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Application of CAE-modeling for the study of the influence of the sensor location on the flow-through water heater operation

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Abstract. The article deals with issues related to increasing the efficiency of the system of automatic maintenance of the temperature of liquid media entering the pipes to the place of consumption. For this purpose, a flowing water heater model is proposed, made in the SolidWorks environment, the construction parameters of which can be changed using the appropriate macro and screen form. It is shown that the choice of the location of the temperature sensor has a significant effect on such parameters of the device as the accuracy of maintaining a given temperature regime and the duration of the transient process caused by a change in the temperature of the liquid entering the heater. On a concrete example, it is shown that by changing the distance between the sensor and the heating module, it is possible to achieve minimum temperature fluctuations of the heat-transfer-agent at the heater outlet.

1. Introduction

Automatic control and regulation systems have recently become increasingly important, since the quality of the operation of such systems largely influence on the quality of products, the amount of energy consumption, the ease of operation of equipment and a number of its other technical, consumer and economic properties [1, 2]. The issues of developing such systems and increasing the efficiency of their work in a variety of applications have been the subject of a large number of works since the middle of the last century, for example [3–8]. Among the whole variety of such systems and the devoted to them publications, it is especially worth mentioning the works devoted to the control and regulation of temperature processes, because the temperature is one of the main factors, the sustentation of which at a proper level is important both in production and in an everyday life. And among them, in turn, can be distinguished regulators of the temperature of liquid media, and water first of all, since a water is used both in everyday life and at enterprises as a heat-transfer-agent or like a component of the technological process.

Typically, temperature control systems are implemented using microcontrollers and PID algorithms to ensure the rapid completion of transient processes and to minimize temperature fluctuations during regulation [9], but in the simplest systems, threshold regulators are also used. At present, industry produces a wide range of such regulators for liquid media [10], including regulators controlling the operation of flow heaters [11–14]. Their feature is both the instability of the flow of the liquid passing through the heater due to a change in the degree of water consumption, and the changeability of the water temperature entering the heater. In addition, the spreading in the space the heat source, the temperature sensor and the place of water consumption leads to the appearance of a so-called transport delay, as a result of which the use of pure PID algorithms for maintaining the temperature at a constant level becomes ineffective [15]. For this reason, the calculation of such regulators becomes extremely complex and approximate, because it is practically impossible to take into account all features of the structural design of the heating module analytically, as proposed in [16, 17].

In this regard, it becomes urgent to develop a methodology that allows to ensure high quality of temperature control for flow heaters of various designs by choosing optimal parameters that define the geometry and the relative position of components of the heater. In particular, the aim of this work was the development of a technique based on the application of a computational experiment on the CAE model of flow heaters constructed in the environment of the corresponding simulators of dynamic temperature processes occurring in liquid and solid media.

2. Environment and Stages of Modeling

Among the many software products that allow solving the tasks of fluid dynamics and heat transfer on personal computers, the CFD (Computational Fluid Dynamics) packages from AutoDesk [18] and ANSYS [19], as well as the Flow Simulation module [20] from Dassault Systèmes SolidWorks [21] are widely distributed. Although SolidWorks is a CAD system, the use of the included CFD module for the given task solved was recognized as the most suitable, because it provides the optimal combination of performance, interface simplicity and sufficient functionality on limited computing resources of a personal computer. This conclusion is confirmed, in particular, by the results presented in [22–24].

The entire process of conducting research in the Flow Simulation environment is divided into four stages. The first one creates the actual model of the object under study, that is the assembly consisting of individual components that are included in it. This stage can be performed completely manually, using the appropriate interface means. In this case all or part of the components of the assembly can be imported from other development environments that support formats for the exchange of CAD data. An alternative solution is to use your own macro that automates the process of creating a model in accordance with specified requirements. At the second stage, the mesh is superimposed on the model and the shape of the cells is chosen, since the solution of the problem is reduced to the solution of nonlinear inhomogeneous partial differential equations by the finite element method. At the next stage, the environmental conditions and parameters of various external factors that are stationary or dynamically affecting the simulation object are set. The process of simulation and obtaining of temperature distributions and distributions in space and time of other parameters of interest are performed at the last, final stage.

