Possible way of control of heat output in hot-water piping system of district heating

Pavel Navratil, Libor Pekar and Jindrich Klapka

***Abstract*—**The paper deals with the description possible method of control of a heat output in district heating systems. This control method is called qualitative-quantitative control method of heat output with utilization of prediction of daily diagram of heat supply in hot-water piping systems of district heating. The control method 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. The control method should enable elimination of the influence of transport delay between the heat source and heat consumption of individual relatively concentrated consumers. Transport delay can be in the range up to several hours and depends on the length of feeder piping, which can be up to several kilometers, and on the flow speed of heat transfer medium.

***Keywords*—**Control method, district heating system, heat output, transport delay.

I. Introduction

THE district heating systems (DHS) are developed in cities in according to their growth. DHS has to ensure supply of energy to all heat consumers in quantity according to their requirements variable in time. The energy supply must always be in accordance with the specified quality standards. In case of hot-water piping it means to maintain prescribed temperature of hot water in intake piping. DHS is used in larger cities of some European countries e.g. in France, Denmark, Finland, Sweden, Germany, Poland, Czech Republic and others. Production technology of heat via combined production of heat and power is an important way to increasing of thermal efficiency of closed thermal loop. Features of DHS are given by its locality and therefore, it is necessary to design a control strategy for each of them. [1], [2]

District heating system is possible to consider as a technological string containing three main parts (see Fig. 1), i.e. heat production, transport + heat distribution and heat consumption [3]. The paper deals with one of the possible approaches to control of a heat output in district heating systems. Contents of the paper is possible at least partially include into all three parts of the technological string (see Fig. 1). Other possible approaches to control of district heating system can be found e.g. in [4] where the predictive approach to control is used and in [5] where the robust predictive approach to control is used. Possible approaches to solve of the individual parts of technological string can be found e.g. in [6], [7] where is solved the part "heat production", in [3] where is solved the part "transfer + heat distribution" and in [8]–[10] which deal with also the part "heat consumption".

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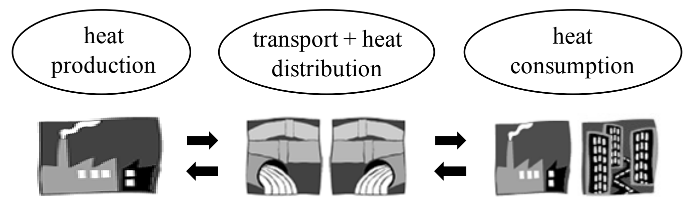


Fig. 1 technological string of district heating system, i.e. heat production, heat distribution and heat consumption

At the control of heat output of heat supply via hot-water piping is usually used the dependence on water temperature in intake piping of heat feeder or also even the dependence on outside air temperature. For the control of heat output of hot-water piping from heat source there are available two manipulated variables [11]–[13], i.e.

- change of difference of water temperature in intake and return piping of how-water piping which is realized by means of the change of heat input on intake to heating plant exchanger - so called qualitative control method of heat output,
- change of mass flow of hot water by means of the change speed of circulating pump - so called quantitative control method of heat output.

These above mentioned manipulated variables are usually used as acting separately and namely only one of them. If both manipulated variables were used it concerned a case when qualitative control method was the main method of control and quantitative method was used for starting and stopping pumps with different transported rate of mass flow. Quantitative changes were carried out once in a season at a change of the yearly period (summer, transition period, winter). Two or three sizes of circulating pumps were usually used for this purpose. Disadvantage of the mentioned approach to control is that they are not covered completely dynamic properties of the controlled plant. Transport delay in intake branch of heat intake piping and the response of inertia members of heating plant exchanger remain omitted. If the heat output consumed at any place of hot-water network is changed, then the corresponding heat output of sources (i.e. production), controlled via classic qualitative way adapts itself but with a considerable delay even when the change of mass flow of hot water occurs due to self-controlling properties of static characteristic of transport pump caused by the change of operating point position of the pump. The change of heat output consumption is realized via acting of autonomous controllers of temperature in secondary networks of consumers' transfer stations. Thus non-fulfilment of some requirements on the specified quality indexes of the heat transfer medium comes into being. [2], [12]

II. Qualitative-Quantitative Control Method of Heat Output in Hot-Water Piping System

Algorithm of the so called qualitative-quantitative control method with utilization of prediction of heat supply daily diagram in hot-water systems of district heating should enable elimination of the influence of transport delay between the heating plant exchanger in the source of heat and relatively concentrated heat consumption of all consumers. The transport delay depends on the flow speed of heat transfer 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 (i.e. change of difference of water temperature in intake and return piping and change of mass flow of hot water) influencing transferred heat output and in using prediction of required heat output in a specific locality. The designed control method was considered for a case when the transport delay was supposed in the range up to several hours depending on the heat output consumed by all consumers. [12], [13]

A. Analysis of Dynamic Properties of Hot-Water Piping

The basic technological scheme of hot-water piping is shown in Fig. 2. In this case, the circulating (transport) pump is included at the end of return piping, i.e. before exchanger station.

