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Diesel Engine Efficiency under Varying Loads and Engine Oil Contaminated with Safe levels of Glycol

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Abstract: Although allowable amounts of glycol contamination in diesel engine oil, no research has been conducted on how these levels and varying loads affect engine performance. The research used a four-stroke diesel engine to investigate the effect of different glycol contamination levels (0, 120, and 220 ppm) under two engine loads (4.5 and 9 kW). Brake specific fuel consumption, brake thermal efficiency, friction power, and exhaust gas temperature were measured to determine the engine performance. The experiment used the factorial arrangement in a completely randomized design (CRD) with three replicates. Increasing the contamination levels from 0 to 120 and then to 220 ppm under constant engine load significantly increased brake specific fuel consumption, friction power, and exhaust gas temperature and decreased brake thermal efficiency. Increasing the engine load from 4.5 to 9 kW with constant oil glycol contamination levels significantly increased brake thermal efficiency, friction power, and exhaust gas temperature and decreased brake specific fuel consumption. The results of the statistical analysis showed significant differences in the interaction between glycol contamination levels and load levels. Lower friction power (5.6 kW) and exhaust gas temperature (165.33 °C) were produced by combining the first contamination level (0 ppm) with the first load (4.5 kW), while the lowest brake specific fuel consumption (0.24 kg/kWh) and highest brake thermal efficiency (32.14%) were produced by combining the first contamination level (0 ppm) with the second load (9 kW). The study concluded that diesel engine performance decreases when engine oil is exposed to the permissible levels of contamination above with changes in engine load. This study can aid diesel engine maintenance and operational instructions, particularly in glycol-contaminated diesel engine oil.

Keywords :Engine performance, Exhaust gas temperature, Friction power, Glycol contamination, lubricating oil.

Introduction

Engine oil is exposed to contamination and oxidation (Abdul-Munaim *et al*.,2019), which affects its efficiency (Abed Hasan *et al*., 2024) and lifespan (Abdul-Munaim, et al., 2016). One of these contaminants is glycol, which flows into the lubricating system from the engine's cooling system due to an ineffective gasket or seal (Abdulmunem *et al*., 2020). Mixing glycol with oil causes damage to the engine (ASTM, 2013). References differ in the percentage of glycol allowed in engine oil. One study considers 150 parts per million to be harmless (Booser, 1994; Abdulmunem *et al*., 2020), while another study considers 500 parts per million to be harmless as well (Wang & Lee, 1997). However, limited studies have examined the effect of permissible glycol contamination levels on diesel engine performance (Kadhim *et al*., 2023).

Synthetic lubricating oils have been showen to improve engine efficiency and reduce specific fuel consumption compared to conventional oils (Musthafa, 2016). Specific fuel consumption is the amount of fuel pumped into the combustion chamber to produce power. In other words, it measures the engine's effectiveness in converting fuel after it reaches the combustion chamber into work (Ferguson & Kirkpatrick , 2015) The brake-specific fuel consumption is affected by contaminants such as glycol because the viscosity of the oils is affected. Thus, fuel consumption increases due to the internal friction force between the engine parts, which requires more fuel per kilowatt of power (Kadhim *et al*., 2023). Meanwhile, the brake-specific fuel consumption decreases when the load on the diesel engine increases (Singh *et al*., 2016).

The relationship between brake thermal efficiency (BTE) and brake power in a diesel engine, as the engine load increases, can be understood through various studies that explore engine performance under different conditions. Generally, BTU tends to increase with engine load. For instance, one study found that BTU increased by 6% at full load compared to the base engine (Saravanan *et al*., 2020). Another study noted that BTU increased with higher brake power and load (Mallikappa *et al*., 2012). Brake thermal efficiency refers to the ratio of brake power to the energy generated by the combustion of fuel (Ferguson & Kirkpatrick , 2015). Exposure of engine oil to glycol contamination increases braking thermal efficiency due to damage to the oil's properties (Kadhim *et al*., 2023). At the same time, increasing engine load causes increased braking thermal efficiency (Singh *et al*., 2016) due to the increase in pressure inside the cylinder, and the combustion temperature increases, which leads to an increase in thermal efficiency (Syamsiro *et al*., 2019).