Since the aim of the work was to develop a technology for designing and researching water heaters, at the first stage, to automate the process of creating a model, an appropriate macro was developed, launched from the user's dialog box, allowing you to vary the geometric dimensions of the structural elements of the heating block, for example, to choose there optimal relation for the given criterion of quality. As a basis for the design of this unit, the variant shown in Figure 1*a* was chosen, which is most often found in models of different manufacturers. Appearance of the form for specifying the geometric dimensions of the structure is shown in Figure 1*b*, and in Figure 1*c* the variants of assemblies obtained using the developed macro are presented. The algorithm of its operation is shown in Figure 2. From it, as well as from Figure 1*b*, it can be seen that with the help of this macro, the basic details of the heating module are separately constructed for such parameters as the diameter of the inlet and outlet nozzles, the diameter and the length of the tank: the tank body (cylinder), its covers, heating element and its base. In this case, the dimensions of the details that are not specified in the dialog box (except for the base of the heating element having a fixed value) were set proportionally to the dimensions set by the interface. The final construction of the assembly of the heating module is performed by pressing the button "Construct the tank". For convenience, a separate additional button was added to the SolidWorks toolbar for calling the macro.

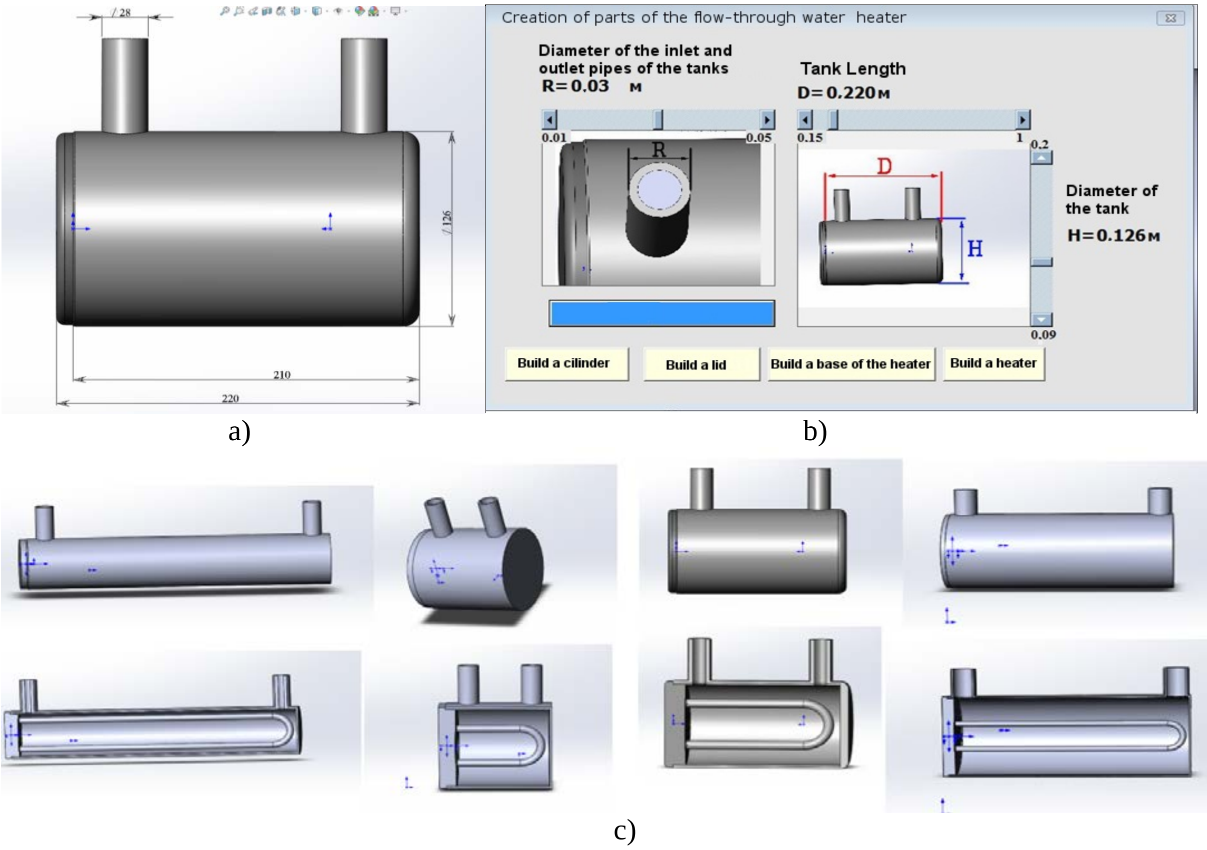

Figure 1. The design of the heating module (*a*), the dialog form of the macro for entering the parameters of its assembly (*b*), and the various variants of such assemblies, constructed with this macro (*c*).