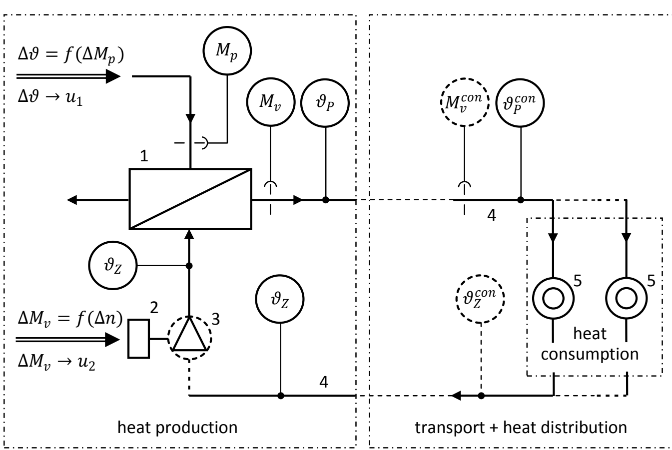


Fig. 2 basic technological scheme of hot-water piping

Legend: 1-heating plant exchanger in the source of heat, 2-speed-changing device of pumps, 3-circulating pump, 4-hot-water piping (pipeline of heat feeder), 5-consumers (exchangers in consumers' transfer stations)

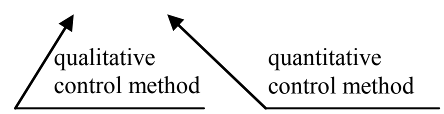
Key to Fig. 2: u_1 - manipulated variable no. 1 (it is used for qualitative control method), u_2 - manipulated variable no. 2 (it is used for quantitative control method), $M_p\,[\mathrm{kg\cdot s^{-1}}]$ - mass flow of steam at intake into heating plant exchanger, $n\,[\mathrm{s^{-1}}]$ - speed of circulating pump, $\Delta\vartheta\,[°\mathrm{C}]$ - temperature gradient (difference between water temperature in intake and return branch of the hot-water piping), $\vartheta_P\,[°\mathrm{C}]$ - temperature in intake branch of hot-water piping (behind heating plant exchanger), $\vartheta_P^{con}\,[°\mathrm{C}]$ - temperature of hot water in intake branch at the place of consumers, $\vartheta_Z\,[°\mathrm{C}]$ - temperature in return branch of hot-water piping (before heating plant exchanger), $\vartheta_Z^{con}\,[°\mathrm{C}]$ - temperature of hot water in return branch at the place of consumers, $M_v\,[\mathrm{kg\cdot s^{-1}}]$ - mass flow of heat transfer medium at outlet from heating plant exchanger, $M_v^{con}\,[\mathrm{kg\cdot s^{-1}}]$ - mass flow of heat transfer medium in intake branch of hot-water piping at the place of consumers.

As already mentioned in the paragraph I, there are two manipulated variables for the control of heat output of hot-water piping for heat supply to the heat network [13], i.e.

- for qualitative control method it is the change of difference between water temperature in intake and return piping of the hot-water piping $\Delta\vartheta$ which is realized by the change of heat input of steam on intake to heating plant exchanger ΔM_p,
- for quantitative control method it is the change of mass flow of hot water ΔM_v realized via the change of circulating pump speed Δn.

Further, it is considered the following relation that serves to determination of heat output of hot-water piping, i.e.

$$P_T = M_v \cdot c \cdot \Delta\vartheta \qquad (1)$$



where $P_T\,[\mathrm{W}]$ is the heat output of hot-water piping, $\Delta\vartheta\,[°\mathrm{C}]$ is temperature gradient, $M_v\,[\mathrm{kg\cdot s^{-1}}]$ is mass flow of heat transfer medium and $c\,[\mathrm{J\cdot kg^{-1}\cdot K^{-1}}]$ is specific heat capacity.

Behavior of hot-water piping at qualitative control method

At qualitative control method the hot-water piping behaves as a proportional controlled system with inertia of the higher order with transport delay. The mentioned behavior can be expressed by means of the following transfer function, i.e.

$$G^{qual}(s) = \frac{\Delta\Theta_P^{con}(s)}{\Delta M_p(s)} = \frac{k^{qual}}{(T_1 s+1)(T_2 s+1)(T_3 s+1)} \cdot e^{-sT_d} \qquad (2)$$

where $\Theta_P^{con}(s)$ is Laplace transform of variable $\vartheta_P^{con}\,[°\mathrm{C}]$ which represents temperature of hot water in intake branch at the place of consumers, $M_p(s)$ is Laplace transform of variable $M_p\,[\mathrm{kg\cdot s^{-1}}]$ which represents mass flow of steam at intake to heating plant exchanger, k^{qual} [°C·s·kg^{-1}] is gain of proportional controlled system in qualitative part, T_i [s] (i = 1, 2, 3) [s] are time constants of the controlled system and T_d [s] is transport delay.

Dynamic properties are defined by the behavior of heating plant exchanger and they can be described by properties of a proportional system with inertia of third order. Time constants of transition process (dead time, rise time, transit time) can assume values up to tens of minutes and depend on the mass flow of the heated water through the heating plant exchanger. The response on the Fig. 3 expresses the time course of temperature in intake branch of hot-water piping ϑ_P, where the mass flow of heat transfer medium (circulating water) M_v is changing parameter.

