A Trainer–Simulator for Improving and Assessing the Professional Skill of the Personnel of Heat-Supply Networks

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Abstract—Considered are the technique of creating for the first time a computer trainer–simulator for dispatchers of heat-supply networks and the experience gained from its application in the regional and first all-Russia competitions in the professional skill of the personal servicing heat-supply networks.

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The branch Standard of the Organization of Professional Training, Retraining, and Improving the Qualification of Personnel (SO-EES-PP-1-25) requires carrying out once every 3 years all-Russian and regional competitions in professional skill, which are one of the forms of the professional training of the personnel of power enterprises of RAO United Power Systems of Russia (RAO EES Rosii) [1]. Recently, when carrying out such competitions, one has used fairly actively various simulators and programming software, as well as technical means, allowing one to simulate the basic technological processes and clarify the readiness of the personnel to service power equipment [2–4].

In conformity with a decision made by RAO EES Rossii in September 2006, the first all-Russian competition among personnel of heat-supply networks was implemented on the basis of TGK-10 heat networks (in Chelyabinsk). A trainer–simulator was developed on the basis of the TVT Shell [5] by specialists of OOO Trieru (www.trie.ru) and MEI (www.mpei.ru) for implementing two basic stages of the competition of dispatchers, namely, operation on managing the equipment of the heat-supply networks during accident regimes and in the course of normal operation. Such simulators had not yet been developed earlier. The trainer–simulator has been included into the TVTHeating Systems complex (see the certificate on the conformity with the norms of suitability of the means for training the personnel of power units No. 50 of May 30, 2006). A demonstration version may be borrowed from http://twt.mpei.ac.ru/ochkov/trenager/ThermoNet/index.html.

When creating the trainer–simulator, the problem was posed to develop software allowing one to train and check the level of knowledge of a dispatcher of the heat-supply network and his or her capability of correctly operating the equipment and localizing accident situations. The main working document for making decisions on controlling the heat-supply network for a dispatcher is an operative technological scheme showing the state of accessories (valves) and readings of control instruments. In the chief window of the trainer–simulator (Fig. 1) such a scheme occupies a great part of the screen. If the scheme cannot be located entirely on the screen, the user may move over it with the help of scroll bands or a special binoculars window, in which the entire scheme is shown in a diminished scale.

The active elements are arranged on the scheme (such as accessories, heat chambers, instruments, and the like), which can be addressed either with the aid of a mouse or by selecting the denomination of an element in the Elements [E] menu. Thereafter, the window linked with the element appears on the screen, on which the user may then perform manipulations.

In Fig. 2 the window of the element of the basic scheme—the heat chamber TK-105 and a menu of buttons designated as Elements [E]—is represented. For operation with valves (opening and closing), a dialog is employed that is shown in the scheme in Fig. 3.

The valves can be opened and closed with the help of the following:

(i) preassigning the final degree of opening in the text field; in so doing, it is possible to carry out both the figure entry and the use of buttons with arrows;

(ii) using active regions close up (C) and open, (O);

(iii) a triangular runner; and

(iv) an interactive, three-dimensional model of accessories (valves).

