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SIMULATION OF ONE OF POSSIBLE METHOD OF CONTROL OF HEAT OUTPUT OF HOT-WATER PIPING FOR HEAT SUPPLY TO DISTRICT HEATING SYSTEM: BASIC METHOD OF CONTROL

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Abstract: The paper deals with the simulation verification of one of possible approaches to heat output control of hot-water piping for heat supply to wide district heating system. It is described algorithm of the so called qualitative-quantitative control method of heat output control with utilization of prediction of daily diagram of heat supply in hot-water piping systems of district heating. Designed algorithm enables elimination of the influence of transport delay between the source of heat and heat consumption of relatively concentrated consumers. Distance between the source of heat and consumers is in the rank of kilometres. Transport delay depends on flow speed of heat-carrying medium (hot water) and on the length of feeder piping. This method of hot-water piping output control consists in simultaneous and continuous acting of two variables influencing the transferred heat output and in using the prediction of required heat output in a specific locality.

Keywords: hot-water piping, heat output control, qualitative-quantitative control method.

1 INTRODUCTION

District heating system has to ensure supply of energy to all heat consumers in quantity according to their requirements variable in time. Energy supply has always to comply with prescribed quality index. In case of hot-water piping it means to maintain prescribed temperature of hot water in intake piping.

Algorithm of so called qualitative-quantitative method of control using prediction of the course of heat supply daily diagram in hot-water systems of district heating enables to eliminate influence of transport delay between the source of heat and consumption of heat by relatively concentrated consumers. Transport delay depends on the speed of flow of heat-carrying medium (hot water) and on the length of feeder piping. The method of hot-water piping output control consists in simultaneous and continuous acting of two manipulated variables influencing transferred heat output and in utilization of required heat output prediction in the specific locality. The designed method of control was considered for a specific case when the transport delay was supposed to be in the range of six up to twelve hours depending on consumed heat output by all consumers.

The following 3 methods of application of qualitative-quantitative method of hot-water piping output control are elaborated at present namely according to technologic equipment of the source of heat:

I. Basic method – it is created for the case of heat supply from the exchanger at power and heating plant as the source of heat – the principle
Qualitative-quantitative method of control of hot-water piping heat output using prediction of the course of heat supply daily diagram in district heating systems.
It is created for the case of heat supply from the exchanger at power and heating plant at the source of heat. It enables to eliminate the influence of transport delay between the source of heat and relatively concentrated heat consumption of all consumers (Balátě *et al.* 2008a). Technologic scheme is presented on Fig.1.

II. Modification of the basic method
Adaptation of qualitative-quantitative method of control of heat supply by hot-water piping for the case using part of the piping for heat accumulation.
The method of control is created for the case when part of the feeder piping can be used for heat accumulation

and enables to eliminate influence of transport delay between the source of heat and relatively concentrated heat consumption by all consumers. At combined production of heat and electric energy it enables to use heat accumulation for heat supply for combined heat and power purposes aside from the time interval of peak supply of electric energy (Balátě *et al.* 2008b). It is created for the case of heat supply from power and heating plant exchanger at the source of heat.

III. Modification when hot-water boilers with grate are sources of heat
Algorithm of qualitative-quantitative method of output control with grate hot-water boilers as sources of heat.
The algorithm enables the method of control of technological string "production – transport+ distribution" of heat in radial or circular hot-water network. It enables to eliminate the influence of transport delay between the source of heat (hot-water grate boilers) and relatively concentrated heat consumption by all consumers (Balátě *et al.* 2008b).

2 QUALITATIVE-QUANTITATIVE CONTROL METHOD OF HOT WATER PIPING HEAT OUTPUT

Algorithm of so called qualitative-quantitative control method with utilization of prediction of heat supply daily diagram in hot-water systems of district heating enables eliminating the influence of transport delay between the power and heating plant exchanger in the source of heat and relatively concentrated heat consumption of all consumers. The transport delay depends on flow speed of heat-carrying medium (hot water) and on the length of feeder piping. The proposed method of hot-water piping output control consists in simultaneous and continuous acting of two manipulated variables influencing transferred heat output an in using prediction of required heat output in a specific locality. The designed method of control was considered for a specific case when the transport delay was supposed to be in the range of six up to twelve hours depending on the heat output consumed by consumers.

