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Experimental Analysis of Engine Cooling Performance in a Real Passenger Car, Considering Various Radiator Fan and ECU Strategies

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ABSTRACT

One of the most important aspects of designing passenger cars is the engine cooling. This process would significantly affect the vehicle performance. Despite various related works, there exists no research in the available literature to analyze the effects of various parameters such as ECU strategy on engine cooling process. Therefore, for filling the mentioned research gap, this study has been conducted both theoretically and experimentally to reveal the influences of different involved parameters on engine cooling process of passenger cars. The current research is implemented in order to examine the effects of 2-speed radiator fan utilization rather than the 1-speed type. For this aim, the new modified fan is considered and the experimental data are obtained to compare the results with those of the old one. Additionally, the effects of parameters such as ECU strategy, radiator fin density as well as the radiator plate geometrical properties are considered in the analysis. As a prominent result, the experimental results show a substantial effect of considering 2-speed radiator fan and choosing a better strategy for ECU on the cooling performance in the vehicle. The experimental results show that employing 2-speed fan instead of single-speed and 900 fin/m fin density instead of 780 fin/m decreases coolant outlet temperature of radiator by 6.1% and 7.1% in the same condition, respectively.

1. Introduction

Cooling system plays a vital role for optimizing vehicle performance. The allowable maximum temperature of engine is controlled by cooling system. The lubricating, exhaust, ignition, fueling systems and etc., are the systems which are in direct relation with cooling process. Therefore, matching and selecting appropriate cooling system parts are very important for the proper operation of the vehicle.

The experimental study of vehicle under hood cooling module for reducing energy consumption has been conducted by Khaled et al. [1]. In their study, three cooling pack positions including radiator and shroud fan were tested on actual vehicle body. Consequently, temperature and velocity change were reported on various fan rotational speeds, radiator water flow and under hood geometries. Peyghambarzadeh et al. [2] conducted experimental research to consider cooling enhancement with nanofluids for coolant in the specific vehicle. The heat transfer performance of pure water, many mixed ratios of water and ethylene glycol and additive were reported. The cooling flow rate was changed for adding different amounts of Al_2O_3 nanoparticle. According to the obtained experimental results, the heat transfer increased by 40% compared to pure water coolant. Comprehensive review research was carried out by Pang et al. [3]. They considered different parameters such as under

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hood air flow, and heat transfer at radiator and coolant for presenting an experimental and numerical research on vehicle cooling system and enhancing cooling method capacity. Cipollone et al. [4] introduced a new engine cooling system with two circuits. The low temperature circuit operates in flow range (15-25 l/min) and temperature range (35-45℃). The novel schematic was installed in Citroen C3 and the pollution and fuel consumption test were done with WLTP cycle. The results revealed 3.5% fuel consumption reduction by COP optimization of HVAC system and thermal management.

A new thermal management- nonlinear radiator fan matrix control system was investigated by Tianwei and Jhon [5]. The mechanical driven coolant pump and radiator fans were substituted with computer-controlled actuator fan and 3-way variable position for thermostat. Transient engine temperature was traced for optimizing cooling operation with nonlinear control strategy fan. According to the results, the fuel consumption decreased as a result of reducing resistance load.

Shojaeefard et al. [6] investigated thermal balance and valve cover heat transfer in small internal combustion engine experimentally. A single cylinder, air-cooled, four-stroke gasoline engine was employed for testing. K-type thermocouples were used for valve cover and exhaust gases temperature. They reported that by increasing engine speed, a reduction in heat transfer to brake power ratio occurs. Shariff et all. [7] performed research to consider the effect of fins under the atmospheric condition by modelling and simulation of car radiator. Fins were installed on the current Honda Civic 2000 car radiator for increasing the cooling effects of radiator. The experimental results showed that when fins are attached to the modeled radiator, the outlet temperature decreases by 25%. Additionally, finned radiator dissipates 74% of the cooling energy while radiator without fin releases 40.8% approximately.

An intelligent cooling system and control model for improved engine thermal management was introduced by Haghighat et al. [8]. This new control system benefits from reducing fuel consumption and emission. An electrical water pump, an electrical fan, and a heated thermostat were utilized for controlling cooling system. The experimental results of the research revealed that the fuel consumption decreases by 1.1%. Furthermore, the results disclosed that hydrocarbon and carbon monoxide emissions reduce 5.3% and 6.1%, respectively.