The objective of sustainable resource preservation is a significant factor in the ongoing efforts to reduce friction power losses in combustion engines (Deuss *et al*., 2010). Increased contamination of engine oil with glycol is accompanied by a direct increase in the power lost due to friction, and the reason is that the engine oil loses its lubricating properties, which increases friction between engine parts (Kadhim *et al*., 2023). Increasing the load on the diesel engine at low speed (1000 rpm) decreased the friction power (Singh *et al*., 2014).

The exhaust gas temperature is a measure of the efficient utilization of the thermal energy produced by fuel, and thermal dissipation in the exhaust pipe or a rise in exhaust temperature diminishes the efficiency of converting fuel's thermal energy into mechanical work (Enweremadu & Rutto , 2010).

The exhaust gas temperature limits for diesel engines are crucial for various operational and regulatory reasons. Modern diesel engines require a minimum exhaust gas temperature of approximately 200 °C to initiate emissions control operations effectively (Guan *et al*., 2019). Exposure of diesel engine oil to different levels of glycol contamination causes an increase in exhaust gas temperature (Kadhim *et al*., 2023) due to the oil losing its lubricating properties when mixed with glycol (Liddell & Marshall, 1952) An increase in engine load accompanies increasing exhaust gas temperatures because increasing engine load causes a decrease in the rate of heat transfer across the cylinder wall (Kumar, 2009).

This study aims to determine the effects of three allowable levels of glycol contamination (0, 120, and 220 ppm) in fresh engine oil (SAE 20W 50) and two loads (4.5 and 9 kW) of a diesel engine and their interaction on brake-specific fuel consumption, brake thermal efficiency, friction power, and exhaust gas temperature by applying a factorial experiment utilizing a completely randomized design with three replications.

Materials & methods

The experiment was carried out using a four-stroke diesel engine, specifically the J2 model, which has a volume of 2.7 liters and a water-cooling system, Table 1 shows the engine specifications. The engine was operated at a speed of 1500 rpm and two load levels, the first at 4.5 kW and the second at 9 kW. The reason behind choosing the two loads (4.5 and 9 kW) was due to the possibility of controlling the experimental conditions. At the first load, the engine was left for 10-15 minutes, observing the stability of the speed and load. Then, the required readings were taken, and the same procedure was repeated by taking the data when changing to the second load. The following performance indicators were evaluted: brake specific fuel consumption, brake thermal efficiency, frictional power, and exhaust gas temperature. The anti-freeze (Glycol), mixed with the oil in different proportions, was ARAL G-OIL. The reason for choosing this type of engine oil was due to its widespread use by most diesel engine operators. Oil contamination was at three glycol levels; the first level was 0 ppm - uncontaminated oil, 120 ppm, and 220 ppm according to (Abdulmunem *et al*., 2020)

Table (1): Engine specifications

Engine Manufacturer	Kia Bongo (Korea)
Type of engine	J2 2701
Piston Displacement	2694cm^3.
Stroke	95 mm.
Bore	95 mm.
Nominal Output	80 hp at 4000 rev/min.
Maximum Torque	16.8 kg.m at 2400 rev/min.

Sample preparation:

The experiment used SAE 20W50 engine oil purchased from the local market. Contaminating the oil with glycol was conducted using a plastic container with a capacity of 5 liters following the procedure outlined by (Kadhim *et al*., 2023).

Test System

The test system used in the experiment consists of a four-stroke diesel engine with four cylinders connected to a three-phase electric generator. A panel was prepared alongside the test system, with a graduated tube installed to measure fuel consumption, a device to measure electrical power, voltage, and current, switches to operate loads connected to voltage-regulating devices, a meter to determine engine speed and a sensor to measure exhaust gas temperature.

The braking power was quantified utilizing an electric generator, and its value was determined by using the following equation (Mahon, 2004)

$$BP = \frac{Tp}{1000 \times \eta_g} \quad ---(1)$$

Where:

BP represents the brake power in kilowatts (kW), Tp represents the electric power delivered to the load

in watts (W), and ηg represents the efficiency of the generator (80%).

