Thermal analysis of natural gas as an alternative fuel for gasoline engine

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Abstract. Transport sector is one of the highly emerging industries which consume a million barrels of petroleum fuels like gasoline and diesel per day. Consequently, petroleum fuels are getting exhausted day-by-day. Energy supply for growing demand from the transport sector would be difficult to combat in the near future. This crisis has led to the avenue for alternative fuels to be one of the solutions. Compressed Natural Gas (CNG) has been successfully used as one of the alternative fuel worldwide. However, the design features of the gasoline operated engines are facing certain issue related to performance, consistency and reliability of the engine when it was switched to CNG as prime fuel. Distinct researchers have worked on the issue to find an appropriate solution. In the current work, the thermal behaviour of engine and its effect on engine cooling mechanism is considered as part of the study to analyse the effect of applying CNG as prime fuel on a gasoline operated engine.

1. Introduction

Growing global petroleum crisis has been forcing for the necessity of dual-fuel/multifuel engines, that are internal combustion engines capable of operating by two or more different fuels. Commonly, the prime fuel is being gasoline with spark ignition (SI) system, or diesel with compression ignition (CI) system. Due to economic infeasibility of diesel or gasoline fuel, today's transport sector has been slowly adapting to the alternative fuel to replace the petroleum-based fuels. Prominent and readily available alternative fuel is the Compressed Natural Gas (CNG). As per NGV Global Knowledgebase, as of July 2019, there are 27,765,376 Natural gas vehicle is on road (*Current Natural Gas Vehicle Statistics - July 2019*, 2019). Natural gas is characterized by low-carbon, cleaner-combustion and comparatively lower emission due to the higher ratio of Hydrogen in comparison with Carbon, it is also lighter than air and readily mixes with air [2]. Switching to natural gas in transport applications can result in a substantial reduction in atmospheric emissions like hydrocarbon, carbon monoxide, oxides of nitrogen, and greenhouse gas emissions. It can be noticed that the United Nations has set the guidelines for transforming the automotive sector on CNG based vehicles(York, 1993).

Jahirul et. al. (2010) has conducted a comparative study on the engine performance and emission of CNG and gasoline of a retrofitted car engine. The result has shown that for engine running with 50% throttle position at 4000 RPM, the peak brake power of gasoline is 27.7kW whereas CNG is 22.67kW.

The CNG produced 19.25% less brake power in this case. Similarly, with 80% throttle position at 4000 rpm, the maximum brake power for gasoline and CNG are 54.97kW and 50.44kW respectively, CNG fuel being 10.86% less in brake power when compared to gasoline. However, the specific fuel consumption (SFC) for CNG fuel was always lower than the gasoline due to the higher heating value and slow combustion ability of CNG in comparison with gasoline. The exhaust gas temperature of CNG was 5.91% - 24.21% higher than gasoline at both 50% and 80% throttle conditions. This is because of the higher heating value and the ignition temperature of the CNG(Jahirul et al., 2010). Research studies have shown that the emission characteristics for CNG based engines are better than gasoline for various operating conditions(Cho & He, 2009)(Joyanta, Md. Arafat, Shubhra Kanti, & Rezaur, 2013). CNG also proposed as a catalyst for gasoline engine as bi-fuel to improve the volumetric efficiency and to promote anti-knocking characteristics by boosting the octane number(Tabar, Hamidi, & Ghadamian, 2017). Under direct injection engines, CNG can improve the compression ratio to 14 without any combustion instability, in addition, it can promote better cold start(Kalam & Masjuki, 2011). CNG has been promoted as promising alternative fuel for both gasoline and diesel engines in many countries to meet the emission standards (Amrouche, Benzaoui, Harouadi, Mahmah, & Belhamel, 2012). As per the survey conducted in April 2018, there are 3045268 Natural Gas Vehicles on road in India (Kadam & Kar, 2019).

For any IC engine, maintaining relatively constant operating temperature is essential for better emissions control, good fuel economy and improved performance. Repeated combustion cycles in engine cylinders can cause the temperature to rise beyond operating condition. Unwanted heat should be dissipated to the surrounding to keep the engine under steady temperature. An effective cooling system is most essential to circulate a water-based coolant to convey the unwanted heat from the cylinders and engine head, and dissipating it to the atmosphere by the movement of air at the radiator. The coolant used in the cooling system should have various properties like improving the heat transfer ability, prevention of freezing and boiling, protection from corrosion, prevention of sludge and scale formation. In addition, they also expected to be compatible with cooling system components and hoses to avoid leakage. Many IC engine failures like cracking of cylinder head, piston seizure, pitting of cylinder liner or cylinder block are due to failure of the cooling system. Distilled or demineralized water is the prominent coolant used in IC engines. In case deionized water not available, it is recommended to use water with appropriate chemical properties. However, many synthetic coolants are used as additives for water to protect from boiling and freezing. Ethylene glycol-based coolants are the most popular type of antifreeze in car engine cooling systems with a proportion of 50:50 with water (Caterpillar, 2016).