The method of actuating the valves in the trainer–simulator differs from the real one. The point here is not that instead of real valves located, for example, in the
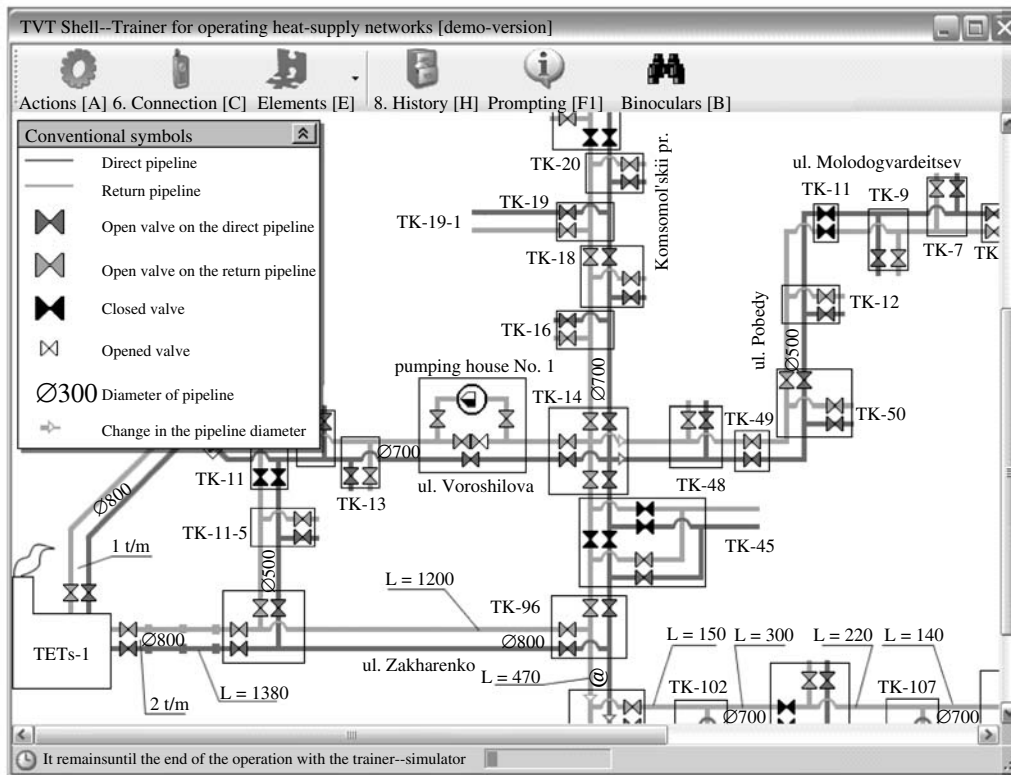
Fig. 1. The screen of the trainer–simulator for the personnel of heat-supply networks.

underground heat chamber, there is employed a three-dimensional model found in the window of the computer program. The basic difference consists in that, in the great majority of cases, the dispatcher's work involves using only the communication means in order to indirectly control the operation of the heat-supply network. This is due to the fact that the equipment of the heat-supply network is distributed over the region, and nodal points (such as cogeneration stations (TETs), heat distribution stations, pump houses, etc.) are serviced by local operators governed by their own dispatchers. For servicing the other equipment the dispatcher has other operative teams subordinated to him. When working with real equipment, it is the foreman with his team that receive an order from the dispatcher, leave for the spot of a heat chamber, and there perform the working operations required. In so doing, they have to implement the preliminary work to prepare the heat chamber for servicing, involving the operations of measuring the concentration of harmful gases, the organization of ventilation, the pumping of water if necessary, etc.

At the earlier stages of work on the trainer–simulator, the attempt was made to implement a similar scheme of the interaction with valves.

The complete lists of equipment had been prepared with all the possible orders that the dispatcher could transmit by telephone or through radio communication to the technical personnel under his supervision, such as the TETs' shift head, the foreman of the service team, etc. The dispatcher's work with the trainer–simulator reduced to his choosing from one list the equipment to be applied, from another list the personnel, and from the third list the order to be fulfilled (for example, TK-105 ⇒ valve 1 ⇒ foreman together with his team of workers ⇒ closed). It turned out, however, that it is rather inconvenient to operate with such lists, whereas the process itself of the interaction with the trainer–simulator was still far from the real actions (giving orders by telephone) and was very strongly formalized. In addition, the ergnonomics of such a variant of the trainer–simulator left much to be desired. Because of such a circumstance, a decision was taken to apply direct actuating of valves by the dispatcher, as if directly at his working place he could open and close them. However, it is understood that all the work with the valves in the trainer–simulator consists of giving orders to the foreman with his team, who just fulfill the direct actions, for which purpose in the window for the operation with the valves (see Fig. 3) the following text is reflected: "Attention! Actuation is implemented by the foreman authorized for this by an order."