The fuel mass consumption was calculated using the formula suggested by (Al-Hasan, 2003):

$$\dot{M}_f = \frac{\rho \times V \times 0.001}{t} \times 3600 \quad ---(2)$$

Where”

$\dot{M}f$ stands for average fuel use (kg/h), ρ is fuel density (kg/cm^3), V is the amount of fuel going down the burette and its volume (50 cm3), and t is the time it takes to use up a certain amount of fuel (sec).

The brake-specific fuel consumption (kg / kW.hr), was determined using the equation (Ferguson & Kirkpatrick , 2015)

$$BSFC = \frac{\dot{M}_f}{BP} \quad ---(3)$$

The brake thermal efficiency (%) is determined by using the following equation (Ferguson & Kirkpatrick , 2015):

$$\eta_{bth} = \frac{BP}{\dot{M}_f \times CV} \quad ---(4)$$

where "CV" represents the calorific value of diesel fuel, which is measured in kilojoules per kilogram (kJ/kg).

Indicated power (kW) was obtained using the Morse test, and friction power (kW) was calculated by subtracting indicated power from brake power (Eastop & McConkey, 1993).

The temperature was recorded using a Max6675 thermocouple probe equipped with a K-type thermocouple, which was coupled to an Arduino Mega 2560 controller board. This sensor, positioned in the exhaust pipe, is capable of measuring temperatures within the range of 0–1024°C.

Practical Test

The engine oil was contaminated with three different levels of anti-freeze fluid (Glycol) (uncontaminated oil, 120 and 220 ppm). During this experiment, the engine's rotational speed was set at a constant rate of 1500 revolutions per minute. The initial load applied to the engine was 4.5 kW, followed by a second load of 9 kW. The engine was checked before work in terms of the fuel level in the tank, the amount of water in the radiator, and the oil level in the engine, and the electric generator worked well. Parameters such as speed, load, and exhaust gas temperature were verified. The engine was started after preparing it with the first oil contamination level (0%), with speed held at 1500 rpm without load for 10 minutes. Then, the load gradually increased, with nine heaters and three heaters for each phase, while maintaining the speed required to work using the speed limiter until the load reached the first required load (4.5kW). The engine was left for 15 minutes to stabilize, observing speed and load, then fuel consumption, water entering and exiting the engine, and exhaust gas temperature were measured. After that, the Morse test was carried out to obtain the indicated power at a speed of 1500 p.p.m.

Three replicates were performed for each treatment in a random manner to enhance accuracy and minimize experimental error, with a total of 18 replicates. This was done because a completely randomized statistical design was chosen for two factors: the first being the percentage of oil contamination with glycol and the second being the amount of load applied to the diesel engine. The objective was to determine the impact of these two factors on the engine's performance.

Results & discussion

The study was conducted to measure brake specific fuel consumption, brake thermal efficiency, frictional capacity, and exhaust gas temperature using a diesel engine. The objective was to study the effect of engine oil, which was contaminated with three levels of glycol and two levels of engine load.

Brake specific fuel consumption:

Figure 1 shows the effect of the percentage of oil contamination with glycol and the load on Brake specific fuel consumption. Significant differences appeared when contamination levels gradually changed from 0 ppm to 120 ppm and 220 ppm. The lowest specific fuel consumption rate was recorded at a 0-ppm contamination level of 0.31715 kg/kW.h, 0.3345 kg/kW. h at a contamination level of 120 ppm and 0.36285 kg/kW.h at a contamination level of 220 ppm, which gave the highest specific fuel consumption rate; thus, the increase rates were 5.47% and 8.5%. The presence of glycol in the oil resulted in a loss of its lubricating characteristics (Abdulmunem *et al*., 2020)

Figure 1 indicates that the load significantly affects specific fuel consumption. The specific fuel consumption rate was lowest during the second load, which was 9 kW and amounted to 0.26043 kg/kW.h, compared to the first load, gave the highest specific fuel consumption rate, 0.4159 kg/kW.h. Increasing the load causes an increase in fuel pumping per kW, but on the other hand, the increase in braking power is higher than the increase in the amount of fuel pumping. this is because frictional power increases only by a relatively limited amount when the load increases and when applying Equation 8 using values related to different loads, as the ratio of braking power to indicated horsepower increases as the load increases, thus reducing the rate of braking specific fuel consumption according to equation 4. The specific fuel consumption rate is inversely proportional to the load placed on the engine.

