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Analysis of the effect of using variable speed electric water pump on the engine cooling system of a passenger car

Mansour Baghaeian [1*], Khajeh Morad Sharghi [2]

[1]Assistant Professor, Department of Mechanical Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran

[2] Masters in Automotive Engineering, Department of Mechanical Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran

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A B S T R A C T

In this article, the effect of the usage of variable speed electric water pump on the cooling system of a type of passenger car engine has been investigated. The engine water circulation in most of today's cars uses a mechanical method, the power required for its circulation is provided by a belt with a ratio of 1:1 from the crankshaft. This action makes the changes of the water pump speed a function of the engine speed and there is no control over it. One way to solve this problem is to use an intelligent thermal management system. In this method, some components of the cooling system, including the electric water pump, are controlled based on the working conditions and engine temperature. In this research, GT Suite and Simulink software were used simultaneously, and for this purpose, the engine cooling circuit with a mechanical water pump was simulated in GT Suite software and the accuracy of laboratory values was verified in terms of heat transfer. Then the mechanical connection of the water pump was disconnected and the water pump circuit was controlled with an electric motor. In the next step, in order to obtain the control pattern, the electric water pump was replaced with the mechanical water pump in the simulation pattern. The results of the software and experimental simulations of the intelligent cooling system showed a 13.4% reduction in engine warm-up time. To avoid large changes in the electrical water pump speed, the electric water pump speed equal to 100 rpm (13.4% difference) can be fast time to reach the normal temperature. Also engine speed of 300 rpm (3.2% difference) can be the closest to the mechanical water pump to cool the engine with this new model, to be followed at speeds below 1000 rpm.

1. Introduction

Cooling systems are one of the parts that are always studied and investigated in internal combustion engines, and the temperature of the cooling liquid in internal combustion engines is of particular importance. The time to reach the normal temperature at the beginning of the engine operation, especially in cold weather, has a great effect on the production of polluting gases, and also at temperatures higher than the

*Corresponding Author
Email Address: Ma.baghaeian@iau.ac.ir
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normal temperature, the proper circulation of the coolant has a good effect on the engine performance and reducing the emission of engine gases.

In engines, in the traditional way, the thermostat valve is opened with the increase in temperature and opens the water path of the engine to the radiator. This cooling system cannot accurately control the temperature of the engine, and lowering the water temperature does not prevent the water pump from circulating. Operating the engine at a temperature lower than the normal temperature increases fuel consumption and pollution, which can be improved to a large extent with the electric water pump and its rotation control [1].

Fuel consumption, engine efficiency, pollutants such as CO, HC, NOX, friction, engine wear, etc. are affected by the temperature of the cooling air. A study on the engine cooling system is used more as a reduction method to increase efficiency and reduce emissions. Most of the studies and tests conducted in the field of engine cooling system point to the improvement of engine power and the reduction of pollutants by bringing the engine closer to normal in a short time [2].

In addition, by reducing the energy required for the cooling system in the engine, the energy produced in the engine is stored [3]. Improving the engine warm-up time and reaching a stable state is also one of the advantages of increasing the temperature of the cooling system in the shortest time. Reducing engine cooling time reduces oil density, increases lubrication and reduces power losses due to friction. These effects are greater on gasoline engines due to the cooler oil temperature and the majority of HC and CO pollutants [4]. In recent years, a lot of research has been done on the performance of internal combustion engines in different work conditions, most of the research has been on reducing the size of the radiator [5], exhaust pollutants [6, 7] and fuel consumption [8-11] .

A lot of research has been done in increasing the performance of the engine cooling system, Ghiasi et al showed a 28.7% increase in heat transfer by using the coolant produced from carbon oxide nanoparticles [21].

Si et al focused on the hydraulic optimization of automotive electronic pumps by CFD and DOI. The optimized hydraulic scheme was obtained in a limited 375 h by using a normal desktop computer without running in parallel and was proven to improve the pump efficiency by 4.2% through the experiment [22].