The proposed method is the solution of heat output control method in the source of heat. Two manipulated variables are available for the control of hot-water piping heat output from the source of heat

- the change of water temperature difference in intake and return piping of hot-water piping realized in practice by changing heat input at intake into power and heating plant exchanger, so called *qualitative method of heat output control*,
- the change of mass flow of hot-water by means of changing speed of circulating pump, so called *quantitative method of heat output control*.

The algorithm for such control method was designed and verified by simulation. It has been called qualitative-quantitative control method of hot-water piping heat output with utilization of prediction of the course of daily diagram of heat supply. The algorithm of the above mentioned control method i.e. with using two manipulated variables namely separately for qualitative method and for quantitative method of control is displayed in the Fig.1. (Balátě *et al.* 2006).

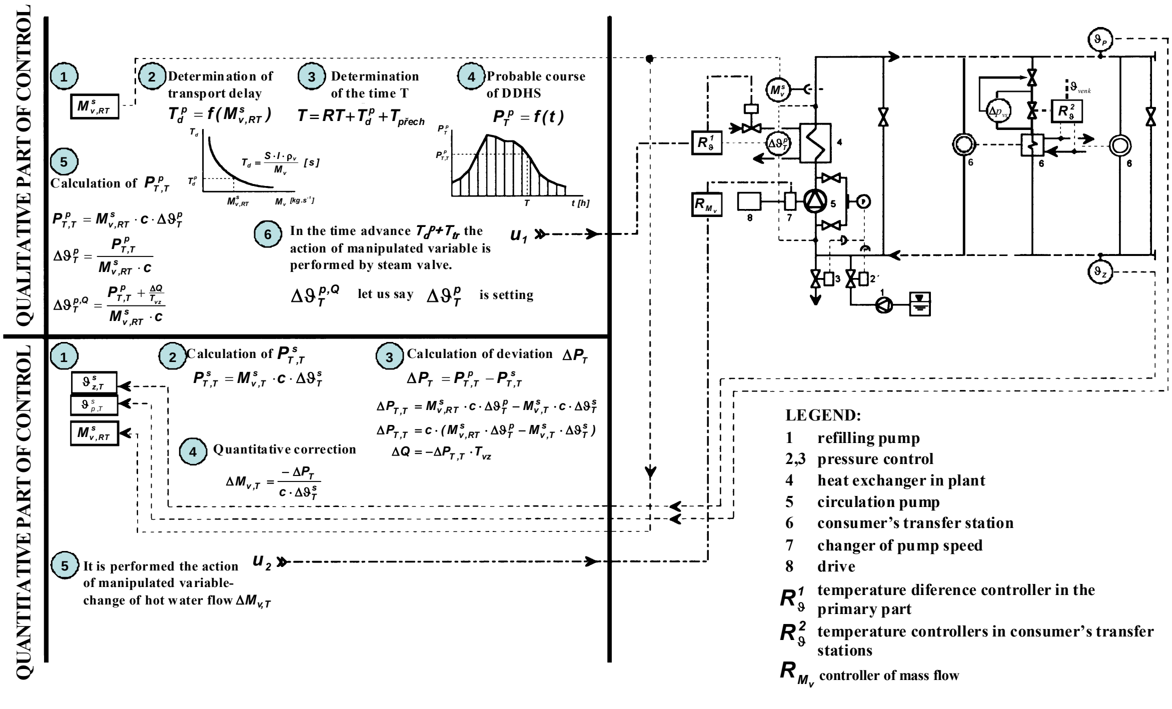

Fig. 1. Algorithm of qualitative-quantitative method of control of heat supply by hot-water piping