Today’s car manufacturers promote their products by installing the CNG kit for dual-fuel supply system, considering CNG as an alternative for Gasoline. Many light motor vehicles can be seen on road with retrofitted CNG kits to convert the Gasoline engine vehicles to Natural Gas Vehicles to save the fuel cost. Due to the higher hydrogen content, the heating value of CNG (13Kcal/g) is higher than the Gasoline (11.3Kcal/g). Thus there is a tendency for overheating of engine and possibility for engine components to deteriorate faster under CNG than the Gasoline usage. An appropriate study is required to understand the thermal behaviour of the Gasoline based IC engines and to recommend an appropriate cooling system or coolant for the improved life of the engine and its components.

2. Objectives

The main objective of the current research is to conduct the thermal analysis for the IC engine used for light motor vehicles under CNG as an alternative fuel. The specific objectives of the current study are to:

- investigate the influence of engine speed and operating time on the temperature of a gasoline operated engine.
- investigate the effect of engine speed and operating time on the temperature by using CNG as an alternative fuel for a gasoline engine.
- investigate the influence of synthetic coolants on the temperature of the engine.

3. Methodology

A four-stroke, four-cylinder gasoline engine fitted with CNG conversion kit is used in the present work. Specification of the engine is listed in Table 1. In order to track the temperature of the cooling water, for both gasoline and CNG operated the engine, thermostat housing in the cooling system need to be modified by inserting a thermocouple. The thermostat housing is drilled with a hole to insert thermocouple. Figure 1 illustrates the location and modification of thermostat housing and Figure 2 illustrate the installation of modified thermostat housing to the engine. The thermocouple is connected to data logger to track the temperature for every 10 milliseconds using OM-CP-TCTEMP2000 thermocouple temperature recorder by Omega Engineering Inc.

Table 1. Specification of Engine used for the Experiment

Engine Capacity	1,332 cc
Engine Configuration	4-cylinders in-line 16-valves DOHC
Compression Ratio	10
Bore x Stroke	(76 x 73.4) mm
Fuel Type	Gasoline
Modified with	CNG Conversion Kit

Before conducting the experiments, the following precautions need to be taken to avoid the inconsistency among the results obtained.

- Make sure the engine in good working condition after the installation of the thermostat housing.
- Run the engine until it warms up so that the temperature of the engine reaches the atmospheric temperature 40°C.
- Make sure the thermocouple connections are appropriate and the readings are consistent.
- Make sure the engine is operated within the range of 1000 RPM to 4000 RPM throughout the test conditions.

The engine is tested for the temperature conditions when operated under various speed and various time durations. Initially, the engine was made to run with gasoline at constant 1000 RPM. Engine throttle was maintained in steady-state to obtain the prefixed RPM. The temperature data logger was programmed to trace the temperature data for every 5 min, 10 min, 15 min, 20 min and 25 min so as to draw the temperature characteristic curve with Temperature on Y-axis and various engine speeds in X-axis. Similar experiments were repeated for three times to take the average of data under each time-step. Similar experiments were repeated for 2000, 3000 and 4000 RPM using gasoline and CNG as fuels. Temperature data were tabulated and then plotted with curves to study the temperature behaviour of the engine. The sequential steps involved in the experiments conducted under the present study is illustrated in a flowchart as shown in Figure 3.

By using CNG as an alternative fuel, the engine will run as smooth as that of gasoline fuel. However, the operating temperature of the engine will rise to a higher level due to the higher heating value of CNG. In such circumstances, it may require highly efficient cooling to keep the engine under operating condition. In the present work, ethylene glycol-based synthetic coolant is mixed with the radiator water in two proportions to form synthetic coolant 1 and 2. The proportion of Synthetic Coolant 1 is 90% of water with 10% of ethylene glycol and Synthetic Coolant 2 is with 80% water and 20% ethylene glycol. While replacing the synthetic coolants, engine cooling system was drained completely to remove the existing coolant followed by filling the new coolant, so that traces of the previous coolant should not affect the cooling performance of the testing coolant.