Galip Caltak increased thermal efficiency by 5.34% by installing an electric water pump on an internal combustion engine. In addition, they had positive effects on the reduction of greenhouse gas emissions so that the specific fuel consumption under different loads improved by 5.2% [12]. Markus Kisenhofer used a 48-volt electric water pump to cool the engine of a 12.4-liter in-line 6-cylinder diesel engine, and the results of this research show a reduction in fuel consumption by 0.94% [4]. Zhang et al tested the intelligent control system simulation of electric water pump instead of conventional mechanical water pump in diesel internal combustion engine by using AMI SIM software and checked the heating time in cold mode and fuel consumption. 2.5% and the reduction of the heating time was 21.3% and the engine heating time in the electric cooling system was reduced by about 85 seconds compared to the normal mode [13]. In a study, Nasim and Zhang simulated a 4-stroke 6-cylinder engine with a compression ratio of 17.5. The simulation has been done with the help of GT Suite software and with the aim of reducing the engine warm-up time with the help of control systems. In this study, a water pump and an electric thermostat are used in the simulation to reduce the engine warm-up time. At first, the normal engine was simulated with the help of software and after validation with laboratory data, the desired changes were applied. The results obtained from this simulation showed that the engine warm-up time in the electric cooling system was reduced by about 200 seconds compared to the normal mode [14]. Santhosh and Sharma simulated the intelligent cooling system for internal combustion engines with Lab View software, in this simulation two factors of coolant temperature and coolant level were used to

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control the fan and water pump speed, the results of which were a 15% reduction in fuel consumption and It resulted in an increase in the thermal efficiency of the engine [15]. In a study, Shin et al used electro-magnetic clutch for water pump cooling system. First, they used a solar clutch that has the ability to reduce speed up to 65%, which resulted in a reduction in heating time by 7.3% and a reduction in fuel consumption by 1.7%. Also, they used an electro-magnetic clutch that had an on - off mode, which resulted in a 24.7% reduction in heating time and 4% in fuel consumption [9]. Chastin conducted experimental tests on a medium-sized vehicle that was equipped with an intelligent thermal management system and investigated factors such as improvement in fuel consumption, full load mode and thermal operating conditions [16]. Settler et al presented a thermal system with a set of mathematical patterns and a controllable electro-mechanical actuator. In this system, a simple cooling set was used. In this way, they used an electric element to heat the cooling fluid instead of the heat of the combustion engine. In this research, non-linear modeling was used to adjust the temperature, and in the experiments, the speed of the water pump and fan were considered constant, while the smart thermostat valve controlled the temperature of the coolant [17]. Brace and Burnham investigated the effect of different strategies on the engine warm-up time, which resulted in improving the temperature control process and reducing %8 energy losses by replacing the electric water pump instead of the mechanical water pump in a 1.6 liter combustion engine and using the pre-heating system [18]. Lenher et al presented a simulation model of engine cooling system with electric water pump for vehicles and validated the model with real test results including system components such as radiator, water pump, expansion source and pipes. The result of this simulation was an increase in engine power [1]. Ap et al were able to use a 30-80 watt electric water pump for a separate cooling system for a 1.2 liter engine, instead of a 1 kilowatt mechanical cooling water pump; the result of this research was a 2.5% reduction in fuel consumption and a 6% reduction in power loss [19]. Chanfreau et al replaced a 600-watt electric water pump with a 3kW mechanical water pump by using a separate cooling system for a 3.8 liter engine. They have also reported a reduction of HC by 17% and CO by 15% in their work by increasing the coolant temperature from 90 to 110 degrees Celsius [3]. Lim et al investigated the fluid flow and thermal characteristics of the electric water pump and the integrated inverter under the effects of heat generation and showed a 10°C decrease in the engine temperature and this temperature decrease with the inverter also reached a temperature of about 18.7°C [20].

In this research, the working process of the mechanical water pump was investigated and it was used to validate different parts of the engine system, including the effect of pressure drop, temperature, time and speed of the water pump in GT Suite and MATLAB software, and the tests of the mentioned cases It was carried out by a laboratory instrument at 100 to 1000 revolutions per minute and its graphs were drawn, analyzed and validated, and at the same time, according to these data, an electronic circuit was designed, assembled and installed on the system, which is possible to control the speed of the electric motor from the output data of the sensor. As explained in the past researches, they have only shown the effect of the electric water pump in reducing the engine warm-up time and the reduction of polluting gases, but no research has been done to find the appropriate engine speed to avoid large changes in the water pump speed. The novelty of this research, in addition to the fact that it has been shown that the speed of the engine, or in other words, the speed of the electric water pump, can be the fastest time to reach normal temperature, while we do not have thermal stresses in the cylinder walls, how far can it be The closest speed to the water pump should be mechanical, so that with this new pattern, engine cooling can be followed at speeds below 1000 rpm.

