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RESEARCH ARTICLE

A Study on the Effects of Coolant Strategy on the Instantaneous Energy Balance During the Warm-up Period in a Spark Ignition Engine

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HIGHLIGHTS

- > Engine warm-up time and brake specific fuel consumption improved at different levels under different thermal energy management strategies with integrated mechanical and electrical pumps.
- > Instantaneous energy balance variations during the warm up period were analyzed on the engine test bed.
- > The total energy losses were observed to have reduced with the engine coolant flow rate control strategy.

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ABSTRACT

It is very important to examine the instantaneous effects of energy losses on each other in order to ensure high efficiency during the warm-up period in internal combustion engines. In this regard, the effects of energy losses can be examined and some improvements can be achieved with different thermal energy management strategies involving various electromechanical components. Two different thermal energy management strategies were implemented in this study under different operating conditions of the engine. These strategies comprise of applications with mechanical and electrical water pump integrated cooling system components. In the configuration with mechanical pump, the coolant is circulated in the engine block in proportion to the engine speed. Under the same operating conditions, the coolant flow rate was reduced to 50%, in the configuration with the electric water pump. The warm-up time of the engine, instantaneous change in the coolant flow rate and temperature during the warm-up period of the engine, instantaneous input fuel energy balance and specific fuel consumption were investigated under all operating conditions. As a result, thanks to the electric pump strategy, the engine efficiency was observed to have improved and the total unaccounted energy loss to have reduced. Furthermore, engine warm-up time improved by 2.6% to 8.3% and the specific fuel consumption by 17.9% to 2.1%, respectively, under low and high load conditions. Thus, the coolant control strategy has been shown to have a significant effect on engine efficiency.

Contents

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1. Introduction

Internal combustion engines have an important place in the effort to manage the basic energy sources, which have a serious importance across the world. In this context, many studies are carried out on internal combustion engines in the historical development process. Some of these researches focus on thermal energy management strategies implemented to improve energy efficiency and fuel saving as well as to reduce pollutant emissions in internal combustion engines.

Thermal energy management is based on the principle of adjusting the temperature of engine block in order for the engine to reach the stable operating conditions as soon as possible and to maintain its operation under these conditions. Thanks to a proper thermal management of the engine, both the protection of engine parts and the improvement of engine performance can be achieved. With an optimal cooling system, many benefits can be obtained, for instance, friction losses can be reduced, fuel saving can be attained, engine thermal efficiency can be increased, pollutant emissions can be improved or interior comfort can be increased [1]. Some of the researches in the literature addressing the engine reach stable operating conditions as soon as possible involves management of engine coolant temperature and mechanical components. In this regards, automotive manufacturers prefer controllable water pumps instead of mechanical pumps in engine cooling systems [2]. In addition, studies have been carried out to mitigate the problems caused by mechanical pumps by using electronically controlled electric pumps and controller components in classical cooling systems [3, 4]. The main cooling system component that determines the warm-up time of the engine is the thermostat, which is a mechanical temperature sensor. The thermostat acts as a valve, either enabling the engine to warm up as soon as possible by short-circuiting the cycle or preventing overheating by directing the coolant to the radiator. It thus ensures that the engine maintain a stable operating temperature range [5]. So much so that, it was stated in a study to comprehend the effects of the thermostat, that the coolant temperature, engine block temperature and coolant flow rate could be improved by using a controllable variable position electromagnetic thermostat [6]. The variable position thermostat and electric pump were engaged and operated in a coordinated manner in order to control the coolant flow rate under stable operating conditions [7, 8]. The effects of the temperature of metal, oil and coolant on friction and thereby fuel economy have been shown by means of coolant control under different operating conditions in engines [9].

In the literature, the use of an electric pump as a component in the engine cooling system can ensure optimization of coolant independently of the engine speed [10]. It is an important strategy to improve thermal efficiency, especially in cold start conditions during which 2.6% can be saved on fuel consumption [11]. However, the flow rate limits must be well optimized for the control of the coolant. Because boiling may occur in the cooling circuit and may cause damage to the engine head and block. In this case, the temperature of the coolant circulating in the engine block should be set to be in a range close to the nucleate boiling point and the temperature values in this range have to be monitored with PID controllers. Thus, the engine warm-up time can be improved by providing optimum heat transfer thanks to the determined flow rate limits [12]. In addition to numerical studies where the flow rate of the coolant is changed in order to increase the efficiency of the engine, three-dimensional CFD simulations making use of simplified lumped models and stand-alone models have been used to increase engine efficiency [13].

