Performance of single cylinder diesel engine using triple fuel HSD-LPG- Steam

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Abstract. Fuel system modification techniques to improve engine efficiency could be the way to slow down the energy crisis caused by the lack of new fuel inventions. The Compression Ignition (CI) diesel engine is one of the most preferred engines for both in-land and marine transportation motors. The advantages of compact dimensions and large generated power make CI diesel engine superior to other engine types. The large number of single CI diesel engines use in small fishing vessel engines and agricultural machinery will contribute substantially to fuel consumption in a cumulative manner. Previous researchs on the modification of fuel system with bi-fuel system High Speed Diesel (HSD)oil – Liquified Petroleum Gas (LPG) system capable of reducing Brake Specific Fuel Consumption (BSFC) up to 24% and exhaust gas opacity up to 68%. Subsequent studies focused on engines with single fuel HSD oil but were injected with superheated steam in 1 atm (abs) 130 °C by utilizing Heat Recovery Generating System (HRSG) using heat of exhaust gas for a flowrate of 1.5 - 4.5 kg/hour. It is capable of delivering the performance improvement of Specific Fuel Consumption (SFC), which is reduced by 8.92% compared to diesel engines without steam injection. Recent research combines the above two modification methods so that diesel will adopt two types of fuel- oil-LPG with additional superheated steam injection resulting from exhaust gas heat cogeneration system. Experimental results of the diesel engine with LPG injection maintained at 0.4 kg/h and 3.5 kg/h superheated steam with an engine variation loading of 0.3-0.7 kWh provide an average AFR of 30.09 and SFC improvement up to 37.2% lower than SFC engine standard with a single fuel HSD oil.

1. Introduction

Single cylinder diesel engines are used in large quantities for small fishing boats and agricultural machinery due to considerable maintenance and operational costs. The disadvantage of diesel engines is high exhaust emissions that have negative effects on the environment. Fishermen and lower farmers tend to ignore the consideration and awareness of the level of negative effects of exhaust emissions compared to economic considerations. The population of fishermen and farmers of very large diesel engine users will give a cumulative effect of the quantity of exhaust emissions produced. Hence, research to decrease the exhaust emissions of single cylinder diesel engines and simultaneously raise their efficiency will be an important long-term program in the effort to save the environment. The characteristics of high temperature combustion diesel engines generate high power and high side effects of exhaust emissions. The negative effects of exhaust emissions on diesel engines are regulated nationally and internationally and continue to be limited by regulation annually. One of the exhaust emissions generated by combustion at high temperature diesel engines is NOx. There is a wide variety
of methods inside and outside the cylinder to reduce NOx emissions. One method of NOx reduction is the injection of water into the combustion chamber. Water injected into the combustion chamber in the emulsion form of oil fuel with water directly or injected directly into the intake manifold (fumigation) on the diesel engine. Based on existing literature studies, the maximum reduction in combustion temperature by water injection will be followed by a decrease in NOx gas emissions [1,2]. Same et al. emphasizes that NOx and soot emissions will be reduced by 20% and 50% respectively when using 10% and 15% water-fuel emulsions. On the other hand, it does not cause a decreasing effect of combustion efficiency with marked increase in SFC [3]. Abu-Zaied et al evaluated the performance of diesel engines in torque, power, effective efficiency, SFC temperature and exhaust chamber when water/fuel ratio increased [4]. Lin and Wang point out that the exhaust, O2, NOx and exhaust gas temperatures drop, while CO2 and CO emissions increase when the three-phase oxygen fuel (water/fuel/water or fuel/water/fuel) is injected into diesel engines and materials three-phase emulsions have higher exhaust chamber gas temperatures and lower CO and NOx emissions compared to two phases (water/fuel) [5].

