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# The performance improvement of the combustion process in diesel engines with fuel heater

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***Abstract***

*The incomplete combustion process will be a problem in the development effort of the diesel engine's performance. The non-homogeneous air-fuel mixing process is one of the factors which causes incomplete combustion. Heating the diesel fuel to a certain temperature before it goes through the high-pressure injection pump will lower its density and viscosity. Therefore, when injected in the combustion chamber, it forms smaller droplets of fuel spray which results in a more homogeneous air-fuel mixture. Moreover, using higher temperatures will make the diesel fuel easier to ignite to compensate for the limited time that is available in high-speed operating conditions. Diesel fuel heating can improve the combustion process to increase the power and decrease fuel consumption optimally.*

***Keywords****: combustion process; decreased fuel consumption; diesel engine; increased power*

## 1. INTRODUCTION

The use of diesel engines for transportation remains despite the development of alternative fuel technologies. Diesel engines give advantages for heavy-load transportation (1). It generally offers fuel efficiency and power performance (2). Therefore, vehicles with diesel engines are popular due to their efficiency in performance (3,4). It appears to result in longer operational hours and lower fuel costs for heavy-duty vehicles (1). It is designed to withstand high compression stresses and is typically more robust. This performance is obtained from the high torque at low RPMs, which is principally advantageous for heavy-duty transportation (5–7). Therefore, industries utilize it for their load transportation for long-distance places or more goods and cargo.

However, even though diesel engines offer benefits, they also bring pollution and emissions reduction challenges. The result of the fuels combustion becomes one of the diesel engines problems. Diesel engines result in substances that pollute the environment. Those include nitrogen oxides (NOx) and particulate matter that contributes to air quality issues (8,9).

In improving the performance of diesel engines and reducing the emissions of vehicles with this type of engine, the combustion needs to be customized. Research on improving combustion in diesel engines has been conducted. An experiment on the determination of the size of cylinder valve clearance gap has proven to influence the performance of diesel engines significantly (10). This research found that a 0.6 mm valve gap size results in the most optimum performance for the vehicle. The modification of the diesel engines with biodiesel-diesel blends gives an improvement on the diesel engines (11–13). It relates to the combustion management to achieve the completion of the combustion cycle. The management includes the fuel injection pressure, recirculation of exhaust gases to the engine inlet, the design of the fuel nozzle, and the design of the combustion chamber.

The solution to the problems of the emission combustion process of diesel engines was to deal with the use of swirl piston bowls and a reentrant piston bowl on baseline diesel engine (14,15). It has a significant influence on engine performance and emission. Moreover, it overcomes incomplete combustion processes in diesel engines. The other improvement of diesel engines is by changing the injection strategy and creating more turbulence in the combustion chamber to mix the fuels and air better (16–18). The double-layer combustion chamber also can improve the fuel-air mixing process (19,20). The research mainly deals with the problem of the insufficient amount of fuel in the combustion chamber that causes the fuel in the injection process to be not properly fine.

Research on diesel engines has been conducted by modifying the combustion chamber and injection strategy but little research was conducted on heating the fuel before injecting it into the combustion chamber. This research focuses on adding a fuel heater for diesel engines to reduce fuel viscosity before being injected into the combustion chamber. The purpose is to form finer granules and produce more homogeneous air fuel. The test was conducted on the diesel engine to identify the performance improvement of the engines. The higher fuel temperature in diesel engines is aimed at generating more power and more efficient fuel consumption compared to baseline engines.

## 2. METHODS

This is experimental research on improving the performance of diesel engines by using fuel heaters. It was conducted on diesel engines with fuel direct injection. The experiment aimed to observe the effect of fuel heating on the combustion process, engine performance, and emission.