2. Methods

2.1. Simulation of engine cooling system

Laboratory data for all components of the cooling system are needed to carry out accurate simulation of the engine. These data were

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obtained from tests and available information. Data such as friction pattern, fuel consumption and mechanical performance pattern of the engine were used to simulate the engine in GT Suite software.

In addition to the data obtained from the experimental test which is used to perform the simulation, a series of tests are needed to validate and ensure the accuracy of the simulated model's performance; for this purpose, an experimental test was conducted to determine the pressure drop and the flow rate for the fluid validation of the simulated model.

The equations on the studied system are done from the numerical solution of the flow in the simulated circuit, with the help of the continuity equation, the momentum equation and the energy equation, which are shown in relations 1 to 3.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_k}(\rho u_k) = 0 \quad (1)$$

$$\rho\left(\frac{\partial u_j}{\partial t} + u_k \frac{\partial u_j}{\partial x_k}\right) = \frac{\partial \sigma_{ij}}{\partial x_i} + \rho f_i \quad (2)$$

$$\rho \frac{\partial e}{\partial t} + \rho u_k \frac{\partial e}{\partial x_k}) = \sigma_{ij} \frac{\partial u}{\partial x_i} - \rho \frac{\partial q_j}{\partial x_i} \quad (3)$$

In the cool circuit, to achieve the result of the mixing of two flows with a certain temperature and flux, equation 4 is used [17] where u, r and x are the speed, density and short components.

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \quad (4)$$

At constant pressure, h can be defined as 5:

$$h = C_p T \quad (5)$$

The heat transfer of the radiator in GT Suite software is also obtained with the equation 6.

$$Nu = CRe^m Pr^{\frac{1}{3}} \quad (6)$$

C and m values by matching the mapping curves.

The performance of the converter is obtained by the equation $CRe^m Pr^{\frac{1}{3}}$ and defined in GT Suite software.

Also, a test was conducted to determine the amount of coolant temperature change in terms of time under certain conditions to validate the thermal circuit of the simulated model.

All the tests were carried out by installing the necessary equipment on a real engine as shown in Figure 1.

These experiments have been carried out in the following three sections.

• Examination the flow through the radiator at different speeds

• Examination the engine output water pressure drop at different speeds

• Examination temperature changes over time in certain applied conditions.

Figure 1: Motor setup, electric motor and inverter

2.2. Flowmeter and flow through the engine radiator

In order to measure the amount of current passing through the radiator, a positive displacement current meter installed on the radiator was used. This flowmeter has accuracy with an error of less than 1%. As seen in Figure 2, the flowmeter is installed on the inlet hose.

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Figure 2: Installing a flowmeter to measure the flow through the radiator

After completing the test circuit, the engine speed was set to 1000, 2000, and 3000 rpm, respectively, and the amount of current measured at these speeds was extracted according to Table 1, which indicates the reasonable flow rate in the cooling system fluid.

Table 1: The results of the amount of current passing through the radiator at different engine speeds

engine speed (rpm)	Current flux obtained from experimental results (lit/min)
1000	19/3
2000	26/4
3000	44/5

2.3. The water pressure drop of the engine output in different revolutions

To perform this test, the results of two pressure sensors were checked with an accuracy of 0.25 psi. The first pressure sensor was installed on the engine inlet, after the water pump. This sensor measures the pressure of the coolant entering the engine. The second sensor was installed in the outlet of the engine after the thermostat and it measures the pressure of the coolant coming out of the engine, which is the result of the test according to Table 2. A small difference between the input and output pressure at low speeds and an increase in the difference at low speeds indicates the accuracy of the measuring device.

Table 2: Engine inlet and outlet pressure results at different engine speeds

engine speed (rpm)	Engine inlet pressure (kPa)	Engine output pressure (kPa)
1000	128	127/1
2000	163	154/6
3000	195	189/4

2.4. Examining the temperature changes according to time in certain applied conditions

To perform this test, which shows the changes of temperature in terms of time, after putting the engine under the initial conditions, the temperatures obtained by the Diag device were recorded with an accuracy of ±1℃ in 5 second intervals. After installing the sensor to collect data, the following conditions were applied to the engine.

The initial conditions of the test were performed at 1000 rpm with the temperature of the cooling fluid and the ambient temperature of 29 degrees Celsius. Figure 3 shows the graph of temperature changes in terms of time resulting from this test at 1000 rpm. In order to increase the accuracy of the test with a mechanical water pump, two repetitions were performed, and the numbers obtained were close to each other with good accuracy.