Key to Fig. 1: c- specific heat capacity, *l*- length of intake branch of heat feeder, *RT*- real time (time in which manipulated variable of qualitative method of control is acting on exchanger in power and heating plant), *S*- cross section of intake branch of feeder, *T*- time in which acting of manipulated variable of quantitative method of control shows itself at locally concentrated consumers, T_d - transport delay, T_d^p - presupposed transport delay, T_{pr}- time advance, T_{prech}- time of transition of exchanger in power and heating plant at action of manipulated variable, T_{VZ} - period of sampling (approx. 15 minutes), M_v- mass flow of circulating water, $M^s_{v,RT}$ - real mass flow of circulating water in time *RT*, $M^s_{v,T}$ - real mass flow of circulating water in time *T*, P_T - heat output of hot-water piping, P_T^p - presupposed heat output read from predicted daily diagram of heat supply *(DDHS)*, $P^p_{T,T}$ - presupposed heat output in time *T*, $P^s_{T,T}$ - real measured (calculated) heat output in time T, $\vartheta^s_{P,T}$ - real temperature in intake branch of feeder at consumers in time *T*, $\vartheta^s_{Z,T}$ - real temperature in return branch of feeder at consumers in time *T*, $\Delta P_{T,T}$ - deviation between presupposed and real consumed heat output in time *T*, $\Delta M_{v,T}$- quantitative correction, i.e. change of mass flow of circulating water, ΔQ- change of heat content in intake branch of feeder caused by quantitative correction, $\Delta\vartheta^s_T$ - real temperature difference at consumers in time *T*, $\Delta\vartheta^p_T$ - presupposed temperature difference on exchanger in power and heating plant in time *T* which is calculated from $P^p_{T,T}$ and which is manipulated variable of qualitative method of control, $\Delta\vartheta^{p,Q}_T$ - presupposed temperature difference on exchanger in power and heating plant in time *T* which includes correction of heat content in intake branch of feeder ΔQ. It is necessary to bring in this heat or possibly to decrease heat admission by it in dependence on sense (sign) of quantitative correction $\Delta M_{v,T}$, ρ_v- specific mass of circulating water in intake branch of feeder.

The sequence of the qualitative control method is as follows

- measuring the mass flow of heat carrying medium (hot water) (step 1),
- determination of the transport delay (step 2),
- determination of the time after which the action (intervention) of the qualitative control method appears at consumers - time *T* (step3),
- determination of presupposed heat output $P^p_{T,T}$ in time *T* from DDHS (step 4),
- calculation of manipulated variable u_1 - $\Delta\vartheta^{p,Q}_T$, from presupposed heat output $P^p_{T,T}$; u_1 including also correction of heat content in the intake branch of the feeder (step 5),
- change of control signal to manipulated variable i.e. to the position of control valve of intake steam at intake to power and heating plant exchanger (step 6).

The sequence of the quantitative control method is as follows

- measuring the real (actual) values of parameters necessary for further calculation $\vartheta^s_{P,T}$, $\vartheta^s_{Z,T}$, $M^s_{v,T} \equiv M^s_{v,RT}$ (step 1),
- calculation of the real consumed heat output at the place of consumers $P^s_{T,T}$ (step 2),
- calculation of the deviation of qualitative control method and real consumed (actual) output at consumers - $\Delta P_{T,T}$ (step 3),
- calculation of quantitative correction of heat output $\Delta M_{v,T}$ (step 4),
- change of control signal to manipulated variable i.e. to the value of speed of circulating pump (step 5).

2.1 Description of control algorithm of qualitatively-quantitative control method

Control algorithm of qualitatively-quantitative control method is shown in Fig. 2. The output of the controlling algorithm is two manipulated variables

- temperature in the intake branch of the hot-water piping system which in practice varies with a change of the heat input at the inlet into the heat exchanger of the power and heating plant
- mass flow of hot water varies with a change of speed of the circulating pump

After intervention in the change of supplied heat output by applying the quantitative part of control (mass flow) it is necessary to establish *qualitative correction I* in order to maintain heat volume in the intake branch of the hot-water piping system. In the controlling algorithm, this correction is marked ΔQ and is determined on the basis of a positive or negative deviation of expected heat output and real heat output. The consequence of this intervention is the aim that the quantitative part of control by varying the speed of the supply pump should return the resistance curve of the piping into its initial position (into the preset position for the purpose of increasing or decreasing the mass flow).

