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*Наведені результати розробки аналітичної моделі контуру гарячого водопостачання з котлом, сонячним колектором та баком-акумулятором тепла. Розглянуто варіанти структур та алгоритмів автоматичних регуляторів температури гарячої води на подачі до користувача. Описано процедуру налаштування регулятора з внутрішньою моделлю за допомогою отриманої аналітичної моделі. Показано умови ефективного застосування запропонованого рішення*

*Ключові слова: система гарячого водопостачання, алгоритм керування, регулятор з внутрішньою моделлю, енергоефективність*

*Приведены результаты разработки аналитической модели контура горячего водоснабжения с котлом, солнечным коллектором и баком-аккумулятором тепла. Рассмотрены варианты структур и алгоритмов автоматических регуляторов температуры горячей воды на подаче к потребителю. Описана процедура настройки регулятора с внутренней моделью с помощью полученной аналитической модели. Показаны условия эффективного применения предлагаемого решения*

*Ключевые слова: система горячего водоснабжения, алгоритм управления, регулятор с внутренней моделью, энергоэффективность*

UDC 621.311: 681.5.015

DOI: 10.15587/1729-4061.2016.73385

# AN ALGORITHM OF REGULATING AN ENERGY-EFFICIENT HOT WATER SYSTEM WITH THE OBJECT MODEL IN THE CONTROLLER

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## 1. Introduction

Energy conservation is a priority of the state policy. Economic growth in Ukraine largely depends on the rate of power supply, the potential of energy efficiency and its use in industry. The main requirements of energy conservation in Ukraine are set out in the Comprehensive state program “Energy conservation in Ukraine of 2005–2020” [1–3].

Ukraine increases energy efficiency and provides comprehensive industry development by taking measures aimed at technical upgrading of production, the use of scientific and technological potential of the country, and high-tech manufacturing.

An extensive use of automated engineering equipment helps save energy sources, improve the quality and increase reliability of production, which can be more efficient if we integrate automation means in network structures.

By 2020, according to the International Energy Agency (IEA), up to 75 % of heating units in developed countries will be based on energy-saving technologies [4].

In modern conditions of insufficient fuel resources and problematic heat production, it is important to create an alternative system of autonomous heating and hot water supply through innovations in energy efficiency. Therefore, there is a need to develop a special methodological and methodical apparatus. New conditions of fair competition in the sector are likely to improve the quality of services and lower the tariffs [5].

## 2. Analysis of the previous studies and formulation of the problem

Improving the energy efficiency of units that use renewable energy sources is quite an urgent problem to be solved in different ways that upgrade the technical and economic characteristics of the power equipment and optimize its energy balances and modes depending on a variable load and the power of a renewable source. Ways to solve these problems are sought in many countries, such as China, Japan, France, and the Philippines [6], and include, in particular, the creation of new materials and technologies, the integration of alternative sources in systems of existing power plants, and algorithms to optimize the interaction of multiple sources.

Heating supply units based on alternative energy sources have prospects in terms of saving fuel resources [7]. Involvement of automation in this type of systems allows subsequent increase in the lifetime of units and quite a precise control of heat and fuel efficiency.

According to the International Energy Agency (IEA) [8], given the urgent environmental issues and the existing need of energy conservation, more attention is paid to the use of renewable energy worldwide. The ABB company (Switzerland) has studied and considered possible areas of the application of renewable energy [9]. According to the statistics summary, it is proved that significant opportunities of power supply to buildings are offered by installation of solar collectors for hot water

and heating supplies. Solar collectors allow producing energy without harmful impact on the environment. A properly designed solar system can cover up to 50–60 % of energy costs that are usually spent on hot water supply.

Each solar power unit is meant for a particular technological object, which explains [10] the existing varieties of the system configurations, coolant recirculation, and principles of the controllers' work. The system of alternative energy sources and additional water heating is double-circuit with an induced coolant recirculation (Fig. 1). These circuits are structurally separated.