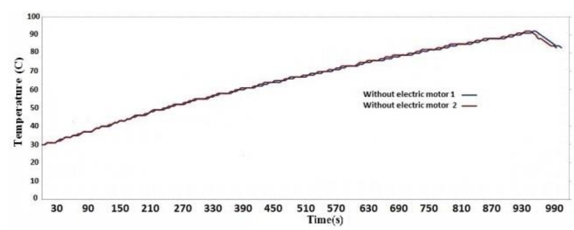

Figure 3: Temperature diagram of the cooling fluid exiting the engine at 1000 rpm in the first and second stages of the test.

2.5. Simulation of engine cooling system

The engine cooling circuit includes flow channels such as pipes, tees, openings, as well as other system components such as radiators, fans, water pumps, etc. Therefore, after simulating all the components of the cooling system in the software, by connecting all the parts to the map created in the software, the simulation of the

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fluid circuit was completed according to Figure 5, and the pressure and flow of the cooling fluid were obtained at different points of the circuit of the engine cooling system.

2.5.1. Simulation of electric water pumps cooling system:

To simulate the intelligent cooling circuit with an electric water pump in the engine, the thermal circuit obtained for the conventional engine cooling system is used. The control system for controlling the speed of the water pump based on the engine output temperature uses the data of the water temperature sensors (water cartridges) embedded in the water paths of the engine, and this information is sent to the engine management, and based on this, the activation time of the slow fan and the fast fan, as well as determining Water pump speed is possible. In this way, after completing the model of the conventional engine cooling system, the connection between the water pump and the engine speed is lost. Then the management system to control the speed of the water pump based on the engine output temperature is designed in Simulink MATLAB environment and it is paired with GT Suite model. In this system, according to Figure 4, the water pump speed is determined based on the engine output temperature.

Figure 5 shows how to use the interface between GT Suite and Simulink in the engine cooling circuit.

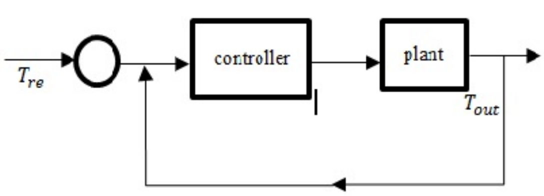

Figure 4: Water pump speed control view of engine cooling system

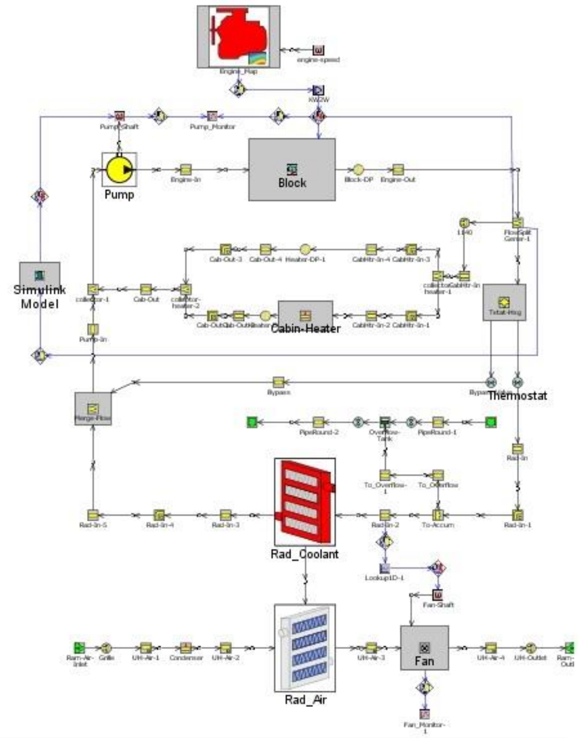

Figure 5: Simulation circuit of engine cooling system management with electric water pump in GT Suite and Simulink MATLAB software.

2.5. Electric water pump starting system:

2.5.1. Practical OP-AMP circuit

The circuit in this system is used with 12 volt dc power supply, also the 0 to 5 volt output signal of the engine temperature sensor is connected to the input of this circuit and according to the changes in the engine output temperature, the temperature sensor creates a variable voltage and This variable voltage is connected to the circuit input. According to table 3, the resistance used in the circuit of the engine cooling system due to temperature creates variable resistances and its output signal also changes. Therefore, the signals given to the relevant circuit are sent to the input of the inverter after amplification, and according to these values, the electric motor can control the speed of the water pump from 100 to 1000 rpm without the intervention of the operator and the influence of the engine crank speed.