Experimental and numerical study on an air-cooled, single cylinder, and four-stroke gasoline IC engine was conducted by Qasemian et al. [9]. They reported thermal balance of the engine after engine simulation and validation. According to their analysis, it was concluded that by increasing engine speed, heat transfer to brake power ratio decreases. Throughout their analysis, two correlations for estimation of heat transfer and exhaust power to brake power ratios were introduced.

Enhancing vehicle radiator performance using different porous fin configurations and materials was studied by Baou et al. [10]. Different porous fins in the radiator channels were tested in the same porous media volume. Various geometry effects on heat transfer and pressure drop were investigated in detail. The results exhibited better thermal performance for corrugated pattern compared to the horizontal, vertical, and wavy-corrugated configurations. It was reported that the optimum radiator configuration increased the thermal performance up to 237%.

Hadi et al. [11] discovered thermostat effects on cooling system experimentally. Decreasing warm-up effect on optimal performance and suitable engine temperature was investigated in the research. The results reported the comparison study between the cases with and without thermostat to highlight the properties including engine temperature, fuel consumption, warm-up duration and emissions for both models.

The air pressure drop variations effect on cooling performance in engine radiators was considered experimentally by Kamari et al. [12]. In their research, pressure drop was measured at speeds of 3, 5, and 8 m/s and the best method was introduced for measuring pressure drop obtained from installing the static pressure and dynamic pressure respectively inside and outside the wind tunnel. Baghaeian et al. [13] performed a research to examine the effect of using variable speed electric water pump on the engine cooling system of a passenger car. They simulated and validated a mechanical water pump in GT Suite software. The experimental and numerical results of the intelligent cooling system indicated 13.4% reduction in engine warm-up time.

Noghabi et al. [14] considered pressure drop and heat transfer coefficient of graphene oxide, titanium oxide and aluminum oxide on the radiator of a car experimentally. Three nanoparticles including 0.1, 0.2 and 0.3 nano weight percent and flow rates of 10, 20, 32 and 40 liters per minute were considered at normal

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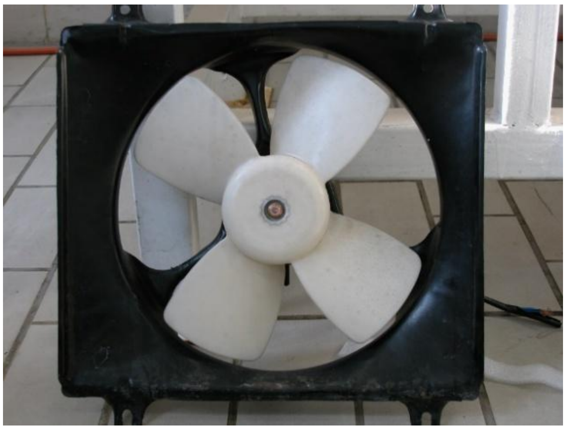
engine temperature for the experiments. The results indicated that increasing the weight percentage of nanoparticles to the base fluid enhances the heat transfer coefficient at 0.3 weight percent to an approximate value of 5.2% in aluminum oxide, 11.9% for titanium oxide and 28.7% for graphene oxide higher than that of the base fluid. Kumar et al. [15] analyzed composite fins and nanoparticles effect on vehicle radiators. The research considered the parameters like velocity path, pressure variations, and temperature distribution in the radiator setup. The final results indicated 12% improvement with nanoparticles, where the velocity and the radiator system's pressure volume were 1.61 m/s and 2.44 MPa, respectively. In the fin condition, the stress rate was 3.60 N/mm2 is reported.