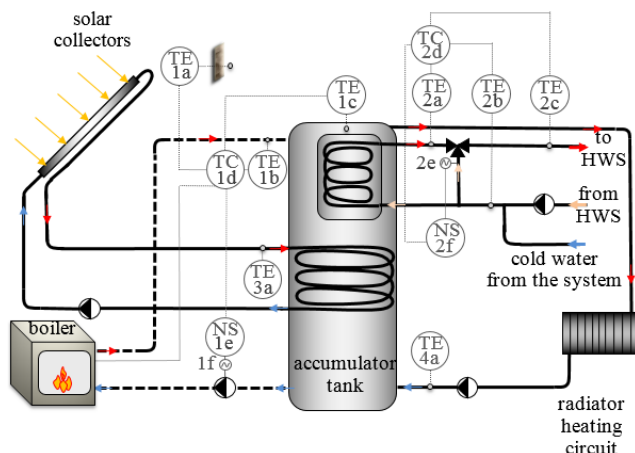


Fig. 1. A generalized functional scheme of the solar power unit

The authors of [11] consider basic principles of controlling the engineering systems of solar units. Automatic control devices are needed to coordinate all elements of the system. This is based on data from various sensors that are installed in the collector, heat accumulator tank, boiler, and pipeline equipment. A circulation pump or additional heating equipment is switched on the basis of the temperature data analysis. This allows adjusting the operating parameters, namely: the temperature of water in the storage tank, the maximum HWS temperature, and time limits on the boiler operation during the day. More complex systems allow using automatics for changing the tilt angle of the collector and orientation by the sun to increase the production of hot water by 30–35 %.

The unit provides accumulation of the maximum available amount of solar heat energy. The collector circuit maintains a constant use of the coolant by the circulating pump. In the circuit of an additional energy source, there is a weather-dependent temperature control of the coolant in the accumulator tank. The specified value of temperature in the accumulator tank (1c) is maintained by the controller (1d) depending on the information from sensors of outside temperature (1a and 1b) at the feeding pipeline from the boiler and 1c due to the command “start/stop” of the boiler and a signal to the actuator (1e) of the electric motor of the circulation pump (1f). The controller (2d) adjusts the temperature of water supplied in the HWS system (2c) by sending control signals to the electromagnetic relay (2f) of the three-way valve (2e), which leads to changes in the volume ratios of the hot (2a) and cold water (2b).

The accuracy of the mathematical model of the control object is the basis for calculating the controller settings and

the main factor affecting the quality of transition processes. Therefore, there is a problem of mathematical formulation of a maximally universal transfer function that would provide accurate calculations of the control systems. One object allows developing a mathematical formula that will be universal for such objects if constant values of the technical specifications of some system units are eliminated. The main requirements of the described control system include a maximally quick reach of the desired temperature of hot water with a minimal dynamic deflection.

### 3. The purpose and objectives of the study

The purpose of the study is to develop an algorithm of controlling the system of hot water supply to buildings when the heat source is the combination of a classic boiler and a solar collector, which allows creating an energy efficient system, although simultaneously aggravates maintaining a comfortable temperature of water that is supplied to consumers.

To achieve this goal, it is necessary to solve the following tasks:

- to determine the nature of dynamics and to develop an analytical model of the control object;
- to consider the options of automatic controllers of the HWS circuit;
- to carry out comparative studies of control algorithms (on the basis of selected structures of controllers) to determine their compliance with the requirements and the prospects of their use.

### 4. Devising a model of the control object

A model of the control object and control system is developed for the system of hot water supply (HWS) and heating of dwelling houses. Water is heated by a solar system and a boiler combined [12].

It is assumed that the temperature of cold water from the centralized network is 15 °C. The desired hot water temperature is specified as 55 °C, and the flow in the heating system – 70 °C.

A block diagram of the control object is shown in Fig. 2.

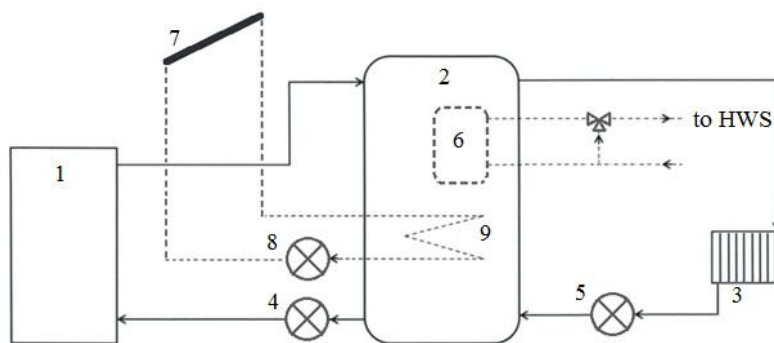


Fig. 2. A block diagram of the control object

The notation of Fig. 2 is as follows: 1 – the boiler; 2 – the accumulator tank; 3 – devices for room heating; 4 – the circulation pump in the reverse pipeline between the boiler and the tank; 5 – the circulation pump in the reverse pipeline between room heating devices and the tank; 6 – the heat exchanger for hot water supply; 7 – the solar

collector; 8 – the circulation pump of the solar collector circuit; 9 – the heat exchanger connected to the solar collector circuit.