The studies mentioned above are aimed at improving performance and warm-up time as well as reducing mechanical friction in internal combustion engines. As a result, it is obvious that various improvements can be achieved by using in the cooling circuit the electric water pumps and adjustable thermostatic valves. Nevertheless, it is important a parameter to analyze the fuel energy entering the control volume of the engine. At this point, energy losses or gains determined by energy analysis become prominent. Energy balance analysis is therefore necessary in order to understand more clearly what kind of effects the use of such components induce on the engine characteristics. The importance of this analysis has been shown in a study [14] in the literature, carried out at different engine loads and speeds, with the finding that the thermal efficiency of the engine can be improved up to 38% by performing energy analyzes. It has also been shown that significant savings on fuel consumption could be achieved by due thermal management of the engine, especially in part load conditions. On that account, the theoretical minimum fuel consumption of an automobile was tried to be calculated with a new method. The simulation results supported the approach that the time it takes the engine to reach stable operating conditions and the thermal management of the engine provide significant benefits in terms of fuel saving [15].

In addition to examining the effects of different thermal energy management strategies with energy and exergy balance analyzes, the effects of using various alternative fuels and mixtures thereof in engines were also investigated [16–19]. How much of the fuel energy is expelled from the engine by exhaust gases and coolant during the driving cycles other than stable operating conditions of the engine, such as NEDC, throughout the warm-up period of the engine was tried to be revealed. The analyzes were generally made using the average values from different driving cycles and revealed that the thermal loss accounted for more than 30% of the total fuel energy. Exhaust gas and coolant energy ratios were calculated to be 3.75kW and 4.31 kW, respectively, by putting in the average values of the driving cycle [20].

Considering the studies presented in the literature, it is easily understood that different thermal energy management strategies are applied on engines. In this study, energy balance analyzes were carried out on a gasoline spark-ignition engine based on real-time experimental data acquired during the warm-up period, from the first start of the engine. The effects of mechanical and electrical water pump configurations on coolant flow control strategies under constant engine speed and under different braking loads were investigated. The effects of the engine's energy efficiency, specific fuel consumption and different fractions of input fuel energy on one another were analyzed during the entire warm-up period. Analyzes were based on real-time experimental data acquired during the engine warm-up period, rather than average driving cycle data.

This study is thought to be of particular importance in that it is capable of making significant contributions to several future thermal energy management strategies.

2. Material and Method

2.1. Experimental Section

The experiments have been conducted with a gasoline SI engine on a hydraulic dynamometer bench. The engine test setup basically consisted of electronic modules used for measuring and recording real-time data, a Labview program prepared for data measurement, an electronic control unit, an exhaust gas calorimeter, and an electric water pump. The technical specifications of the engine are given in Table 1 and a schematic view of the experimental setup is illustrated in Figure 1.

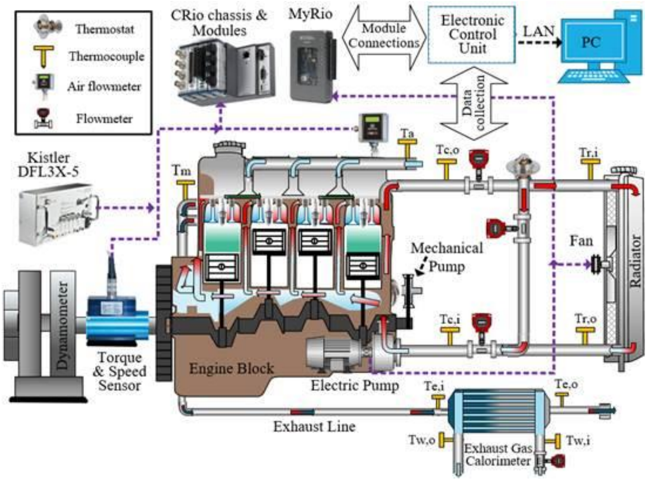

Figure 1 A schematic view of the experimental setup.

Table 1 The technical specifications of test engine.