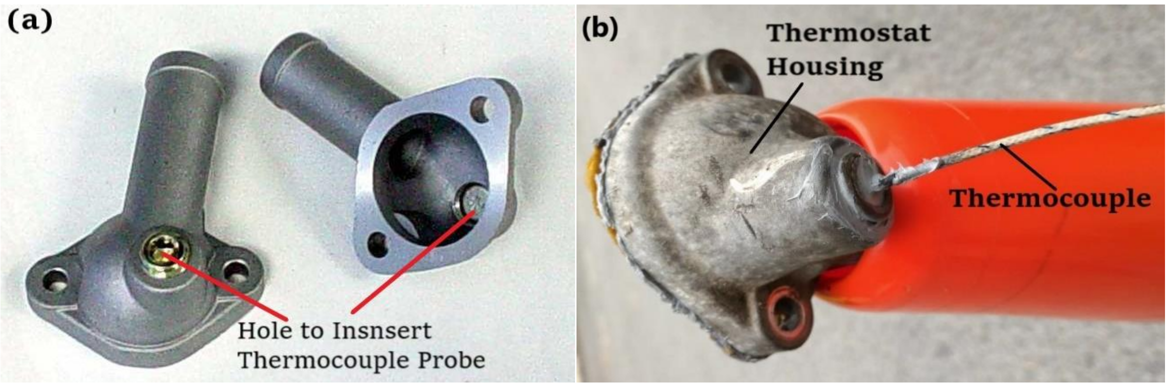

Figure 1. Thermo housing fixed with (a) before fixing (b) after fixing thermocouple for data logging

Figure 2. Thermostat housing with thermocouple fixed to the engine.

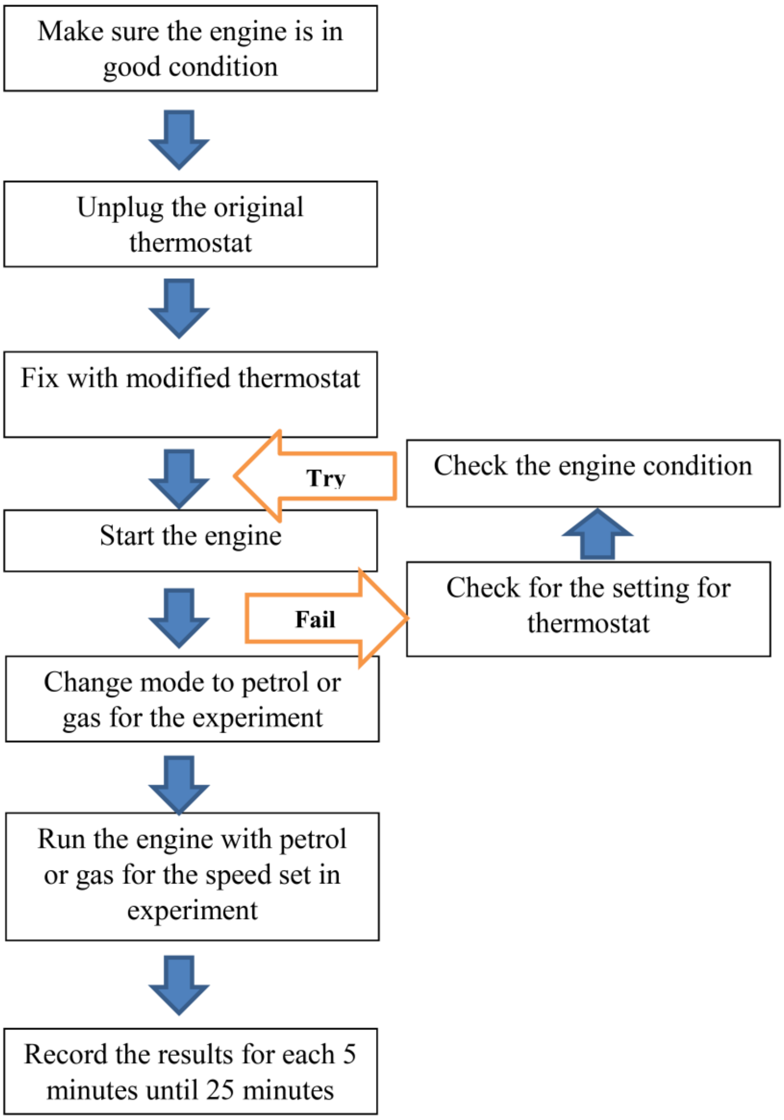

Figure 3. Flowchart for Experimental Conduction under the Current Study

4. Results and discussion

As illustrated in Figure 4, the graph plotted for 1000 RPM for Gasoline and CNG with water cooling. For the first 15 minutes of engine run, the temperatures for gasoline is slightly higher than CNG. Thereafter, the temperatures for CNG started to increase more than gasoline temperature. The final difference between gasoline and CNG for the last readings is 1.03°C which has no significant effect on the engine components. The temperature curve for gasoline and CNG are not in parallel which implies, the temperature rise is a function of time when the engine is running under higher calorific fuels. As time increases, the temperature keep increases rapidly.