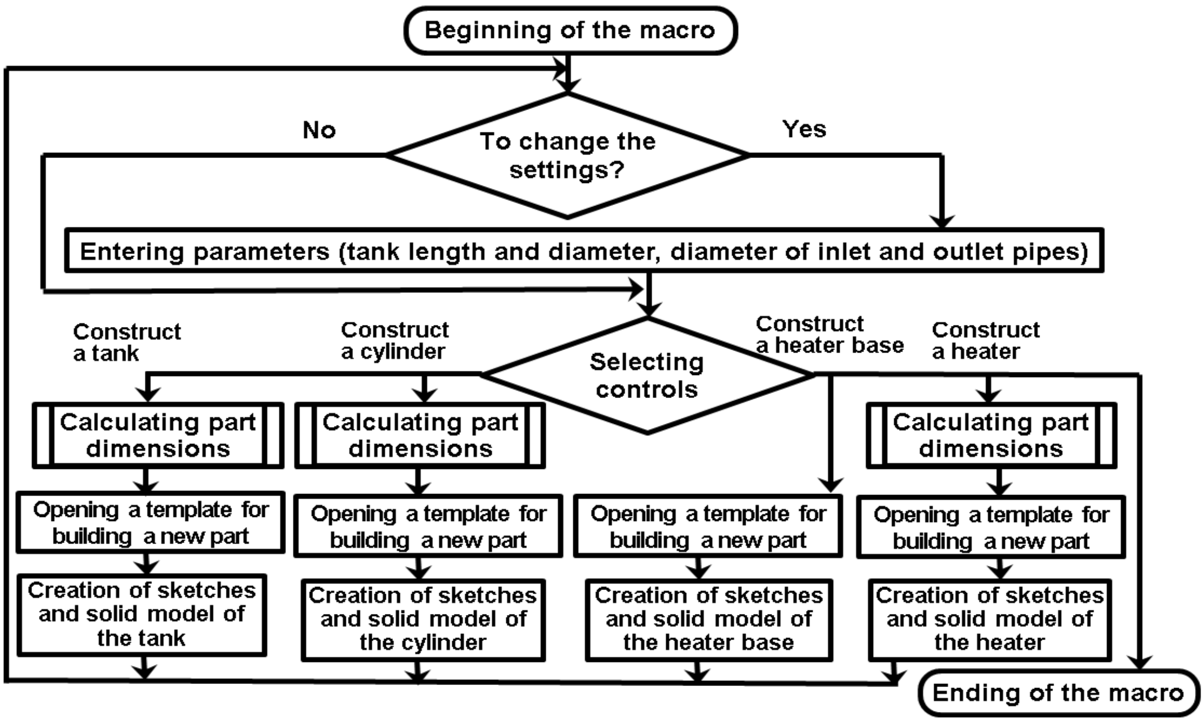

Figure 2. Simplified algorithm for the operation of the macro for forming the assemblies of the heating module.

The main material of the assembly was stainless steel. For the base of the heating element an insulating material with low thermal conductivity "insulator" was used, and for the case of the heating elements themselves, either copper or also stainless steel. The maximum dimensions of the parts shown in Figure 1*b* were chosen based on the maximum allowable power of the 15 kW heater. The construction of a larger tank would require a change in its design in connection with the need to install several heating elements. In the future it is planned to realize this possibility, as well as to expand the number of different configurations of flow water heater assemblies for other models of flow heaters.

At the next stage the model was placed in the design area, the size of which was set approximately 5–10 times larger than the size of the heating module. The shape of the 3D cells was set rectangular everywhere with using the adaptive property. Their size for solid elements was set 5–10 times smaller than the cells in the calculation area (Figure 3).