Specification	Value
Engine model	Ford MVH418,
Engine type	Spark ignition, fuel injected
Stroke number	4 stroke
Engine cooling system	Water cooled engine
Cylinder type-number	In line – 4 (DOHC-16V)
Firing order	1-3-4-2
Stroke/ Diameter	88 mm / 80.6 mm
Total displacement	1796 cm 3
Compression ratio	10:1
Maximum power	93 kW @ 6250 rpm
Maximum torque	157 Nm @ 4500 rpm
Idle speed	900 ± 50 rpm
Fuel	Gasoline
Fuel injection system	BOSCH KE-Jetronik
Dynamometer load type	Mechanical load

The coolant circuit in the experimental setup was as illustrated in Figure 1.

2.2. Measurement Procedure

The temperatures of the engine and all other components before the start of the experiments was at the dead state temperature (298K). All experimental temperatures were measured instantaneously, throughout the experiments, with the K-type thermocouples with 0.5 ˚C accuracy located as shown in Figure 1. In the experiments, Kistler 4503A model torque sensor (±0.1 Nm accuracy) was used to calculate the power obtained from the engine crankshaft, and a hydraulic dynamometer was used to provide real operating conditions under different braking loads with ±1 rpm accuracy. NI-AD combo analog input module attached on a NI-9075 Compact RIO chassis were used to obtain some measurement parameters (temperature, coolant flow, fuel-air flow rate, camshaft and crank information, etc.). Turbine type FS300A flowmeters with 3% accuracy were used to measure the coolant flow rate in the experimental system, Sierra-628S model flow sensor (1% accuracy) to measure the engine intake air flow rate, and Kistler DFL3X-5bar fuel flow meter (0.5% accuracy) to measure the fuel consumption. In order to implement the controlled flow strategy, an electric water pump and a wax-type thermostat that starts to open at approximately 83 ˚C were used instead of the mechanical pump.

3. Experimental Configurations

Two different engine operating points were determined with a constant engine speed of 1750 rpm and under two different brake torque conditions. The experimental procedure is based on the analysis of instantaneous energy balance and engine performance characteristics during the warm-up period of the engine. In the experimental configuration, a thermal management strategy was designed based on the utilization of two different components, a mechanical pump and an electric water pump, integrated with the engine cooling system. Each strategy was carried out under constant engine speed (1750 rpm) and different brake loads (18Nm and 27 Nm). The details of the configurations are given in Table 2.

Table 2 Details of the thermal management strategies.

Test Number	Engine Speed (rpm)	Brake Torque (Nm)	Coolant Flow Rate (L/min)	Experimental Strategy
1	1750	18	11.5	Mechanical pump
2			5.75	Electric pump
3		27	11.5	Mechanical pump
4			5.75	Electric pump

In the experimental study, the engine warm-up time through instantaneously controlling the coolant temperature and flow rate, specific fuel consumption, energy balance analyses were examined during the engine warm-up period. The period during which the coolant is circulated through the bypass line of the cooling circuit, as seen in Figure 1, until the thermostat opens is called the warm-up period. The whole strategy is based on examining the events that occur in this cooling circuit. After the thermostat opens, the coolant is circulated through the radiator line during the entire operating time of the engine. Here, the flow rate of the coolant circulated with the mechanical pump was measured to be 11.5 L/min. Then, with the activation of the electric pump, this flow rate was reduced by 50% to 5.75 L/min and thus was it circulated through the cooling circuit. By means of this strategy, the effects of coolant flow rate on energy efficiency and on instantaneous energy balance could be experimentally investigated during the engine warm-up period. All relevant experiments were commenced when the temperature of the engine block, coolants (lubricating oil and coolant), and calorimeter was equal to the ambient temperature of 18-20 ˚C. The variable effects caused by the strategies applied in the experiments during the entire warm-up period of the engine were observed and a general evaluation of the information obtained was made in the "Results and Discussion" section. The explanations of the mathematical equations used in the thermodynamic energy balance analyzes are given under section 4 in detail.

4. Theoretical Considerations

Instantaneous energy analysis in an internal combustion engine can be performed mainly using the law of conservation of energy. Therefore, the first law analysis in an internal combustion engine can be expressed as:

$$\dot{Q}_f + \dot{Q}_a = P_b + \dot{Q}_c + \dot{Q}_e + \dot{Q}_u \tag{1}$$

where, $\dot{Q}_f$ is the energy of fuel (kW), $\dot{Q}_a$ the energy of air (kW), P_b the brake power (kW), $\dot{Q}_c$ the energy loss rate due to engine coolant, $\dot{Q}_e$ the heat loss rate by exhaust gases (kW), and $\dot{Q}_u$ the unaccounted energy loss rate (kW).