Until the time *T(0),* which is the time when the control of delivered power output shows at the consumers´ places, the control of expected heat output is only carried out according to the forecast of the daily diagram of the heat supply. In a time lesser than *T(0),* only the qualitative part of control is active, i.e. the quantitative part of control is not active. For this reason, another correction, the so-called *qualitative correction II* is added to the controlling algorithm, the purpose of which is to maintain approximately heat content in the intake branch until the time when the quantitative part of control starts to be active. ***The qualitative correction I and qualitative correction II are used for maintenance of heat content in the intake branch of the hot-water piping system. Until the time is lower than T(0), the qualitative correction II is active, from the time greater than or equal to T(0) it is the qualitative correction I that is active.***

As input values for the control algorithm, such variables may be considered that characterize the dimensions of the piping and properties of the heat-carrying medium, i.e. length of piping, cross-section of piping, density of heat-carrying medium and specific heat capacity. Other inputs required are the daily diagram of heat supply, for determination of heat output and determination of real time *(RT)*. Other description it is possible to find in (Eliáš 2006).

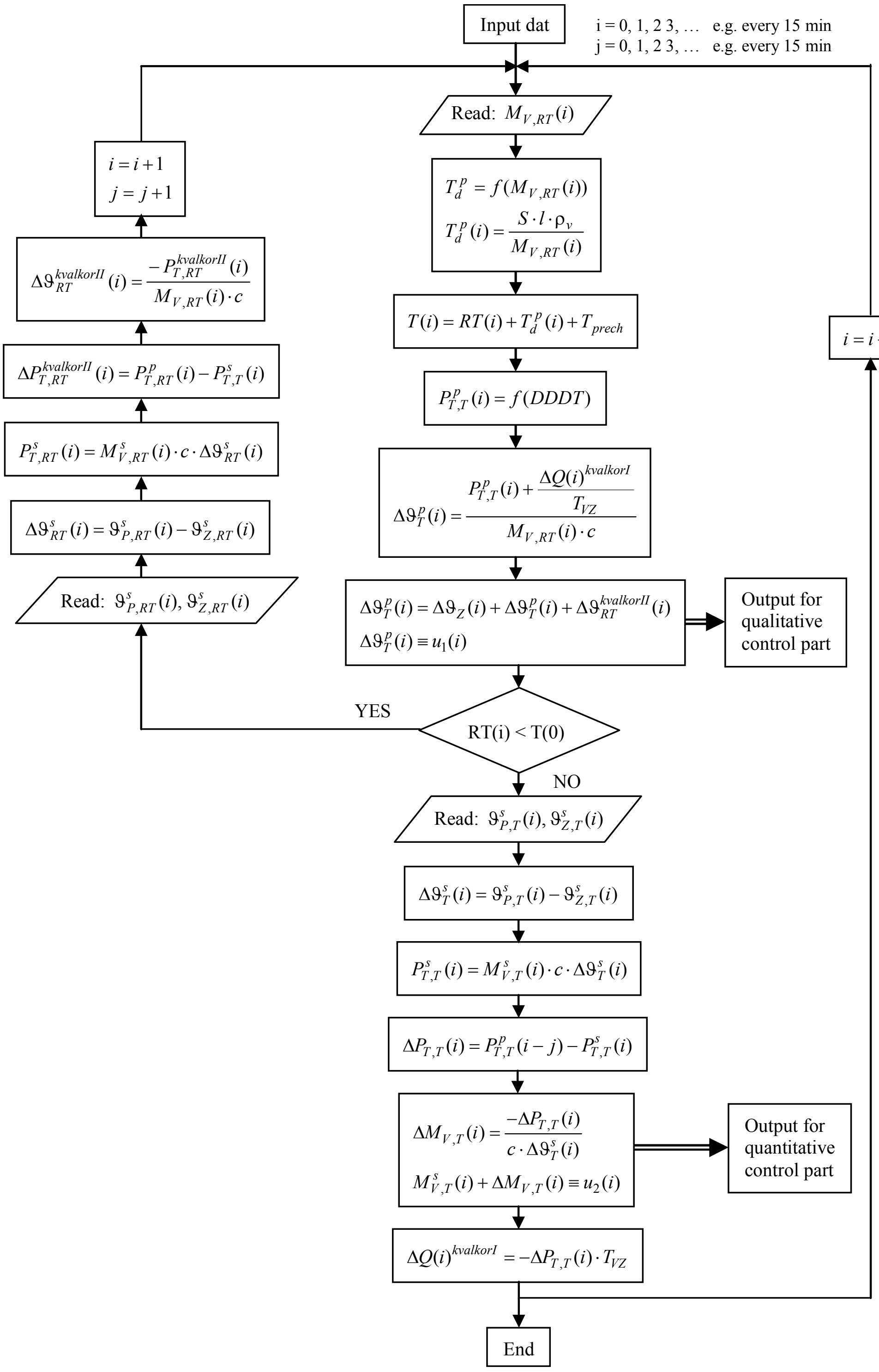

Fig. 2. Algorithm of qualitative-quantitative method of control of heat supply by hot-water piping

2.2 *Evaluation of control method*

Using the above described method is suitable in cases that the heat consumers are relatively locally concentrated, e.g. the system of centralized heat supply is distant from the heat source (heat exchanger) and with the control method currently used, quite a large delay in supply occurs necessarily. In such a case, when controlling the power output delivered by the hot-water pipeline, the impact on delay in supply must be eliminated. For the control, it is necessary to make use of the prediction of the course of daily heat supply diagram. It is possible to calculate it in real time, but only for a time interval a little longer than current delay in delivery is.

3. PREDICTION OF DAILY DIAGRAM OF HEAT SUPPLAY

In the past, lots of works were created which solved the prediction of daily diagram of heat supply (DDHS) and its use for controlling the District Heating System (DHS). Most of these works are based on mass data processing. Nevertheless, these methods have a big disadvantage that may result in out-of-date real data. From this point of view it is suitable to use the forecast methods according to the Box-Jenkins methodology (Box and Cox 1976). This method works with a fixed number of values which are updated for each sampling period. This methodology is based on the correlation analysis of time series and works with stochastic models which enable to give a true picture of trend components and also that of periodic components. As this method achieves very good results in practice, it was chosen for the calculation of DDHS forecast.