In the fumigation method, water in the liquid phase is injected into the air intake manifold. Tauzia et al. states that if 60 - 65% of water is injected into a diesel engine air intake manifold with a common rail type injection system, NOx emissions may drop up to 50% and heat losses occur in cylinder walls, which will result in reduced efficiency [6]. Donahue and Ishida et al. investigating the injection of water into a diesel engine will produce NOx, soot emissions in the flue gas and SFC reduction when the diesel engine is given a low loading but otherwise the soot emissions and SFC will rise and the NOx emission decreases when the engine is loaded high [7].

Referring to existing literature reviews, direct injection of water into the combustion chamber such as emulsion or fumigation methods into the intake manifold will be able to reduce NOx emissions [3,5,6,8]. But the exhaust gas parameters for HC, CO and SFC will increase [4]. Additionally, water especially in the fumigation method will damage the lubricant specification and cause increased wear of moving parts of the engine [9]. One method that can be used to reduce NOx emissions is water injection into the intake manifold that previously in the liquid phase is converted into steam phase. Parlak et al explains that NOx emissions will be reduced by 33%, power and effective torque increased by 3% and SFC value decreased to 5% as a result of full load test with electronically controlled steam injection system with optimum steam ratio determined by 20% [10]. In this study, single cylinder diesel engine modification system is focused on the use of two types of fuel, namely HSD (high speed diesel) oil - LPG (liquified petroleum gas) plus steam injection on superheated steam phase to improve power performance and SFC fuel efficiency.

2. Material and methods

2.1. Method of experiment
The experimental method is carried out on a single cylinder diesel engine, where the air injection system is natural, 4 (four) strokes engine and uses water cooling system. This type of engine is chosen because the construction is simple to undergo the process of modification and this type of machine is much and commonly used for engine engine propulsion small fishing vessel and agricultural machinery.

Table 1. Engine diesel –dongfeng specification.

| No | Specification | Model R180 |
|----|---------------|------------|
| 1  | Displacement  | 402        |
| 2  | Diameter      | 80x80 mm   |
| 3  | Compression Ratio | 21 : 1    |

To generate steam to reach the superheated phase of this system utilizes the engine heat exhaust cogeneration process by using a steam generator unit installed after the exhaust gas flows from the exhaust chamber. Temperature and pressure gauges mounted on the steam to ensure steam quality is in the superheated phase. This steam generator unit is called a Heat Recovery Steam Generator (HRSG)
– Cogenerator that works to reuse the energy that has been wasted on the exhaust chamber. HRSG is self-fabricated by using heat transfer design with stainless steel material as shown in Figure 2 (a). The amount of water mass converted to steam is adjusted by flowmeter. The steam injection system that enters the manifold water is fabricated as shown in Figure 2 (b).

To monitor the exhaust gases coming out of the steam generator, Air Fuel Ratio (AFR) is used to provide information on combustion quality that occurs in the combustion chamber. The single cylinder diesel engine in the experiment is operated on a variety of electrical loads on the 0.3 kWh, 0.45 kWh, 0.6 kWh and 0.75 kWh electrical generators to get the engine performance picture at low to high loads at steady engine rotation at 2500 RPM. To convert the resulting mechanical energy, the diesel engine is coupled with an electric generator using a V-belt. Electric generator has power specification name plate 7.5 KW and 1500 RPM.

\[ \text{Figure 1. Experiment’s set up.} \]

\[ \text{Figure 2. (a) Steam generator (b) Steam injector on air intake manifold.} \]

As a benchmark standard, single cylinder diesel engines are operated without modifications to the fuel system in order to obtain the performance of the original engine. The data is used as reference
benchmark data on the performance of the engine undergoing modification process in its fuel system with steam injection utilizing heat exhaust gas cogeneration.