The accumulator tank used in the study has a capacity of 500 liters because of the requirements of an efficient use of the collectors' floor space. This allows accumulating the maximum amount of heat energy in the tank and increasing the efficiency of the solar system [13]. The unit uses solar collectors with the specifications given in Table 1.

Table 1

Specifications of the solar collector

Parameter	Value
Manufacturer	RUCELF
Model	SCV-58-1800-30
The quantity of tubes, pcs	30
Weight, kg	95
Productivity, kW h/day	22
Absorbing surface, m <sup>2</sup>	3.9
Capacity of the heat exchanger, l	2.1
Material of the internal heat exchanger	Copper
Heat capacity $C_p^c$ , kJ/(kg K)	0.385
Heat irradiation $\alpha$ , W/(m <sup>2</sup> K)	13.1
Coolant (a 45% propylene glycol solution)	
Volume of the coolant in the reservoir, cm <sup>3</sup>	683.9
Density $\rho$ , g/cm <sup>3</sup>	1.036
The maximum flow rate, m <sup>3</sup> /h	0.04
$T_{min}$ , °C	-30
$T_{max}$ , °C	120
$C_{pT}^c$ , kJ/(kg K)	0.68

Consider separately each circuit of the control object. A block diagram of the solar circuit is shown in Fig. 3.

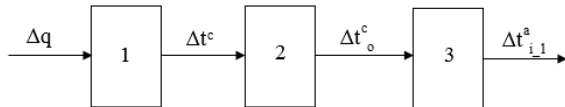


Fig. 3. A block diagram of the solar collector

Fig. 3 schematically shows the solar circuit, where 1 is absorption of a solar flow by walls of the collector tubes; 2 is heat transfer from the collector walls to the coolant (a 45 % propylene glycol solution); 3 is heat exchange between the collector coolant and the solar system coolant (water). The following notation is used:  $q$  – a solar heat flow;  $\alpha$  – a coefficient of heat irradiation from the wall of the solar collector to the coolant ( $\alpha=3.1$  W/(m<sup>2</sup> K));  $t^c$  – temperature of the wall of the solar collector;  $m^c$  – the collector weight ( $m^c=95$  kg);  $m_T^c$  – the collector weight ( $m_T^c=0.7$  kg);  $F^c$  – an absorbing surface area of the collector ( $F^c=3.9$  m<sup>2</sup>);  $t_{out}^c$  – the coolant temperature at the outlet of the solar collector;  $G_T^c$  – consumption of the coolant in the solar collector ( $G_T^c=0.04$  m<sup>3</sup>/h);  $G_T^h$  – consumption of the coolant in the solar circuit (5.76 m<sup>3</sup>/h);  $m_T^h$  – the weight of water circulating in the solar circuit ( $m_T^h=12.5$  kg);  $t_{i1}^a$  – the temperature of the solar circuit coolant at the tank inlet.

The block diagram in Fig. 3 allows developing a system of heat balance equations (1) [14].

$$\begin{cases} F^c \Delta q = F^c \alpha \Delta t^c + m^c c_p^c \frac{dt^c}{d\tau}, \\ \alpha F^c \Delta t^c = G_T^c c_{pT}^c \Delta t_{out}^c + m_T^c c_{pT}^c \frac{dt_{out}^c}{d\tau}, \\ m_T^h c_{pT}^h \frac{dt_{i1}^a}{d\tau} = m_T^c c_{pT}^c \Delta t_{out}^c - G_T^c c_{pT}^c \Delta t_{i1}^a. \end{cases} \quad (1)$$

On bringing the equations to the standard form and using the constant values, we obtain (2):

$$\begin{cases} 715,9 \frac{dt^c}{d\tau} + \Delta t^c = 0,076 \Delta q, \\ 17,5 \frac{dt_{out}^c}{d\tau} + \Delta t_{out}^c = 3,32 \Delta t^c, \\ 2,17 \frac{dt_{i1}^a}{d\tau} + \Delta t_{i1}^a = 1,59 \Delta t_{out}^c. \end{cases} \quad (2)$$

Consider thermal processes in the accumulator tank (Fig. 4).