The energy of the fuel $\dot{Q}_f$, the energy of air $\dot{Q}_a$, and the brake power of engine P_b are calculated using Eqs. (2), (3), and (4), respectively.

$$\dot{Q}_f = \dot{m}_f \cdot LHV \tag{2}$$

$$\dot{Q}_a = \dot{m}_a \cdot \Delta h_a \tag{3}$$

$$P_b = \frac{N \cdot T_b}{9549.3} \tag{4}$$

where, $\dot{m}_f$ is the fuel consumption by the engine (kg/s), LHV the lower heating value of the fuel (44 MJ/kg), $\dot{m}_a$ the input air flow rate (kg/s), Δh_a the enthalpy difference of input air (kJ/kg), N the engine speed (1/s), and T_b the brake torque (Nm).

In this study, a calorimeter was used in the experimental setup to calculate the energy loss by the exhaust gases ($\dot{Q}_e$). The total thermal energy of the exhaust gases consists of three main components on the exhaust line, namely, the heat energy lost between the exhaust manifold and the exhaust gas calorimeter, the heat drawn by circulating water in the exhaust gas calorimeter, and the heat of the gases released from the exhaust gas calorimeter to the atmosphere.

The heat loss rate by exhaust gases ($\dot{Q}_e$) is determined by:

$$\dot{Q}_e = \dot{m}_e \cdot C_e \cdot (T_m - T_{e,i}) + \dot{m}_e \cdot C_e \cdot (T_{e,i} - T_{e,o}) + \dot{m}_e \cdot C_e \cdot (T_{e,o} - T_a) \tag{5}$$

In the cross-flow exhaust gas calorimeter, exhaust gases pass through the inner pipe whereas in the outer pipe circulates the water at a certain flow rate whereby the thermal energy of the exhaust gases is transferred to the water. The heat balance between the exhaust gases and the water within the exhaust gas calorimeter can be obtained as:

$$\dot{m}_e \cdot C_e \cdot (T_{e,i} - T_{e,o}) = \dot{m}_w \cdot C_w \cdot (T_{w,o} - T_{w,i}) \tag{6}$$

When Eq. (6) is plugged in Eq. (5), thus $\dot{Q}_e$ can be calculated as:

$$\dot{Q}_e = \frac{\dot{m}_w \cdot C_w \cdot (T_{w,o} - T_{w,i})}{(T_{e,i} - T_{e,o})} \cdot (T_m - T_a) \tag{7}$$

where, $\dot{m}_e$ is the mass flow rate of exhaust gases (kg/s), $\dot{m}_w$ the mass flow rate of cooling water in the calorimeter (kg/s), C_w and C_e the specific heats of cooling water exhaust gases in the exhaust calorimeter (kJ/kgK), T_m and T_a the temperatures of exhaust manifold and the ambient, and as seen in Figure 1, $T_{e,i}$, $T_{e,o}$, $T_{w,i}$, and $T_{w,o}$ are, respectively, the temperatures of the exhaust gases and cooling water at the inlet and outlet of the calorimeter (K).

The heat loss rate through the engine coolant, $\dot{Q}_C$, is determined by:

$$\dot{Q}_C = \dot{m}_c \cdot C_c \cdot (T_{c,o} - T_{c,i}) \tag{8}$$

where, $\dot{m}_c$ is the coolant flow rate (a mixture of pure water and antifreeze) (kg/s), C_c is the specific heat of coolant (kJ/kgK), $T_{c,i}$ and $T_{c,o}$ are the temperatures of the coolant at the engine inlet and outlet (K), respectively.

The unaccounted losses included in the energy balance equation are the heat of the unburned exhaust gas components, friction losses, and thermal losses through the engine block. The unaccounted losses are calculated by:

$$\dot{Q}_u = \dot{Q}_f - (P_b + \dot{Q}_c + \dot{Q}_e) \tag{9}$$

As of the very first start of the engine, the temperature of all components and the coolants increases over time until they reach the balanced operating conditions. The changes were instantaneously monitored and recorded with real-time data acquisition devices. Thus, the first law of thermodynamics used in steady-state operating conditions becomes applicable for the warm-up period as well. During the warm-up period, the temperature of the engine coolant increases rapidly. Therefore, a new approach should be developed in order to calculate instantaneous heat loss by the engine coolant more accurately.

