AMERICAN Journal of Engineering, Mechanics and Architecture
Volume 4, Issue 3, 2026 ISSN (E): 2993-2637

Mechatronic Control of A Car Cooling System

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Abstract: This article examines the modeling of passenger car internal combustion engine cooling systems based on mechatronic control. In this work, the mechatronic engine cooling system of a passenger car was studied using a mathematical model. The dynamics of the cooling system were described using heat balance equations and modeled using MATLAB/Simulink. In the study, the effect of the cooling fan on the process was taken into account through the radiator heat transfer coefficient. Based on the developed model, four control strategies were analyzed and compared: conventional thermostat control, ON/OFF electronic control, PID control, and Lyapunov-based control. The simulation results show that conventional and ON/OFF methods exhibit larger temperature deviations and oscillations, while the PID and especially the Lyapunov-based controller ensure faster and more stable convergence of engine temperature to the desired value. The obtained results confirm that the application of advanced mechatronic control algorithms significantly improves the thermal regulation and stability of automotive cooling systems.

Keywords: Internal Combustion Engine, Cooling System, Mechatronic Control, Mathematical Model, Nonlinear Control, PID Control, Liapunov Method.

1. Introduction

Currently, the efficient operation of internal combustion engines in modern cars largely depends on the correct and uninterrupted operation of the cooling system. The engine generates a large amount of heat during operation, and a cooling system is necessary to maintain this heat and protect the engine from overheating. If the engine temperature rises above the specified level, this will lead to its failure or a decrease in operating efficiency. During the operation of automobile internal combustion engines, a large amount of heat is generated as a result of fuel combustion. Approximately 40-50% of this heat is converted into useful work, i.e., mechanical energy. However, the remaining 70-80% of thermal energy is released as waste heat. While some of this excess heat is released through exhaust gases, another large portion accumulates in the engine block and its surrounding parts. If this heat is not effectively dissipated in time, the engine temperature will rise sharply, which will negatively affect its normal operation.

Therefore, any internal combustion engine is equipped with a cooling system. The cooling system removes excess heat generated in the engine in a timely manner, releases it to the external environment, and maintains the engine temperature in optimal operating mode. This system is one of the most important functional components that ensure the long-term, reliable, and efficient operation of the engine [1], [2].

The problem of improving the cooling systems of internal combustion engines was formulated primarily on the basis of mathematical modeling. In particular, in the work, a method for selecting additional equipment for the ICE cooling system is considered, and it is proposed to control the fan speed through a logic controller. The process of thermal stabilization is modeled using Fuzzy Logic Toolbox in the MATLAB/Simulink environment. This approach can be considered as the first step in the transition of the cooling system management problem from traditional mechanical control to the intelligent control stage [3].

This direction was further developed in studies and, where issues of automatic control of the engine's thermal state and control of water-chemical regimes during the transition to high-temperature cooling were considered. If in the work, mainly functional diagrams and control structures were improved, then in the study, the possibilities of controlling the pressure in the internal circuit of the cooling system and automatic regulation of the physicochemical properties of the coolant were analyzed more deeply. These studies indicate the need to control the thermal process based on complex parameters [4].

The issue of linking the modeling of the cooling system with experimental studies was considered in the work, in which a comprehensive experimental system was created, including a smart valve, an electric pump, and a radiator with an electric fan. The authors developed nonlinear control based on a mathematical model and proved the stable operation of the system under various loads and rapid heating modes. Thus, the theoretical models are confirmed by practical tests [5].

The influence of the mathematical model on the accuracy and quality of control was highlighted in the work, and a model was developed that reflects the physical processes of the cooling system. The authors substantiated the need to replace mechanical actuators with electrically controlled pumps and thermostats. Thus, the transition from modeling to mechatronic integration occurs [6].

The issue of structural improvement of electronic control systems is considered in the work, and actively controlled elements and flexible thermal control circuits are proposed. This approach makes it possible to improve fuel efficiency and environmental indicators by stabilizing the thermal state of the engine. The necessity of applying these structural changes on an industrial scale is substantiated in the study [7]. The authors showed that cooling systems are less developed than other control systems and proved that optimal heat exchange control significantly affects engine efficiency. Here, a robust control approach is applied, and the optimization of the coolant temperature and flow rate profiles is proposed [8].