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Table 3: Water pump performance index

Water pump speed (v)	Inverter voltage (v)	Equation response voltage (v)	Temperature sensor output voltage(v)	Time (min)	Temperat (K) ure
100	0/69	0/45	4	7	300
150	0/82	0/82	3/75	16	305
285	1/65	1/57	3/25	18	308
375	1/97	1/96	3	34	313
482	2/63	2/32	2/75	130	323
540	2/96	2/7	2/15	250	328
634	3/48	3/45	2	300	333
753	4/13	4/2	1/5	614	353
1000	4/96	4/95	1	870	365

2.6. Validation

Checking the results of the flow through the engine radiator

After the simulation and numerical solution of the engine cooling system, the simulation results should be compared with the results obtained from the engine test. At the beginning of the work, the cooling fluid flow passing through the radiator circuit of the cooling system in question was checked at different times. In Table 4, it can be seen that the maximum error percentage of the current flux in the radiator between the laboratory results and the simulation results is 6%, and this error percentage decreases with increasing speed. The error may be caused by an error in the data defined in the GT Suite software, including the operating model of the water pump. Considering that the values obtained from the real test are almost the same as the values obtained from the simulation, the simulated model is acceptable in terms of current flux.

• Examining the results of engine output water pressure drop in different cycles

Table 4: Values and errors from the results obtained for the current flux of the radiator circuit of the engine cooling system

engine speed (rpm)	Current flux from numerical solution (lit/min)	The flow rate obtained from the laboratory results (lit/min)	percentage error
1000	18/2	19/3	6
2000	25/1	26/4	5/18
3000	43/9	44/5	1/30

Table 5: Values and errors from the results obtained for the pressure drop in the engine cooling system

Engine speed (RPM)	pressure drop resulting from numerical solution (kPa)	Pressure drop from laboratory results (kPa)	percentage error
1000	1	0/9	11
2000	9	8/4	7/14
3000	17	16/5	3/03

Now, in order to be surer of the accuracy of the simulated fluid pattern, we will examine the pressure drop resulting from the simulation and compare it with the laboratory data given.

As can be seen, the pressure drop values obtained from the real test and the simulation are almost the same, the information related to the pressure drop in the channels, engine ducts and pipe angles are among the data that affect the pressure draft. It is also possible that part of the error is caused by the errors of laboratory measurements.

• Examining the results of the numerical solution of the thermal circuit of the engine cooling system

After the fluid analysis of the engine cooling system, we compare the results of the numerical solution of the thermal circuit of the system with the results of the engine test. For this purpose, the simulated model for working conditions according to Table 6 was considered and implemented.

Table 6: Initial conditions of the engine cooling circuit simulation model

Engine speed (RPM)	1000
Coolant temperature (K)	300
ambient temperature (K)	300
Temperature of the internal parts of the engine (K)	300

The results obtained from the numerical solution of the simulated cooling circuit in the mentioned working conditions compared to the laboratory results in the same conditions are shown in Figure 5.

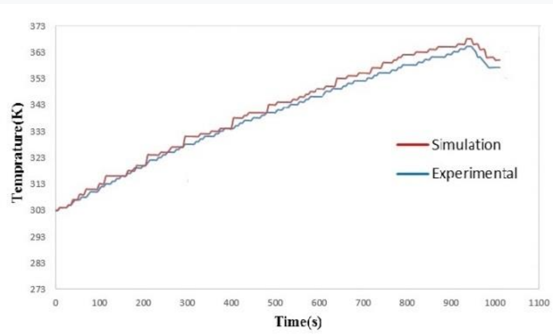

Figure 6: Diagram of the temperature of the cooling fluid leaving the engine

According to Figure 6, a number of numerical values and errors in the results are presented in Table 7.

Table 7: Values and errors from the results obtained for the time of the temperature of the cooling fluid in the engine cooling system.

Time(s)	The temperature of the cooling fluid obtained from the numerical solution (K)	Coolant temperature from laboratory results (K)	Percentage of relative error
135	315	313/2	0/57
319	329/1	327	0/64
606	345/4	342/6	0/81
957	360/3	356	1/19

According to the obtained results, it can be seen that the temperature of the cooling fluid fluctuates about 874 seconds after the start of cold work, due to the opening of the flow path in the thermostat, and it reaches a stable state after 120 seconds.