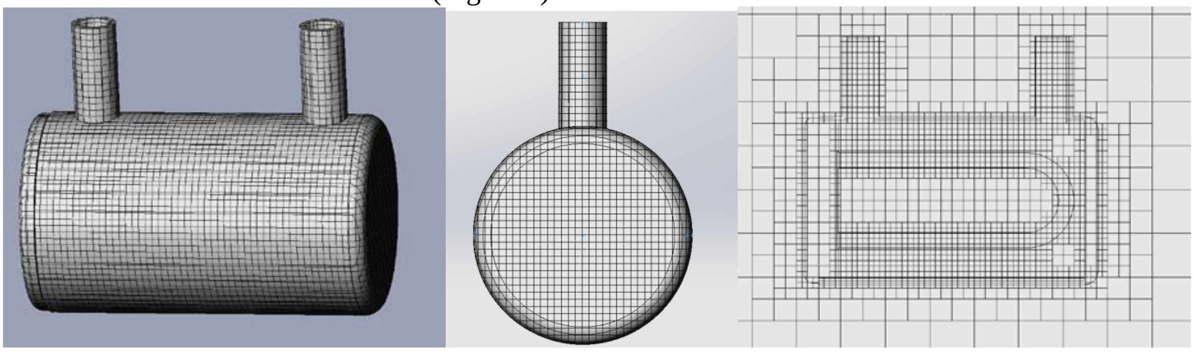

Figure 3. The type of the calculated grid for the design area and the flow heater model.

After the superposition of the grid, the subregions of the flow and the initial and boundary conditions were specified for the model. For the surrounding water heater, air was chosen as the fluid, and water was selected for the internal cavity of the flow water heater model. The temperature of the air and the walls of the design area was set at 22 ° C, and the water temperature was set at 15 ° C. The pressure in all cases was 101325 Pa. The mass flow of water at the inlet branch was set at 0.15 kg / s, and the heating element power was 15kW. The Appearance of the model after performing all the listed procedures is shown in Figure 4. To study the change in the temperature of the heated water, the length of the outlet branch pipe was increased, the design area was stretched in a vertical direction. On this area are marked points for which temperature plots were calculated. On this step the preparation for study a flow heater can be considered complete.

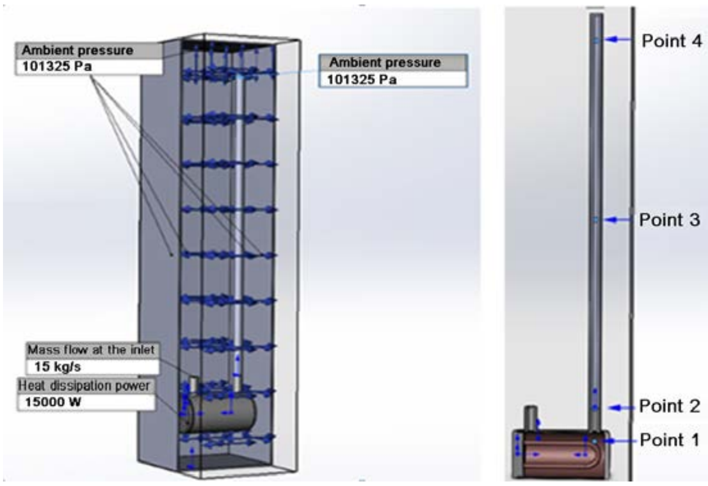

Figure 4. Type CAE model for the study of heat distribution in a flow-through water heater with specified boundary and initial conditions (*a*) and placement of points on it for monitoring the temperature of heated water (*b*).

3. Investigation of the operation of the flow-through heater in the static mode

Within the framework of this work two kind of computational experiment were carried out. The first one was to assess the inertial properties of the heating module and to analyze the heat distribution along the volume of the heating module and in the outlet branch pipe. The

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second was the research of operation of the heater using various methods of temperature control.