Table 2. Time Versus Temperature Data for Gasoline and CNG Engines @ 1000 RPM with Water Cooling

Engine Run Time (min)	Coolant Temperature (℃)	
	Gasoline Engine with Water Cooling	CNG Engine with Water Cooling
5	87.27	87.03
10	87.80	87.30
15	87.57	87.27
20	87.20	88.03
25	88.17	89.20

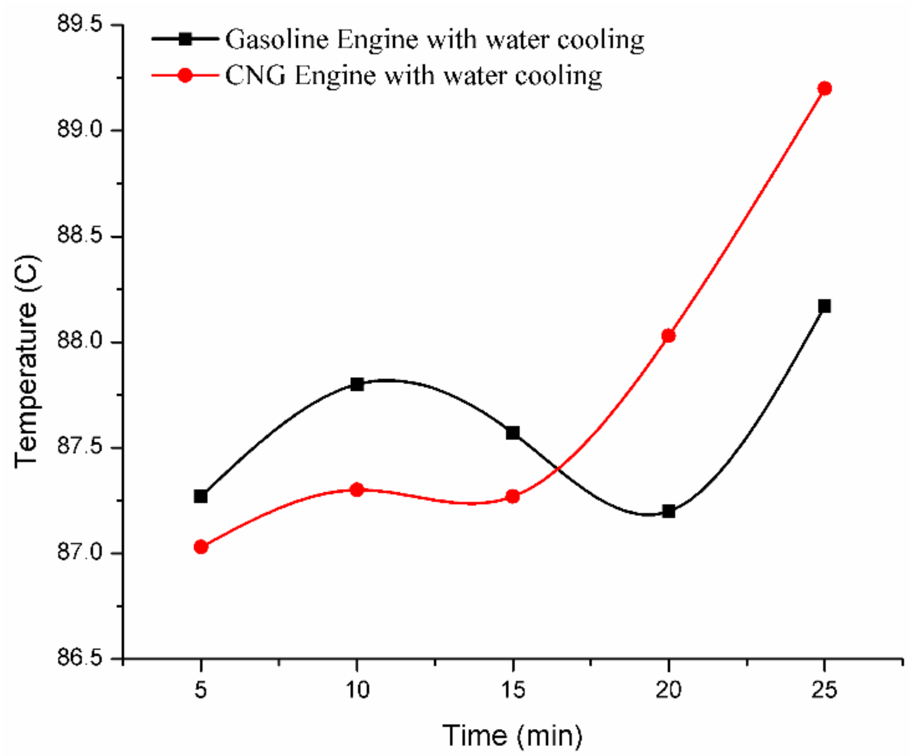

Figure 4. Time Versus Temperature Graph for Gasoline and CNG Engines @ 1000 RPM with Water Cooling.

For engine operating at 2000 RPM which is illustrated in Figure 5, the curve is similar to that of 1000 RPM. In both the curves, there is a sudden sink in the curve after the temperature reaches to 88℃ and above. This effect is due to the thermostat operation causing fresh coolant to enter the system pushing the hot coolant to the radiator for heat exchange. It can also be noticed that the temperatures in the case of CNG are higher than gasoline.

Table 3. Time Versus Temperature Data for Gasoline and CNG Engines @ 2000 RPM with Water Cooling

Engine Run Time (min)	**Coolant Temperature (°C)**	
	Gasoline Engine with Water Cooling	**CNG Engine with Water Cooling**
5	88.47	88.70
10	87.63	87.73
15	87.27	88.53
20	87.27	88.97
25	88.70	89.20