After simulating the system cooling and fluid and thermal numerical analysis, it is observed that the results of the simulation and laboratory results are almost identical; therefore, the simulated model can be used to simulate the intelligent cooling circuit of the engine with an electric water pump.

3. Results

- **The tests were performed at different water pump speeds (between 0-1000 rpm).**

In this case, the engine speed is transferred to the water pump with a ratio of 1:1; Therefore, in this case, due to water circulation, the engine cools down later and the temperature of the engine reaches the working temperature later.

After performing the test in the normal mode where the water pump and engine speed are 1000 rpm, according to Figure 7, it can be seen that after 15 minutes and 35 seconds, the engine reaches a temperature of 92 degrees Celsius and the car fan turns on. In this case, the mechanical connection of the water pump and the engine is disconnected and the water pump speed is set to 1000 rpm by the inverter, which can be seen after starting, after 15 minutes and 30 seconds, the engine temperature reaches 92 degrees Celsius, the starting temperature of the fan.

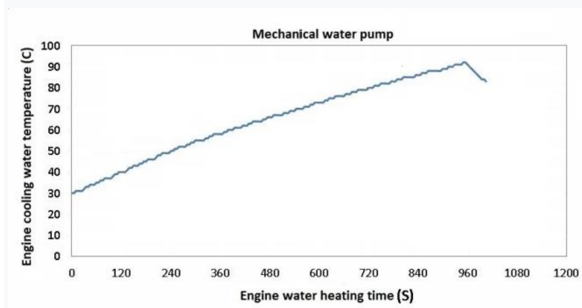

Figure 7: Diagram of temperature changes over time in normal mode (mechanical water pump)

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As can be seen in Figure 8, at 1000 rpm, the performance of the cooling system by the electric and mechanical water pump of the engine had a difference of about 0.6%.

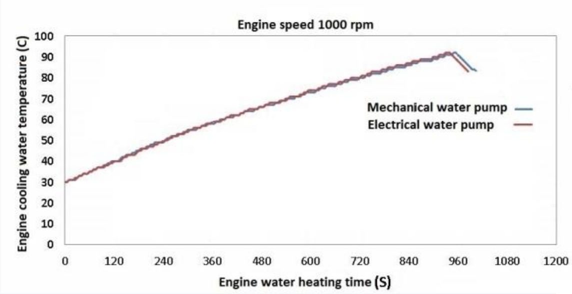

Figure 8: Comparison of the graph of temperature changes in terms of time in normal mode (mechanical water pump) with electric water pump at 1000 rpm

- **Performing other tests:**

In order to perform other tests with different water pump round, the inverter reduced the water pump revolution by 100 steps until it reaches zero revolutions per minute.

In the first step, the water pump speed is set to 900 rpm by the inverter device and the temperature graph output will be as shown in Figure 9.

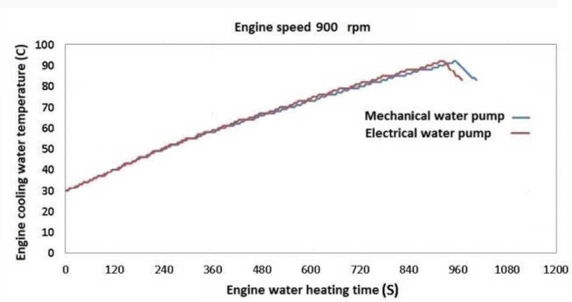

Figure 9: Comparison of temperature changes in the electric water pump with 900 rpm compared to the normal state

As can be seen in Figure 9, at around 900 rpm, our temperature rate increases slightly and the water temperature of the cooling system heats up earlier and reaches the starting temperature of the fan (92 °C) and there is a difference of 6%.

According to Figure 10, it can be seen that the water temperature rate has increased appreciably and compared to the normal water pump, the water temperature reaches the starting temperature of the fan (92°C) about 1 minute earlier, and it is 7% different.

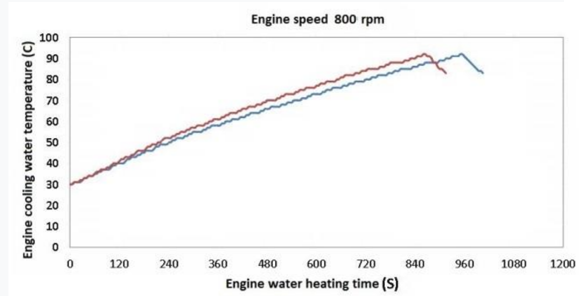

Figure 10: Comparison of temperature changes in the electric water pump with 800 rpm compared to the normal state

Figure 11 shows that at 700 rpm, the temperature rate has not increased significantly compared to 800 rpm, but it is still higher than the normal water pump that is powered by the engine and is 7% different.