The practice of training and competitions has demonstrated that the chosen method is much more graphi-
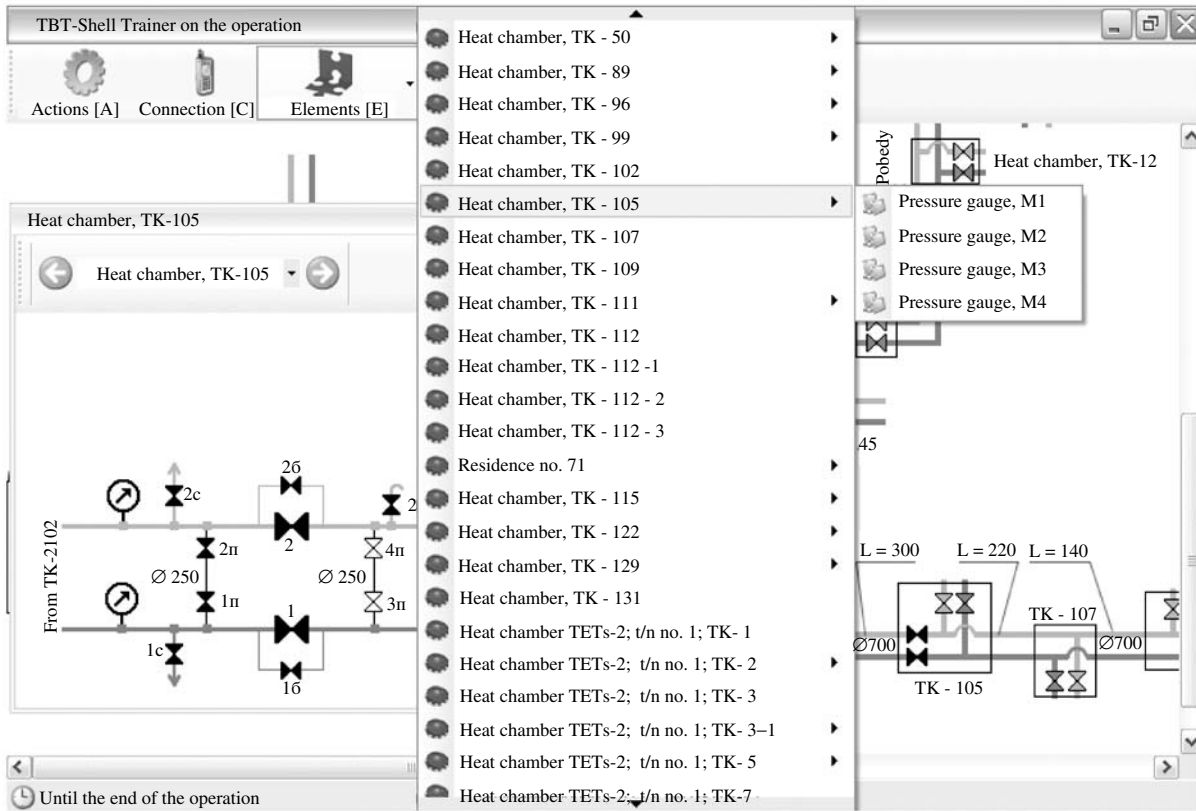
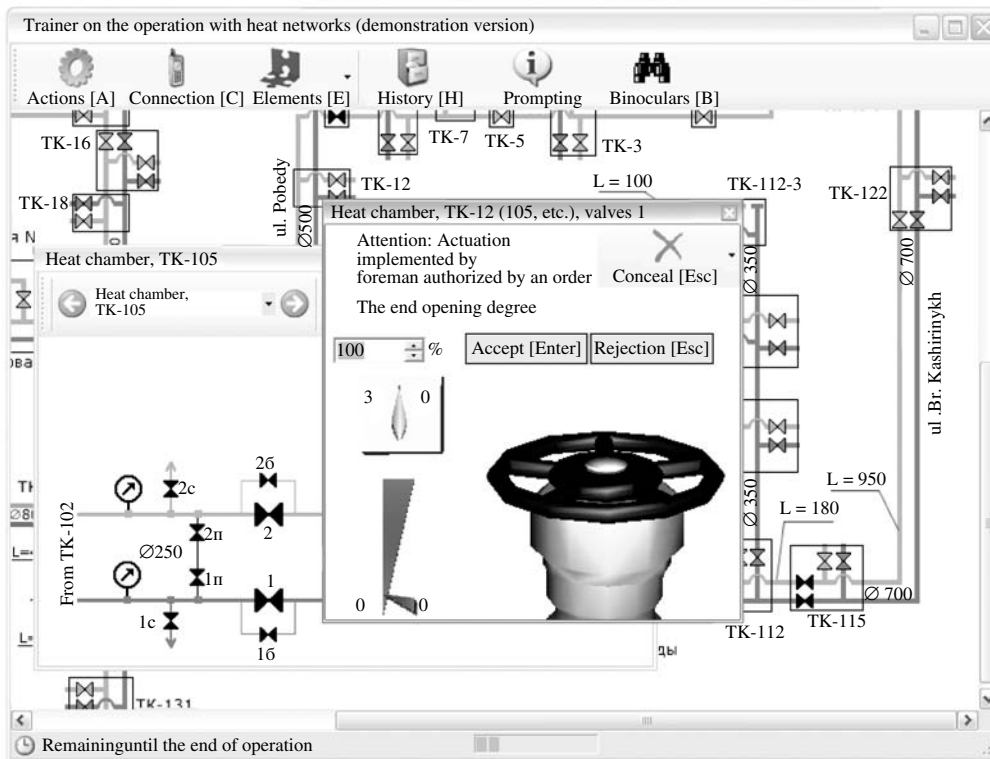**Fig. 2.** The element of the basic scheme—heat chamber TK-105.