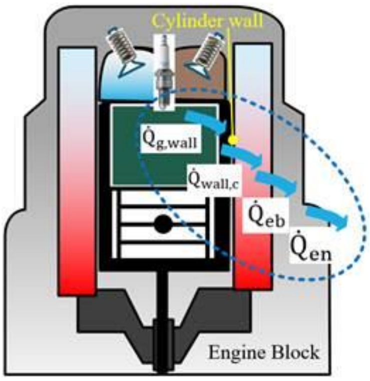

Figure 2 Heat transfer balance of the coolant circuit.

The control volume, determined in the engine cooling circuit for instantaneous energy balance, is shown in Figure 2. The energy balance for the open system can be expressed as:

$$\dot{Q}_{wall,c} + \dot{m}_c \cdot C_c \cdot (T_{c,i} - T_{c,o}) - \dot{Q}_{eb} = m_c \cdot C_c \cdot \frac{dT_{c,o}}{dt} \tag{10}$$

where, $\dot{Q}_{eb}$ is the heat loss rate from the coolant to the engine block (kW), m_c the total mass of engine coolant in the cooling circuit (kg), $\dot{Q}_{g,wall}$ the heat transfer rate from gas to wall (kW), $\dot{Q}_{wall,c}$ the heat transfer rate from wall to coolant (kW) and $\dot{Q}_{en}$ the heat loss rate from the engine block to environment (kW).

5. Results and Discussion

In internal combustion engines, the engine to reach stable operating conditions as soon as possible is of great importance in terms of fuel saving, engine performance characteristics as well as low emission values. In this regards, the rate of energy drawn by the coolant, which is an important topic of energy distribution in engines, becomes prominent. Therefore, it is essential to examine the temperature and flow rate of the engine coolant. Here, the engine inlet and outlet temperatures of the coolant, the radiator inlet and outlet temperatures, and the changes in the flow rate are monitored instantaneously with real-time measurements. The effects of temperature, coolant flow rate and instantaneous energy distribution on one another were calculated for all experiments. The instantaneous coolant temperature and energy distribution change values for Test 1, the details of which are given in Table 2, are presented graphically in Figure 3 and Figure 4 and results for all experiments are given in comparison in Figure 5, Figure 6, and Figure 7.

Examining Figure 3, the engine inlet and outlet temperatures can be seen to have increased rapidly after the engine was started. This increase continued until the activation temperature of the thermostat, which indicates that the engine has reached stable operating temperature. As can be seen from Figure 3, this warm-up period lasted for 303s for Test 1 and afterwards with the thermostat opened and redirected the coolant to the radiator line, the radiator inlet and outlet temperatures began to rise gradually.

The coolant in the radiator and hoses at low temperatures mixes with the hot coolant returning from the engine block, leading a decrease in the outlet temperature, which causes the thermostat close again to allow the temperature of the coolant increase to its optimum value again. As a result of thermostat repeating this action for a few times, the temperature of the entire coolant in the bypass and radiator line equalize, whereby the thermostat is forced to stay open all the time. The instantaneous change of this fluctuations caused by the thermostat is seen in detail in Figure 3. With the thermostat opened, on the other hand, the flow rate of the coolant directed to the radiator line, where a lower pressure was present, can be seen to have increased, as expected.

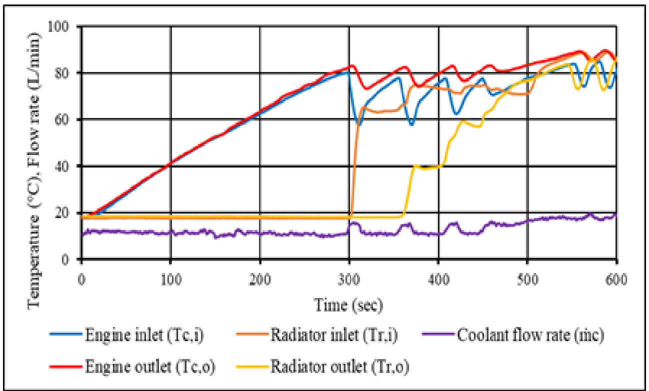

Figure 3 Variation in the flow rate and temperature of engine coolant (Test 1).