The steam mass generated by the steam generator is measured by flowmeter to vary from 1.5, 2.5, 3.5, to 4.5 kg/h with a temperature of 130°C with a pressure of 1 (bar) which has reached the superheated steam phase with a specific volume parameter \( h = 2736 \, \text{kJ/kg} \), \( V_s = 1.841 \, \text{m}^3/\text{kg} \). Entropy (s) = 7.517 \, \text{kJ/kg.C}. In the saturated steam conditions, the parameters are \( h = 2676 \, \text{kJ/kg} \), \( V_s = 1.674 \, \text{m}^3/\text{kg} \), Entropy (s) = 7.354 \, \text{kJ/kg.C} [11]. The superheated steam is injected into the combustion chamber mixed with combustion air and LPG gas in the air intake manifold so that steam and LPG enter the combustion chamber through the process of the air intake manifold step mixed with the outside combustion air.

![Figure 3. Diesel engine system with HRSG - cogeneration.](image)

Experiments were repeated on each variation of engine load as well as steam and LPG injection to obtain overall performance descriptions from low to high loads. The AFR quality of the combustion process gas is compared with the diesel engine operating conditions when operating under standard conditions without modification.

3. Results and discussion

The effect of the addition of superheated steam and LPG gas to the performance of single cylinder diesel engine was analyzed with SFC, Air-Fuel Ratio (AFR) parameters and exhaust gas temperature. The SFC value shows the ratio of total fuel consumption to electric power that can be generated by an engine-connected alternator to determine the ratio of efficiency of the engine system. In the SFC measurement study, it was carried out at a fixed load for one hour of engine operation to obtain stable condition so an AFR value representing stable engine operating conditions.

AFR shows the ratio of the amount of air mass to the fuel mass in the combustion process, especially the type of internal combustion engine. The AFR value will show the condition of the fuel mixture with the air, the amount of fuel that can be released by the process and how much mass of the pollutant produced by the combustion reaction. Enough air mass combustion will provide a perfect stoichiometric combustion process. A low ratio of stoichiometric values will provide a rich mixture of fuel. The fuel-rich air mix will produce a low-efficiency combustion process but will be capable of producing greater power and lower combustion temperatures. A low mixture of stoichiometric ratio will result in more efficient combustion but will cause engine damage and produce NOx exhaust emissions in the exhaust gas.

3.1. Performance of standard diesel engine

Diesel engine operation test with original fuel system is done using single fuel HSD oil with variable loading using alternator, the variation of loading conditions on the alternator will lead to an increase in fuel consumption on the engine so that the engine works not only rely on the large inertia
moment on the flywheel to be able to achieve stable engine rotation but requires more fuel consumption to be able to achieve stable engine RPM (Revolutions Per Minute) at 2500 RPM reduced by transmission to 1500 RPM on the alternator.

**Table 2.** Performance of standard diesel engine.

| Load (kWh) | SFC (Litre/kWh) | AFR  |
|------------|-----------------|------|
| 0.30       | 2.80            | 35.5 |
| 0.45       | 2.67            | 33   |
| 0.60       | 2.33            | 31   |
| 0.75       | 2.00            | 26   |

A decrease in engine AFR indicates that fuel consumption will rise to reach a constant engine RPM while generating an appropriate power supplied by the alternator. The above correlation is shown by table 1 which explains the linear relationship between fuel consumption (SFC) on the engine power generated along with the HSD oil combustion characteristics. The stable load of the engine will cause the AFR of the flue gas combustion to be close to the AFR of stoichiometric burning of HSD oil for 14-15.

The performance of SFC standard diesel engines works on loads raised from 0.3 kWh to 0.75 kWh. Trends in SFC performance improvements occur as the load continues to increase. This indicates that the better combustion efficiency and AFR value in the exhaust gas approach AFR stoichiometry. A good combustion reaction process will result in improved SFC performance so as to decrease HSD oil fuel consumption per minute.