The design directions for the implementation of electronic control were analyzed in the work and it was shown that the most promising direction is the introduction of electronic control into the cooling system in modern high-performance engines. Logically, in the study, under conditions of increased emission requirements, a hydraulic fan-drive system was proposed, which increased the compactness and efficiency of the system by controlling the fan speed using a proportional solenoid [9].

After structural and functional improvements, scientific research is focused on advanced control algorithms. In particular, a strategy based on the Robust Model Predictive Control was developed, which showed the possibility of reducing engine heating time and reducing energy consumption in steady-state mode through optimal control of coolant consumption. This approach is based on predicting the thermal process [10].

The problem of nonlinear control based on the model is further developed in the work , taking into account the wide range of changes in the parameters of the engine and cooling system. The author proposes a physically based nonlinear model and an advanced control algorithm, substantiating that traditional linear control does not provide sufficient accuracy in all working conditions.

Practical improvement of nonlinear control was carried out in the work using a fractional order PID controller. Parameters adjusted based on nonlinear optimization provided high-precision temperature monitoring. The fact that very small error values are recorded in constant mode confirms the stability of the system [11]. However, along with high accuracy, resistance to external disturbances is also important. For this reason, robust nonlinear control based on the integral sliding mode is proposed in the work [12]. With the help of a Gain-scheduled observer, heat flows were assessed, and the stability of the system was increased.

In the logical continuation of this direction, a flexible cooling system was proposed, and the issues of increasing engine fuel efficiency and reducing harmful emissions were comprehensively considered.

In general, the analyzed literature shows the development of cooling systems in the following sequence: mathematical modeling → electronic and mechatronic integration → nonlinear and robust control → adaptive and optimal thermal control. However, in existing studies, the integration of these directions within a single integrated mechatronic model has not been sufficiently developed. Therefore, the complex modeling of a mechatronic controlled cooling system is an urgent scientific task [13].

The operating principle of cooling systems is based on thermal conductivity and convection. The coolant flows through the engine, dissipates heat through the cooler, and then circulates again.

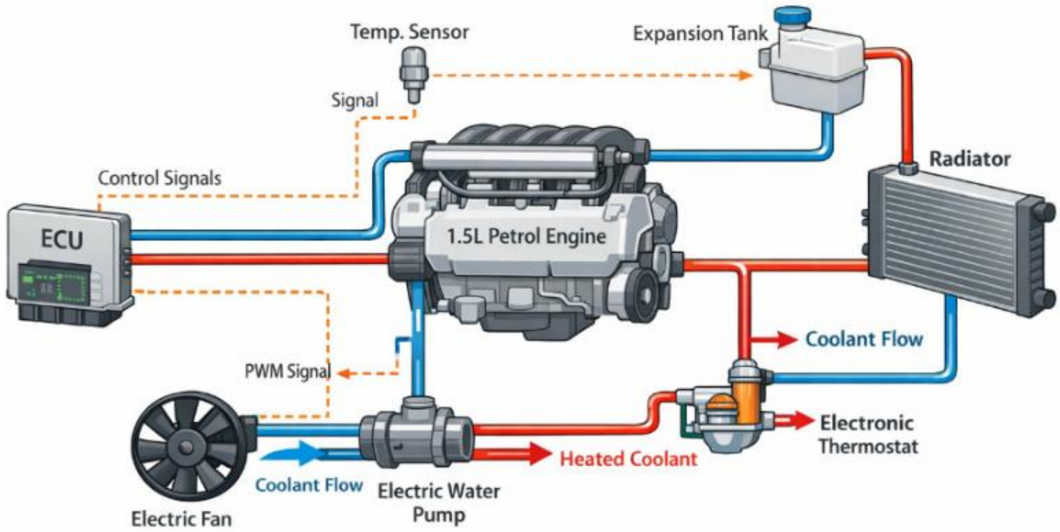


Figure 1. Functional diagram of the mechatronic controlled cooling system of a gasoline engine.