Fig. 3. Dialog for operation with valves.

cal and simpler for the user's perception though it differs from the real situation as well.

Control of the valves is not the sole duty of the dispatcher. When controlling the heat-supply network, he should also interact by telephone or radio communication with technical personnel. For this purpose, a button is provided with the designation "Communication" [C]. By pushing on the button, a customer-selecting dialog appears on the screen; after selection of the customer, a dialog with the enumeration of the current topics of the conversation with a given customer. After the selection of the topic of talk and pressing on the button with the label "Ready" there appears a window allowing one to talk with a corresponding customer. The example of using the button "Communication" [C] is illustrated by Fig. 4.

The program in the automatic mode depicts the so-called history of operation with the trainer–simulator, into which are entered the entire information, actions, and negotiations up to the current moment of time. The history is helpful in simplifying the work with the trainer–simulator; for the user can in any moment of time know what occurred earlier.

The trainer–simulator provides for the operating mode complete with prompting. If this mode has been included by the instructor, then the user may know what action according to the scenario laid into the trainer–simulator has to be performed at the current moment. This enables the user to pass over to the following stage, even if he does not know what has to be done at the given stage of the process. The button "Prompting" additionally allows one to apply the trainer–simulator in the training regime, with which the program will guide the person being instructed. There exists a possibility to adjust the trainer–simulator in such a manner that the number of recourses taken to prompting will be limited, or even fully prohibited. The evaluation points may also be cancelled for having recourse to prompting.

In the bottom part of the screen (see Fig. 1), one attends to the output of a status line, at which are represented the current time of the trainer–simulator model at the time interval until the end of its functioning.