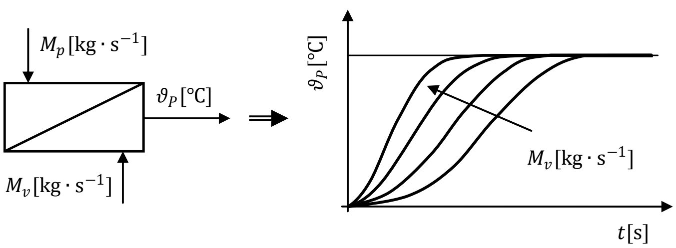


Fig. 3 response of the time course of temperature in the intake branch of hot-water piping ϑ_P

Transport delay T_d in hot-water network is a function of mass flow of circulating water and it is given by the relation

$$T_d = f(M_v) = \frac{S \cdot l \cdot \rho_v}{M_v} \tag{3}$$

where S [m^2] is cross section of piping of heat feeder intake branch, l [m] is the length of observed section of the piping, ρ_v [kg·m^{-3}] is density of circulating water and M_v [kg·s^{-1}] is mass flow of heat transfer medium (circulating water).

Described consideration is well-founded in localities where relatively concentrated heat consumption is considerably distant (in the range up to several tens of kilometers) from the heat source. Thus, it is obvious from above that the qualitative method of control takes effect at the consumer of heat with a time shift corresponding to the transport delay, i.e.

$$\vartheta_P^{con}(t + T_d) = \vartheta_P(t) \quad , \quad \vartheta_P^{con}(t) = \vartheta_P(t - T_d) \tag{4}$$

The manipulated variable u_1, which corresponds to the change of temperature difference $\Delta\vartheta$ between water temperature in intake branch (i.e. behind heating plant exchanger) ϑ_P and return branch (i.e. before heating plant exchanger) ϑ_Z of the hot-water piping, is determined by using the following relation

$$\Delta\vartheta \to u_1,\ \Delta\vartheta = \vartheta_P - \vartheta_Z = \frac{P_T}{M_v \cdot c} \to \vartheta_P$$
$$\vartheta_P = \vartheta_Z + \frac{P_T}{M_v \cdot c} \equiv u_1 \tag{5}$$

Behavior of hot-water piping at quantitative control method

Quantitative control method realizes a change of the mass flow of heat transfer medium (circulating water) M_v and thus a change of the delivered heat output (1) by means of speed-changing device circulation pump. Quantitative control method includes inertia of speed-changing device and also time constant (constant of inertia) of piping. The time constant of piping covers the time necessary to acceleration or deceleration of circulating incompressible heat transfer medium. At quantitative control method the hot-water piping (pipeline) behaves as a proportional controlled system without inertia and without transport delay. The mentioned properties can be expressed via the following transfer function

$$G^{quant}(s) = \frac{\Delta M_v^{con}(s)}{\Delta M_v(s)} = \frac{k^{quant}}{(\tilde{T}_1 s + 1)(\tilde{T}_2 s + 1)} \doteq 1 \tag{6}$$

where $M_v^{con}(s)$ is Laplace transform of variable M_v^{con} [kg·s^{-1}] which represents mass flow of heat transfer medium in intake branch of hot-water piping at the place of consumers, M_v(s) is Laplace transform of variab le M_v [kg·s^{-1}] which represents mass flow of heat transfer medium at outlet from heating plant exchanger, k^{quant} [-] is gain of proportional controlled system in quantitative part, $\tilde{T}_1$ [s] is the time constant of speed-changing devices and is defined by the kind of speed-changing device (hydraulic clutch, electric speed-changing device), $\tilde{T}_2$ [s] is the time constant of piping and is defined by the speed of the heat transfer medium, length of piping and transport height of the circulating pump.

Time constant $\tilde{T}_2$ [s] (7) is the time which hot water needs to gain the maximum speed c_{max} [m·s^{-1}] from the rest. The maximum speed corresponds to maximum mass flow of heat transfer medium $M_{v,max}$ [kg·s^{-1}] by acting of transport height of pump H_{max} [m]. Parameter l [m] is the length of observed section of the piping and g [m·s^{-2}] is acceleration of gravity.

$$\tilde{T}_2 = \frac{l \cdot c_{max}}{g \cdot H_{max}} \tag{7}$$

Time constants $\tilde{T}_1, \tilde{T}_2$ are generally much smaller (the order of seconds, tens seconds) than time constants in the relation (2) i.e. than time constants of heating plant exchanger (the order of minutes, tens minutes).

The manipulated variable u_2, which corresponds to the change of mass flow of hot water ΔM_v, is determined by using the following relation

$$\Delta M_v \to u_2,\ M_v = \frac{P_T}{\Delta\vartheta \cdot c}, M_v + \Delta M_v \equiv u_2 \tag{8}$$

It is obvious from the above that from the point of view of dynamic properties the quantitative control method of hot-water piping output has advantage. The behavior the hot-water piping at the quantitative control method can be described by means of proportional system without transport delay, i.e. by means of transfer function (6) which does not include the transport delay. Transport delay in the transfer function (2) can be in the order of several hours.