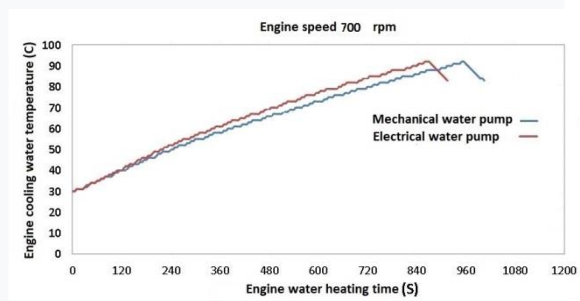

Figure 11: Comparison of temperature changes in the electric water pump with 700 rpm compared to the normal state

At 600 rpm, Figure 12 shows that our temperature rate continues to increase, and after 14 minutes and 5 seconds, our temperature reaches 92 degrees Celsius, which represents a 1-minute time difference from the normal water pump cycle and is 7% different.

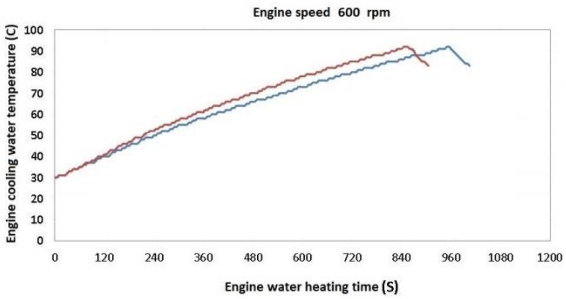

Figure 12: Comparison of temperature changes in the electric water pump with 600 rpm compared to the normal state

Figure 13 shows that at 500 rpm the water temperature of the cooling system reaches 92 °C after 14 minutes and 25 seconds and the fan starts to work, which indicates that the engine temperature increased faster and reached the appropriate working temperature sooner reaches and this increases the efficiency of the car and a 7% difference is observed.

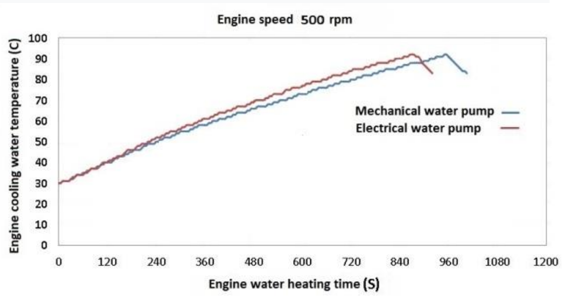

Figure 13: Comparison of temperature changes in the electric water pump with 500 rpm compared to the normal state

Figure 14, at 400 rpm, our temperature rate is reduced compared to 500 rpm, which can show that the behavior of the temperature rate in the car cooling system is not linear and has a 7% difference and increase.

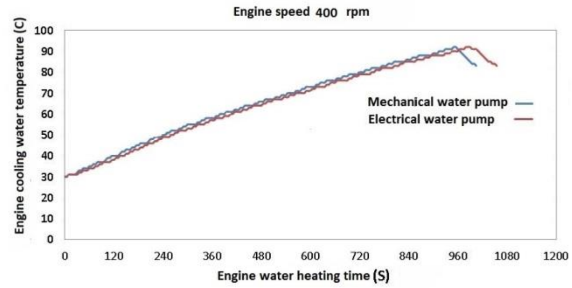

Figure 14: Comparison of temperature changes in the electric water pump with 400 rpm compared to the normal state

Figure 15 also shows that at 300 rpm, there is a noticeable increase compared to 400 rpm, and in this round, after 15 minutes, the water temperature reaches 92 degrees Celsius, and there is a difference of 3.2%.

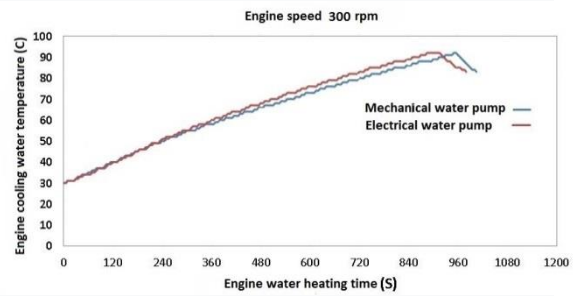

Figure 15: Comparison of temperature changes in the electric water pump with 300 rpm compared to the normal state

At 200 rpm, according to Figure 16, it can be seen that the water temperature rate in the cooling system is almost the same as the higher cooling system rate of the normal engine pump, and both reach a temperature of 92 degrees Celsius after 15 minutes and 30 seconds.