The specific features of the problem put forth during the development of the trainer–simulator for the heat-supply network involved not only the formulation of a mathematical model of the heat-supply network, but also the trainer–simulator imitating the dispatcher's actions connected with monitoring the network. The latter means that, apart from simulating the processes occurring in the heat-supply network, it is necessary to simulate the network dispatcher's behavior and his possible actions, such as negotiations, orders, impacts on the valves, etc. In connection with this, the trainer–simulator was split up into two interacting parts, as follows:
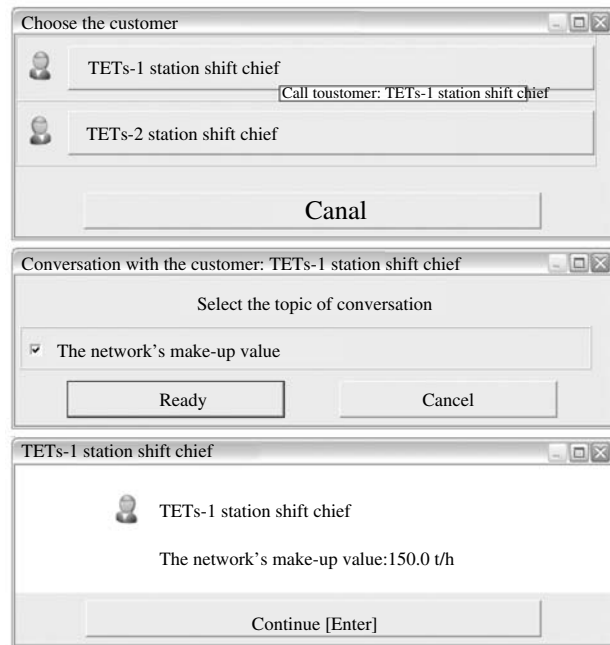
Fig. 4. Example of using the "Connection" [C] button.

(i) a mathematical model of the heat-supply network; and

(ii) a logical model of the dispatcher's actions.

In the calculation module of a mathematical model of a heat-supply network, the working body (water) is considered a homogenous compressible fluid. The basic peculiar feature of the calculation module, which is employed in the trainer–simulator, consists in that it uses a dynamic model of thermohydraulic processes in the network, which has been developed on the basis of the differential equations of hydro- and thermodynamics. This makes it possible to calculate real transient processes, including those accounting for the compressibility of the fluid, for example, such as a water hammer.

In the majority of program products of other developers that are being used at the present time for the calculation of the heat-supply networks, the calculation is carried out for a static (steady) state and the working body is considered incompressible. In this case, iteration calculations are usually carried out with the use of Kirchhoff equations. If every iteration step is made in a separate quantum of time, then one can simulate transient processes with a changing operating mode of the heat-supply network (for instance, with the valve on the pipeline being closed). This quasi-static calculation model can represent only a qualitative character of transient processes. It is impossible, however, to calculate the water hammer in such models.

The quasi-static model has advantages, the chief of which is a calculation rate that is higher by an order of
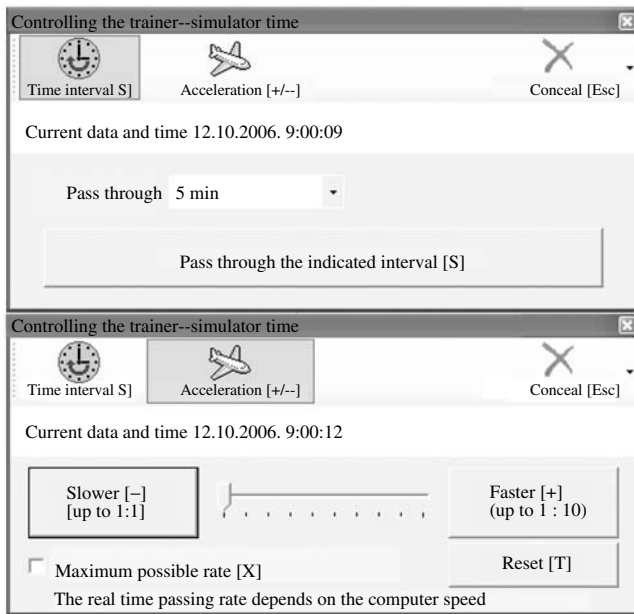
Fig. 5. Dialog function "Controlling the Trainer–Simulator Time."

magnitude. This circumstance may be important when operating on so-called slow-rate computers.