Figure 1 illustrates that the interaction between contamination and load levels significantly affects brake-specific fuel consumption. The contamination rate of 0 ppm and the engine load of 9 kW gave the lowest specific fuel consumption rate, which was 0.2436 kg/ kW.h. The highest rate of brake-specific fuel consumption was obtained at a contamination level of 220 ppm and a load of 4.5 kW, which was 0.4459 kg/ kW.h.

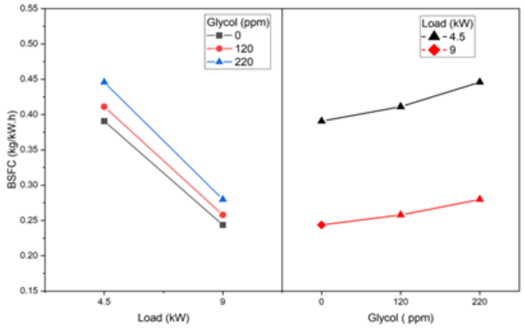

Fig. (1): The effect of glycol and engine load levels on brake specific fuel consumption.

Brake thermal efficiency

Figure 2 illustrates the oil contamination with glycol and the load on braking thermal efficiency. The effect of oil contamination by glycol in this characteristic was significant. When the oil contamination changed from 0, 120, and 220 ppm, the braking thermal efficiency decreased from 26.09 to 24.7 to 22.77%, which decreased by 5.32% and 8.09%. The reason is that Brake thermal efficiency and specific fuel consumption are inversely correlated (Kasbergera *et al*., 2011).

The same table illustrates that changing the engine load had a significant effect. When the engine load changed from 4.5 to 9 kilowatts, the braking thermal efficiency increased from 18.885% to 30.163%. Despite pumping a higher amount of fuel in the second load, the increase in braking power outweighed the increase in the rate of fuel consumption, which led to an increase in braking thermal efficiency according to Equation 4, as the increase in friction power is relatively limited, which allows brake power to increase at a high pace. Therefore, the specific fuel consumption is inversely proportional to the thermal efficiency, causing a decrease in its value.

the interaction between glycol contamination levels and engine load was significant, as the highest brake thermal efficiency (32.14%) was obtained from the combination of 0 ppm contamination with a load of 9 kW. The oil not contaminated with glycol increased the engine's brake thermal efficiency compared to the contamination level of glycol 220 ppm, which gave the lowest brake thermal efficiency (17.56%) with a load of 4.5 kW.

Figure 3 illustrates the effect of oil contamination levels and engine load on the rate of friction power. When the contamination levels changed from 0, 120, and 220 ppm, the friction power increased by 16.24% and 11.91%, respectively. One of the most important properties of oils is reducing friction between moving parts. Therefore, when the oil is exposed to contamination, it loses this property (Liddell & Marshall, 1952).

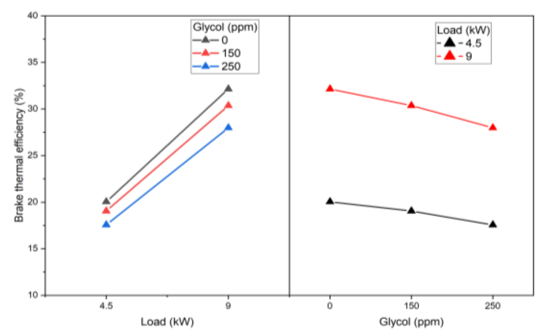

Fig. (2): The effect of glycol and engine load levels on Brake thermal efficiency

Friction Power

Figure 3 indicates that the engine load significantly affects friction power. Increasing the engine load from 4.5 kW to 9 kW resulted in an increase in friction Power from 6.82 kW to 7.67 kW due to the increase in friction within the engine parts, which led to an increase in the friction Power.