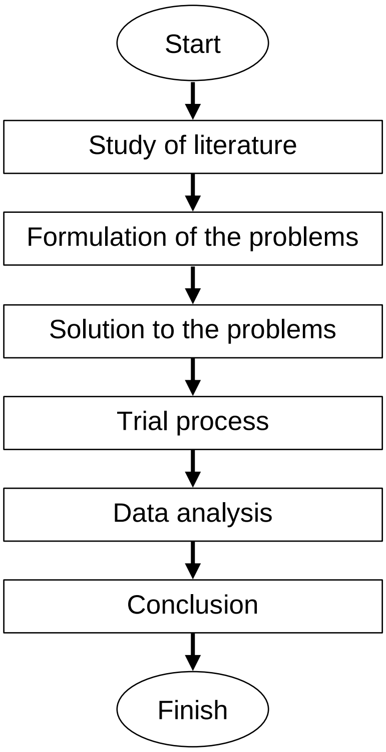


*Figure 1. Research procedures*

The research began with determining the experimental design, observing the engine's performance, and the potential problems during the operation. It was also conducted with defining variables and procedures. The subsequent steps were finding references to obtain information on the previous problem and findings conducted by other researchers. Studying and comparing the results of those researchers raises new issues and possible solutions in diesel engines that need a higher fuel temperature to improve the combustion process and decrease emissions. Furthermore, the experiment was conducted by doing a trial process. It was conducted by increasing the motor rotation at 1000 rpm, 1250 rpm, 1500 rpm, 1750 rpm, 2000 rpm, 2250 rpm, and 2500 rpm. The data obtained from the experiment was analyzed using data processing techniques and statistical formulas and interpreted as the research results. Hereinafter, the results of the analysis were presented in graphs and the researcher conveyed the conclusion based on the findings.

### 2.1 Experimental Procedures

The experiment with fuel heaters in diesel engines focused on improving the combustion process and the procedures were conducted in this research. It included engine and experiment preparation, engine positioning, increasing rpm, data collection, returning the engine to idle condition, and repeating the experiment three times with an increasing 10$^o$ C of fuel temperature in each experiment.

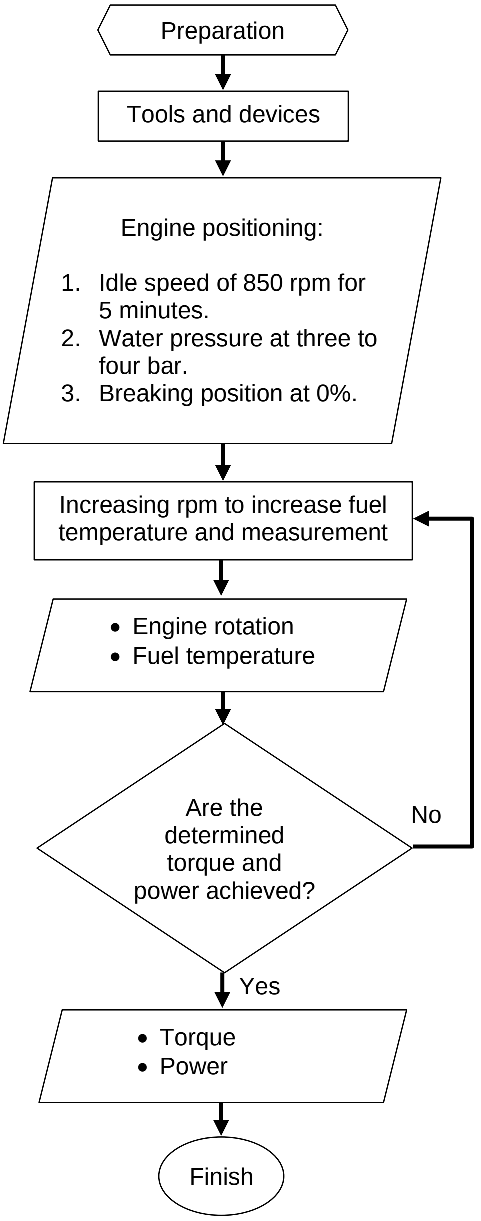


*Figure 2. Experimental procedures*

The engine and experiment preparation were conducted by inspecting the availability and the condition of lubricating oil, coolant, and fuel. It was aimed to avoid errors in the experiment because of the insufficient quality or amount of lubricating oil and coolant in the engine. Moreover, an inadequate amount of fuel is also needed to prevent the experiment's failure. The tools and devices in this experiment were also prepared at this step. It was provided to collect the data required for this research.