The presented literature review revealed various strategies and findings of recently published works dedicated to analyze the engine cooling process of the passenger cars. According to the available literature, there exist various works on engine cooling process analysis in passenger cars, considering different viewpoints. However, no comprehensive research was found in order to implement a comprehensive experimental examination considering various radiator fan speed and ECU calibration strategy. Therefore, this study is devoted to fill the mentioned research gap throughout experimental evaluation of the effects of parameters such as fan speed and calibration according to various ECU strategies. For obtaining the experimental data, a new modified cooling system considering 2-speed fan instead of 1-speed, radiator with higher fin density and bigger plate width has been designed and employed in a real passenger car to investigate the possible effects. In addition, various calibration methods employing two different available ECU strategies have been taken into account and the related data have been reported. According to the acquired data, utilizing 2-speed radiator fan and the type of ECU strategy substantially affect the cooling performance and this effect becomes clearer in higher distances driven by the car. Therefore, considering these parameters besides the other effective factors would lead us to reach an efficient and reliable cooling performance.

2. Test set-up and model

In what follows, the model of the improved cooling system is discussed. One of the changes which is modified for new model, is the length of the cross-sectional area of the radiator plate. Furthermore, fin density has been changed from 780 fin/m to 900 fin/m. In addition, by adding a resistor to the radiator electrical system, the 2-speed model of radiator fan will be hired in cooling process. Figure (1) illustrates various radiator fans (i.e. the old and modified models) which are employed for experimental analysis in passenger car. Also Figure (2) shows the schematics of the cross-sectional area with modified length. Additionally, in the present research, the fin density parameter will be analyzed and the related results will be reported. The schematic figure implying the fin density property in the radiator has been indicated in Figure (3).

(a) Modified radiator fan



(b) Old radiator fan

Figure 1: Various models of radiator fans designed and considered for experimental study (a) modified model (b) old model

For attaining experimental data, the vehicle is equipped with four thermocouples and one volt-meter. The location of these sensors and volt-meter are shown in Table 1 and Figures (4), (5) and (6), respectively. It should be mentioned that, the accuracy of the hired special K-type thermocouple is ± 1.1 ℃ in the range of $0-275$ ℃. Furthermore, the volt-meter accuracy is about $\pm 0.001\ V$.

Table 1: Measuring items and position of measuring point

Object	Position	Measuring instrument
Temperature	Inlet water to Radiator	K-Type thermocouple
Temperature	Outlet water from Radiator	K-Type thermocouple
Temperature	Inlet air to Fan	K-Type thermocouple
Temperature	Outlet air from Fan	K-Type thermocouple
Voltage	Fan Electromotor	Volt meter