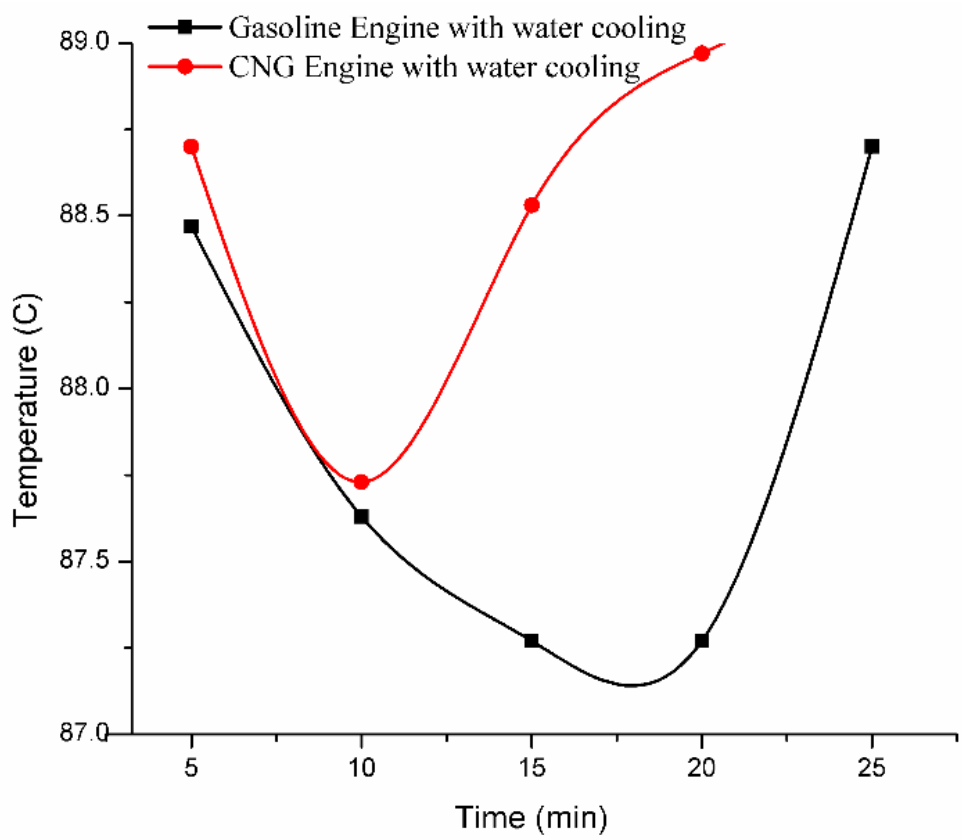

Figure 5. Time Versus Temperature Graph for Gasoline and CNG Engines @ 2000 RPM with Water Cooling.

When the engine was running at 3000 RPM, temperature versus time curves for gasoline and CNG are with the same pattern, where CNG is slightly higher for the entire duration of the test as illustrated in Figure 6. At this speed, the compression ratio in the engine cylinder increased due to an increase in fuel and air intake. Thermostat at this stage remained open without closing to let the water continuous circulate through the radiator for heat exchange. The difference in the temperature between gasoline and CNG for the entire duration of the test is approximately 3°C.

Table 4. Time versus Temperature Data for Gasoline and CNG Engines @ 3000 RPM with Water Cooling

Engine Run Time (min)	**Coolant Temperature (℃)**	
	Gasoline Engine with Water Cooling	**CNG Engine with Water Cooling**
5	85.77	88.63
10	87.27	90.83
15	88.20	92.03
20	90.43	93.43
25	91.90	94.63

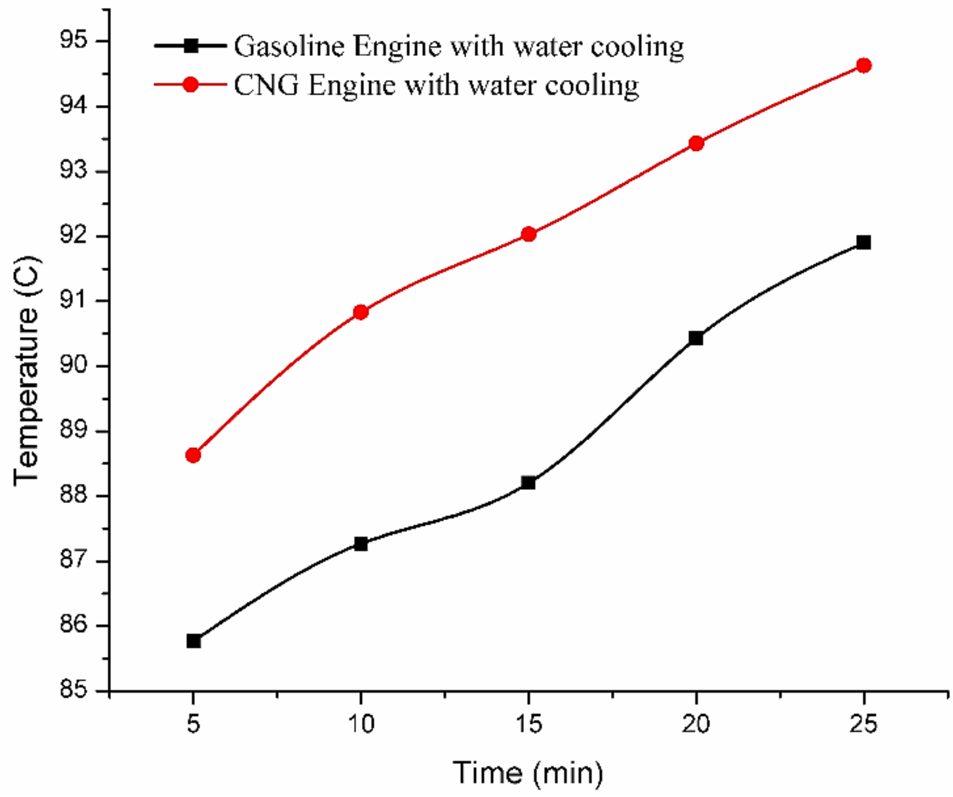

Figure 6. Time versus Temperature Graph for Gasoline and CNG Engines @ 3000 RPM with Water Cooling.

For engine operating at 4000 RPM, the temperature was higher than that of 3000 RPM. The operation of the thermostat similar to that of 3000 RPM, which has remained open and let the coolant circulate through the radiator. As the amount of work done by the engine running at 4000 RPM is more than 3000 RPM, the heat generation also more causing a significant rise in temperature. Figure 7 illustrates that from the difference in the temperature between gasoline and CNG is approximately 7°C.