The further procedure was the engine positioning. It was conducted by igniting the engine at idle speed (850 rpm) for five minutes to prepare the engine for working conditions. Meanwhile, the water inlet valve was opened to the dynamometer with three to four bars the water pressure and the breaking position were determined at 0%. In this procedure, the data was collected on engine speed, diesel temperature, the amount of diesel return flow in measuring cup 2, the time of fuel consumption for 50 ml in measuring cup 1, and dynamometer action force for initial measurement. While the engine was prepared, the breaking position was increased to 30% and maintained constant.

In the experiment phase, the engine speed was increased at 1000 rpm, 1250 rpm, 1500 rpm, 1750 rpm, 2000 rpm, 2250 rpm, and 2500 rpm. With this increase in engine speed, the data were re-collected. The data included the engine speed, the temperature of diesel fuel, the amount of diesel return flow in measuring cup 2, the time of fuel consumption for 50 ml in measuring cup 1, and the dynamometer action force for each change in motor rotation.

When the experiment phase finished, the engine was returned to idle position. The break was reduced to 0%, the speed was 0 rpm, and the pump water and dynamometer were turned off. The engine was allowed to off but the fuel temperature was measured at 40$^{o}$C.

The experiment was conducted three times to obtain the required temperature of the diesel fuel (50$^{o}$C, 60$^{o}$C, and 70$^{o}$C). The increase in temperature was observed to identify its effect on the improvement of diesel engine performance. The procedure was conducted by igniting the engine at 40$^{o}$C and returning it to idle conditions until the temperature was 50$^{o}$C and it was repeated for further temperature increase. The increase in temperature was determined at 10$^{o}$C increment. The increase in temperature was observed whether there was a decrease in engine power. Otherwise, it was observed that the power decreased when the temperature was at a high rate.

After the data were collected and the experiment had been conducted, the engine was positioned in idle conditions before it was off. The break was reduced to 0% and the rotation was decreased to idle.

## 2.2 Experimental Tools

### *2.2.1 The specifications of diesel engines*

The diesel engine in this research was a direct-injection diesel engine and was coded with 4JA1-L. The specifications of the engine are shown in Table 1.

*Table 1. Specifications of 4JA1-L diesel engine* (21,22)

| Parameter | Specifications |
|---|---|
| Engine type | Four-cycle, overhead valve, water cooled |
| Combustion chamber type | Direct injection |
| Cylinder liner type | Dry type, chrome plated, stainless steel tube |
| Timing gear train system | Gear drive |
| No. of cylinders-bore × stroke, mm(in) | 4 - 93 × 92 (3.66 × 3.62) |
| No. of piston rings | Compression ring: 2/Oil ring: 1 |
| Total piston displacement, $cm^3(in^3)$ | 2,499 (152.4) |
| Compression ratio (to 1) | 18.5 |
| Compression pressure, $kPa(kg/cm^2/psi)$ | 3040(31/441)-200rpm |
| Fuel injection order | 1 - 3 - 4 - 2 |
| Fuel injection timing BTDC, deg | 12 |
| Specified fuel type | SAE No. 2 diesel fuel |
| Idling speed (no load), rpm | 750 (MT), 850 (AT) |
| Maximum power | 86 ps / 3900 rpm |
| Maximum torque | 19.5 kg.m / 2300 rpm |

### 2.2.2 Fuel Heating Device

This fuel heating device consists of a tube with 1 inlet and 1 outlet. There is a heating element installed at the bottom and it is equipped with a temperature measurement sensor placed near the outlet pipe in the tube. It is connected to a signal conditioning circuit to measure the fuel temperature. The data from the sensor was displayed on a digital multimeter.

The heating element used is connected to an alternating current power supply but is first passed through a series of potentiometers which are used to regulate the amount of heat produced by the heating element.