### 3.2. Performance of diesel engines with the addition of LPG injection (Bi-fuel HSD oil – LPG System)

In this mode of operation, the diesel engine is modified into a dual fuel system that is bi-fuel system HSD oil - LPG. LPG is injected into the combustion process through an air intake manifold with a unit converter kit to avoid extreme machine construction modifications. The regulator converts the LPG liquid phase into a vapor phase. The LPG mass is injected constantly 0.4 kg/hour and the combustion process quality is analyzed using the AFR parameters of the flue gas at each loading variation. LPG is injected to the compressed air from the Bottom Dead Centre (BDC) to the Top Dead Centre (TDC) so that the mixing of air with LPG gas occurs. A high compression ratio of single-cylinder diesel engine is designed 21:1 will not cause premature ignition of LPG + air mixture due to LPG fuel characteristics determined by an octane fuel- ignition characteristic in which the ignition process still requires spark (ignitor). LPG-fueled diesel engines will still require an ignitor so that the design of this machine only allows a combination of HSD oil and LPG fuel for its operation. LPG with higher calorific values has the effect of decreasing HSD oil fuel consumption to achieve the same load condition compared to standard engine without LPG fuel injection [12].

**Table 3.** Performance of diesel engines with the addition of LPG injection (bi-fuel HSD oil – LPG system).

| Load (kWh) | HSD (Litre/Hour) | LPG (kg/hour) | AFR  | SFC (Litre/kWh) |
|------------|------------------|---------------|------|----------------|
| 0.30       | 0.60             | 0.40          | 55   | 2.00           |
| 0.45       | 0.88             | 0.40          | 41.5 | 1.96           |
| 0.60       | 1.00             | 0.40          | 31.5 | 1.67           |
| 0.75       | 1.20             | 0.40          | 29.5 | 1.60           |
3.3. Diesel engine performance with the addition of superheated steam injection from exhaust gas cogeneration system

In this mode of operation, the diesel engine modified the fuel system using HSD oil with the addition of superheated steam. Steam is produced by a steam generator utilizing heat recovery exhaust gas. Engine can decrease the exhaust gas temperature and also regenerate heat from the exhaust gas for converting water into superheated steam. Steam is injected in the air intake manifold and combustion chamber due to the suction stroke process. The study was conducted with variations of superheated steam flowrate injected at 1.5, 2.5, 3.5 to 4.5 kg/hour to provide correlation between engine performance with steam injection value. The combustion quality that occurs in the combustion chamber can be analyzed and shown by the parameters of the AFR value of the flue gas in each loading variation and the mass of the steam injection. Figure 5 shows the AFR engine combustion characteristics at a constant load. It can be seen in the figure that the injection of steam causes a decrease in the AFR value compared to the standard engine AFR. This decrease occurs because part of the space combustion chamber is occupied by steam. The occupancy process causes the percentage of air in the combustion chamber will be reduced. This reduction of combustion air does not reduce the combustion quality of HSD oil in the combustion chamber, as indicated by the engine power generated. The process also causes the engine to consume lower fuel HSD oil at the same load. This significant result can be a reference that the gas cogeneration system for steam generators is able to work well to increase engine power and decrease the consumption of fuel oil HSD oil. The superheated steam injection process will increase the enthalpy value of air entering the engine combustion chamber so that the air in the combustion chamber has higher energy and temperature than standard engine conditions [13].
Figure 5. Graph of Comparison between AFR Value of Exhaust Gases with loading variation on Diesel engine with Steam Injection of 1.5, 2.5, 3.5, 4.5 kg/hour.

Figure 6. Graph of Comparison between Specific Fuel Consumption (SFC) with load variation on Diesel engine with steam injection of 1.5, 2.5, 3.5, 4.5 kg/hour.

Increased energy and temperature of air in the combustion chamber can speed up the preparation of HSD oil burning at the compression step. These conditions will increase the combustion pressure and generate greater engine torque at the same RPM with lower fuel consumption. Engine performance is analyzed with SFC parameters and exhaust gas temperature shown in Figure 6. Variations of injection flowrate are given to determine the effect of steam injection on engine performance on SFC, AFR and exhaust gas values shown the burning process occurring in the engine cylinder shown in Figure 5 and 6. At low engine loading at 0.3-0.45 kWh superheated steam injection of 1.5 -1.5 kg/hour can decrease the SFC of the engine. However, in addition to steam up to a flowrate of 4.5 kg/hour, the SFC increase again. The increase in SFC is caused by the effect of steam occupancy in the combustion chamber that reduces the air mass coming into the combustion chamber which makes the combustion process more difficult to occur.
The air mass for the combustion process is reduced rapidly as shown by low AFR numbers when the steam injection reaches 4.5 kg/hour. This causes the combustion process to require more HSD fuel oil consumption to produce the same power compared to operating conditions with steam injection under 4.5 kg/hour and performance of standard engine without steam injection. Rich AFR values show higher fuel consumption to generate per unit of power generated. This condition will cause an increase in the SFC of the combustion process and reduced combustion efficiency.