One of the problems arising during the use of a dynamic model consists in the necessity in some moments of sharply increasing the calculation rate of the heat network. This is associated with the fact that when operating on the heat-supply network some operations are of long duration. Let us consider, for example, the filling up of a section of the network with water (one of the assignments to be fulfilled in the trainer–simulator). With a considerable length of pipes of large diameter and the filling rate being limited by technical requirements, this process may continue from several hours to a day, or even longer. There is no sense in the user spending this time at the screen of the trainer–simulator when he has already established the regime of filling up the pipeline and performed all the operations required. This is also limited by the rules to which competitions are subject, when a stage of it, that is, the fulfilling of the assignment, has been allocated 1–2 h. One of the solutions of the given problem is to be sought in accelerating the implementation of the model, when 1 s of real time corresponds to several seconds of the internal time of the model. For the user, this will appear to be the acceleration of all the processes taking place in the trainer–simulator: the gates will be opened or closed more quickly, the internal time of the trainer–simulator will pass more swiftly, etc.

Such an acceleration in the passage of time, however, is not sufficient for solving the problem of the long duration of some processes in the heat-supply network. The point is that the maximum value of acceleration depends on the calculation rate of the model and

the latter, in turn, on the complexity of the model, the power of the computer, and the perturbance of the operating mode of the heat network[1]. For a relatively simple heat-supply network model (see Fig. 1) implemented in the trainer–simulator, an acceleration of computation by as much as 10–15 times had been attained on the 3.2-GHz Pentium 4 computer. This allowed one to reduce the waiting time from 10 h to 40–60 min, which also cannot be considered acceptable from the viewpoint of the operation on the trainer–simulator.

The use of the quasi-static model for the computation of the heat-supply network cannot afford advantages either, for a reduction of time by an order of magnitude as compared to the time of using a dynamic model will be insufficient in the course of processes demanding several days for their completion. Even a reduction in the waiting time to 4–6 min in the example under consideration would be insufficient in the course of the processes that need several days for their completion because the given time interval does not carry any methodological load in the case of the organization of training the personnel of heat-supply networks, but presents rather a technical restriction in using the trainer–simulator.

The optimal solution to the problem described above consists of the possibility for the user to set the required mode of operating of the heat-supply network and then at once to (jumpwise) pass through a required interval of time of any duration, even up to several days. Just such an approach was implemented in the trainer–simulator being described. The user can with the help of a special dialog function (Fig. 5) choose the time interval as required by pushing a button, as is recommended—"Pass through a time interval"—and the operating time of the trainer–simulator will be changed in a stepwise manner by the interval referred to. In addition to this, in the same window the user can accelerate the time more than tenfold. It is also possible to set the maximum computation rate for the model of the heat-supply network.

A question arises regarding the implementation of instantaneous passage of a time interval. It is impossible to know what will occur with the model of the heat network, say, in 10 h after a perturbation has been entered into its operation. In order to learn it, one has to calculate in detail the operation of the model during the entire time interval given. Now, such a type of calculation is impracticable (because in the given case it will not be instantaneous, but will take about 1 h) and there exist restrictions on the application of the method of instantaneous passage of a time interval. First, the passage of the time interval is automatically stopped by the program in the course of entering perturbations into the operation of the network (a change in the degree of opening of the valves, the switching-on of a pump,

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[1] With insignificant perturbations (gradual change in the valve opening, etc.) the rate of calculating a dynamic model is higher than that in the case of abrupt ones (simultaneous actuation of different valves, switching off of a pump, etc.). This is associated with a smaller volume of calculations, because some might be neglected.

etc.). Only with steady-state operation of the heat-supply network can the user implement the passages of the time interval. Second, because of the impossibility of instantaneous calculation of the state of the heat-supply network after the passage through a time interval, this calculation is not conducted, and thermohydraulic parameters of the network model operation are identical to those existing before the moments of pushing on the button with the designation "Pass through time interval."