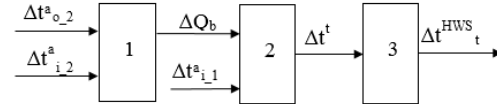


Fig. 4. A block diagram of the accumulator tank

Fig. 4 schematically shows heat exchange processes in the accumulator tank, where 1 is heating of the system coolant in the boiler; 2 is heat exchange between water in the heating system tank and a heated coolant from the circuits of the solar system and the boiler; 3 is heat exchange between tanks of the heating system and HWS. The following notation is used:  $t_{i1}^a$  – the temperature of the solar circuit coolant at the tank inlet;  $t_{i2}^a$  – the temperature of the boiler circuit coolant at the tank inlet;  $t_{out,2}^a$  – the coolant temperature at the tank outlet to the boiler circuit;  $t_{i3}^a$  – the coolant temperature at the tank inlet from the reverse line of the heating system ( $t_{i3}^a=40$  °C);  $t_{out,3}^a$  – the coolant temperature at the tank outlet to the heating system ( $t_{out,3}^a=70$  °C);  $t^t$  – the boiler temperature;  $t^m$  – the temperature of water in the heating system ( $t^m=15$  °C);  $G_T^b$  – water consumption in the boiler circuit ( $G_T^b=6.2$  m<sup>3</sup>/h);  $m_T^{out}$  – the weight of the coolant that circulates in the heating system ( $m_T^{out}=20$  kg);  $m_T^b$  – the weight of the coolant in the tank ( $m_T^b=500$  kg);  $m_{HWS}^t$  – the weight of coolant in the HWS tank ( $m_{HWS}^t=200$  kg);  $t_{HWS}^t$  – the temperature of the coolant in the HWS tank;  $c_{pT}$  – specific heat capacity of the coolant (water) ( $c_{pT}=4.218$  kJ/(kg K));  $Q_b$  – the amount of heat produced by the boiler.

According to the block diagram shown in Fig. 4, we get a system of equations of the thermal balance (3).

$$\begin{cases} m_T^t \frac{dt^t}{d\tau} + G_T^b \Delta t^t = (\Delta t_{i2}^a - \Delta t_{o2}^a) G_T^b + G_T^t \Delta t_{i1}^a, \\ \Delta Q_b = G_T^b c_{pT}^b (\Delta t_{i2}^a - \Delta t_{o2}^a), \\ m_{HWS}^t \frac{dt_{HWS}^t}{d\tau} + (\Delta t_{HWS}^t - t^m) m_{HWS}^t = m_T^t \Delta t^t - m_T^{out} (\Delta t_{o3}^a - \Delta t_{i3}^a). \end{cases} \quad (3)$$

From the second equation of system (3) follows:

$$(\Delta t_{i2}^a - \Delta t_{o2}^a) = \frac{\Delta Q_b}{G_T^b c_{pT}^b}. \quad (4)$$

Equation (4) is applied for the first equation of the system (3). After transformations and integration of the constant values, we get the following:

$$\begin{cases} 80.6 \frac{dt^t}{d\tau} + \Delta t^t = 3.8 \cdot 10^{-5} \Delta Q_b + 0.93 \Delta t_{-1}^a, \\ \frac{dt_{HWS}^t}{d\tau} + \Delta t_{HWS}^t = 2.5 \Delta t^t + 12. \end{cases} \quad (5)$$

Equation (5) estimates the water temperature in the HWS tank. But according to the accepted block diagram of the object and taking into account the processes of heat exchange, the resulting value will be dependent on the set coolant temperature in the heating system that is much higher than the temperature at the inlet to the HWS system. The situation is improved due to a three-way valve that is installed after the boiler and allows mixing the flows of hot and cold water, and getting water of the desired temperature in the HWS system.

The equation of the heat balance for the segment is as follows:

$$\begin{aligned} \Delta G_{HWS}^t (\Delta t_{HWS}^t - \Delta t^{HWS}) = \\ = \Delta G^s (\Delta t^{HWS} - t^s), \end{aligned} \quad (6)$$

where  $G_{HWS}^t$  is consumption of hot water from the HWS tank;  $G^s$  – consumption of the system water;  $G^{HWS}$  is consumption of water from the HWS;  $t_{HWS}^t$  is the temperature of the coolant in the HWS tank;  $t^{HWS}$  is the temperature of hot water supplied to the user;  $t^s$  is the temperature of water in the heating system ( $t^s=15^\circ\text{C}$ ).

Taking into account (2), (5), and (6), we model the transition process is modeled with the help of the application package Matlab (Fig. 5, 6). The experiment is based on the disturbance by the change in the discharge of hot water from the tank; the initial hot water temperature corresponds to a 50 % opening of the valve, and the final – a 60 % opening.

Consequently, the dynamics of the hot water temperature at its supply to users can be described by means of the system of transfer functions:

$$T_{HWS}(s) = \left[ \left( \frac{0.076}{715.9s+1} \cdot \frac{3.32}{17.5s+1} \cdot \frac{1.59}{2.17s+1} \cdot \frac{0.93}{80.6s+1} + \frac{3.8 \cdot 10^{-5}}{80.6s+1} \right) \cdot Q(s) - \frac{2.5}{s+1} \cdot U(s) + (1-U(s))T_{cold}(s) \right] \frac{0.78}{2.9s+1} e^{-0.2s}, \quad (7)$$

where  $U(s)$  is the hot water valve position;  $Q(s)$  is the solar heat flow;  $T_{cold}(s)$  is cold water temperature;  $T_{HWS}(s)$  is the temperature of hot water at its supply.