B. Principle of the Qualitative-Quantitative Control Method with Utilization of Prediction of Heat Supply Daily Diagram in Hot-Water Systems of District Heating

Schematic diagram of the qualitative-quantitative control method of heat output in district heating systems is displayed in the following figure (see Fig. 4). [11]–[13]

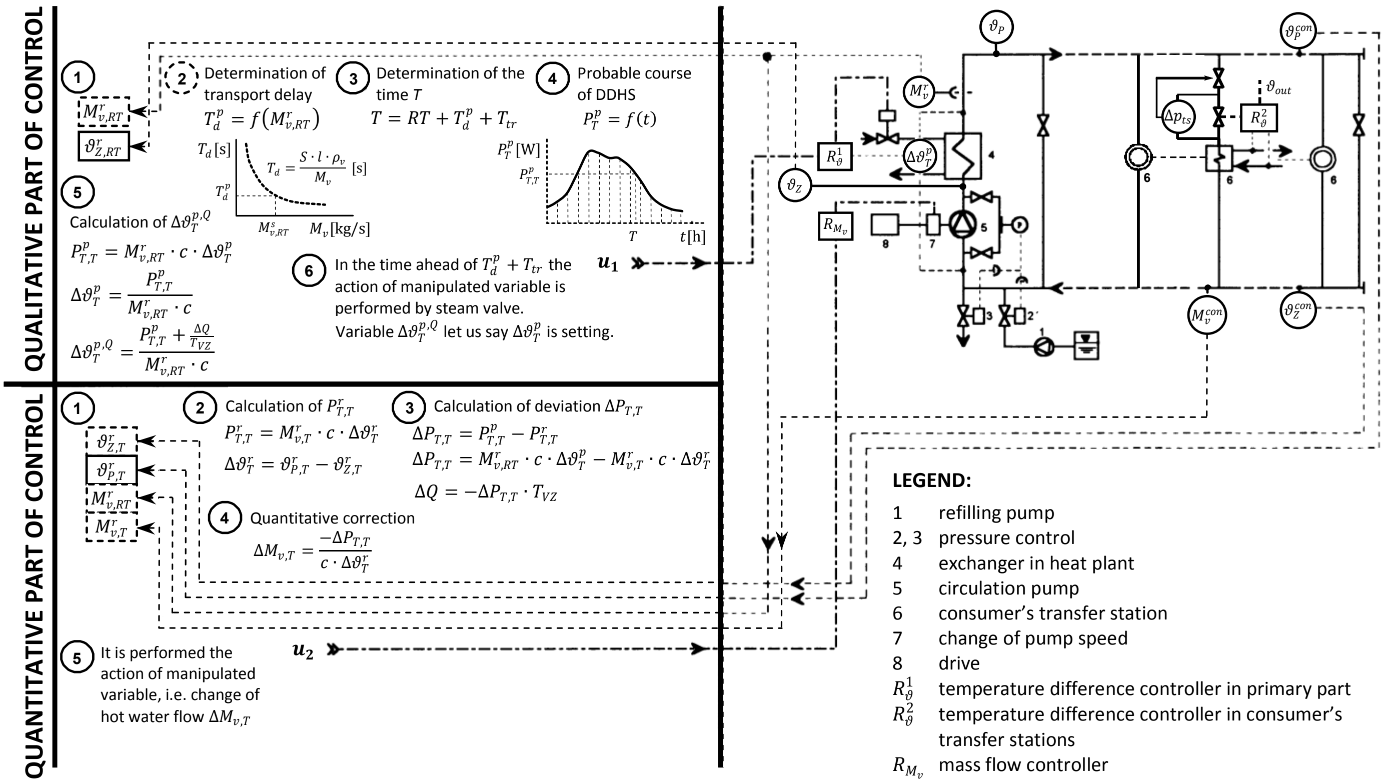


Fig. 4 schematic diagram of the qualitative-quantitative control method of heat output with utilization of prediction of daily diagram of heat supply in hot-water piping systems of district heating

Key to Fig. 4: S - cross section of intake branch of feeder, l - length of intake branch of heat feeder, ρ_v - density of circulating water in intake branch of feeder, c- specific heat capacity, RT - real time, i.e. time in which manipulated variable of qualitative method of control is acting on exchanger in heating plant, T - time in which acting of manipulated variable of qualitative method of control shows itself at locally concentrated consumers, T^p_d - presupposed transport delay, T_{tr}- transit time of exchanger in heating plant at action of manipulated variable, T_{VZ} - sampling period (e.g. 10, 15, 30 minutes), M_v - mass flow of circulating water, $M^r_{v,RT}$ - real mass flow of circulating water in time RT, $M^r_{v,T}$ - real mass flow of circulating water in time T, $\Delta M_{v,T}$ - quantitative correction, i.e. change of mass flow of circulating water, P_T - heat output of hot-water piping, P^p_T - presupposed heat output read from predicted daily diagram of heat supply (DDHS), $P^p_{T,T}$ - presupposed heat output in time T, $P^r_{T,T}$ - real measured (calculated) heat output in time T, $\Delta P_{T,T}$ - deviation between presupposed and real consumed heat output in time T, ΔQ - change of heat content in intake branch of feeder caused by quantitative correction, $\vartheta^r_{P,RT}$ - real temperature in intake branch of hot-water piping in time RT, $\vartheta^r_{Z,RT}$ - real temperature in return branch of hot-water piping in time RT, $\vartheta^r_{P,T}$ - real temperature in intake branch of feeder at consumers in time T, $\vartheta^r_{Z,T}$ - real temperature in return branch of feeder at consumers in time T, $\Delta\vartheta^r_T$ - real temperature difference at consumers in time T, $\Delta\vartheta^p_T$ - presupposed temperature difference on exchanger in 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 heating plant in time T which includes correction of heat content in intake branch of feeder ΔQ (this heat is necessary to bring or possibly to decrease heat admission by it in dependence on sense (sign) of quantitative correction $\Delta M_{v,T}$).