3.1 *Calculation methods of prediction of DDHS*

The course of time series of DDHS contains two periodic components (daily and weekly period). Firstly it is daily period (fluctuation during the day) and secondly it is weekly period (heat consumption loss on Saturday and Sunday). But general model according to Box-Jenkins (BJ) enables to describe only one periodic component. We can propose two eventual approaches to calculation of forecast to describe both periodic components (Dostál 1986).

- The method that uses the model with double filtration
- The method - superposition of models

Method that uses model with double filtration

It is important to adhere to this general plan for using the method that uses model with double filtration for calculation of DDHS prediction (Dostál 1986), (Chramcov 2006).

a) The filtration of time series is executed for the reason of elimination of weekly periodic component.
b) This filtered time series can be described by means of general model according BJ and then calculation of forecast by means of course can be executed; that is provided in work.
c) It is important to do back transformation that is inverse to the point a), because we have executed elimination of weekly periodic component.

Method of superposition of models

We can use second method i.e. superposition of models for elimination of regular influence of calendar. This method was published in the work (Dostál 1986). This method used two models. These models are discerned by means of symbols * and **. The time series inscribed with symbol *, is series of values of DDHS outputs e.g. in every hour (the sampling period is 1 hour). And the time series inscribed by means of symbol ** is series of values of heat consumption per day (the sampling period is 1 day). The plan of calculating prediction by means of the method of superposition of models is shown on the Fig. 3. (Chramcov 2006)

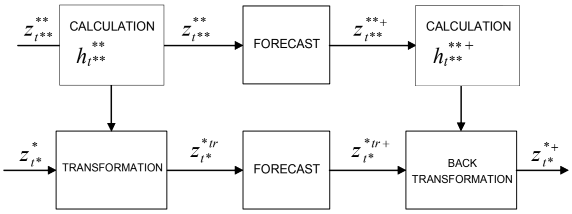

Fig. 3. Superposition of models - plan of calculating prediction

3.2 *Inclusion of influence of outdoor temperature on course of DDHS*

Two eventual approaches to calculation of forecast (The method that uses the model with double filtration, the method - superposition of models) enable to describe both periodic components of DDHS (daily and weekly period). These methods enable also to give a true picture of trend components. Trend of DDHS is attributed to fluctuation of outdoor temperature during the course of season. Above mentioned methods do not describe sudden fluctuation of meteorological influences. In this case we have to include these influences in calculation of prediction.