This device is installed between the diesel filter and the high-pressure pump so that the temperature of the diesel that enters the high-pressure pump can be regulated.

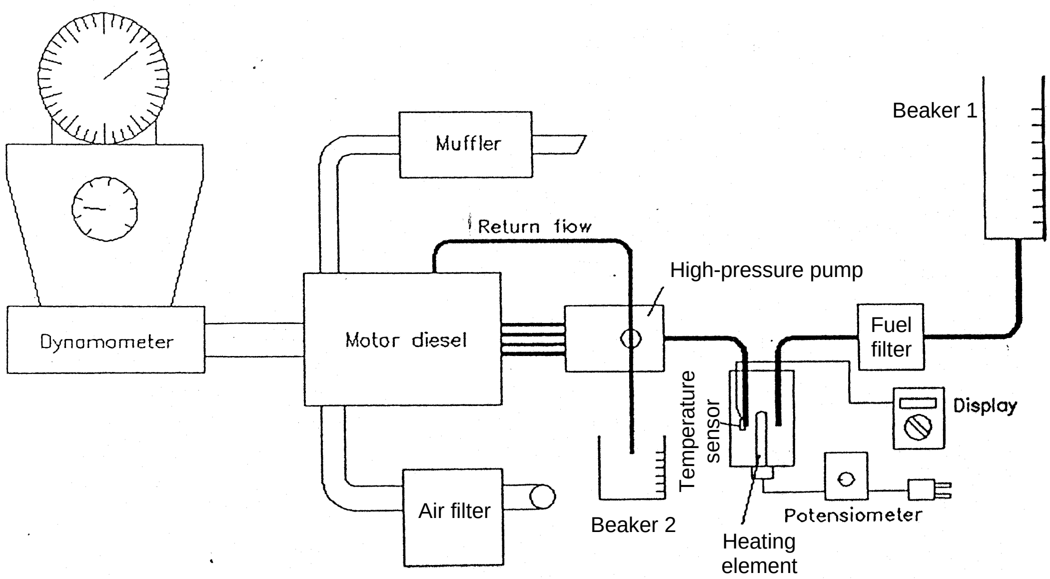


*Figure 3. Series of Equipment Used in the Experiment*

## 3. Result and Discussion

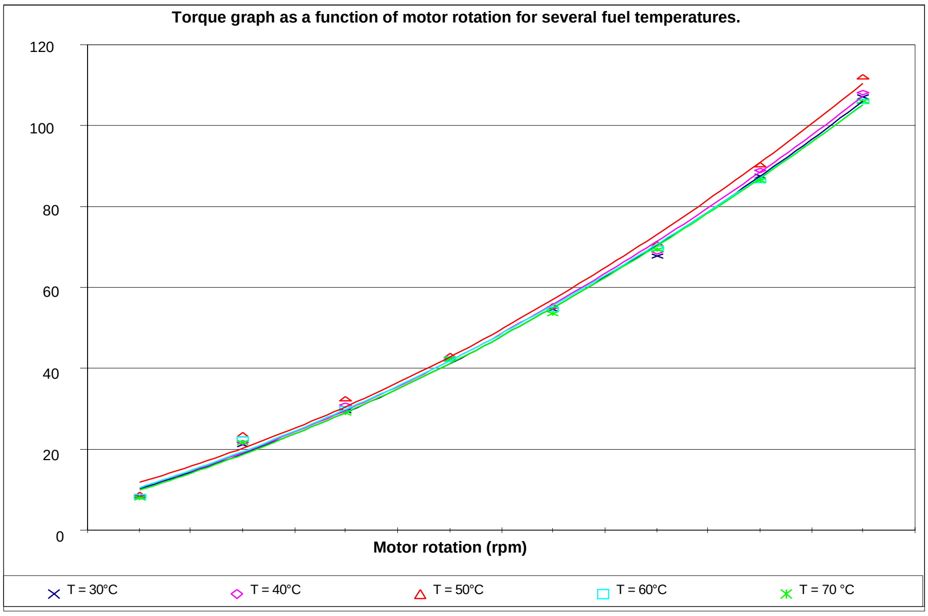


*Figure 4. Torque graph as a function of motor rotation for the same fuel temperatures*