The sequence of the qualitative part of the control method is as follows

- measurement of the mass flow of heat transfer medium (hot water) $M^{r}_{v,RT}$ and temperature in return branch of hot-water piping $\vartheta^{r}_{Z,RT}$ (step 1),
- determination of presupposed transport delay T^{p}_{d} (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 daily diagram of heat supply (DDHS) (step 4),
- calculation of presupposed temperature difference on exchanger in heating plant in time T, i.e. $\Delta\vartheta^{p,Q}_{T}$ including also correction of heat content in the intake branch of the feeder $\Delta Q / T_{VZ}$ (step 5),
- change of control signal to manipulated variable i.e. to the position of control valve of intake steam at intake to exchanger in heating plant (step 6).

The sequence of the quantitative part of the control method is as follows

- measurement of the real (actual) values of the parameters necessary for further calculations $\vartheta^{r}_{P,T}$, $\vartheta^{r}_{Z,T}$, $M^{r}_{v,T} \equiv M^{r}_{v,RT}$ (step 1),
- calculation of the real consumed heat output at the place of consumers $P^{s}_{T,T}$ for determined temperature difference $\Delta\vartheta^{r}_{T}$ (step 2),
- calculation of deviation between presupposed and real (actual) heat output at consumers, i.e. $\Delta P_{T,T}$ and calculation of heat content in intake branch of feeder ΔQ (step 3),
- calculation of quantitative correction of heat output $\Delta M_{v,T}$ (step 4),
- change of control signal to manipulated variable u_2 i.e. to the value of speed of circulating pump (step 5).

As already mentioned above, described qualitative-quantitative control method of heat output in hot-water piping system should enable elimination of the influence of transport delay between the heating plant exchanger in the source of heat and relatively concentrated heat consumption of all consumers.

The influence of transport delay at control of heat output of hot-water feeder should be possible to eliminate by simultaneous and continuous control via two manipulated variables, i.e. by control of the heat gradient at the heating plant exchanger u_1 and by control of the mass flow of heat transfer medium u_2 (circulating water). The essence of the control method consists in correction of the deviation $\Delta P_{T,T}$ arising at the use of the qualitative control method including transport delay (see transfer function (2) and manipulated variable u_1 (5)) by using a quantitative control method which does not include transport delay (see transfer function (6) and manipulated variable u_2 (8)) and can act almost immediately. The calculation of deviation $\Delta P_{T,T}$ is realized via following relation, i.e.

$$\Delta P_{T,T} = P^{p}_{T,T} - P^{r}_{T,T} \tag{9}$$

where $\Delta P_{T,T}[W]$ means the difference between the predicted heat output $P^{p}_{T,T}$ according to predicted course of DDHS for time T and really consumed heat output by all consumers $P^{r}_{T,T}$, $P_{T,T}$ [W] is heat output in the time T in which shows manipulated variable u_1 at locally concentrated consumers, and $P^{r}_{T,T}$ [W] is really consumed heat output by all consumers in the time T, $P^{p}_{T,T}$ [W] is presupposed heat output in time T. Time T is determined from the relation

$$T = RT + T^{p}_{d} + T_{tr} \tag{10}$$

where RT[s] is the real time in which the manipulated variable u_1 acts on heating plant exchanger, T^{p}_{d} [s] is calculated (presupposed) transport delay ($T^{p}_{d} = f(M_v)$), T_{tr}[s] is transit time of heating plant exchanger read from the measured step response characteristic (($T_{tr} = f(M_p, M_v)$, see Fig. 3).

The described control method (see Fig. 4) represents the principle of control and uses

- self-regulating features of circulating (transport) pump

This fact is obvious from the characteristic of circulating pump (see Fig. 5) where displacement of operating point position of the pump is indicated both at decreased withdrawal of volume flow (decrease of heat consumption by consumers) and also at increased withdrawal of volume flow (increase of heat consumption by consumers). Quantitative part of control acts as the control to constant position of resistance characteristic of the piping (see Fig. 5),

- correction of heat contents in intake branch of heat feeder

This fact results from the necessity to keep heat contents of intake branch of hot-water piping also after intervention of supplied output correction by acting of the quantitative part of control. With regard to the heat output determined by quantitative control method, any quantity of withdrawn heat or not withdrawn heat (therefore at outlet from intake branch of hot-water piping) has to be put in accord with the control signal of qualitative part of control at the intake to hot-water piping. The mentioned correction results from the following relation

$$\Delta\vartheta^{p,Q}_{T} = \frac{P^{p}_{T,T} + \dfrac{\Delta Q}{T_{VZ}}}{M^{r}_{v,RT} \cdot c} = \frac{P^{p}_{T,T} - \Delta P_{T,T}}{M^{r}_{v,RT} \cdot c} \tag{11}$$

where $\Delta\vartheta^{p,Q}_{T}$ [°C] is presupposed temperature difference on exchanger in heating plant in time T which includes correction of heat content in intake branch of feeder ΔQ, $P_{T,T}^{p}$ [W] is presupposed heat output in time T, ΔQ [W·s] is change of heat content in intake branch of feeder caused by quantitative correction, $\Delta P_{T,T}$ [W] is deviation between presupposed and real consumed heat output in time T, $M_{v,RT}^{r}$ [kg·s^{-1}] is real mass flow of circulating water in time RT, T_{VZ} [s] is sampling period and c [J·kg^{-1}·K^{-1}] is specific heat capacity of the heat transfer medium.