The result of the computational experiment on the study of the dynamics of the temperature field changes during static heating is shown in Figure 5. It can be seen from this that the temperature inside the volume of the heater is highly inhomogeneous. This heterogeneity remains in the outlet branch pipe and the temperature in it is equalized at a distance greater than the linear dimensions of the heater itself. In this case, the termination of the transient and the establishment of the static regime occurs in the interval from 50 to 90 s after the heater is turned on. °

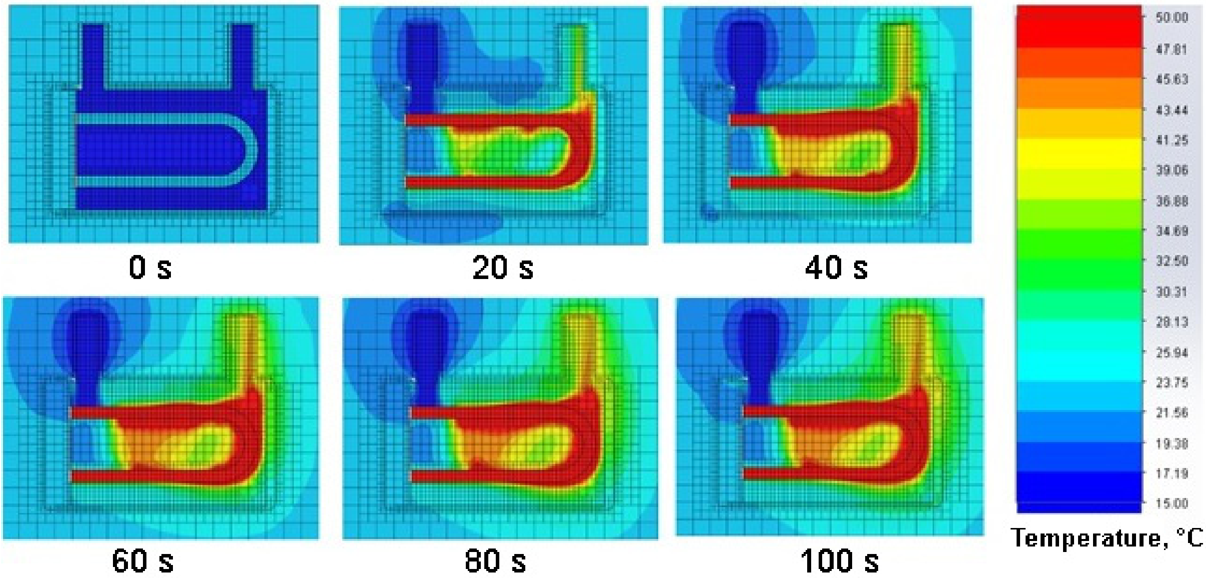


Figure 5. Dynamics of temperature fields change in the flow heater after the heating element is switched on.

To more accurately establish the time constant and determine the distance after which the temperature of the liquid in the outlet tube could be considered homogeneous, temperature measurements were made at four points on the outlet pipe, as shown in Figure 4. The plots of dependence of the temperature vs. time at these points are shown in Figure 6.