Given in Figure 4 are the instantaneous effects of four different energy distributions, on one another, resulted from the energy of the combusted fuel entering the engine under conditions of Test 1. It is clearly seen from Figure 4 that the rate of energy lost with coolant and exhaust gases increases with the operation of the engine. At the very first moment, the portion of the fuel energy that turns into net power (P_b) increases gradually with the engine warming up. At this moment, the amount of unaccounted energy $(\dot{Q}_u)$, which is the sum of the heat transferred from the engine block, friction loss and unburned fuel energy, begins to decrease with time. With the gradual improvement of combustion during the warm-up period of the engine as well as the engine block warming up, both the losses due to the energy of the exhaust gases $(\dot{Q}_e)$ and the rate of heat drawn by the coolant $(\dot{Q}_c)$ can be observed to have increased. It is clearly seen that the energy consumed is gradually increasing. As can be seen in Figure 3, the difference between the engine inlet and outlet temperatures increases with the opening and closing of the thermostat after 303s with mechanical pump integration at low load conditions. As can be seen from Figure 4, this led to an increase in the energy lost to the coolant. The energy stored in the coolant at the end of the warm-up period corresponds to approximately 30% of the fuel energy. The significant reduction of the unaccounted energy rate $(\dot{Q}_u)$ at low and high loads with the electric pump integrated coolant control strategy shows that any thermal strategy proposed to shorten the warm-up period will provide significant advantages.

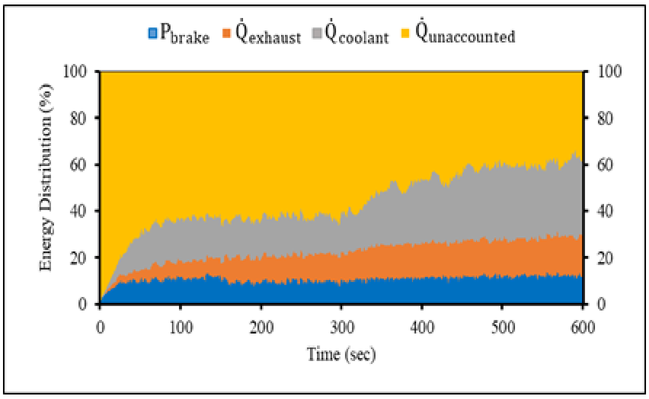

Figure 4 The instantaneous energy balance variation of input fuel energy (Test 1).

The moment when the thermostat first opened and the coolant temperature began to decrease was taken as reference for determining the engine warm-up time, and accordingly the engine warm-up times for all experiments are shown in Figure 5. In Figure 5, the effects of different cooling strategies, obtained by using mechanical pump and electric pump, on engine warm-up times are presented. In the case of using the mechanical pump, which is a classical cooling system component, the engine warm-up time was 303s and 288s at low load and high load, respectively. The engine warm-up period is prolonged as the selected engine speed, 1750rpm, was low and operated under low load. It has been observed that the engine warm-up time shortened when 50% of the flow provided by the mechanical pump was circulated in the engine by using an electric pump instead. In this way, the engine warm-up times were measured as 295s and 264s under low and high brake loads, respectively. Controlling the coolant flow rate with an electric pump, rather than circulating the coolant at an excessive flow rate in the cooling circuit with a mechanical pump, shortened the engine warm-up time. Therefore, an improvement of 2.6%

and 8.3%, at low and high load, respectively, was achieved in the engine warm-up times. It can be said that the improvements are not effective enough due to relatively lower fuel energy at low load and engine speed. However, it is thought that these improvements will be more pronounced at higher brake load and engine speed because the fuel energy entering the engine, hence the rate of energy transferred to the coolant, increases under increased speed and load conditions. The warm-up time was reported to have improved by about 50% in another study with similar results [21]. Based on these results, reducing the coolant flow rate by 50% was shown to provide significant benefits on engine warm-up time.

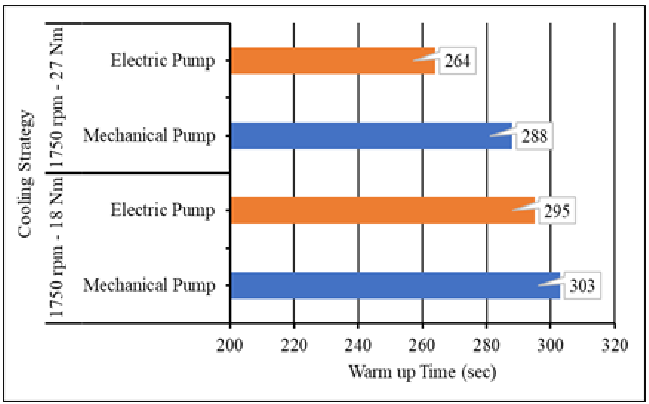

Figure 5 Comparison of the engine warm-up times for all experiments.