**Figure 7.** Comparison chart between the exhaust gas temperature and the load variation.

In standard machines without steam injection, conditions where there are low fuel and high amounts of air will result in high combustion temperatures. This condition does not occur in engines with steam injection system because the steam mass in superheated conditions can reduce the temperature of the combustion temperature without decreasing the power due to the increase of air enthalpy value in the combustion chamber. This gives an increase in the energy of the combustion process shown by figure 7 on the comparison gas temperature graph of the flue gas. Literature and previous studies show that combustion in diesel engines with lower combustion temperatures can reduce exhaust emissions released into the air [10,14-16].

3.4. **Performance of Diesel engine with triple fuel (HSD oil + LPG) + Superheated steam injection from exhaust gas cogeneration**

This mode combines two initial diesel engine modification studies with LPG (Bi-fuel HSD + LPG) and Steam (Bi-fuel HSD + Steam) injection systems at varying loads. Standard single-fuel diesel engine is modified with the addition of LPG injection system and superheated steam injection simultaneously to obtain SFC and AFR characteristics on engine load variation. In this test, LPG injection is kept constant 0.4 kg/hour and steam is maintained at a mass of 3.5 kg/hour on load variations performed from 1200 to 3000 watts. In this condition the machine is able to work normally and well with stable power according to the loading. In this mode, diesel fuel consumption is very small when compared to the standard engine at the same load. So it can be concluded that this system is able to work well with lower fuel consumption.
**Table 4.** Performance of diesel engines with the addition of triple fuel (hisd oil + lpg) + superheated steam injection from exhaust gas cogeneration.

| Load (kWh) | HSD (litre/h) | LPG (kg/h) | STEAM (kg/h) | AFR | SFC (litre/kWh) |
|------------|---------------|------------|---------------|-----|-----------------|
| 0.30       | 0.45          | 0.40       | 3.5           | 31  | 1.50            |
| 0.45       | 0.80          | 0.40       | 3.5           | 29.6| 1.50            |
| 0.60       | 0.90          | 0.40       | 3.5           | 29.3| 1.33            |
| 0.75       | 1.00          | 0.40       | 3.5           | 29.3| 1.33            |

**Figure 8.** Comparison of SFC performance.

**Figure 9.** Comparison of AFR parameters.

4. **Conclusion**

Research on the performance of single cylinder diesel engine with LPG injection and superheated steam 130 °C by utilizing the recovery of wasted energy in an average temperature flue gas of 624 °C with cogeneration system proved to be one of the alternative energy saving breakthroughs. The conclusions that can be drawn from the research results are:

- Maximum performance was achieved at 1200 watt loads due to superheated steam phase and LPG added constantly to the engine. In addition to the load, the engine will automatically add fuel injection HSD oil mass to keep the engine can spend maximum power. The process is seen with the decreasing number of AFR (Air to Fuel Ratio).
- High calorific value of LPG mass injection at Bi-fuel fuel system is able to maintain AFR when load is added to the system so that engine efficiency is maintained.
- Superheated steam injection adds air enthalpy value inserted into the machine. The addition of heat from superheated steam and LPG will increase the temperature of air entering the engine and accelerate the preparation of combustion of diesel fuel. This condition increases the speed of HSD oil combustion so that the combustion pressure increases and improves SFC performance compared to standard engine mode.

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