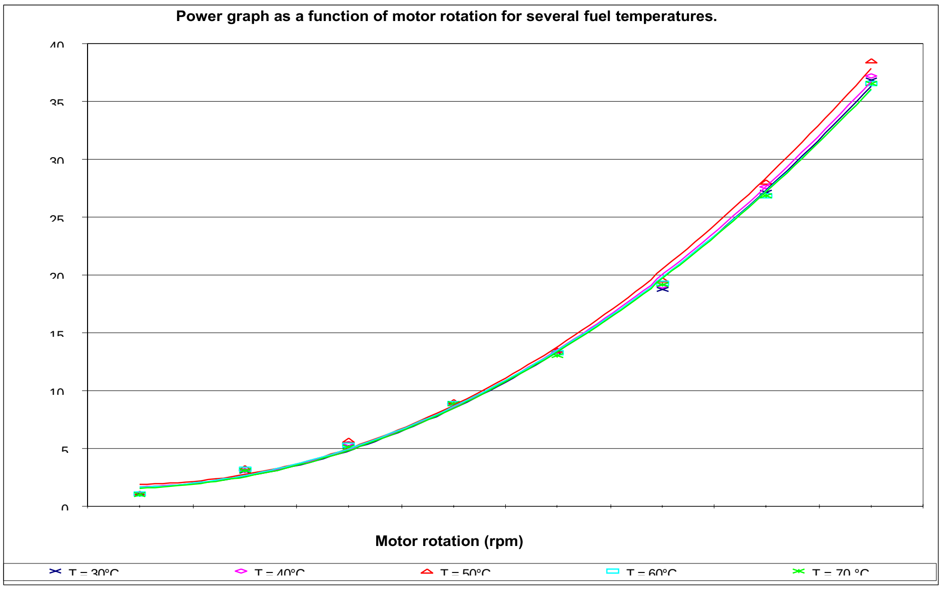


*Figure 5. Power graph as a function of motor rotation for the same fuel temperatures*

Figures 4 and 5 show that the change in fuel temperature is in line with the changes in torque and motor power, and it is seen that increasing the temperature of the diesel will increase the torque and motor power. Theoretically, it can be explained that this increase is caused by heating the diesel which causes the viscosity of the diesel to decrease. Therefore, when injected into the combustion chamber it can form finer fuel mist droplets. In this condition, the process of mixing fuel with air will be more homogeneous and the fuel will be easier to burn and cause the percentage of fuel burned to increase.

As the amount of fuel burned increases, the pressure in the combustion chamber increases and subsequently inclines the torque and power produced by the combustion engine. This increase in power does not continue with the increase in temperature, as the increase in motor power only occurs until the diesel reaches a temperature of $500^o$ C and beyond. If the temperature of the diesel continues to increase, the power produced by the motor will be smaller compared to the power when using diesel with a temperature of $500^o$ C.

The decrease can occur because increasing the fuel temperature causes it more flammable, thus shortening the combustion preparation period (ignition delay). The combustion preparation period can be defined as the fuel preparation time measured from the time of fuel injection until the fuel reaches its self-ignition condition ($2200^o$ C). Increasing the fuel temperature of a diesel engine causes it to reach its self-ignition condition faster.

The change in power is not very visible at engine speeds below 1750 rpm, as can be seen from the overlapping curves, but for engine speeds higher than 1750 rpm, this change appears to be increasingly large, as indicated by the tendency for the curves to be further apart. This shows a tendency that the use of heated diesel will have more effect on higher engine speeds, considering that higher engine speeds require fuel that burns faster due to the limited time available for increasingly shorter combustion.