Brake specific fuel consumption (BSFC) values during the warm-up period of the engine are given in Figure 6 for all experiments. The BSFC values were calculated by taking the average of the instantaneous BSFC values until the temperature of the coolant drops with the opening of the thermostat. The BSFC value decreased from 858 g/kWh to 704 g/kWh due to the shorter engine warm-up time with the strategy of using the electric pump under low brake load. This decrease can be explained by the improvement of fuel consumption due to the stable operating conditions of the engine in a shorter time period, the reduction of the load on the crankshaft due to the deactivation of the mechanical pump, and the improvement of the in-cylinder combustion characteristics with the rapid warming of the engine block. Thus, the strategy of reducing the coolant flow rate by 50% resulted in the improvement of in-cylinder combustion characteristics.

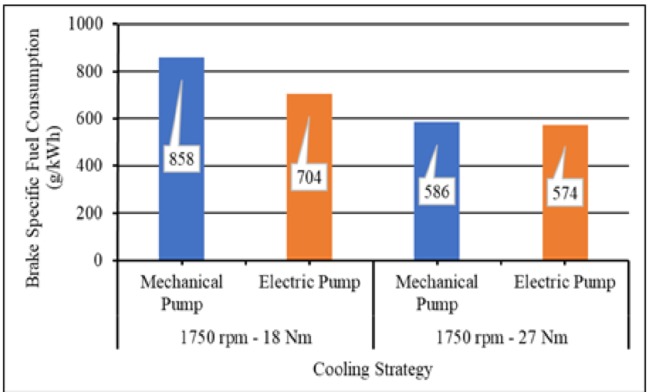

Figure 6 Comparison of the BSFC during the warm-up period for all experiments.

Under low brake load, the BSFC value was reduced by 17.9% thanks to the strategy of reducing the coolant flow rate by 50% with the electric pump. However, it was observed that this was not effective enough under high brake load conditions and that the BSFC value decreased from 586 g/kWh to 574 g/kWh, having improved by 2.1%. The recovery percentage of the BSFC value decreased because the strategy applied here increased the engine block temperature while at the same time negatively affecting the combustion.

Energy balance analysis or energy fraction method is used to evaluate in detail all the energy constituents of fuel energy resulting from combustion. Fuel energy fraction analyses have been included in various applications in the literature [16, 17]. In Figure 7, useful energy obtained from fuel energy (brake power), energy lost through exhaust gases, energy lost to coolant and unaccounted energy loss distributions are presented. Given the fuel energy is defined as 100% input energy; the distribution of other energy types was obtained as proportions to the fuel energy. When Figure 7 is examined in detail, it is seen that only 9.81% and 15.54% of the fuel energy is converted into useful work during the warm-up period of the engine in experiments with integrated mechanical pumps in low and high load conditions, respectively. On the other hand, the effective efficiency increased from 9.81% to 12.06% with the controlled flow application at low load. In the experiment conducted under low brake load with the mechanical pump, the remaining part of the fuel energy comprised of exhaust energy (9.25%), energy lost to coolant (14.70%) and unaccounted energy losses (66.24%). According to the mechanical pump integrated test results under high braking load, 15.54% of the fuel energy is converted to useful work whereas approximately 84.46% was lost, to the coolant, to exhaust gases and as heat loss from the engine block. The engine efficiency reached the highest value at 1750 rpm engine speed and at 27 Nm brake load conditions and there was no significant change in efficiency (14.27%) with the application of flow rate control under same operating conditions. During the warm-up period of the engine, the useful work was relatively low, but after the warm-up period, the efficiency of the engine increased and the rate of lost energies decreased in the steady state conditions [22].

As the engine speed and load increase, the rate of conversion of fuel energy into useful work, i.e., the effective efficiency increases [18, 23]. Reducing the engine coolant flow rate by 50% at high load during the warm-up period increased the rate of energy lost to the coolant and exhaust gases. As such, the ratios of the energy lost to the coolant to the input fuel energy were 14.70% and 16.41% in the use of mechanical and electric pumps at low brake load, respectively. These values are 14.31 % and 17.55% respectively under high load operating conditions.