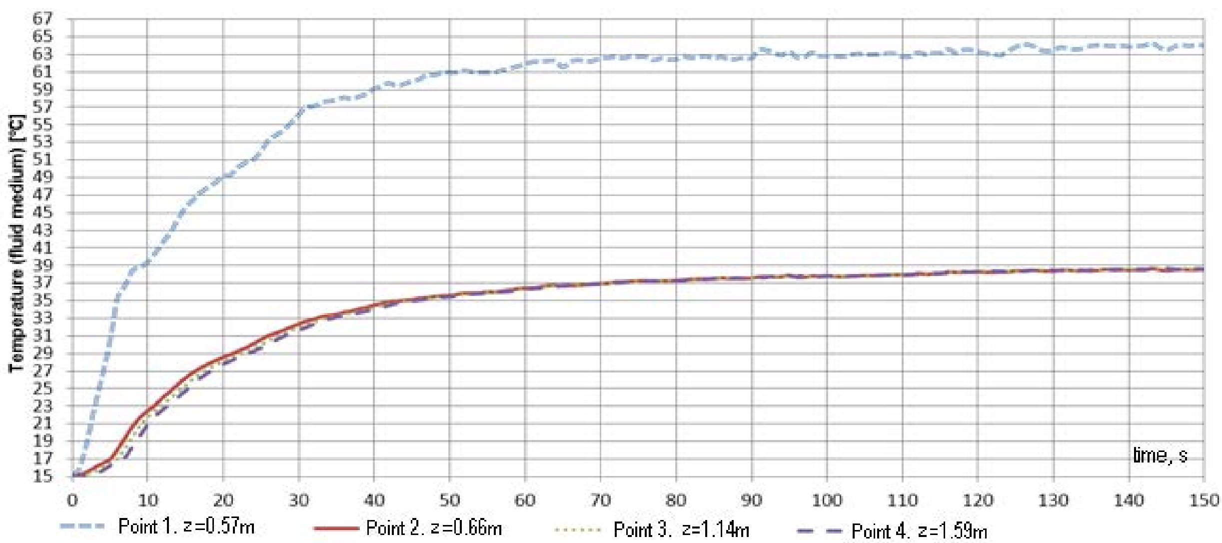


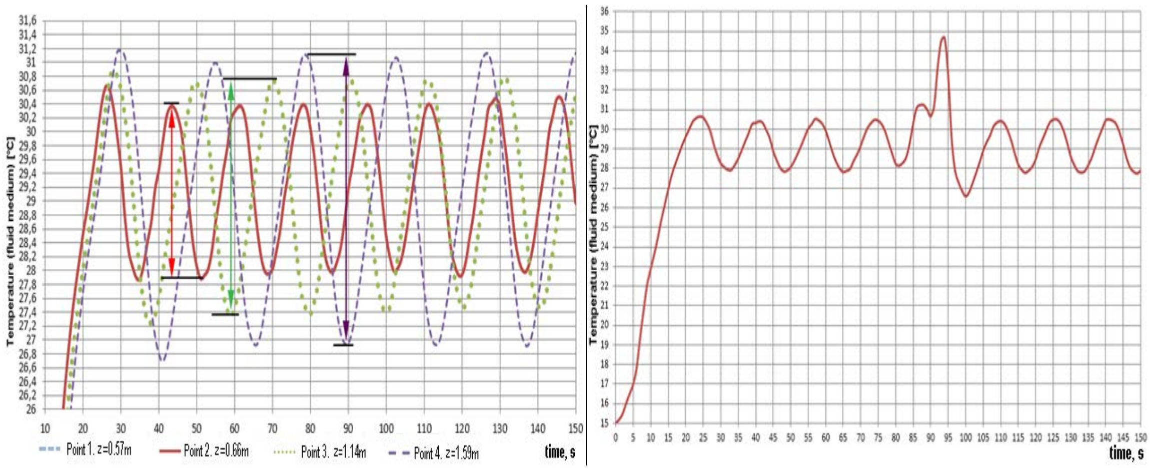
Figure 6. Graphs of temperature change in time in the outlet pipe at different distances from the heater with static heating. In all cases, x = 0.969m, y = 0.988m.

It can be seen from this that the installation of a temperature sensor in the immediate vicinity of the heater outlet does not at all reflect the temperature of the water entering to consumer. And besides, because of convection processes, this temperature is subject to significant fluctuations, which makes it difficult to use point 1 to place the temperature sensor of the automatic control system. For these purposes, other points more remote from the heater for a distance of 0.5 m or more are more suitable.

4. Investigation of the operation of the flow-through heater in the thermal control mode

At this stage of computational experiments, the operation of a flow-through heater in the circuit of the automatic temperature control system was investigated. Two control modes were considered: threshold and proportional. In the threshold mode, the heating element was switched on when the temperature of the water exceeded the set threshold value. In linear mode with proportional control, the heating element was switched off when the set temperature was reached the set threshold value, and if it did not exceed this value, the power supplied to it linearly depended on the difference between the preset and the actual temperature.

Figure 7*a* shows the temperature of the heated water as a function of time for different locations of the temperature sensor. The cutoff threshold of the heating element in this experiment was set equal to 30 ° C, and the inclusions to 29 ° C. From these graphs it is seen that with a smaller distance from the sensor to the heater, the amplitude of the oscillations decreases, which is explained by the smaller value of the transport delay. To study the transient processes due to the change in the flow velocity, the flow rate was linearly reduced from 0.15 kg / s to 0.06 kg / s in the boundary condition "mass flow rate at the inlet" from 80 to 81 seconds, and from 90 to 91 s is linearly returned to the original value. The graph of the corresponding transient process is shown in Figure 7*b*.