The described qualitative-quantitative control method uses two manipulated variables for the purpose of

- minimizing the heat losses of heat feeder which the control method achieves by controlling varying temperature of hot water at intake to the intake branch of hot-water piping. The required heat is supplied at a minimum necessary of thermal potential, thereby heat losses are decreased,
- minimizing pumping work of circulating (transport) pump, which can be achieved by suitable continuous adjustment of the operating point of the pump (see Fig. 5) according to changing requirements to flow of heat transfer medium as well as watching the required pressure gradient at the most distant customer-transfer station.

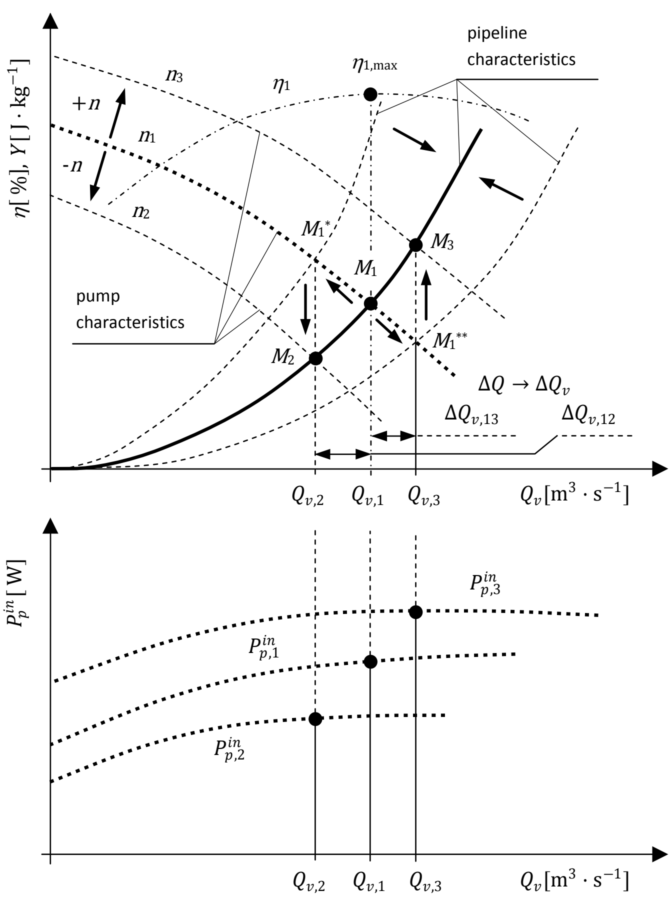


Fig. 5 transport and power characteristics of pump

Key to Fig. 5: Y[kg·s^{-1}] - specific energy, i.e. $Y = H \cdot g$, where H[m] is transport height of pump and g[m·s^{-2}] is acceleration of gravity, Q_v[m^3·s^{-1}] - volume flow of heat transfer medium, i.e. $Q_v = M_v / \rho_v$, where M_v [kg·s^{-1}] is mass flow of heat transfer medium and ρ_v [kg·m^{-3}] is density of circulating water (1000 kg·m^{-3}) in intake branch of feeder, n [s^{-1}] - speed of pump, ΔQ_v [m^3·s^{-1}] - change of volume flow of heat transfer medium, ΔQ [W·s] - change of heat content in intake branch of feeder caused by quantitative correction, η [%] - efficiency of pump, M [-] - operating point, P_p^{in} [W] - pump input power (engine output for the pump).

Pump input power can be determined using following relation, i.e.

$$P_p^{in} = \frac{Q_v \cdot \rho_v \cdot Y}{\eta} = \frac{Q_v \cdot \rho_v \cdot H \cdot g}{\eta} = \frac{Q_v \cdot \Delta p}{\eta} \qquad (12)$$

where Δp [Pa] is differential pressure, i.e. $\Delta p = \rho_v \cdot H \cdot g$, thus, 1 meter water column corresponds approximately differential pressure 10kPa.

According to [14] is more convenient and more efficient to use the pumps so that their working points were in places of characteristic with higher transported quantities (volume flow of heat transfer medium) and with lower pressure loss (lower transport height of pump). This increases the efficiency of energy utilization during the transport of heat energy in pipe networks.

C. Description of the Control Algorithm of Qualitative-Quantitative Way of Control

Algorithm of qualitative-quantitative control method of heat output in hot-water systems is shown in the Fig. 6. As input values for the control algorithm, such variables may be considered that characterize the dimensions of the piping and properties of the heat transfer medium, i.e. length of piping, cross-section of piping, density of the heat transfer 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. Outputs of the control algorithm are two manipulated variables, i.e. first variable is temperature in the intake branch of the hot-water piping system ϑ_P and second variable is mass flow of hot water M_v.

After intervention in the change of supplied heat output by applying the quantitative part of control (mass flow) it is necessary to establish the so called qualitative correction in order to maintain heat content in the intake branch of the hot-water piping system. In the control algorithm, this correction is marked $\Delta Q^{qualcorr}$ 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.

Until the time $T(0)$, which is the time when the control of delivered heat output shows at the places of consumers, 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. In a time greater than $T(0)$, they are active qualitative and quantitative part of control and correction $\Delta Q^{qualcorr}$. Other details to this control algorithm are possible to find in [15].