At first glance, the identity of the parameters of the operation of the model of the heat-supply network, both before and after passing over the time interval, brings the principle itself of the instantaneous passage of time interval to nothing, for it has no sense from the standpoint of the initial problem of introducing the notion of a "jump in time": it was required to calculate as soon as possible the parameters of the operation of the heat-supply network after a long period of time. The notion of the jump in time interval, however, allowed one to implement in the trainer–simulator such a part of the operation of the dispatcher of heat-supply network as the expectation of the arrival of personnel to a specific point in the network and some other moments when it becomes of prime importance for the user of the trainer–simulator not to have a change in the thermohydraulic parameters of the operation of the network during a time interval, but the fact itself that the preassigned period of time has passed through.

Now, introducing the notion of jumping over a time interval was enforced by a necessity of calculating the filling-up of sections of the pipelines of the heat-supply network. All the remaining stages of the operation of the network that have been considered in the trainer–simulator are either transient or do not require knowledge of the change in the thermohydraulic parameters, that is, they may be imitated with the aid of using instantaneous jumping over the time interval without calculating the transient processes. Thus, it remains to solve only one problem, namely, the filling up of the sections of pipelines. For this purpose, a special computation unit has been introduced that forms a superstructure over the chief computation module of the dynamic model of a heat-supply network. The function of this unit consists in determining in each quantum of time the rate of filling the pipeline section being considered (this information is borrowed from the main computation module), the volume of water supplied for filling up, and the degree of the filling up of the pipeline section. During the filling-up period, in the main computation module the leakage is simulated from the point of the network through which the pipeline section is filled up. On completing the filling up of the pipeline section indicated above, a special computational unit introduces changes into the operating mode of the main computational module—the latter is informed that the pipeline is filled up, that is, it simulates the ceasing of water leakage.

In the case of an instantaneous change in the time interval during the filling of the pipeline section, the value of time to be transmitted into a special computational unit is not 0.1 s, but a time interval that is equal to the jumped over (for instance 5 h). This value will be multiplied by the filling rate, added to the volume of water flowing through the pipeline, etc. Thus, the algorithm of operation of the special computational unit is really the same as has been described earlier. This fact allows one to simulate the filling of the pipeline section at instantaneous (from the consumer's viewpoint) jumping of the time interval.

Such a simulation of processes in the heat-supply network was successfully tested both at the stages of preparation for competition and at the competitions themselves. The convenience of the operation with the trainer–simulator was enhanced on the whole. Thus, when the pipeline section was being filled up, the dispatcher established the filling-up mode, while selecting through the valve-opening degree the required flowrate for filling up; then a time interval was instantaneously jumped over, having been calculated beforehand from the values of the volume of the pipeline section and the filling flowrate. After jumping over a necessary time interval, the pipeline section was filled and the dispatcher continued the actions that are required according to the preassignment. For the dispatcher—the user of the trainer–simulator—this practice proved to be both understandable and convenient.

The logical model of the dispatcher's actions during the fulfillment of the operations on controlling the heat-supply network is described by creating a file in a special format, in which there is preset the necessary sequence of actions for fulfilling some assignment. In the file are described both possible user's steps and the reaction of the trainer-simulator's program to these steps.

On the basis of the file describing the logical model, the trainer–simulator's program automatically generates the information for prompting at any moment of time of operating with the trainer–simulator. There are also automatically implemented the control of correctness of actions in the trainer–simulator and its assessment. In the trainer–simulator assessment is performed in points, and for each error committed in performing the assignment the control program subtracts a definite amount of points proportional to the weight of an error made. The total number of points for the fulfillment of an assignment can be changed.

The trainer–simulator prepares an accounting protocol on all the user's actions, which can be saved in the memory, and may then be activated from it, as well as printed on paper.