Previous works on heat load forecasting (Arvastson 2001) show that the outdoor temperature has the greatest influence on DDHS (with respect to meteorological influences). Other weather conditions like wind, sunshine and so on have less effect and they are parts of stochastic component.

It is possible to say, that the time series forecast namely forecast of energy time series has importance to control of technological process. This forecast is significant from the point of view of costs saving and also ecology of operation. (Chramcov 2006)

4. SIMULATING VERIFICATION OF CONTROL ALGORITHM OF QUALITATIVE-QUANTITATIVE CONTROL METHOD

For the simulating verification of the qualitatively-quantitative control method of heat output of the hot-water piping system using the prediction of the course of the daily diagram of heat supply in the systems of centralized heat supply, a simulating program was created in the program environment MATLAB/SIMULINK. The basic simulating diagram is shown in the Fig. 4.

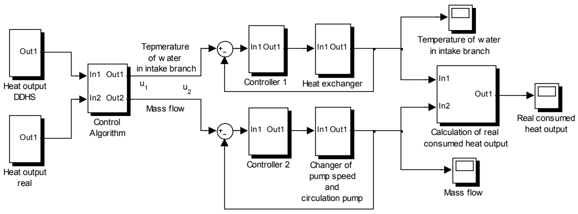

Fig. 4. Simulating schema of the closed control loop of the hot-water piping system

4.1 *Setting-up the simulating experiments*

The simulating verification of the controlling algorithm was based on the following assumptions:

1) Actual heat consumption is known, i.e. the course of real heat output at the consumer' s place $P^s_{T,T}(i)$.

   This assumption has been established in order to be able to perform the simulation of the control algorithm for the regulated system. In real operating conditions, real temperature is measured in intake branch $\vartheta^s_{P,T}(i)$ and in the return branch of feeder $\vartheta^s_{Z,T}(i)$, at the consumer' s place, as described in the controlling algorithm. Real heat output $P^s_{T,T}(i)$ would be determined from difference of these values. During the simulation temperatures $\vartheta^s_{P,T}(i)$ and $\vartheta^s_{Z,T}(i)$ cannot be measured, therefore real heat output are loaded from a data file.
2) The mass flow of the heat-carrying medium $M^s_{V,T}(i)$ will be constant until the time when the quantitative manner of control starts to be active.
3) Expected temperature in the return branch of feeder $\vartheta^p_{Z,T}(i)$ will be constant, as well.

To simulation verification of the control algorithm was used data that was obtained from heat and power plant Litomerice. To prediction daily diagram of heat supply method of superposition of models was used, whereas influence of outdoor temperature was included into calculation. It was used 816 previous values to prediction DDHS, sampling period was 30 minutes. Prediction of DDHS was determined on the day January 29, 2004 from data that were obtained from January 12, 2004 00:00 to January 28, 2004 23:30.

Other parameters required for the simulation are data on the piping. These were chosen as follows: piping length - 11200 m, piping cross section - 0.35 m, density of circulating medium - 1000 kg/m3, specific thermal capacity - 4200 J/kgK, medium mass flow - 141 kg/s, temperature in return branch of feeder - 70 ºC, simulation time - 86400 sec.

For the proposal of discrete regulators (in the diagram, these are the blocks of "Controller 1" and "Controller 2"), the dead beat control method was used (Kozák 1993). In addition to this method of synthesis, it is possible to use for the proposal of parameters of the discrete regulators also some other single-variable discrete synthesis method, such as the discrete version of Ziegler-Nichols step response method, or a method of desired model, etc. (Balátě 2004).