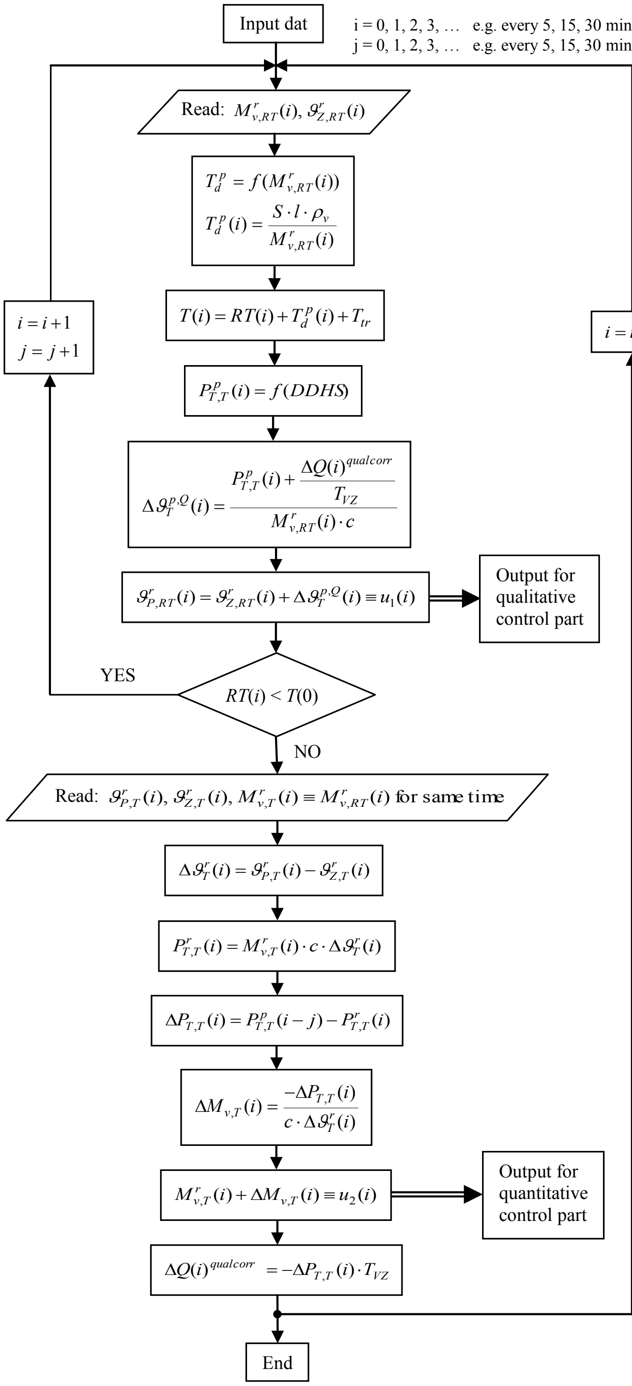


Fig. 6 algorithm of qualitative-quantitative control method of heat output in hot-water systems

D. Prediction of Daily Diagram of Heat Supply

Prediction of daily diagram of heat supply (DDHS) and its use for control the district heating system was solved in many papers in the past. Most of used approaches are based on mass data processing. Methods based on these approaches have a big disadvantage that may result in out of date of real data. Therefore, it is suitable using other methods for prediction daily diagram of heat supply, e.g. statistic method of Box-Jenkins [16], [17]. The Box-Jenkins method used fixed number of values which are continuously updated for given sampling period. It is based on the correlation analysis of time series. It works with stochastic models which enable to give a real picture of trend components and also that of periodic components. The Box-Jenkins method achieves very good results in practice.

Box-Jenkins method allows to model only stationary time series, it is therefore necessary to transform time series DDHS from a non-stationary series to stationary series. The course of time series of DDHS contains two periodic components, i.e. daily period (fluctuation during the day) and weekly period (heat consumption loss on Saturday and Sunday) (see Fig. 7a).

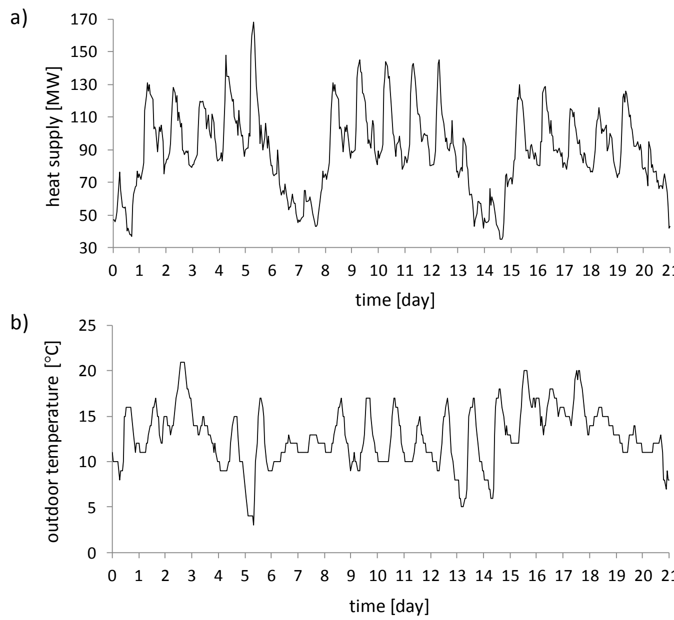


Fig. 7 course example of daily diagram of heat supply (DDHS) (a) at given outside temperature (b)

General model according to Box-Jenkins (BJ) enables to describe only one periodic component. They can be proposed e.g. these two approaches to calculation of forecast of DDHS to describe both periodic components (daily period and weekly period) [18], [19], i.e. the method using model with double filtration and the method of superposition of models. Mentioned two methods enable also to give a real picture of trend components. Trend of DDHS is attributed to fluctuation of outdoor temperature during the course of season. These methods do not describe sudden fluctuation of meteorological influences. It means that it is suitable to include these influences in calculation of prediction of DDHS. The greatest influence on DDHS, with respect to meteorological influences, has the outdoor temperature (see Fig 7b), i.e. other weather conditions, such as the direction and intensity of wind, sunshine and so on have less effect and are part of the stochastic component [20].