On the other hand, the highest rate of unaccounted lost energy decreased significantly. The main reason for this situation is that less work was produced due to combustion efficiency being lower than the total fuel energy consumed under low brake load conditions. While the energy loss rate of exhaust gases was 9.25% and 20.26% in low-load mechanical and electrical pump integrated experiments, respectively, these values were determined as 11.25% and 28.83% in high-loaded experiments. The reason for the energy lost to the exhaust gases to increase significant is due to the fact that increased engine load significantly increases the exhaust gas temperature, even at a constant engine speed.

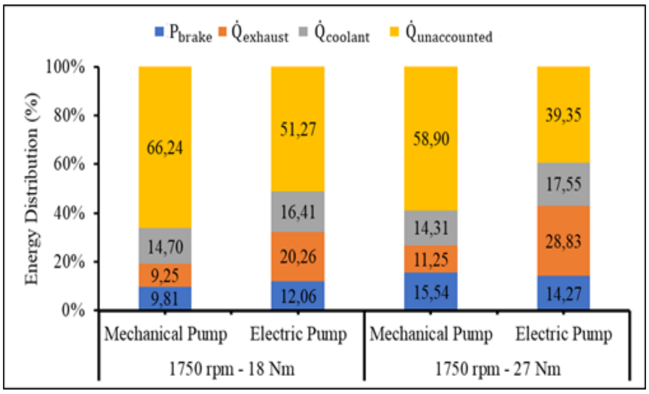

Figure 7 Comparison of the energy balance during the warm-up period for all experiments.

As a result, the coolant control strategy was observed to have significant effects on the effective efficiency and that the total lost energy ratio has started to decrease. This can be explained by the fact that the increased coolant temperature has a positive effect on the engine block temperature and on the in-cylinder combustion characteristics. Considering the warm-up time of the engine and the specific fuel consumption results, it was revealed that the engine could be operated in more effectively thanks to the flow rate control application. In the light of these effective results, further studies on variable coolant flow rate control are thought to be able to provide useful results. However, it is clear that the control application should be designed according to optimum conditions, against the risk of coolant boil due to the fact that the coolant temperature approaches the critical region faster towards the end of the engine warm-up period.

6. Conclusion

In this study, experimental studies were carried out in order to evaluate the events during the warm-up period of a spark-ignition engine under steady operating conditions and to establish the instantaneous energy balance with regards to the coolant control strategy. The important results and various recommendations are presented below;

In the cooling system, the mechanical pump was replaced with an electric water pump and the coolant flow rate was reduced by 50% in the controlled case. Thanks to the electric pump-assisted coolant control strategy under low and high load conditions, an improvement of 2.6% to 8.3% was achieved in engine warm-up time and an improvement of 17.9% to 2.1% in specific fuel consumption.

With the coolant control strategy, the warm-up time and specific fuel consumption were reduced. Therefore, the strategy is seen necessary in terms of engine efficiency and fuel consumption.

The energy efficiency of mechanical and electrical pump cooling strategies was calculated as 9.81%-12.06% at low load and 15.54%-14.27% at high load, respectively. Since the rate of energy entering the thermodynamic system increases with increasing load and hence the warm-up period is short, the improvement of the effective efficiency in the flow rate control application has remained at a low level.

The conversion rate of the fuel energy, consumed in the warm-up period of an internal combustion engine, into useful work is at a very low level, especially at low speeds and loads. In this period, a significant part of the energy is consumed as mechanical losses. The unaccounted energy loss rates of mechanical and electrical pump cooling strategies were 66.24%-51.27% at low load and 58.90%-39.35% at high load, respectively. These values show that the shorter the warm-up period, the more saving on fuel energy and the less energy losses.

As a result, the strategy to control the flow rate of the coolant circulating in the engine cooling circuit has a positive effect on energy efficiency. However, it should not be born in mind that circulating coolant at very low values without ignoring the optimum flow rate may cause boiling in the engine block, especially at high engine loads. Therefore, different control strategies can be applied with the help of effective designs, of which monitoring the coolant temperature forming the basis.

Declaration of Conflict of Interest

The authors declare no conflict of interest.

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