A modern mechatronic controlled cooling system is designed to maintain engine temperature within the optimal range, reduce energy consumption, and improve engine performance. The system operates on the basis of a closed control circuit and consists of such basic elements as: sensors for measuring engine temperature, electronic control unit (ECU), electric pump, electronic thermostat, PWM-controlled fan, radiator and expansion tank (Fig. 1):

When the engine starts, temperature sensors measure the real-time temperature of the coolant and send the signal to the ECU. Based on the received data, the ECU generates control signals to maintain the optimal operating temperature. Through these signals, the rotational speed of the electric pump is changed, the degree of opening of the electronic thermostat is adjusted, and the fan speed is smoothly controlled by the PWM signal.

2. Methodology

This study adopts a systematic engineering approach to investigate the performance and efficiency of a mechatronic-controlled engine cooling system through mathematical modeling and simulation. The research is based on the integration of thermodynamic principles, control theory, and computational modeling to analyze the thermal behavior of an internal combustion engine under various operating conditions.

At the initial stage, a **mathematical model** of the engine cooling system is developed using heat balance equations. The model represents the dynamic interaction between the engine block, coolant flow, radiator, and external environment. The lumped-parameter method is employed to simplify the thermal processes while preserving the essential physical characteristics of heat transfer and fluid dynamics.

Subsequently, the developed model is implemented in the **MATLAB/Simulink environment**, which enables dynamic simulation and real-time analysis of the system. This platform allows for the visualization of temperature variations and the evaluation of system response under different control strategies.

To assess the effectiveness of control mechanisms, several **control algorithms** are applied and compared, including conventional thermostat-based control, ON/OFF electronic control, Proportional–Integral–Derivative (PID) control, and Lyapunov-based nonlinear control. Each control strategy is integrated into the simulation model to regulate the coolant temperature and maintain optimal thermal conditions.

The performance of these control methods is evaluated based on key indicators such as temperature stability, response time, overshoot, and energy efficiency. Comparative analysis is conducted to determine the advantages and limitations of each approach, with particular emphasis on system robustness and adaptability to varying thermal loads.

Overall, this methodological framework ensures a comprehensive analysis of the cooling system by combining theoretical modeling with practical simulation tools, thereby providing reliable insights into the optimization of engine thermal management systems.

Mathematical model of the engine cooling system. The mechatronic controlled cooling system has a closed control loop for real-time control of engine temperature and coolant temperature. The mathematical model of the system takes into account engine heat balance, liquid flow, radiator and fan efficiency, and control signals.

In passenger cars, the engine cooling system is designed to maintain the engine's heat balance and maintain its operating temperature within the optimal range.

The passenger car cooling system plays an important role in increasing engine efficiency and preventing overheating. This system is based on the principle of transferring the heat generated in the engine block to the radiator through the liquid and releasing it into the environment. The heat and mass balance equations are used as the main tool for explaining the cooling process from a scientific point of view. With the Lumped-parameter approach, the system is physically divided into separate energy volumes, the temperature of each of which is taken as a single value. This approach simplifies the mathematical model, but preserves the main thermal processes of the engine and radiator.

The cooling system dissipates heat through two main processes: heat exchange through liquid and heat transfer through air [14].

Part of the heat generated as a result of fuel combustion in the engine block is transferred to the radiator through the liquid. This heat flow is expressed as follows [17], [18], [19].

$$Q_s = \dot{m}_c c_p (T_e - T_c), \quad (1)$$

where $\dot{m}_c = 2\pi\rho_c r_d b u_p$ - mass flow rate of coolant from the pump, kg/s ; c_p - heat capacity of the liquid, $\frac{J}{kg \cdot °C}$; T_e - engine coolant temperature, $°C$; T_c - coolant temperature, $°C$.

When the heat flow from the pump increases, the mass flow rate of the coolant increases, i.e., the liquid quickly removes heat from the engine (the liquid flows rapidly through the radiator at the same time). If the engine fluid and radiator temperatures are close to each other, the engine temperature remains practically unchanged, meaning the system is thermally stable.