In this case, it is also necessary to pay attention to the start of fuel injection when approaching the end of the compression stroke and this must be adjusted to the length of the combustion preparation period. If the combustion preparation period is too short while the fuel injection is quite far before the piston reaches the Top Dead Center (TDC), then the peak pressure due to fuel combustion will occur before the piston reaches TDC, this is a disadvantage because the explosive force that should be used to push piston in the expansion/work stroke is reduced because some are wasted when the piston has not reached TDC, in addition, if the pressure increase in the combustion chamber is too large exceeding the strength of the motor construction, it can cause damage to the motor itself, this excessive pressure increase can occur because the fuel explosion occurs in a space that is increasingly narrow due to the movement of the piston to TDC. Therefore, it is expected that by adjusting the temperature of the supplied diesel fuel with the time of fuel injection, it will be able to avoid wasted power losses so that the power available for the work stroke will be greater. It is even possible that with a combination of diesel temperature and the right injection time settings, greater power can be produced compared to experiments when using diesel with a temperature of 500º C (i.e. a power increase of 4.1%).

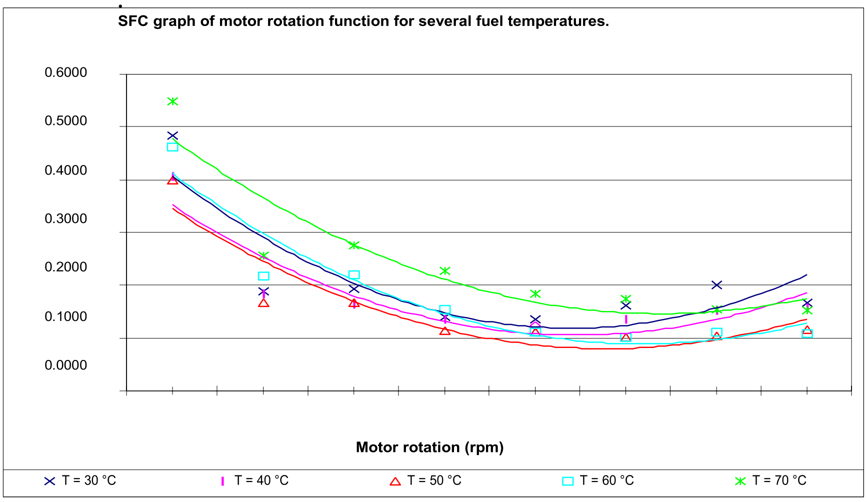


*Figure 6. SFC graph of motor rotation function for several fuel temperatures.*

From the graph above, it appears that there is an increase in SFC when diesel is heated above 500º C (the average SFC decrease of 23.4%). This increase can occur because at higher temperatures the combustion preparation period will be shorter. If it is too short, the rapid combustion period will occur long before the piston reaches TDC (in the compression stroke) so peak pressure also occurs when the piston has not reached TDC and this is a loss because the pressure should be used for the work stroke. Thus, the power generated will be reduced and increase specific fuel consumption.

If the motor works at higher speeds, the SFC value tends to increase. This can be caused by the higher the motor speed, the shorter the time available for combustion. This short time causes some of the fuel not to have time to burn and is ultimately wasted, thus increasing the measured SFC value.

When the motor works at lower speeds, the SFC value also tends to increase. It can be caused by the motor load to run supporting equipment such as fuel injection pumps, where the magnitude of this load is constant. When the motor speed is still low, the power generated is also still small so that if given a load, the power that can be used will be even smaller and will ultimately increase specific fuel consumption. When the motor speed is high enough, the power generated is also higher while the magnitude of this load remains constant so that it does not have much effect on the price of specific fuel consumption.

In the SFC graph, there is also a tendency for the SFC line for heated diesel to have a lower value for high motor speeds (<2000 rpm) when compared to unheated diesel.

This tendency can be caused because heating will make the diesel fuel more flammable so that it requires a shorter time to reach the condition of self-ignition and this is what will later compensate for the limited time available for combustion at high engine speeds so that the percentage of unburned fuel is reduced can reduced And Power Which also produced larger which will ultimately lower the SFC price.