Parameters of discrete controllers $G_{R,TV}(z)$ and $G_{R,C}(z)$ were determined for considered transfer function of controlled system $G_{S,TV}(s)$ and $G_{S,C}(s)$

- Transfer function $G_{S,TV}(s)$ (block „Heat exchanger“) was considered in the form

$$G_{S,TV}(s) = \frac{1}{(100s+1)(100s+1)(100s+1)} \tag{1}$$

- Transfer function of discrete controller $G_{R,TV}(z)$; it was used deadbeat control method (time period was 100 sec)

$$G_{R,TV}(z) = \frac{3{,}96 - 4{,}37z^{-1} + 1{,}61z^{-2} - 0{,}197z^{-3}}{1 - 0{,}318z^{-1} - 0{,}611z^{-2} - 0{,}071z^{-3}} \tag{2}$$

- Transfer function $G_{S,MC}(s)$ (block „Changer of pump speed and circulation pump“) was considered in the form

$$G_{S,MC}(s) = \frac{1}{(0{,}1s+1)(2{,}55s+1)} \tag{3}$$

- Transfer function of discrete controller $G_{R,MC}(z)$ it was used deadbeat control method (time period was 1 sec)

$$G_{R,MC}(z) = \frac{3{,}083 - 2{,}083z^{-1} + 0{,}0001z^{-2}}{1 - 0{,}915z^{-1} - 0{,}085z^{-2}} \tag{4}$$

4.2 *Simulation verification of designed algorithm*

The courses of real heat output and outdoor temperature in the days from 2.1.2004 to 31.3.2004 are shown in the following figures (Fig. 5 and Fig. 6).

The courses of real $P^{s}_{T,T}(i)$ and expected $P^{p}_{T,T}(i)$ heat output are shown in Fig. 7. In Fig. 8, mass flow $M^{s}_{V,RT}(i)$ is constant until the time $T(0)$ marked in the diagram. Temperature in the intake branch of feeder $\vartheta_{P}(i)$ is shown in Fig. 9. Until the time $T(0)$ the temperature is influenced by the qualitative correction *qualitative correction II*, and commencing from the time $T(0)$ also quantitative part of control begins to influence temperature, i.e. thus a change of mass flow and correction of *qualitative correction I* $\Delta Q(i)$. The change of mass flow $\Delta M^{s}_{V,T}(i)$ serves to compensation difference between expected heat output $P^{p}_{T,T}(i)$ and real heat output $P^{s}_{T,T}(i)$.

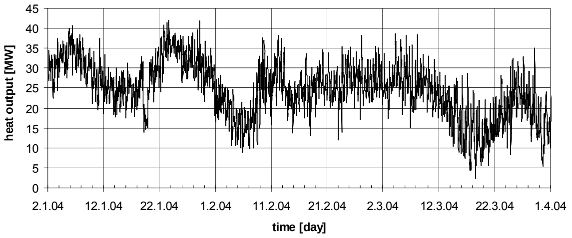

Fig. 5. The course of real heat output (2.1.2004-31.3.2004)

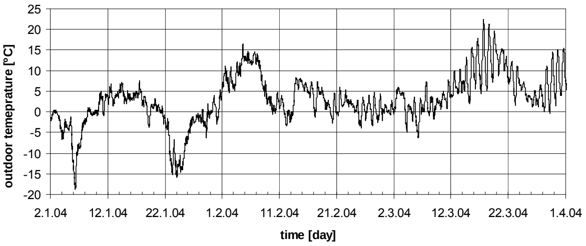

Fig. 6. The course of outdoor temperature (2.1.2004-31.3.2004)