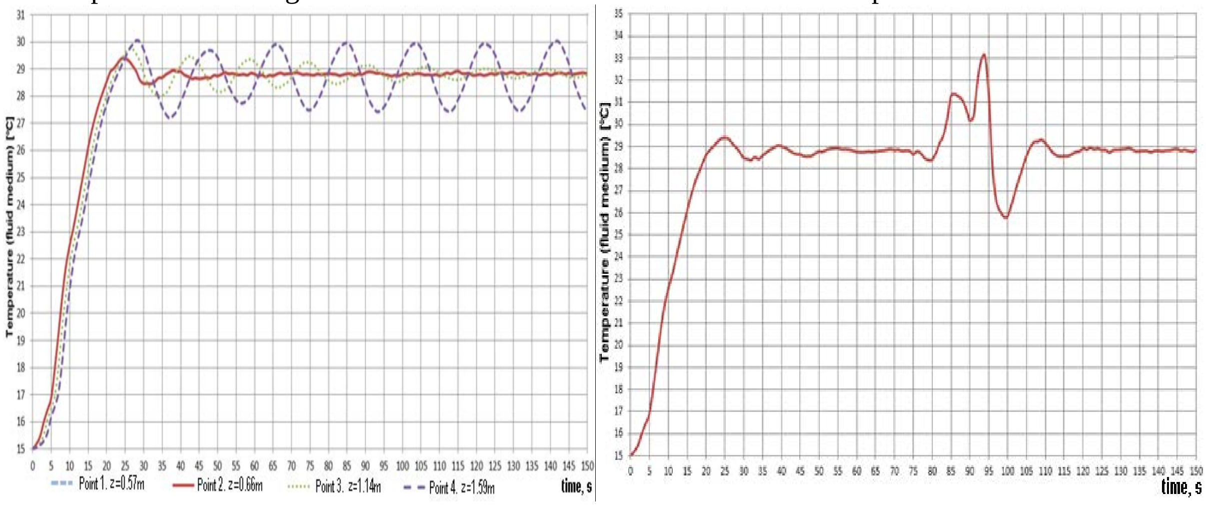
a) b)

Figure 7. The time dependences of the temperature changes during the operation of the thermostat system in the threshold mode for different locations of the temperature sensor (*a*) and the transient diagram when the flow rate is changed (*b*). The sensor is placed in the position z = 0.66m.

Similar studies were carried out with the operation of a temperature control system in proportional control mode. In this mode, the power input to the heating element varied from 0 to a maximum value of 16 kW, with a temperature drop of 30 to 28 ° C. The results of such studies are shown in Figure 8. Comparing the results shown in Figures 7 and 8, it can be seen that the use of linear control has made it possible to reduce the amplitude of the oscillations approximately 4-fold. At the same time, the duration and amplitude of the oscillations of the transient process with a change in the water supply rate in both cases turned out to be approximately equal, which, apparently, is due to the fact that the transport delay is more affected on them.

5. Conclusions

The use of the developed methodology based on carrying out computational experiments using CAE models allows to significantly reduce the time and volume of financial expenses for carrying out studies on optimization of algorithmic and constructive solutions in the development of flow heaters.



a) b)

Figure 8. The graph of the temperature changes during the operation of the thermostat system in the proportional control mode for various locations of the temperature sensor (*a*) and the transient schedule when the flow rate is changed (*b*). The sensor is placed in position z = 0.66m.

Its use in solving a particular development task for the heater design shown in Figure 1*a* has made it possible to optimize the location of the temperature sensor and estimate the value of the pulsations of the heated water for different control regimes of the power supplied to the heater [24] and in case of changing in the water flow rate. Further development of the work is supposed to be done in the direction of expanding the set of structural designs of heating modules and in studying the operation of heaters in other modes. Thus, it can be assumed that the introduction of an additional sensor directly on the housing of the flow heater in combination with the implementation of the algorithms described in [15–17] will significantly reduce the amplitude and duration of the transient processes caused both by the change in the water flow rate and its temperature fed to the input connection of flow heater. A definite effect can also be provided by the transition to the use of algorithms with proportional-differential-integral control.

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