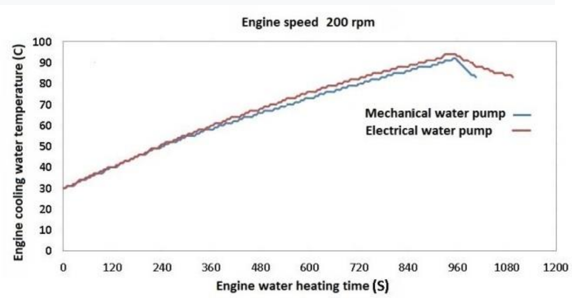

Figure 16: Comparison of temperature changes in the electric water pump with 200 rpm compared to the normal state

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Finally, at 100 rpm, the water temperature reaches 92 degrees Celsius after 13 minutes and 25 seconds, which indicates an increase in the rate of temperature increase, and the time difference with a normal water pump is 2 minutes and 20 seconds, which increases efficiency of vehicle and emission reduction and has a difference of 13.4%, which is shown in Figure 17.

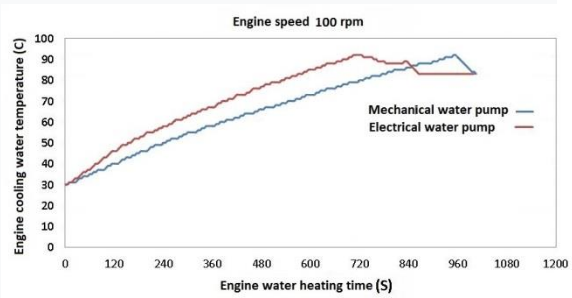

Figure 17: Comparison of temperature changes in the electric water pump with 100 rpm compared to the normal state

4. Summary and conclusion

The purpose of this research is to investigate a suitable and practical method to control the water pump speed of a passenger car engine, which can be used for all other engines as well. In the conducted research, the water pump speed has been controlled in mechanical mode from the start of the engine, which is fixed at 1000 rpm, between 100 and 1000 rpm.

The results obtained are the reduction of engine temperature variations, the control of water pump speed and speed according to the engine heat, the reduction of the time it takes for the engine temperature to reach normal conditions, the cooling of the engine when it is off by the electric pump, and the increase of the useful life of the water pump and engine parts. In fact, in current engines, when the car engine is cold, from the moment the engine starts working, the mechanical water pump is working and circulating water and cooling, while there is no need for the coolant to circulate quickly inside the engine, and this The work will cause the engine to warm up later and increase fuel consumption and even damage the engine parts. By using the electric water pump of the engine, the activation time of the water pump is done at a high temperature of the engine; this work reduces the heating of the engine and also reduces the fuel consumption. In addition, it is obvious that by removing the mechanical water pump from the circuit at a cold engine temperature, it has a significant effect on reducing engine load and power, fuel consumption and exhausts emissions, and reduces engine warm-up time at different speeds between 100 and 1000 rpm and it shows 3.2 to 13.4 percent. As it is shown in the notes and their explanations, the appropriate engine speed to avoid large changes in the water pump speed, the engine speed or in other words the electric water pump speed equal to 100 rpm (13.4% difference) can be fast time to reach the normal temperature, while not having the thermal stress in the cylinder walls. Also 300 rpm (3.2% difference) can be the closest to the mechanical water pump to cool the engine with this model, to be followed at speeds below 1000 rpm.

List of symptoms

h_f	Enthalpy of combustion
K	Thermal conductivity coefficient
L	Length
$\dot{m}_a$	Air mass flux
$\dot{m}_f$	Fuel mass flux
$\dot{Q}$	Heat transfer
$\dot{q}$	Heat flux per unit area
T	Temperature
T_c	Coolant temperature
T_g	Temperature of combustion gases
T_w	Wall temperature
u	Speed
V	Volume
μ	Dynamic viscosity
ρ	Density
∇	Gradient
A	Cross section
C_p	Heat capacity at constant pressure
h_a	Air enthalpy

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