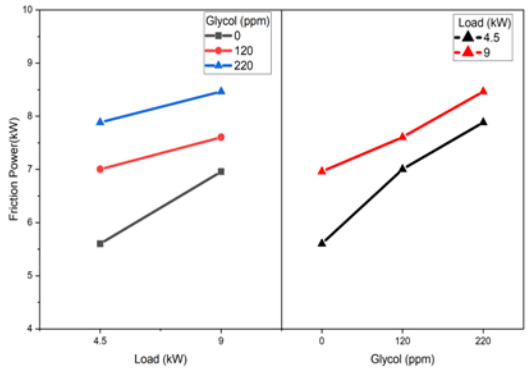

Fig. (3): The effect of glycol and engine load levels on friction power.

The combination of the contamination level of 0 ppm and the engine load of 4.5 kW gave a friction power of 5.6 kW, while the contamination level of 220 ppm with a load of 9 kW was significantly higher, with an average of 8.46 kW. The difference in friction power by higher engine load and higher contamination level was evidence of a change in engine performance, and this may be due to the deterioration of engine oil characteristics.

Exhaust gas temperature:

Engine oil contamination with glycol has an influential effect on increasing the average exhaust gas temperature. Figure 4 indicated significant differences in engine oil contamination levels with glycol. When glycol mixes with engine oil, it causes oxidation and reduces the lubricating properties of the oil (Abdulmunem *et al*., 2020).

Figure 4 shows significant differences between the engine loads and the temperature of the exhaust gases. Exhaust gas temperatures increased at high loads, giving an average of 299.5 ⁰C, while at low loads, they gave an average of 169.5 ⁰C due to the increased fuel consumed to reach the high load.

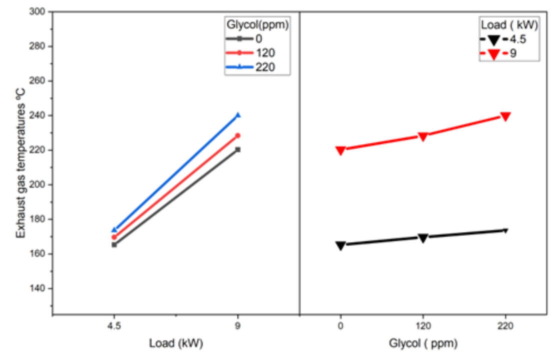

Fig. (4): The effect of glycol and engine load levels on exhaust gas temperature.

The interaction between glycol oil contamination levels and engine loads was significant in this characteristic. The combination of the contamination level of 220 ppm with the highest engine load (9kW) gave the highest value for the exhaust gas temperature (240 ⁰C), while the lowest value was 165.3 ⁰C for the oil contamination level of 0 ppm with the lowest load (4.5 kW).

Conclusion

The SEA 20W 50 engine oil was contaminated with glycol at levels of 0, 120, and 220 ppm. This contaminated oil was tested in a four-stroke diesel engine, with two different engine loads (4.5 and 9 kW) applied to determine the effect probability of the contaminants and loads on the engine's performance depending on the permissible levels of diesel engine oil contamination with glycol. Based on the results obtained, it is concluded that:

1- The effect of the two loads differed on brake specific fuel consumption and brake thermal efficiency at 0.05 level, where the second load was more effective in reducing brake specific fuel consumption and increasing brake thermal efficiency than the first load.

2- The effect of the two loads on the friction power and the temperature of the exhaust gases differed at 0.05 level, where the first load was more effective in reducing the friction power and the temperature of the exhaust gases than the second load.

3- The effect of oil contamination levels with glycol on the brake specific fuel consumption differed at the level of 0.05, as the first level (0 ppm) was more influential in reducing the brake specific fuel consumption, as it gave the lowest brake specific fuel consumption, which is 0.31715 kg/kW.h, than the other two levels.

4- The effect of oil contamination levels with glycol on brake thermal efficiency differed at 0.05 level, as the first level(0ppm) was more influential in increasing brake thermal efficiency as it gave a higher brake thermal efficiency of 26.09% than the last two levels.