The resulting model of the control object (7) is subsequently used for calculating the controller adjustment.

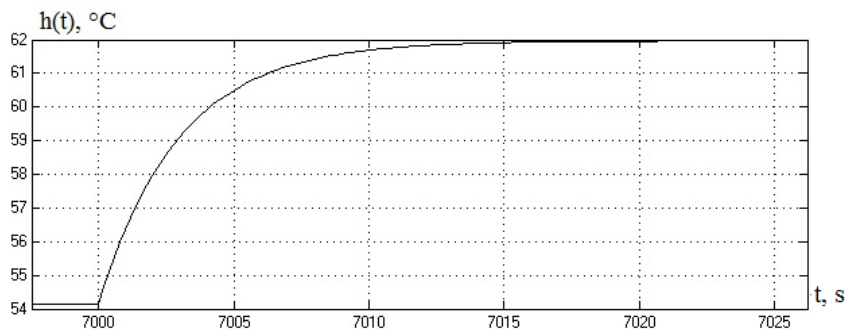


Fig. 6. A diagram of the HWS temperature acceleration under consumption of hot water from the tank

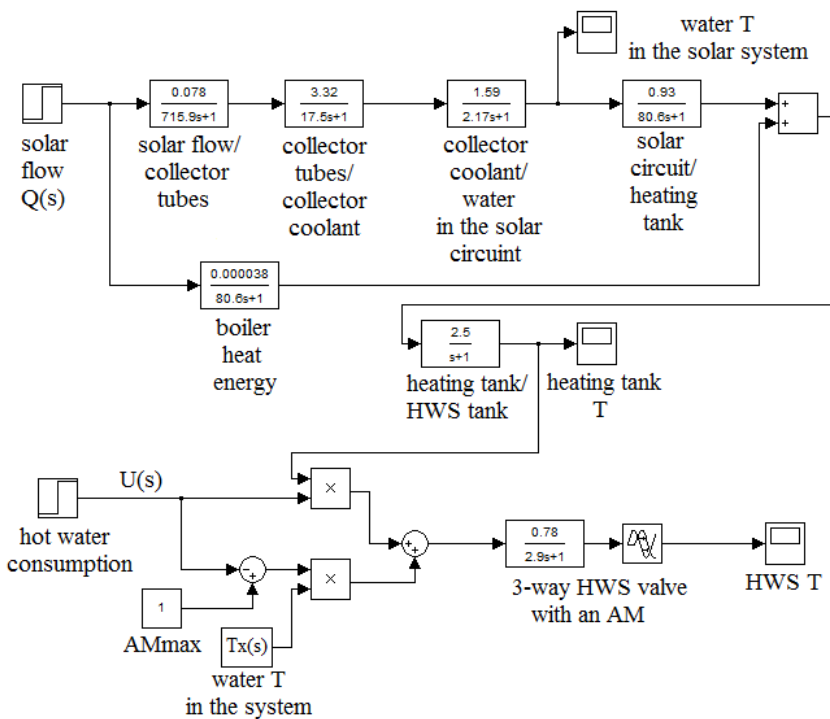


Fig. 5. A model of the control object in Matlab Simulink

### 5. Synthesis of the automatic control system

The study focuses on transition processes in a single-circuit control system with PI- and PID-controllers in terms of achieving a minimum dynamic error and adjustment time (Fig. 7).

We choose the method of enhanced amplitude and phase response that can provide necessary characteristics of the quality of the control system with typical laws of adjustment. We focus on the resulting transition process that corresponds to the degree of attenuation  $\psi=0.95$  and, consequently, the root oscillation index  $m=0.4768$  [15].

The resulting PI-controller has the following settings (8):

$$W_p(s) = 12.596 \left( 1 + \frac{1}{0.64s} \right). \quad (8)$$

Additionally, we consider rapid methods of calculating the settings:

– the PI-controller: Thomasson’s method (1997) [16], which is applicable only if  $\tau_{obj} < 0.5$ .

$$W_p(s) = 3.72 \left( 1 + \frac{1}{3s} \right). \tag{9}$$

– the PID-controller: the Huang and Jeng method (2003) [16] is focused on the minimum IAE and is applicable if  $\frac{\tau_{obj}}{T_{obj}} < 0,33$ :

$$W_p(s) = 14.52 \left( 1 + \frac{1}{2.994s} + 0.09s \right). \tag{10}$$

If the object model can be identified, it is possible to avoid setting up the control system by using IMC (internal model control) [17–20].