The coolant passing through the radiator is cooled by external air and a fan. This process is based on the laws of convection and heat conduction. The propagation of heat through the radiator is expressed Q_r as follows:

$$Q_r = k_r A_r (T_r - T_a), \quad (2)$$

where k_r - heat transfer coefficient of radiator surface, $\frac{W}{m^2 K}$; A_r - radiator surface, m^2; T_a - external environment temperature, $°C$; T_r - radiator exit temperature, $°C$.

For stable operation of the system, the liquid Q_r discharged through the reactor must be in equilibrium with the heat flow Q_s from the pump [15].

The passenger car cooling system performs the function of maintaining engine temperature and coolant temperature within the optimal range.

The mechatronic controlled cooling system allows controlling the heat exchange processes of the engine and radiator in real time. The main purpose of the system is to maintain the engine temperature within the optimal range, adjust the coolant flow through the pump and fan, and the radiator's heat output power. With this approach, excess heat is quickly removed, energy consumption is optimized, and the engine operates stably [16].

The change in heat in the engine block is described by the following differential equation:

$$C_{dv} \frac{dT_e}{dt} = Q_{dv} - Q_s, \quad (3)$$

where $C_{dv} = \dot{m}_c c_p$ - heat capacity of the engine, $J/°C$; T_e - temperature in the engine block, $°C$; Q_{dv} - heat generated by the engine, W;

Substitute expression (1) into expression (3) and rewrite it as:

$$C_{dv} \frac{dT_e}{dt} = Q_{dv} - \dot{m}_c c_p (T_e - T_r), \quad (4)$$

The temperature of the liquid changes as heat is supplied to the external environment through the radiator:

$$C_s \frac{dT_r}{dt} = Q_s - Q_r, \quad (5)$$

Substituting expressions (1) and (2) into (5), we get:

$$C_s \frac{dT_r}{dt} = m_c c_p (T_e - T_r) - k_r A_r (T_r - T_a), \quad (6)$$

where C_c - coolant capacity, $\frac{J}{°C}$; T_a - outside air temperature, $°C$.

Generalizing equations (4) and (6), we write the differential equation of the cooling system as follows:

$$\begin{cases} C_{dv} \frac{dT_e}{dt} = Q_{dv} - \dot{m}_c c_p (T_e - T_r), \\ C_s \frac{dT_r}{dt} = m_c c_p (T_e - T_r) - k_r A_r (T_r - T_a), \end{cases} \quad (7)$$

Based on expression (7), we construct a Simulink model for a traditional engine cooling system (Fig. 2).

The Simulink model is built on the basis of a separate subsystem for each main component of the cooling system, which are integrated into the general model and allow for effective simulation of the entire system (Fig. 2). Subsystem simulations for each component were developed based on their mathematical expressions of heat and fluid flows. While the heat generated in the engine is a function of the engine's torque and speed, the electric water pump, which provides the mass flow of the coolant, operates depending on the density of the coolant, the pump's technical characteristics, and its speed.