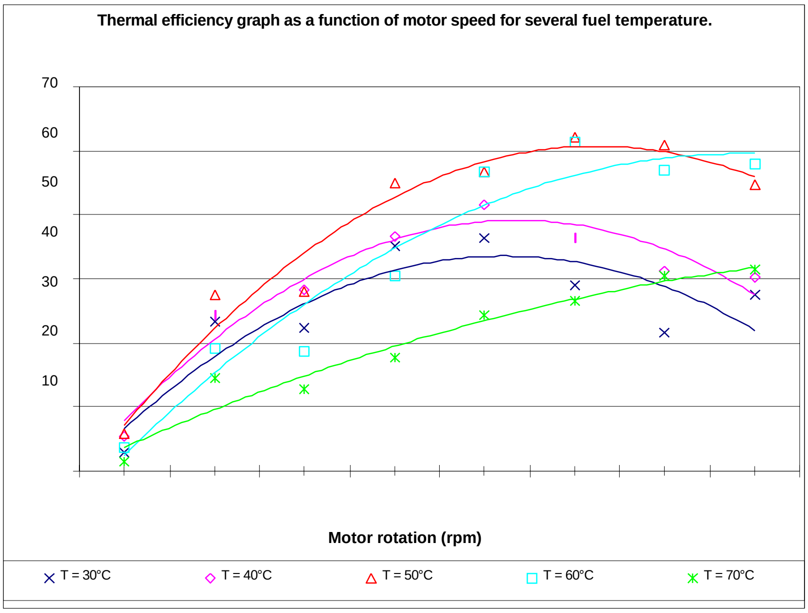


*Figure 7. Thermal efficiency graph as a function of motor rotation for several fuel temperatures.*

The thermal efficiency of a combustion engine can be defined as the amount of heat utilization generated from fuel combustion into mechanical work. The heat/power provided by the fuel can be seen through the amount of fuel consumption, while the amount of mechanical work can be seen from the motor power produced. So, the price of this thermal efficiency will be affected by changes in motor power and changes in the rate of fuel consumed by the motor. Where an increase in power accompanied by a decrease in the rate of fuel consumption of a motor will increase thermal efficiency, conversely, a decrease in power and an increase in the rate of fuel consumption will cause a decrease in the thermal efficiency of the combustion engine.

Thus, it is appropriate if in the graph it appears that the SFC lines have the opposite shape to the thermal efficiency lines, the SFC lines form a parabola that opens upwards while the thermal efficiency lines form a parabola that opens downwards. From the graph above it can be seen that the maximum efficiency occurs at a fuel temperature of 500$^o$ C (with an average efficiency increase of 36.67%).

## 4. Conclusion

After heating the diesel fuel on the 4JA1-L diesel engine, it shows that the heating provides several changes to the torque, power, specific fuel consumption, and thermal efficiency. The changes in the temperature of the diesel fuel to be injected into the combustion chamber of a diesel engine affect its torque, power, specific fuel consumption, and thermal efficiency.

The most ideal diesel temperature for a 4JA1-L diesel engine to produce an optimal increase in power and decrease in SFC value, based on this study, is in the rotation range of 850 rpm to 2500 rpm, and the fuel temperature of 50$^o$C. It resulted in an average power increase of 4.1% and an average SFC decrease of 23.4% when compared to without fuel heating (T fuel = 300$^o$ C).

Currently, the type of fuel heating device that is widely available on the market uses heat from radiator water. The problem that can arise is if the tool cannot produce diesel output at the same temperature expected, there is a need for change in the design of the device. A solution to this problem is to create a radiator water bypass channel before entering the heater. Then by installing a tap on the channel, it can be adjusted the flow rate of the hot water volume through the heater so that the output temperature of the diesel can be changed according to the needs.

The weakness of a heating system like this is that fuel heating can only occur when the radiator water is at a high temperature. Therefore, if the radiator water is at a low temperature, the system does not work properly. It can be overcome by using an electric fuel heater (using a heating element), thus the fuel heating can be conducted without depending on the radiator's water temperature. Moreover, it would be even better if it is also equipped with a control system that can regulate the fuel temperature output.

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