The trainer–simulator's program allows one to limit the operating period, both for the internal time of model and for the user's real time. It is possible to determine the operation with the trainer–simulator as 1 h of real time and/or 15 h of the internal time.

In 2006, the trainer–simulator was applied at eight regional and the first all-Russian competitions in the professional skill of the personnel of heat-supply networks.

For the first all-Russian competitions, the following assignment topics were developed for the trainer–simulator.

The normal operation:

(i) switching-on into operation of a section of heat-supply main at subzero temperatures of the ambient air;

(ii) the planned switching-off of the section of the heat-supply main; and

(iii) implementing hydraulic tests for strength and tightness.

The accident situations:

(i) rupture of the supply main with $D_c = 700$ mm;

(ii) damage to the return pipeline with $D_c = 400$ mm at a branch from the main;

(iii) switching-off of the electric power from the central heating block (CHB); and

(iv) switching of the operating regimes of the CHB.

Prior to the beginning the implementation of competitions for passing a stage dedicated for the normal operation of a heat-supply network, the topic Planned Switching-Off for Maintenance of a Section of a Heat-Supply Main was chosen, whereas for the stage connected with the accident switching, the topic was Rupture of the Delivery Main with $D_c = 700$ mm. The topics of the assignments were not made known to the participants of the competitions until the beginning of the implementation of the stages.

In order to become acquainted with the trainer–simulator, before starting the stages of competition, time was allocated to all the participants to work with the program. In this, they were working in the regime of "What if?" This was a specially developed assignment, in which the user was given the total freedom of managing heat-supply network: it was permitted for him to open or close any valves with the absence of any control of the correctness of the actions performed. The practice demonstrated an interest of the competition participants in such a regime: instead of the allocated 30 min, which were believed sufficient for getting acquainted with the trainer–simulator, they spent more than an hour at the screen while opening and closing the valves and watching the change in the operating regime of the heat-supply network.

All the participants of the competitions have successfully managed to cope with the assignments proposed to them. However, when doing this, they committed the following main errors.

At the stage of the normal operation of the heat-supply network:

(i) prior to starting switching in the planned putting-out of a section of the heat-supply main to the preventive maintenance, the users (customers) connected up to this section were not given notification about it;

(ii) permission for putting equipment up to preventive maintenance was erroneously taken from the power system's dispatcher, although the equipment under consideration actually was under the supervision of the dispatcher of the Enterprise for Operation of the Heat-Supply Network;

(iii) the customers were not switched-off from the heat-supply mains brought out to the preventive maintenance;

(iv) when relieving the load from a TETs, the shift foreman of the TETs was not given notification about it; and

(v) errors were committed when actuating the valves.

At the stage associated with the accident switching over:

(i) when it was reported to the TETs shift foreman that there was an increase in the feedwater makeup to the maximum value and the beginning of reduction in the pressure in the heat-supply network, instead of giving an order to make up the heat-supply network with service nondeaerated water, some participants taking part in the competitions gave an order to close the head gates at the TETs (in the winter season);

(ii) on detecting damages, incorrect orders were given to the foreman of the team;

(iii) before the damaged section of the heat-supply main had been localized, vent cokes were opened;

(iv) in the winter period, at the subzero temperature of the ambient air, the coffer dam of the dead-end section of the overhead heat-supply main was not opened;

(v) one implemented incorrect operations with the valves, when switching a CHB from one operating regime into another; and

(vi) one did not report to the customers connected to the accident section of the heat-supply main about the organization of draining the internal systems of heat-supply systems in the winter season.

At the present time, on the basis of the developed software, the work is being conducted for developing training simulators for the dispatchers of real heat-supply networks, which will make it possible in the future to train dispatchers and carry out their competitions on such trainer–simulators. The "What if?" operating regime of a trainer–simulator will enable one to assess the change in the operating regime of a heat-supply network when changing the control parameters.

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