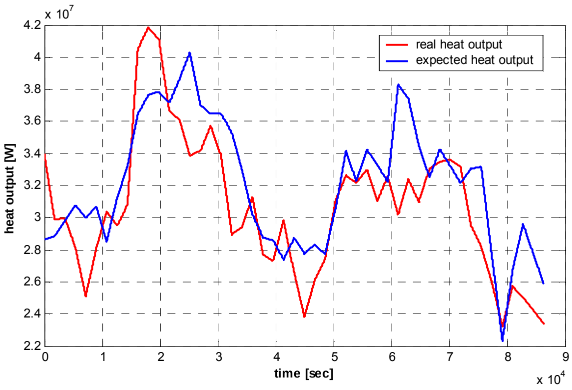

Fig. 7. The courses of expected and real heat output

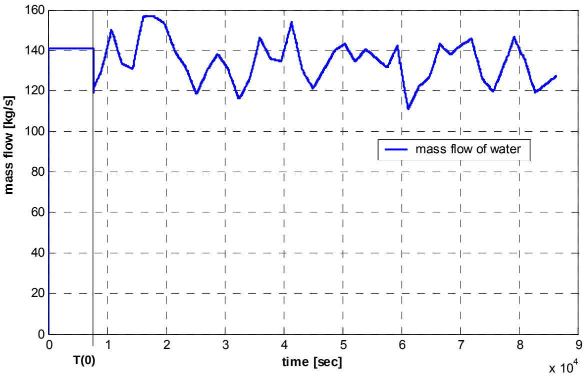

Fig. 8. The course of mass flow of water

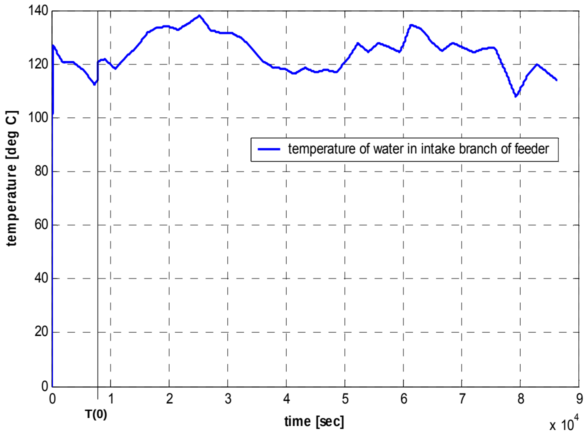

Fig. 9. The course of temperature of water in intake branch of feeder

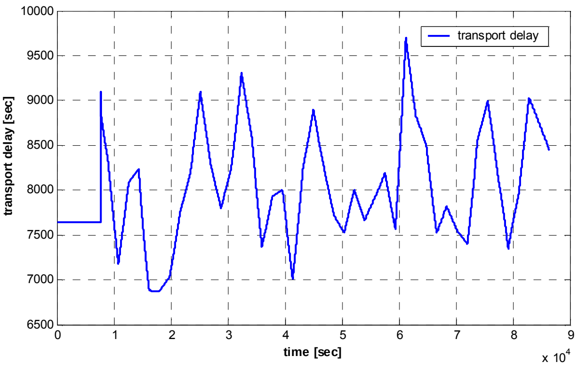

Fig. 10. The course of transport delay

5. CONCLUSION

For the large networks of power and heating plants with a big distance between the heat source and individual consumers´ systems, delay in supply occurs depending on length of the supply pipeline and on the streaming speed of heat-carrying medium. The proposed qualitatively quantitative control algorithm with the use of the prediction of daily diagram of heat supply in the hot-water piping systems of the centralized heat supply eliminates the influence of this delay in supply by means of the quantitative part of control, not being dependent on delay in supply, unlike the qualitative part of control. The output from this control algorithm is two actuating variables. For the qualitative method of control, this refers to the change in a difference between water temperatures in the supply and return pipe manifold of the hot-water pipeline, accomplished due to the change of thermal input in steam at the inlet into the heat exchanger. And for the quantitative method of control, this is the change of mass flow of hot water accomplished due to the change in speed of the circulating pump. After the intervention in the change of the supplied power output by applying the quantitative part of control, it is necessary to establish ***qualitative correction I*** in order to maintain thermal volume in the supplying pipe manifold of the hot-water pipeline. Until the time when the quantitative part of control begins to be active, another quantitative part of control is established, the so-called ***qualitative correction II***, the purpose of which is to maintain approximately thermal volume in the supply pipe manifold of the hot-water pipeline. Due to these two actuating variables, heat supply to the consumer can be controlled more effectively than if only one of them is used.

It should be taken into account that higher temperature in the supply pipe manifold causes bigger thermal losses and higher mass flow results in larger consumption of pumping work. In a way, that is about searching for the minimum of the function of two variables.

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