The IMC principle is based on the assertion that control is effective when the system to some extent includes the features of the control object, i.e. if the ACS (automatic control system) adjustment subsystem includes the object model, then a perfect control quality (in particular, absence of re-adjustment or variability of the process, and the minimum adjustment time) is hypothetically possible.

For the studied control object the following is true:

$$W_M(s) = \frac{0.78}{2.9s + 1} e^{-0.2s} \Rightarrow \Rightarrow W_{M+}(s) = \frac{0.78}{2.9s + 1}, W_{M-}(s) = e^{-0.2s}, \tag{11}$$

where  $W_{M-}(s)$  is a part of the model that can not be reversed;  $W_{M+}(s)$  is a part of the controller.

The effect of errors in determining the model is reduced and the system robustness is enhanced by means of a filter that is introduced in the controller:

$$W_{\phi}(s) = \frac{1}{(\lambda s + 1)^n}, \tag{12}$$

where  $\lambda$  is a configurable parameter that is selected by means of a compromise between the system operational speed and robustness;  $n$  is the filter order.

Let us model transition processes (Fig. 9) and compare the performance of the first- and second-order filters in the studied object if  $\lambda = \tau_{obj} = 0.2$  and  $\lambda = 0.5\tau_{obj} = 0.1$ . The quality characteristics shown in Table 3 prove that if  $\lambda = 0.1$  it is possible to achieve a better performance of the control system compared to the typical adjustment laws.

However, the use of the first-order filter causes generation of a large-amplitude control that can not be fulfilled by the actuator with a finite velocity and can promote the wear of the system components. This aspect can be controlled by selecting the filter constant or order (Fig. 8).

Transients in temperature changes that correspond to the specified controller actions (Fig. 8) prove that the choice of the filter constant and order affect the technological variable and the performance quality of the entire system (Table 3).

Let us compare the values of the direct parameters of quality of single-circuit systems with PI- and PID-controllers (Table 2) and the IMC system (Table 3). According to the requirements of transition processes that are set out in paragraph 2, it can be concluded that being implemented by the IMC system they have the following characteristics: no read-

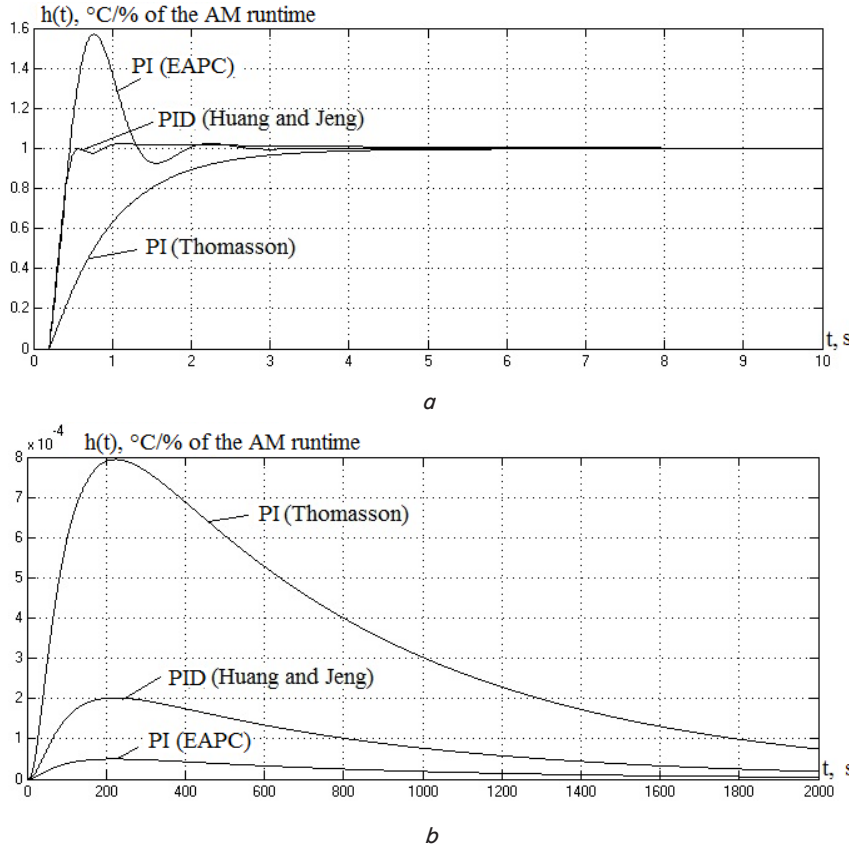


Fig. 7. Transition processes in a single-circuit control system: *a* – in the channel “task-output”; *b* – in the channel “disturbance-output”

Table 2 summarizes characteristics of the controllers’ performance quality that are determined by the above mentioned adjustment methods. They prove the possibility of applying traditional structures of PID-controllers for the object under study.