Table 5. Time versus Temperature Data for Gasoline and CNG Engines @ 4000 RPM with Water Cooling

Engine Run Time (min)	Coolant Temperature (℃)	
	Gasoline Engine with Water Cooling	CNG Engine with Water Cooling
5	91.40	93.37
10	92.67	95.80
15	93.97	97.93
20	95.23	101.00
25	97.83	105.07

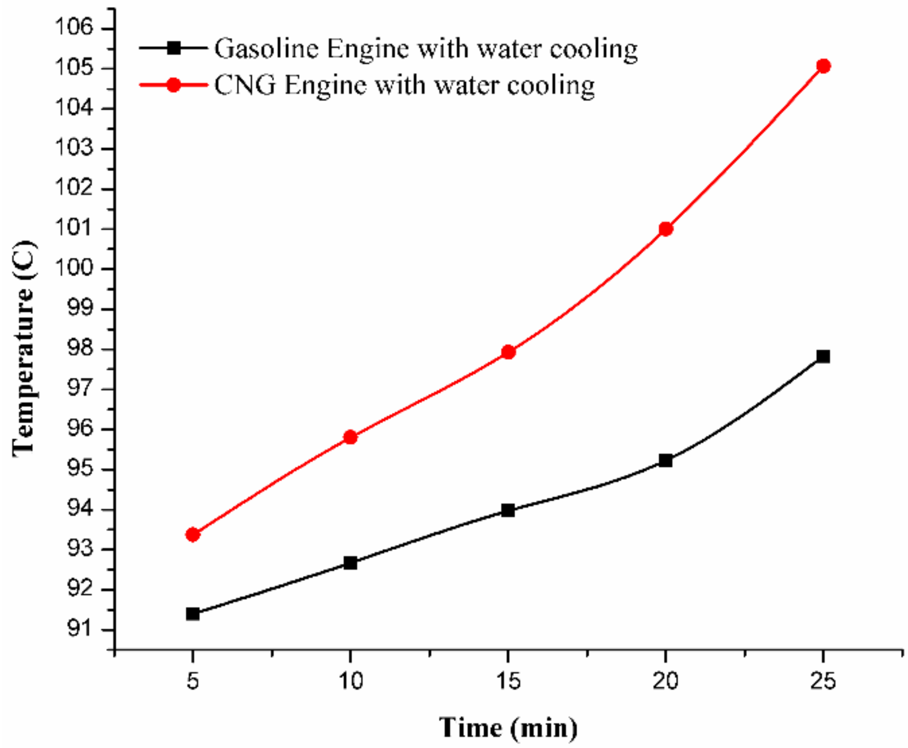

Figure 7. Time versus Temperature Data for Gasoline and CNG Engines @ 4000 RPM with Water Cooling

To analyze the effect of engine operating speed on the temperature, an average of temperature over the period of 25 min running at the same RPM as recorded in Table 6 for both Gasoline and CNG. Temperature versus RPM curves is plotted to understand the effect of operating speed over engine temperature for both gasoline and CNG. It is clear from the comparative graph that, as the engine speed increases, the temperature of the engine working with CNG raises rapidly in comparison with gasoline. Under gasoline operated engine, the temperature remains almost constant until the engine reaches 2500 RPM, above which temperature starts to rise rapidly. This is referred to most of the gasoline engines operates with high efficiency between 2500 to 3000 RPM, which is not same in case of CNG operated engines. Thus, for CNG operated engines, the cooling system needs special attention and alteration to improve the cooling effect.

Table 6. Engine RPM versus Temperature Data for Gasoline and CNG Engines with Water Cooling

Engine Speed (RPM)	Coolant Temperature (°C)	
	Gasoline Engine with Water Cooling	CNG Engine with Water Cooling
1000	87.60	87.77
2000	87.87	88.63
3000	88.71	91.91
4000	94.22	98.63