It is possible to say, that the forecast of energy time series has importance for control of technological process. The forecast is significant from the point of view of costs efficiency and also ecology of operation.

E. Evaluation of the Qualitative-Quantitative Control Method

Described control method is suitable in cases that the heat consumers are relatively locally concentrated. Between the heat source and the customer is usually a considerable distance and using only qualitative way of control can occur quite a large transport delay in heat supply. In such a case, when controlling the heat output delivered by the hot-water pipeline, transport delay in heat supply should be eliminated. For the control of heat output, it is necessary to use of the prediction of the course of daily diagram of heat supply (DDHS). It is possible to calculate DDHS in real time, but only for the time interval a slightly longer than current transport delay in heat supply is.

It is considered that the control system is placed in a heat source, i.e. it should be possible to obtain the data needed to determine instantaneous heat output supplied from the heat source. The data needed to determine instantaneous consumed heat output from all consumers of heat does not have to be always available in real time, e.g. the data from some customers are available only off-line or the data are read only once a month, ... [3]. In this case it would be necessary the actual consumed heat output from the given consumer in a certain way to estimate or approximated, e.g. by using the so called heating characteristic, i.e. by using the dependence consumed heat output of the given consumer on the outdoor temperature [3], [21].

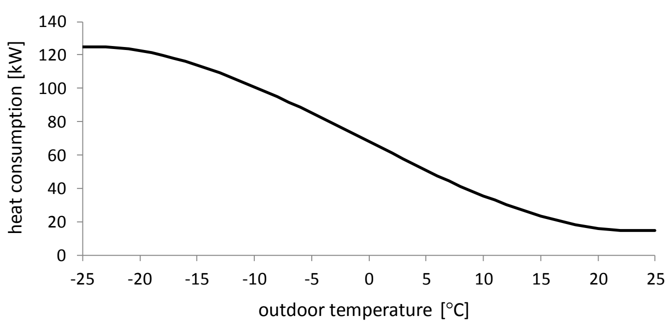


Fig. 8 example of idealized course of the heating characteristic

As already mentioned above, described control method is suitable in cases that the heat consumers are relatively locally concentrated. In other cases, i.e. where the distance between the individual consumers is significant, it is suitable to determine for the given hot-water network the so called average transport delay $\overline{T_d}$ of the hot-water network [3], [21]. From the average transport delay can be determined the so called reference point of the hot-water network [3]. This reference point is a place in the hot-water network that can be perceived as a place of concentration of all customers. Thus the average transport delay can be determined by using the following relation [3], i.e.

$$\overline{T_d} = \sum_{i=1}^{n} r(i) \cdot T_d(i), \quad i = 1,\dots,n \tag{13}$$

where $\overline{T_d}$ [s] is average transport delay, r [-] is weighted coefficient, T_d [s] is transport delay of individual consumers from the heat source and i denotes the i-th heat consumer ($i = 1, \dots, n$). Weighted coefficient r is determined from the relation

$$r(i) = \frac{P_T^{con}(i)}{P_T}, \quad i = 1,\dots,n \tag{14}$$

where $P_T^{con}(i)$ [W] is consumed heat output from all consumers, P_T [W] total heat output supplied from the heat source and i denotes the i-th heat consumer ($i = 1, \dots, n$).

Thus, via determined average transport delay (13) should be possible to use the above described qualitative-quantitative control method of heat output in hot-water piping system (see Fig. 4, Fig. 6) also for the case when the consumers are not relatively locally concentrated.

III. Conclusion

For large district heating networks, where is a big distance between the heat source and individual consumer systems, occur transport delay. Transport delay depends on the streaming speed of heat transfer medium and on length of the supply pipeline. The describe qualitative-quantitative control method of heat output with utilization of prediction of daily diagram of heat supply in hot-water piping systems of district heating should eliminate the influence of transport delay in heat supply via the quantitative part of control, which is independent on transport delay unlike qualitative part of control.

The output of the described algorithm are two manipulated variables. For the qualitative part of control, it is a change of the temperature difference between the water temperatures in the intake and return branch of the hot-water piping, which is realized by changing the heat input in steam at the inlet to the heating plant exchanger. For the quantitative part of control, it is change of the mass flow of hot water realized by changing the speed of the circulation pump. After intervention to a change of the supplied heat output by applying the quantitative part of control is necessary to establish the so called qualitative correction because of a maintenance of a heat content in intake branch of the hot-water piping. By using the two manipulated variables, it is possible to control the heat supply to consumers more efficiently than when only one of them is used. It should be taken into account that higher temperature in the intake piping can cause higher heat losses and higher mass flow can cause higher consumption of pumping work. In a way it is a search for a suitable setting two variables for the purpose of minimizing heat loss and minimizing thermal power supply pumping works circulating (transport) pump.

Advantage of the described approach to control of a heat output in district heating systems consists in simultaneous and continuous acting of two manipulated variables influencing the transferred heat output and in using the prediction of required heat output in a specific locality.

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