5- The effect of oil contamination levels with glycol on brake power and exhaust gas temperature varied at 0.05 probability. The first contamination level (0ppm) had the highest effect on reducing brake power and exhaust gas temperature, as it gave a lower friction power, which was 6.28 kW, and a lower exhaust temperature, 192.83 ºC, than the last two levels.

6- There was an interaction between the levels of loads and the levels of oil contamination with glycol in affecting all the studied characteristics by reducing the brake specific fuel consumption, friction power, and exhaust gas temperature and increasing the brake thermal efficiency when using the first level of glycol (0 ppm) with the two engine load levels. That is, increasing glycol levels above 0 ppm with increasing loads negatively affected the characteristics studied to evaluate the diesel engine's performance.

7- The results of this study can help in the field of maintenance and operation guidelines for diesel engines, particularly under conditions that cause diesel engine oil to be contaminated with glycol.

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Contributions of authors

Authors 1, 2, and 3 contributed to the methodology for preparing the original draft and participated in the review and editing process. All authors have read and approved the final version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest.

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كفاءة محرك الديزل تحت الاحمال المتغيرة وزيت المحرك الملوث بمستويات امنة من الجليكول

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المستخلص: رغم وجود مستويات مسموح بها من تلوث زيت محرك الديزل بالجليكول، إلا أنه لم يتم إجراء أي بحث حول كيف تؤثر تلك المستويات من التلوث مع الأحمال المتغيرة على أداء المحرك. استخدم بالبحث محرك ديزل رباعي الأشواط لمعرفة تأثير مستويات تلوث الجليكول المختلفة (0 و120 و220 جزء في المليون) مع حملين للمحرك (4.5 و9 كيلو واط). تم قياس استهلاك الوقود النوعي الفرملي، والكفاءة الحرارية الفرملية، وقوة الاحتكاك، ودرجة حرارة غاز العادم لتحديد أداء المحرك بتصميم تام التعشية (CRD) وبالترتيب العاملي وبثلاث مكررات. أدت زيادة مستويات التلوث من 0 إلى 120 ومن ثم إلى 220 جزء بالمليون مع حمولة محرك ثابتة إلى زيادة كبيرة في استهلاك الوقود النوعي للفرامل، وقوة الاحتكاك، ودرجة حرارة غاز العادم وانخفاض الكفاءة الحرارية للفرامل. أدت زيادة حمل المحرك من 4.5 إلى 9 كيلو واط مع مستويات ثابتة من تلوث الزيت بالجليكول لزيادة كبيرة في الكفاءة الحرارية للفرامل، وقوة الاحتكاك، ودرجة حرارة غاز العادم وانخفاض استهلاك الوقود النوعي للفرامل. أظهرت نتائج التصميم الإحصائي اختلافات كبيرة في التداخل بين مستويات تلوث الجليكول ومستوي الحمل. تم إنتاج قوة احتكاك أقل (5.6 كيلو واط) ودرجة حرارة غاز العادم (165.33 درجة مئوية) من خلال التداخل بين مستوى التلوث الأول (0 جزء في المليون) والحمل الأول (4.5 كيلو واط)، في حين تم إنتاج أقل استهلاك وقود نوعي للفرامل (0.24 كجم / كيلو واط ساعة) وأعلى كفاءة حرارية للفرامل (32.14٪) من خلال الجمع بين مستوى التلوث الأول (0 جزء في المليون) والحمل الثاني (9 كيلو واط). وخلص البحث إلى أن أداء محرك الديزل ينخفض عندما يتعرض زيت المحرك لمستويات التلوث اعلاه المسموح بها مع التغير في حمل المحرك. يمكن لهذه الدراسة أن تساعد بدليل الصيانة والتشغيل لمحرك الديزل، لا سيما بزيت محرك الديزل الملوث بالجليكول.

الكلمات المفتاحية: أداء المحرك، درجة حرارة غاز العادم، قوة الاحتكاك، تلوث الجليكول، زيت التشحيم.