recovered most effectively from the heat sources that would have been lost to the surroundings, otherwise.

(4) The separated line piping arrangement in the shell and tube heat exchanger produces the higher outlet water temperature and lower exhaust gas temperature than the one line piping system, resulting in the better heat transfer and higher thermal efficiency of the engine boiler system.

(5) The present boiler system has been being installed at the bath house for the practical application and proved to save much of the fuel cost for the bath house.

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References

[1] Cha Sik Park and Yong Chan Kim, Development and Application of an Economic Assessment program of Cogeneration Systems , KSME., Vol. 22, No. 11, (1998), pp.1547~1554.

[2] Eung Sang Kim, A Study on Economic Analysis for Hotel Introduction of Co-generation System, Energy Engineering., Vol. 11, No. 3, (2002), pp.210~215.

[3] Chang Sik Lee, Exhaust Loss and Heat Recovery of Boiler , SAREK., Vol. 18, No.5, (1989), pp.482~487.

[4] Kum Bae Lee, Heat and Mass Transfer between Hot Waste Gas and Cold Water in a Direct Contact Heat Exchanger , KSME., Vol. 16, No. 6, (1992), pp.1171~1178.

[5] Panya Yodovard, Joseph Khedari and Jongjit Hirunlabh, The Potential of Waste Heat Thermoelectric Power Generation From Diesel Cycle and Gas Turbine Cogeneration Plants , Energy Sources., Vol. 23, (2001), pp.213~224.

[6] Chun Sik Shin, Gas fired condensing boiler , SAREK., Vol. 26, No. 5, (1997), pp.396~404.