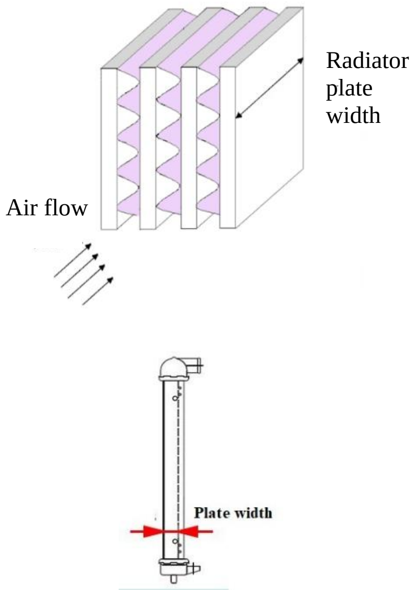


Figure 2: Cross-sectional area of the radiator plate

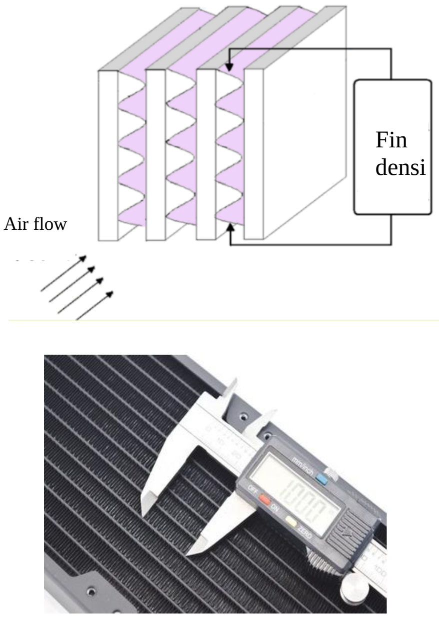


Figure 3: Radiator fin density

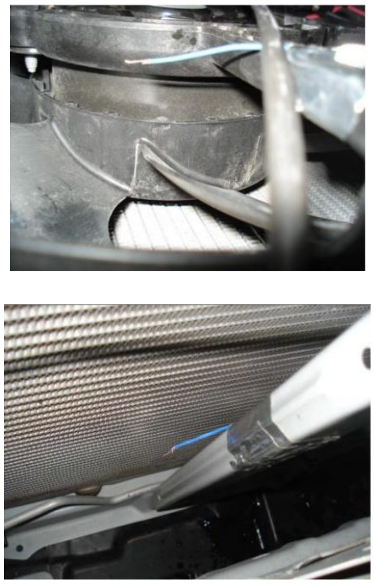


Figure 4: The inlet and outlet air temperature sensors of fan on the vehicle

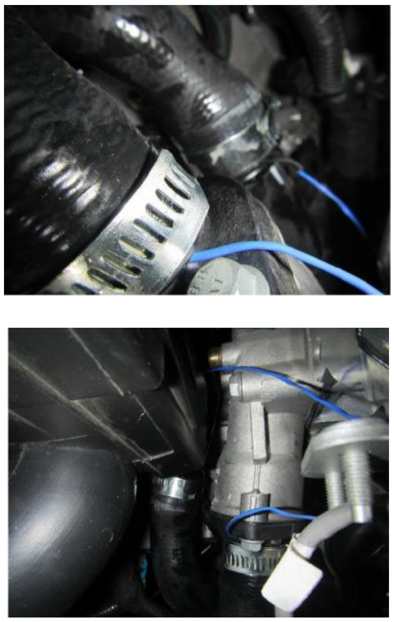


Figure 5: The inlet and outlet water temperature sensors of radiator on the vehicle

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Figure 6: The voltage of fan on the vehicle

Four temperature sensors and the volt meter are connected to portable data logger. The heat rejection to cooling system can be calculated by Eq. (1).

$$\dot{Q}_h = \dot{m}C_{p,w}(T_{w,in} - T_{w,out}) \quad (1)$$

where $T_{w,in}$ and $T_{w,out}$ are the inlet and outlet water temperatures to the radiator and $C_{P,W}$ is the water specific heat capacity in constant pressure. The heat rejection to air can be calculated by Eq. (2).

$$\dot{Q}_{air} = \dot{m}C_{P,a}(T_{a,in} - T_{a,out}) \quad (2)$$

where $T_{a,in}$ and $T_{a,out}$ denote the inlet and outlet air temperatures to the radiator and $C_{P,a}$ is the air specific heat capacity in constant pressure.

The data acquisition system and temperature sensors are shown in Figure (7). The data acquisition system gathers and record information in each millisecond.

3. Results and Discussion

In this section, the obtained experimental results are discussed in detail. For this aim, the tests conditions have been presented throughout Table 2. Also, it should be mentioned that all of the tests have been done when the gear position is 1 and the engine speed is 4000 r.p.m. Additionally, all the consumers like HVAC system are on. In the old design, radiator fin density and plate width equal to 780 fin/m and 23 mm, respectively.

As a consequence, Figure (8) is allocated to demonstrate the coolant temperature for both old and new design of radiator fan. The ambient temperature is about 46℃ . Furthermore, radiator

Figure 7: The data acquisition system and temperature sensors

fin density is considered to be 900 fin/m. As it is obviously seen, by considering the new modified radiator fan in the cooling system, the coolant temperature decreases and this would be a beneficial property of the modified fan for achieving higher efficiency and better performance. As another result, it is observed that as the distance driven by the car enhances, the effectiveness of the 2-speed radiator fan compared to the old one (1-speed) becomes more significant and visible.

To put it differently, the more the distance is driven, the more difference between the coolant temperature regarding the new and old models appears.

The reason behind this behavior would be attributed to the enhancement at the air flow rate which occurs in the new model compared to the old one. As a result, this property gives rise to reduction of about 7℃ for coolant temperature which implies better cooling performance.

Clearly discussing, according to Eq. (3) presented below, by considering the same pressure drop and higher power for 2-speed fan, we will have higher air flow rate leading to lower coolant temperature and better cooling performance.