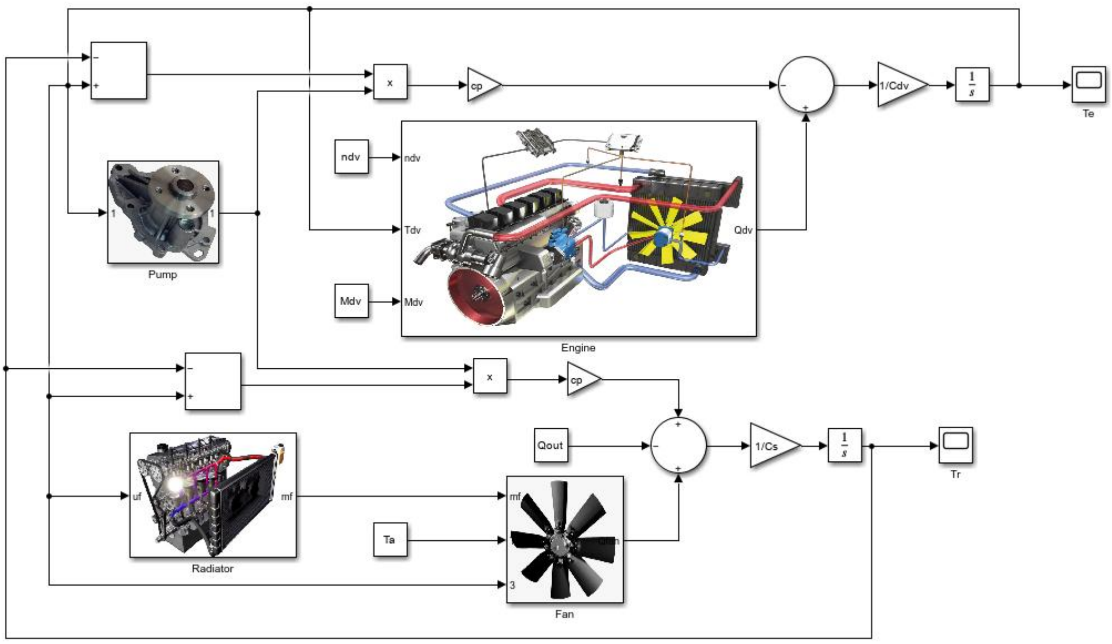


Figure 2. Simulink model of traditional cooling system.

PID-controlled management. The mechatronic control system manages these processes through a feedback control loop.

First, let's consider the classical PID-controlled (PID regulator) control. For the effective operation of the gasoline engine cooling system, its temperature must be constantly monitored. The PID (Proportional-Integral-Derivative) regulator is widely used to automate this process. The PID controller adjusts the operation of the water pump and radiator fan accordingly, calculating the difference between the engine coolant temperature and the target temperature. The proportional component reduces the current error in the system, while the integral component eliminates the long-term error and compensates for the resulting excess or missing heat. The derivative component, responding to the rate of temperature change, protects the system from vibrations. Thus, PID control ensures the engine's operation in the optimal temperature range, increasing its efficiency and reliability [17].

For this, the output signal of the model is returned to the controller for adjusting the control output command signal for the radiator fan. The control output of the PID controller is given as (8).

$$u(t) = K_P + K_I \int e(t)dt + K_D \frac{de(t)}{dt}, \quad (8)$$

The regulator gain coefficients for the cooling system were calculated using the Ziegler-Nichols PID tuning method, which provides a set of heuristic rules for selecting optimal PID coefficients.

With the help of PID control, system stability is ensured. The water temperature for the cooling system is selected taking into account the operating conditions of the engine and its geometry. The temperature of the coolant and the water flowing through the radiator is maintained in accordance with the operating (optimal) temperature. These values are determined experimentally and by the trial-and-error method, i.e., the most suitable parameters for maintaining the temperature at a given point are found $K_P = 50;\ K_I = 0.1;\ K_D = 80.$

Figure 3 shows a diagram of a gasoline engine with a cooling system controlled by PID regulators. The system consists of two main control channels: engine coolant temperature (T_e) and radiator coolant temperature (T_r). A PID regulator is used for control, which controls the radiator fan (ω_f).

The difference between the target temperature and the actual temperature measured is transmitted to the PID unit, which, accordingly, generates a control signal for the radiator fan (Fig. 3). Thus, the system maintains the water flow temperature at the working (optimal) level, which ensures efficient and stable engine operation.