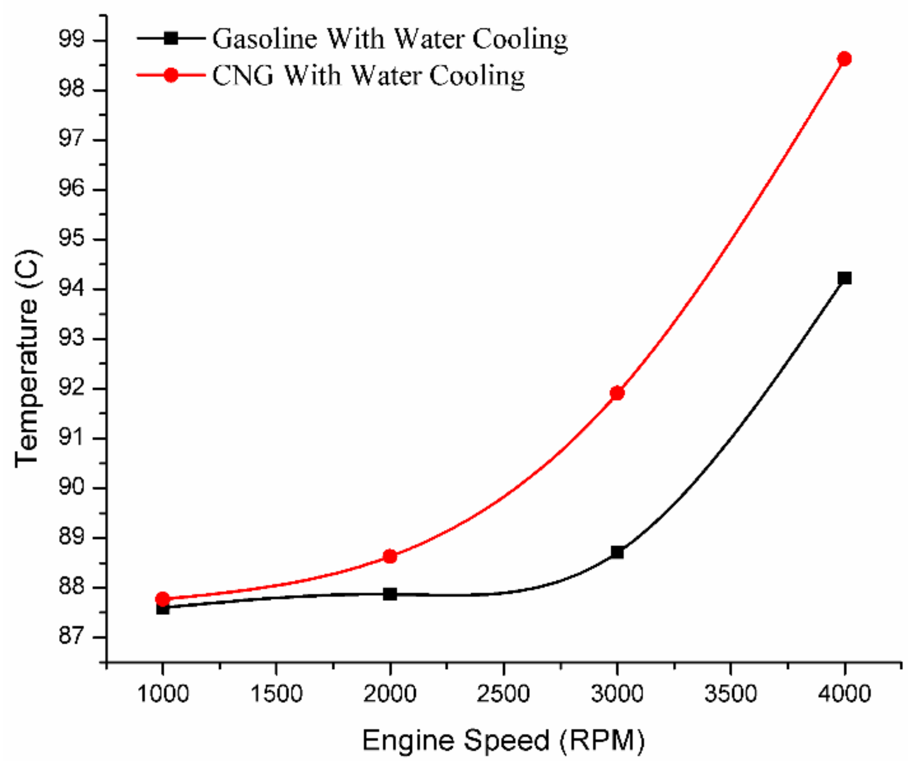

Figure 8. Engine RPM versus Temperature Curve for Gasoline and CNG Engines with Water Cooling

From the preliminary experiments, it is understood that the temperature profile is almost the same for gasoline and CNG for engine speed up to 2000 RPM. Thus for comparison of synthetic coolant, only higher RPMs are chosen. Temperature data for CNG operated engine running with Synthetic Coolant 1 and Synthetic Coolant 2 are operated for 3000 RPM and 4000 RPM, corresponding data were logged and then tabulated with average for three trials.

Figure 9 and 10 illustrate the characteristics of CNG based engine running at 3000 and 4000 RPM respectively with Synthetic Coolant 1 and Synthetic Coolant 2 as coolants. The results obtained were compared with CNG and gasoline-based engines with water as a coolant. The time versus temperature curves shows that the Synthetic Coolant 1 and Synthetic Coolant 2 both are significantly controlling the engine temperature when the engine is operated at a higher RPMs. However, the comparison among the Synthetic Coolant 1 and Synthetic Coolant 2 has shown that the curves under Synthetic Coolant 2 were more smother and stable than the Synthetic Coolant 1.

Table 7. Time versus Temperature Data for Gasoline and CNG Engines @ 3000 RPM with Synthetic Cooling and Water Cooling

Engine Run Time (min)	Coolant Temperature (℃)			
	CNG With Water Cooling	CNG With Synthetic Coolant 1	CNG With Synthetic Coolant 2	Gasoline With Water Cooling
5	88.63	88.30	88.60	85.77
10	90.83	88.27	89.13	87.27
15	92.03	90.17	89.70	88.20
20	93.43	91.77	90.20	90.43
25	94.63	92.23	92.10	91.90

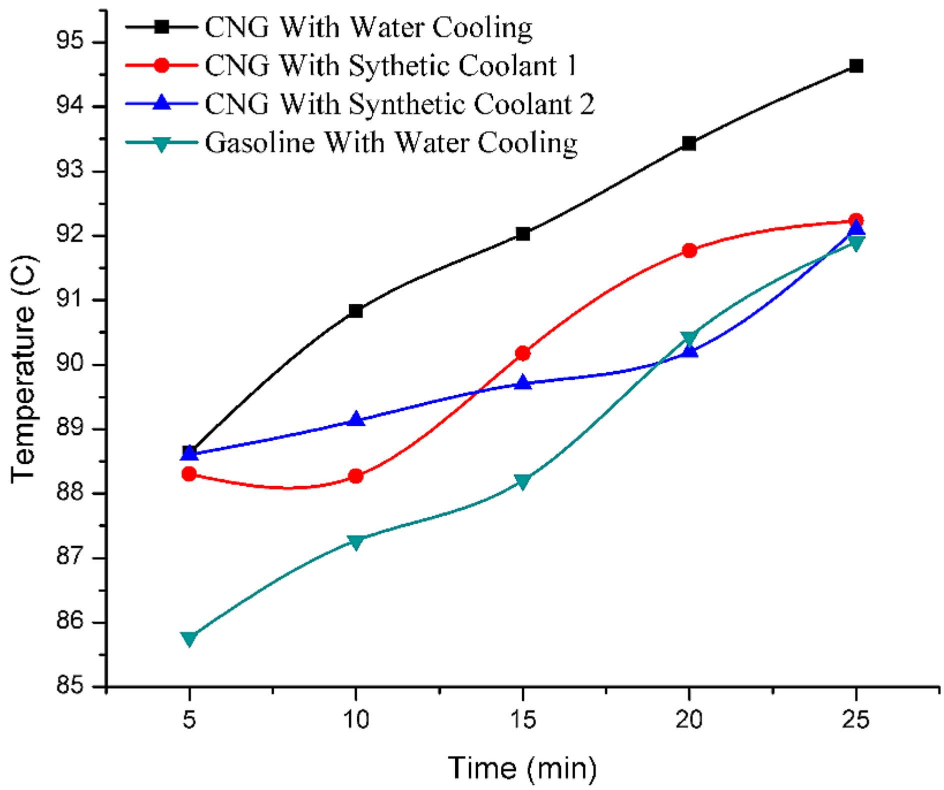

Figure 9. Time versus Temperature Graph for Gasoline and CNG Engines running @ 3000 RPM with Water and Synthetic Liquid Cooling.