The fan power is calculated by Eq. (3) as following [16]:

$$P = Q.\Delta P \quad (3)$$

where Q is flow rate and ΔP is pressure drop during passing the air to radiator and fan. The flow rate and pressure drop are obtained throughout Eqs. (4) and (5) [16]:

$$Q = K_1 \rho N D^3 \quad (4)$$

$$\Delta P = K_2 N^2 D^2 \quad (5)$$

in which ρ , N and D are fluid density, fan speed and fan diameter respectively. K_1 and K_2 are constant numbers which could be calculated according to experimental study diagram or text books. The technical specifications of the new and old fans are tabulated in Table 3. The air flow rate of new fan in high speed is 40.8% more than old fan in the same pressure drop condition. This phenomenon occurs because of using more powerful fan, enhancing fan's effective area as well as blade number and using aerodynamic blade. The new designed fan dimeter and fan speed affect flow rate according to Eq. (2). Consequently, the flow rate is greater and the coolant outlet temperature of radiator is cooled better. As another result, the effect of the ECU strategy on the coolant temperature in a real car situation considering gear position 1, engine speed of 4000 r.p.m and ambient temperature of 36 ℃ has been analyzed and the related experimental data has been shown in Figure (9). For this investigation, two types of the ECU strategies have been considered. As it is seen, considering Sagem ECU strategy instead of Siemens type could considerably reduce the coolant temperature and this effect substantially improves the cooling performance of the system.

This is because of the engine management system (EMS) which is different for both models. For Sagem ECU type, better control system has been designed for calibration which affects directly the fuel consumption, cooling performance and other functional properties of the vehicle. The reason for this difference appeared for various ECU strategies could be ascribed to the function of AC system. The Sagem ECU increases engine speed 200 r.p.m when the AC is on. Thus, the coolant flow increases and better cooling performance is reported in radiator compared to the same condition when AC is off. The Siemens ECU enhances fuel injection for power compensation when AC is on. Therefore, this strategy increases the engine heat load and coolant temperature. As a consequence, choosing a proper ECU strategy would play an important role so as to reach an efficient cooling performance and this factor should be considered for cooling process.

Table 2. Conducted tests conditions

Test No.	Studied item	Fan model	Ambient Temp. (℃)	Ambient Pressure (bar)	ECU Type	Fin density (fin/m)	Plate Width (mm)	Vehicle speed (km/h)	Fig. No.
1	Fan	Old/New	46	1.015	Siemens	900	23	31.4	7
2	ECU	New	36	0.886	Sagem/Simens	900	23	31.4	8
4	Ambient	New	36-47	1.015	Sagem/Simens	780/900	23	31.4	9
5	Fin density	New	47	1.015	Sagem	780-900	23	31.4	10
6	Radiator plate width	New	47	1.015	Sagem	780	23-26	31.4	11

Table 3. The technical specification of new and old fan

Property	Old Fan	New Fan (low speed)	New Fan (high speed)
Electrical fan power (W)	180	260	260
Current (A)	11	9	14.6
Fan speed (r.p.m)	2080	2080	2660
Fan Diameter (mm)	290	300	300
Max flow rate(m^3/h)	1420	1650	2000

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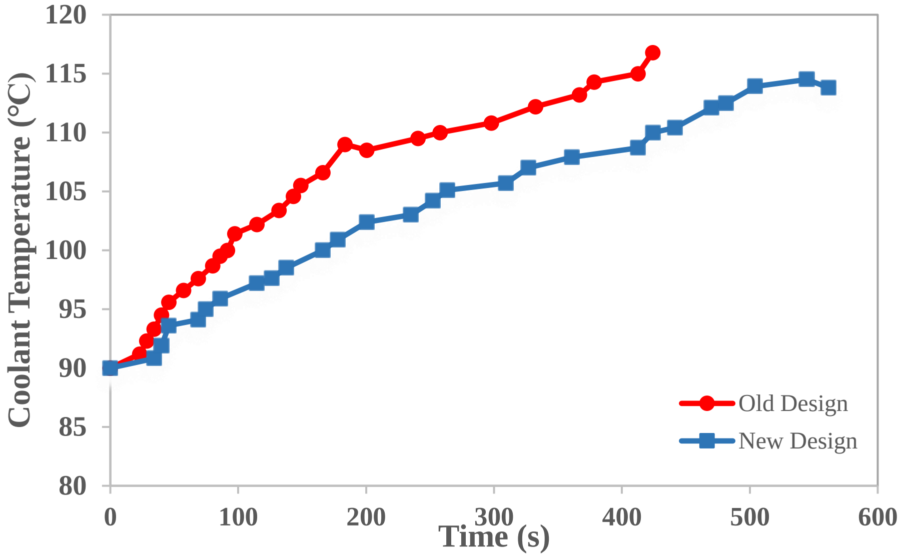