Direct characteristics of the quality of transition processes of a single-circuit control system

Quality parameters	Task-output			Disturbance-output		
	PI (EAPC)	PI (Thomasson)	PID (Huang and Jeng)	PI (EAPC)	PI (Thomasson)	PID (Huang and Jeng)
Static error	0	0	0	0	0	0
Dynamic error	0.585	0	0.175	0.00005	0.00079	0.0002
Attenuation rate	0.94	1	0.71	1	1	1
Readjustment, %	20.5	0	17.5	0	0	0
Control time	1.85	2.65	1.28	807	801	814

Table 2

justment, minimum control time, and dynamic prospects. Selecting an optimal IMC (Fig. 8), it is necessary to pay attention to the AM behavior, which requires a slight effect of the controller.

Thus, a single-circuit control system that uses IMC and a second-order filter with  $\lambda=0.1$  has optimal transients with the least amplitudity of the adjustment body operation (process 4 in Fig. 8, 9).

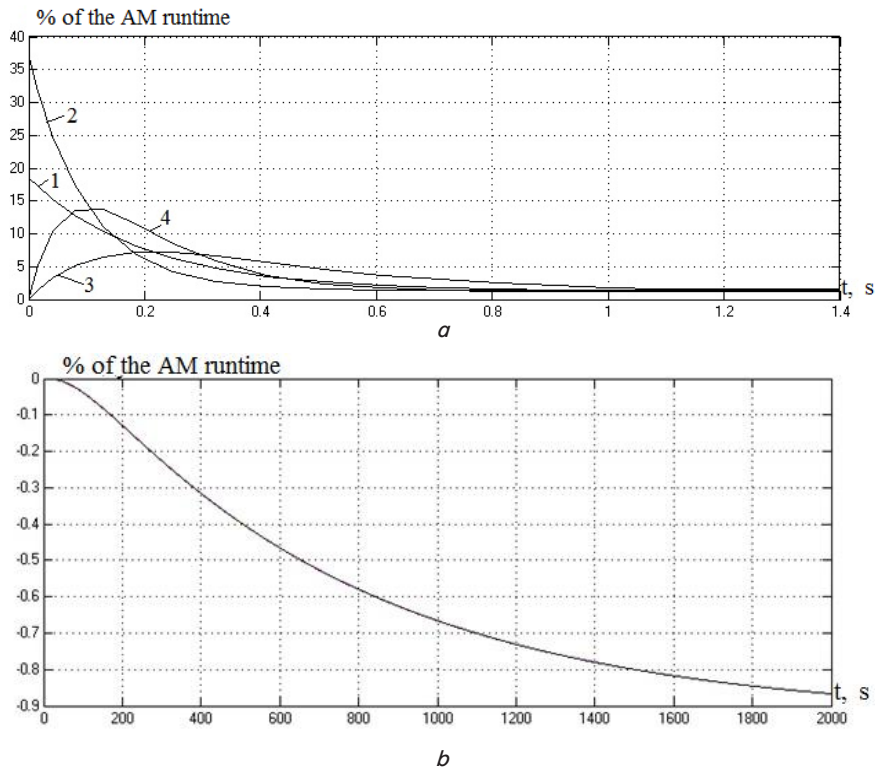


Fig. 8. The AM runtime in a single-circuit IMC system: 1 – the first-order filter,  $\lambda=0.2$ ; 2 – the first-order filter,  $\lambda=0.1$ ; 3 – the second-order filter,  $\lambda=0.2$ ; 4 – the second-order filter,  $\lambda=0.1$ ;  $a$  – in the channel “task-output”;  $b$  – in the channel “disturbance-output”