Table 8. Time versus Temperature Data for Gasoline and CNG Engines @ 4000 RPM with Synthetic Cooling and Water Cooling

Engine Run Time (min)	Coolant Temperature (℃)			
	CNG With Water Cooling	CNG With Synthetic Coolant 1	CNG With Synthetic Coolant 2	Gasoline With Water Cooling
5	93.37	91.97	92.47	91.40
10	95.80	93.83	93.63	92.67
15	97.93	95.97	95.63	93.67
20	101.00	96.53	97.43	95.23
25	105.07	98.13	99.73	97.83

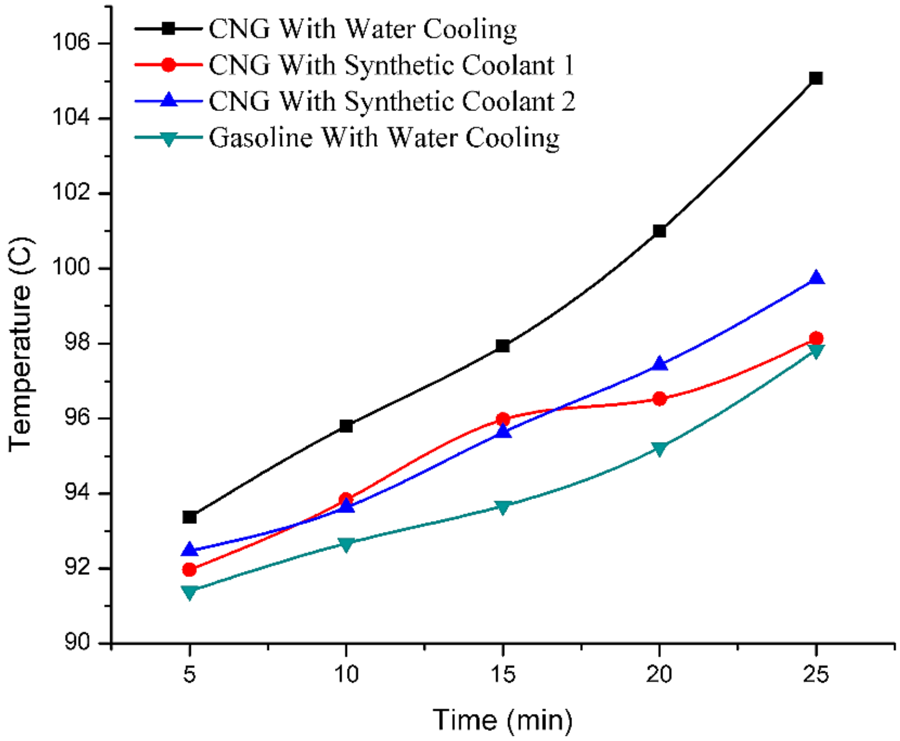

Figure 10. Time versus Temperature Graph for Gasoline and CNG Engines running @ 4000 RPM with Water and Synthetic Liquid Cooling.

5. Conclusion

Compressed Natural Gas as an alternative fuel for the gasoline-based engines is getting more popularity among the car users as well as car manufacturers due to many reasons. CNG is economically cheaper and abundantly available, in addition to this CNG comes with good properties like, higher octane numbers (anti-knock ability) which can assist in running engine with higher compression ratios, better exhaust emissions due to higher hydrogen molecules than the carbon. Being gas, CNG can readily mix with air in the combustion chamber to get complete combustion.

Due to the higher heating value and higher density, combustion of CNG produces a comparatively large amount of heat than the gasoline combustion. Thus, operating CNG as an alternative fuel for gasoline engines causes engine overheating problems. This could affect the engine components, shortens the lifespan of the engine components and also cause pre-ignition in the combustion chamber. Engine cooling system is most essential for both industrial and automotive engines to reduce fuel consumption, minimizing exhaust and fuel emission, to reduce the thermal load on the engine to protect the engine components. Thus, synthetic coolants were used in the present work to study their influence on controlling the temperature. From the results and discussion, it is obvious that synthetic coolants help to bring down the temperature compare to pure water cooling. However, the 20% blend of ethylene glycol with water has slightly better and smoother temperature curves when the engine is operated at higher RPMs for longer durations. Thereby, it is suggested to use synthetic coolants for dual-fuel engines as it can help to control the temperature and can prevent the engine overheating.

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