Figure 8: Variation of coolant temperature for modified and old cooling system, when gear position is 1, engine speed is 4000 r.p.m, environment temperature is 46 ℃ , radiator fin density is 900fin/m and Siemens ECU strategy is considered

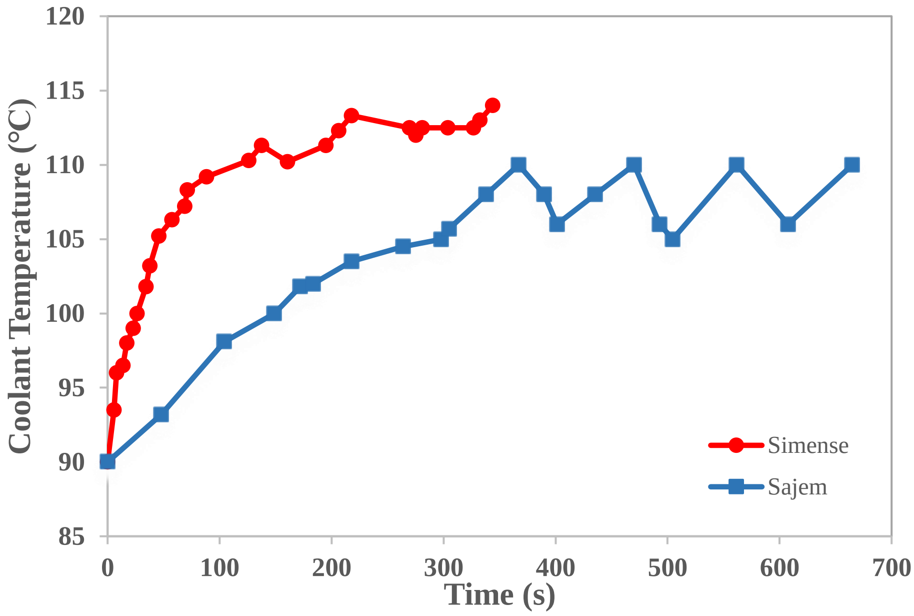

Figure 9: Variation of coolant temperature in presence of modified cooling system for different ECU strategies, when gear position is 1, engine speed is 4000 r.p.m, environment temperature is 36 °C and radiator fin density is 900fin/m

Considering Siemense, Sagem and old sagem ECU strategies, the evolution of the coolant temperature with respect to the time, considering improved cooling system radiator fin density of 900 fin/m as well as the old cooling system with fin density of 780 fin/m has been investigated experimentally and the obtained data has been indicated in Figure (10). It should be noted that the test is performed considering gear position 1, engine speed of 4000 r.p.m and ambient temperature of 47°C. The comparison between Sagem ECU strategies indicates that the time for recaching the point of harmonic behavior is lower for the test done in 47℃ . The cooling system exhibits proper performance for controlling coolant temperature in Sagem ECU for two tests. Also, the comparison study between the results obtained for the car with old cooling strategy, improved Siemens-based strategy has been conducted and the related results have been shown in Figure (10).