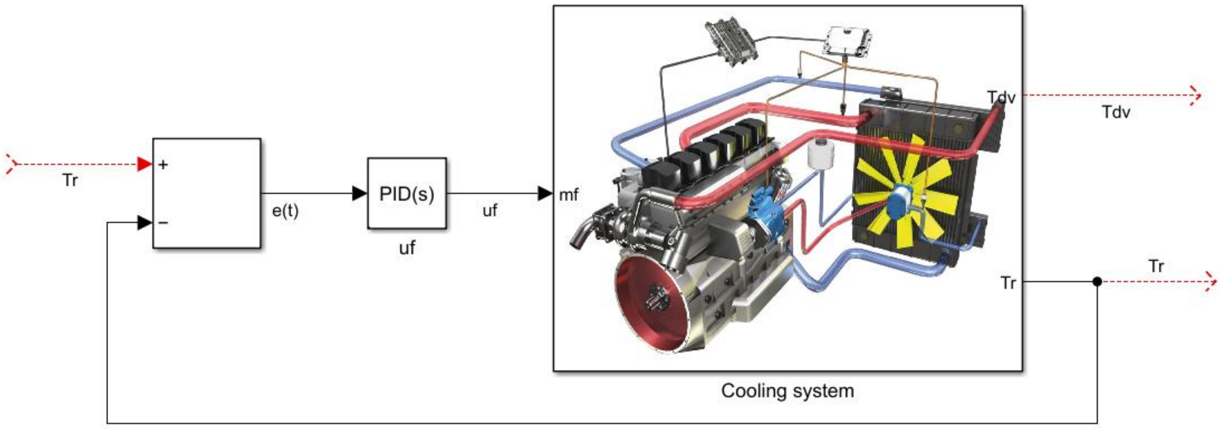


Figure 3. PID-controlled mechatronic cooling system model.

The advantage of control through PID regulators is that they increase the stability of the system, reduce excessive temperature fluctuations, and keep the system in a state of rapid response.

Lyapunov control: The mechatronic control system stabilizes this process by automatically controlling the fan. When developing the mathematical model of the problem, the heat transfer coefficient of the radiator $(k_r A_r)$ and fan control (ω_f) are taken, which accurately expresses the dynamics of the system. Let's rewrite expression (7) as (9):

$$\begin{cases} C_{dv}\dfrac{dT_e}{dt} = Q_{dv} - \dot{m}_c c_p (T_e - T_r), \\ C_s \dfrac{dT_r}{dt} = m_c c_p (T_e - T_r) - k_1 \omega_f (T_r - T_a), \end{cases} \quad (9)$$

where $k_r A_r = k_1 \omega_f$ - heat transfer coefficient; $u = \omega_f$ - control effect.

The problem of stabilizing the radiator temperature is posed as follows. It is necessary to find such a control law $u(x)$ that the radiator temperature in a closed system approaches the given value asymptotically:

$$T_r(x) \to T_r^*, \quad t \to \infty.$$

the control error is determined as follows:

$$e = T_r - T_r^*, \quad (10)$$

then the error is determined by the dynamics of (10):

$$\dot{e} = \frac{dT_r}{dt} = f(x) + g(x)u, \quad (11)$$

here $f(x) = \frac{m_c c_p}{C_s}(T_e - T_r), \; g(x) = -\frac{k_f}{C_s}(T_r - T_a), \; u = \omega_f.$

Let's define the Lyapunov function as follows:

$$V = \frac{1}{2}e^2. \quad (12)$$

we determine the derivative of the function based on the system of equations (12)

$$\frac{dV}{dt} = e\dot{e}, \quad (13)$$

here $\dot{e} = \dot{T}_r.$

Substituting expression (11) into (13)

$$\frac{dV}{dt} = e[f(x) + g(x)u], \quad (14)$$

To ensure the system's stability condition, management must satisfy the following condition:

$$\frac{dV}{dt} \le -ke^2, \; k > 0. \quad (15)$$

Substituting expression (14) into (15):

$$e[f(x) + g(x)u] = -ke^2, \quad (16)$$

if so, then $e \ne 0$

$$f(x) + g(x)u = -ke, \quad (17)$$

From relation (17) we obtain the stabilizing function in the form:

$$u = \omega_f = \frac{-ke}{f(x) + g(x)}, \quad (18)$$

Let's define the stabilizing expression for a mechatronic controlled cooling system:

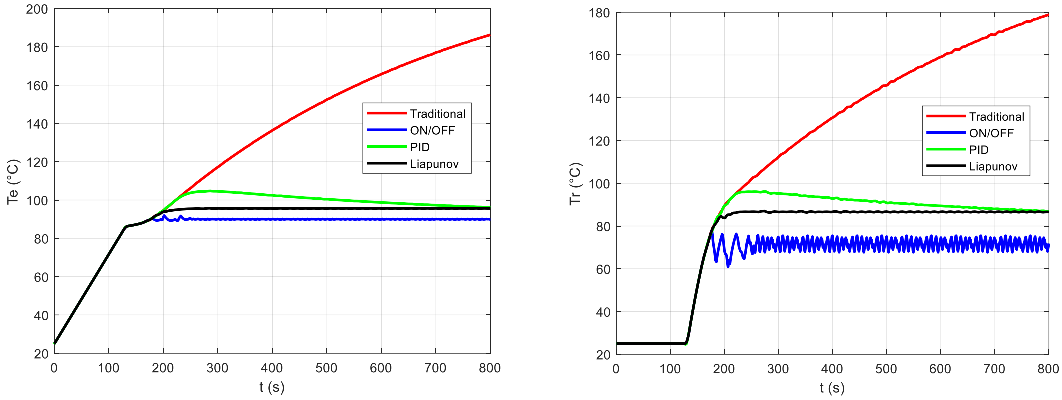
$$u = \omega_f = \frac{C_s k(T_r - T_r^*) + \dot{m}_c c_p (T_e - T_r)}{k_1(T_r - T_a)}. \quad (19)$$

Expression (19) is the law of control of the fan of a mechatronic controlled cooling system.

3. Results and discussions

The results of changes in the temperature of the coolant in the engine and radiator in traditional and mechatronic (ON/OFF, PID, Lyapunov) cooling systems are presented.

In conventional cooling systems, the engine temperature gradually rises after starting and continues to increase steadily over time. When the thermostat's opening temperature (about 90 °C) is reached, cooling begins, but the temperature continues to rise due to the lack of fan speed control. In this system, the temperature does not reach a stable state or occurs late, which can lead to overheating of the engine (Fig. 4 a, b).



a) b)

Figure 4. Change in coolant temperature in traditional and mechatronic cooling systems: a) ICE unit, b) radiator.

In the electronic control system, the fan is controlled electronically (ON/OFF), which allows the system to maintain temperature significantly better. The temperature is more precisely stabilized in the range of 85÷95 °C. Due to the electronic connection between the opening of the thermostat and the fan speed, temperature fluctuations are significantly reduced. This system is more energy efficient than the traditional one and ensures optimal engine operating temperature (Fig. 6).

The PID-controlled system controls temperature faster and provides a high level of stability. In the initial period (0-100 s), the temperature rises rapidly, then approaches the target temperature with the thermostat fully opening (about 90 °C). The PID algorithm optimizes the fan speed in accordance with the temperature, so the temperature is maintained with small fluctuations around the setpoint. As a result, the system works much more efficiently than traditional and simple electronic control [18].

The traditional system cannot effectively maintain the radiator temperature - it continuously increases over time, indicating an increase in heat in the system. The electronic ON/OFF control maintains the temperature within a certain range, but there are strong oscillations (auto-oscillations), which means that the fan is switching on and off frequently. PID and Lyapunov controls provide the most stable result, i.e., the temperature quickly approaches the working zone and is maintained smoothly with a small deviation [19].

4. Conclusion

In the traditional cooling system, the engine temperature stabilizes for a long time in the range of 80-90 °C, but very slowly. The radiator temperature gradually stabilizes after the thermostat opens. The heat transfer efficiency of the system is low and cannot provide optimal control in high-load situations. Analysis of this graph revealed shortcomings in the efficiency of the traditional system compared to mechatronic control systems.

It has been established that a mechatronic controlled cooling system, especially a system operating using a PID control system, works much more efficiently and reliably than a traditional (ON/OFF) system.

Based on a nonlinear mathematical model of a mechatronic cooling system, a stabilizing method for controlling fan speed based on the Lyapunov method was developed. This allows for flexible adjustment of the heat emission intensity through the radiator and ensures a reduction in excessive vibrations compared to PID controlled control.

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