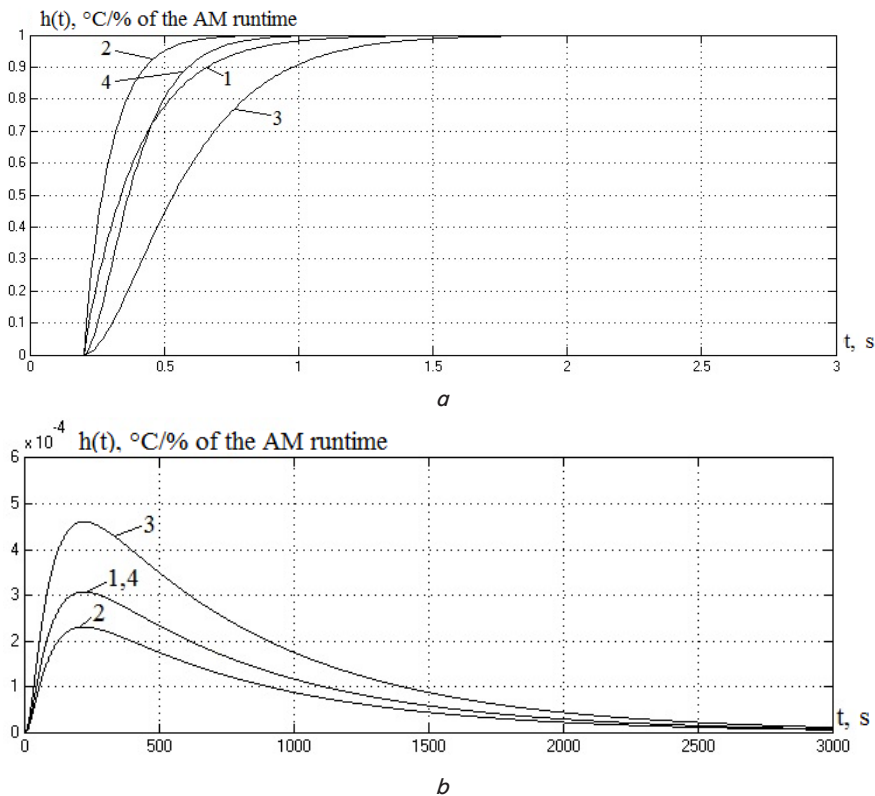


Fig. 9. Transition processes in a single-circuit IMC: 1 – the first-order filter,  $\lambda=0.2$ ; 2 – the first-order filter,  $\lambda=0.1$ ; 3 – the second-order filter,  $\lambda=0.2$ ; 4 – the second-order filter,  $\lambda=0.1$ ;  $a$  – in the channel “task-output”;  $b$  – in the channel “disturbance-output”

Table 3

Direct characteristics of the quality of transition processes in a single-circuit IMC

Quality parameters	Task-output				Disturbance-output			
	1	2	3	4	1	2	3	4
Static error	0	0	0	0	0	0	0	0
Dynamic error	0	0	0	0	0.0003	0.00023	0.00046	0.0003
Attenuation rate	1	1	1	1	1	1	1	1
Readjustment, %	0	0	0	0	0	0	0	0
Control time	0.8	0.5	1.18	0.68	814	807	1100	814

## 6. Discussion of the resulting mathematical models of the HWS control system

The results of mathematical modeling show an effective control of temperature in the hot water system by means of classic PID-algorithms and by using the object model as part of the controller (the IMC approach). The absence of readjustment and fast transition processes in the ACS with an IMC result from its structure, in which (in the channel “setting-the current value of water temperature”) the resulting transfer function is close to  $1(t)$  adjusted for delay in the feed, i. e. dynamics of the temperature change is similar to the dynamics of its tasks.

The duration of transition processes at changing the research tasks is linked to the inertia values of the AM and the temperature sensor and can vary to a large extent. Therefore, the development of an automatic control system involves a particular attention to the choice of technical means and their parameters in the preliminary assessment of the object dynamics. The studies show that

the IMC filter order affects in the following way: the use of high orders is more suitable for practical application since it slows down the actuator motion by slowing the response to the mismatch change in the initial phase of the transition process.

Given the specification of the adjustment procedure in the analytical model, the control system can be supplemented with an autotuning circuit, whereas its input data will be structural and technical parameters of hot water supply, and the operation result – a generated object model that is built into the controller structure.

## 7. Conclusions

1. The resulting analytical model of the control object reflects the effect of the solar radiation flow and quantitative characteristics of the produced and allows specifying the values of temperature for the systems of heating and hot water supply; the dynamics of the effect is described by means of a transfer function, whose parameters depend on the design and technological characteristics of the unit and the geographical location of the object, which affects the total amount of the received solar energy.

2. The enhanced amplitude and phase characteristics method and rapid methods were used in setting PI- and PID-controllers; the designed IMC-based ACS uses a mathematical description of the segment from the control valve to the hot water temperature sensor as the object model in the IMC structure; the intensity of solar radiation that affects temperature in the accumulator tank acts as an external disturbance. The advantage of the IMC structure is that the known object model actually provides a high-quality control system that does not require intermediate calculation of the controller parameters.

3. Optimal values of the assessment criteria, such as the minimum dynamic error and minimum-time control, are received among the considered transients in the IMC-based system, and the second-order filter is recommended to slow down the AM motion while maintaining the high quality of control.

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