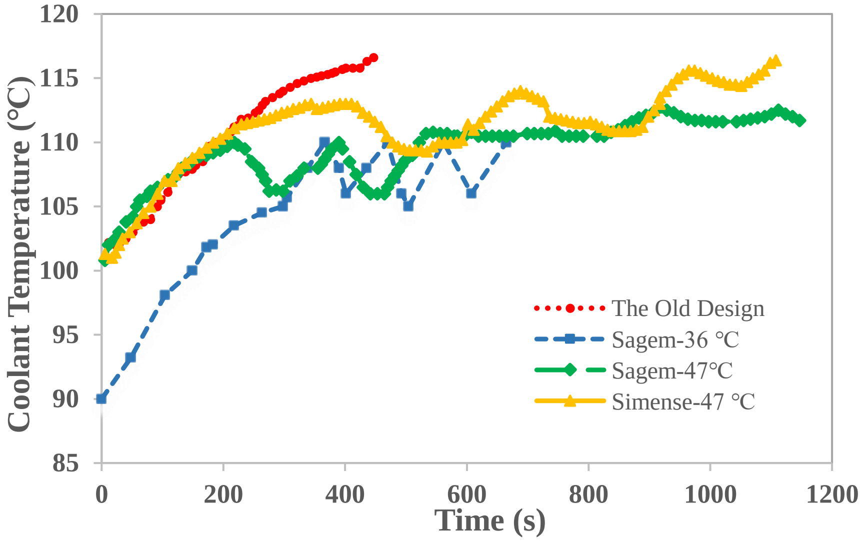

Figure 10: Variation of coolant temperature for cars with old cooling system, Sagem-based modified model and Siemens-based modified model when gear position is 1, engine speed is 4000 r.p.m, environment temperature is 47 ℃ , radiator fin density is 780 fin/m for old and 900 fin/m for modified version

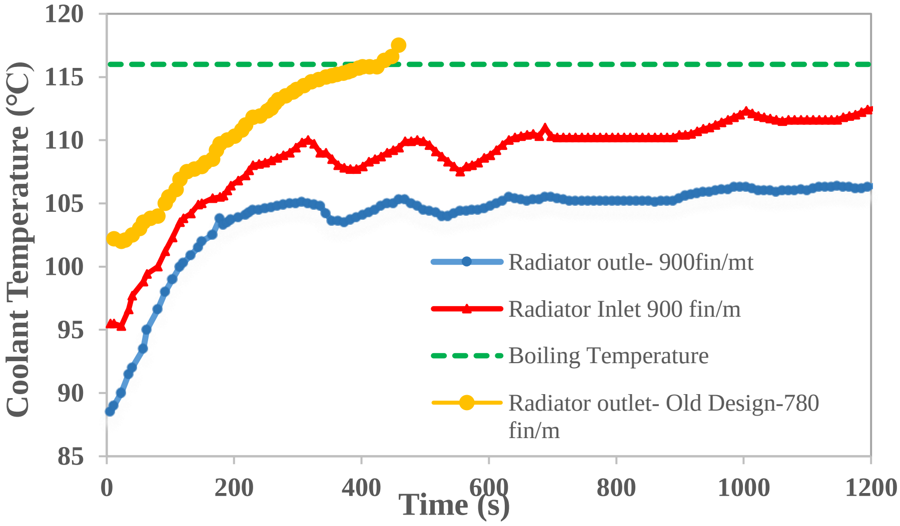

Figure 11: Variation of radiator inlet and outlet coolant temperatures in presence of modified cooling system with fin density of 900 fin/m and 780fin/m for old design, when gear position is 1, engine speed is 4000 r.p.m, environment temperature is 47 ℃ and Sagem ECU strategy is considered

For the initial time, there is no substantial difference between the results of various models. However, by increasing the time, as an overall trend, it is obviously seen that an improved cooling strategy based on the Sagem ECU strategy gives rise to the best cooling performance and a substantial influence of the improved cooling system could be observed. As mentioned before, this trend emerges as a result of various calibrations for Sagem and Siemense ECU strategies when AC is on. It is worth mentioning that according to the figure, even by considering the improved cooling system with 2-speed, the ECU-strategy and calibration play a vital role for obtaining better cooling performance. As a final investigation, the variations of the inlet and outlet coolant temperatures versus the time has been evaluated and the related results have been shown in Figures (11) and (12). The analysis has been performed for cooling system employing 2-speed radiator fan. Also, the environment temperature is 47 C and Sagem-based ECU strategy has been considered. It should be mentioned that, Figure (11) is presented for cooling system exploiting 900 fin/m fin density and Figure (12) is prepared for radiator in which the length of the cross area is 26 mm (instead of 23 mm). The old design results are obtained in 780 fin/m fin density and 23 mm the length of the cross area in Figures (11) and (12).

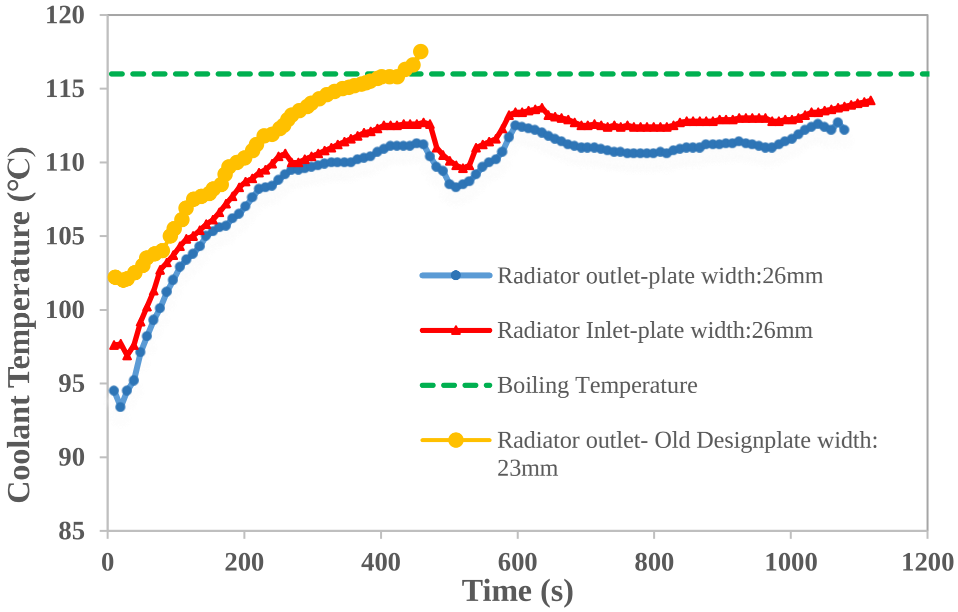

Figure 12: Variation of radiator inlet and outlet coolant temperatures in presence of modified cooling system with radiator plate width of 26 mm and 23 mm for old design, when gear position is 1, engine speed is 4000 r.p.m, environment temperature is 47℃ and Sagem ECU strategy is considered

It should be noted that, for the conducted tests related to the old car (with old cooling system) the coolant temperature raised to 116 C and boiling of cooling fluid was reported (which has been shown schematically in the figures). However, according to the presented results below, considering improved cooling system with higher fin density or wider radiator plate leads to the better cooling process and totally we will have lower coolant temperatures. Additionally, according to the indicated results, the effect of higher fin density is more significant compared to increasing the radiator plate width considering packaging limitations.

4. Concluding remarks

The research aimed to conduct an experimental study on engine cooling system efficiency from a new viewpoint. Accordingly, a new modified cooling system employing 2-speed radiator fan was designed and considered. Additionally, 2 different and available ECU strategies were taken into account to improve the old model and investigate the influence of the calibration regarding various ECU strategies. Moreover, some other improvements such as higher radiator fin density and wider radiator plate were considered. Tests were conducted on a real passenger car in a specific situation. Therefore, the obtained experimental results were reported in detail and compared with those related to the old model. The results exhibited a significant effect of utilization of 2-speed radiator fan instead of the 1-speed model and this effect becomes more tangible for higher distances. Also, it was revealed that choosing a proper ECU strategy is another important and constructive factor affecting the cooling performance and this effect should be considered for efficient design. It was shown that utilizing modified cooling system by employing a better ECU strategy gives rise to not only a lower coolant temperature, but also a constant value for the temperature in higher distances.

In other words, employing a better ECU strategy results better control of the engine cooling process. Furthermore, it was concluded that the effect of fin density parameter is more considerable compared to the radiator plate width parameter. It is hoped that the current research and the reported data would be beneficial for designing passenger cars with efficient and reliable engine cooling system.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

List of symbols

C	Heat capacity
D	Fan diameter
N	Fan speed

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Q	Flow rate
T	Temperature

Greek symbols

ΔP	Pressure drop
ρ	Fluid density

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