DOI: 10.2478/v.10169-010-0012-y

APPLICATION OF NEURAL NETWORKS FOR CONTROL OF DISTRICT HEATING

W.J. CHMIELNICKI[1]

The annual usage of heat for the demand of heating systems in municipal sector has been estimated as about 650PJ. It is mostly addressed for the demand of central heating systems and hot water consumption. The mode of adopted solutions concerning regulation and control, as well as energy management system, essentially influence its consumption. In the case of residential buildings, the costs of energy constitute the greatest share related to the total cost of building maintenance. Providing buildings with modern digital systems for control and regulation of heating installations is a basic condition enabling their rational usage. In currently employed solutions, algorithms *PI* or *PID* are usually applied. However, due to the non-linear properties of heating control systems, they do not secure proper quality. The sequences are often unstable and major control deviations occur. The application of neural networks is an alternative solution to those presently employed. They are especially recommended for adaptive control of non-stationary systems. Such cases occur in heating objects since they demonstrate non-linear properties with a great range of variability of parameters; this especially refers to district heating equipped with flux-through heat exchangers. In this paper, a compile model of heating system control aided by neural networks is presented. The results of the investigation clearly prove the usefulness of such solutions, cause the quality of control is much better than that one applied in traditional systems. Presently, works on the implementation of the proposed solutions are under way.

Symbols and notations

a	–	heat exchanger parameters
e_k	–	discrete deviation of the regulation,
$e(t)$	–	continuous deviation of the regulation,
f_φ	–	a number dependent on heat exchanger flux,
k_d	–	authority of valve,
k_p	–	proportional gain,
k_v	–	relation defining the internal valve property,
k_{z-w}	–	strengthening coefficient of object of regulation,
$u_1,u_2,....,u_N$	–	input signals of neural network,

[1] Warsaw University of Technology, Faculty of Environmental Engineering, Warsaw, Poland. e-mail: witold.chmielnicki@is.pw.edu.pl

$w_1, w_2, \ldots, w_N$	–	weight coefficients,
x	–	control output signal,
y_i	–	neural network output signal,
$y(t)$	–	controllable quantity in continuous form,
y_k	–	controllable volume signal in the discrete form,
y_{0k}	–	setpoint in the discrete form,
$z(t)$	–	continuous deviation,
z_k	–	discrete deviation,
T_d	–	time of differentiated activity of regulation,
T_i	–	time of integrated activity of regulation,
T_p	–	sampling time,
T_{11}	–	temperature of heating medium influx,
T_{12}	–	temperature of heating medium outflow,
T_{21}	–	temperature of heated medium influx,
T_{22}	–	temperature of heated medium outflow,
T_{220}	–	assigned value of temperature at heat exchanger outlet,
$\dot{Q}$	–	power of heat exchanger for random heating medium flux,
$\dot{Q}_N$	–	power of heat exchanger in nominal conditions,
Δp	–	pressure decrease in the considered control system,
Δp_v	–	pressure decrease at the valve of random jump,
Δp_{v100}	–	pressure decrease at the valve fully open,
Δp_{v0}	–	pressure decrease at the valve fully closed,
Δp_i	–	pressure decrease in the system for a random valve,
Δp_{i100}	–	pressure decrease in the system for the valve fully open,
φ	–	relative heat power, $\varphi = Q/Q_N$,
$\psi = \frac{v_s}{\dot{v}_{sN}}$	–	relation of the random flux of the heating medium to the nominal one flowing through the exchanger.

1. Introduction

Mode of adopted solutions concerning control and regulation of heating processes effects to a great extent the energy consumption for heating purposes in residential buildings. In the case of central heating supply of buildings, hot water of high parameters is the most frequent medium used for heating up the installation water in heat centers. In residential buildings it is usually a central heating system and hot water supply. The control system of heating center is dependent on its technological structure. Several regulation circuits is the most common solution. An example of the heating center of serial – parallel structure with a dispenser is shown in Fig. 1. It is a heating system and hot water supply double-function center. The following control systems may be distinguished:

- central heating control system,
- hot water control system,

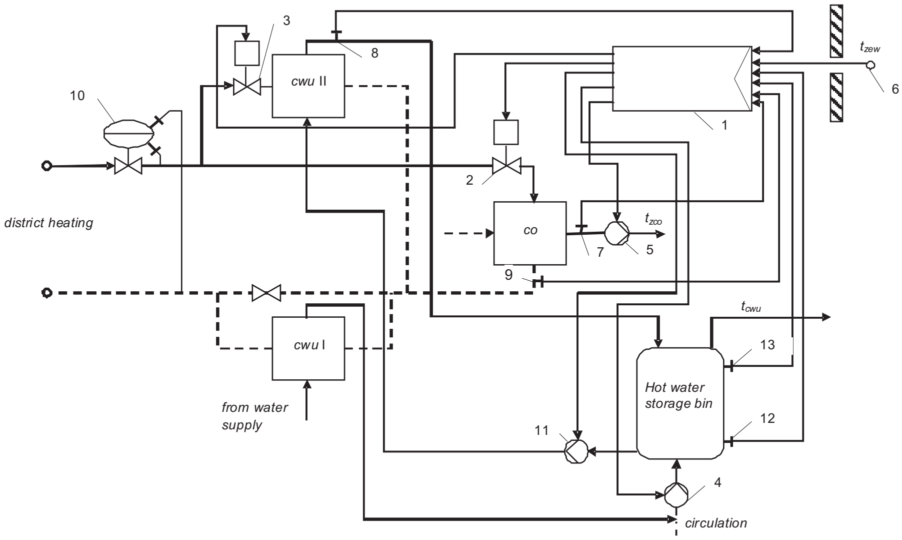

Fig. 1. Double-function governing system of heating and hot water supply, parallel in-series with the storage bin; 1–hardware driver, 2–regulation valve of the central heating system, 3–regulation valve of the hot water supply system, 4–circulation pump of hot water supply, 5–circuit pump of the central heating, 6–sensor of outside temperature, 7–sensor of supply temperature of the central heating installation, 8–sensor of hot water supply, 9–sensor of the return of the heating medium temperature from the heating system center, 10–regulator of difference of pressure with flux reduction, 11–loading pump of the hot water supply, 12–sensor of hot water supply temperature in the bottom part of the distributor, 13–sensor of hot water supply temperature in the upper part of the distributor.

Rys. 1. Węzeł dwufunkcyjny centralnego ogrzewania i ciepłej wody użytkowej szeregowo–równoległy z zasobnikiem; 1–sterownik, 2–zawór regulacyjny układu centralnego ogrzewania, 3–zawór regulacyjny układu ciepłej wody użytkowej, 4–pompa cyrkulacyjna ciepłej wody użytkowej, 5–pompa obiegowa centralnego ogrzewania, 6–czujnik temperatury zewnętrznej, 7–czujnik temperatury zasilenia instalacji centralnego ogrzewania, 8–czujnik zasilenia temperatury ciepłej wody użytkowej, 9–czujnik powrotu temperatury czynnika grzejnego z węzła centralnego ogrzewania, 10–regulator różnicy ciśnienia z ograniczeniem przepływu, 11–pompa ładująca ciepłej wody użytkowej, 12–czujnik temperatury ciepłej wody użytkowej w dolnej części zasobnika, 13–czujnik temperatury ciepłej wody użytkowej w górnej części zasobnika

– pressure difference control system at the heating system terminal,
– system of loading of hot water supply dispenser.

Both, in the central heating center, and hot water supply, the temperature for the heating medium is controlled at the outlet of the exchanger. It is required that it is equal to the assigned value regardless the deviations acting on the system. Often in such systems, changes of the assigned value at some daily or weekly timings are loaded, and then a programmed control is implemented. The control systems of both centers are similar and function in parallel. A variable inlet pressure at the exchanger terminal caused by the influence of heating system network may constitute a significant disturbance for such system. Thus, a regulation of pressure differences between the supply and reflux of network water with a direct function control is applied. A dispenser installed in a hot water supply center plays a role of a storage and is used in the periods of more intensive water consumption by inhabitants. It is required that water gathered in it has a determined temperature. It is secured by a control system functioning in a determined cycle dependently on actual water temperature within the upper and bottom part of it. Thus, periods of loading appear, and water heated up in the second stage exchanger is pumped into the dispenser, and periods of pause, when water can be consumed by recipients. If during the process of water consumption the temperature in the upper part of the dispenser decreases below the assigned value, the process of loading begins. A loading pump is started and the water temperature control system is activated on the second stage of the exchanger. At that time water is sucked up from the lower part of the dispenser, and next heated up in the second stage exchanger and flows into the upper part of it. The process of loading of the dispenser ends at the moment the required temperature is reached in the lower part of the dispenser. Due to the cyclic work of hot water exchangers with dispensers, various algorithms of control of functioning of both central heating centers and hot water supply may be applied. Depending on building thermal properties, and on relation of power of both systems, different modes of limitation of supply of the central heating system may be applied:

– shutting down of the supply of the central heating center,
– reversal function of the control system of heating supply center,
– partial limitation of the central heating supply center.

The required maximum network water flux for the center is thus dependent on the assigned structure. In heat dispenser centers the required maximal power, being one of the main components of centrally supplied heating fee, may be significantly lowered. At the time of limitation or temporary shut off of the central heating supply, the building thermal accumulation would secure against the sensible decrease of internal temperature.

Regardless a kind of a heating center, the temperature of the heating medium at the exchanger outlet is a controllable volume (Fig. 2). In the case of the centrally supplied heating centers, apart from the basic control system of water temperature at the supply point of the internal installation of the central heating, the temperature of heating medium should be also restricted at the exchanger T_{12} outlet. If the temperature exceeds the value of that assigned by the so-called lower regulation diagram, then the flux of network water is reduced regardless the actual temperature value T_{22}, the supply point of the system. In properly designed central heating systems such phenomenon does not usually occur, yet in particular cases it may happen, therefore that kind of control is always required. The way of executing of such kind of regulation system may be different and is dependent on the assigned algorithm of control. Generally functioning of the temperature restriction system T_{12} is implemented through the reduction of heating medium flux. In case the required temperature T_{12} overflow if frequent, functioning of such a system leads to unstable flux, thus causing the oscillatory work of the control valve.

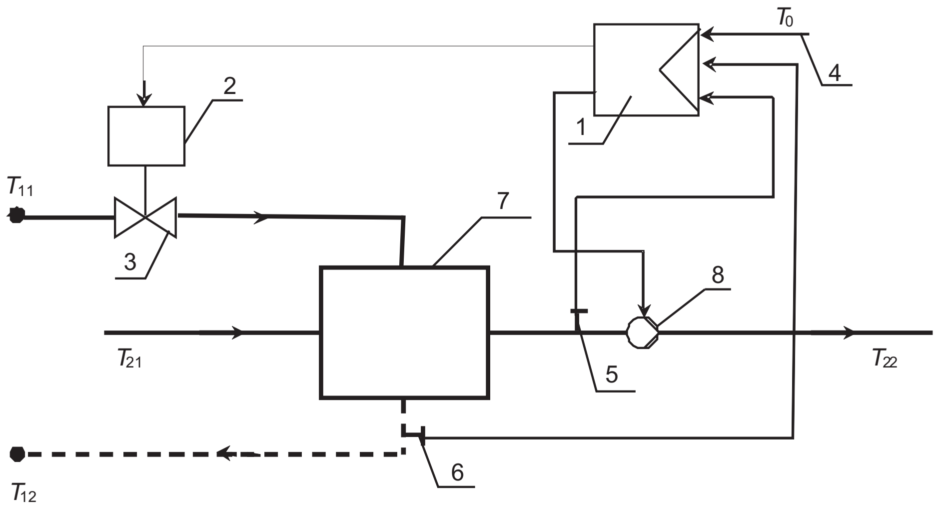

Fig. 2. Basic scheme of the system of water temperature control in governing system: 1 – regulator, 2 – actuator, 3 – regulating unit (control valve), 4 – signal of the assigned value, 5 – temperature sensor at the installation supply, 6 – temperature sensor at the reverse of network water, 7 – heat exchanger, 8 – pump.

Rys. 2. Podstawowy schemat układu regulacji temperatury zasilania wody instalacyjnej w węźle ciepłowniczym; 1– regulator, 2– siłownik, 3– nastawnik (zawór regulacyjny), 4– sygnał wartości zadanej, 5– czujnik temperatury na zasileniu instalacji, 6– czujnik temperatury na powrocie wody sieciowej, 7– wymiennik ciepła, 8– pompa

The essential difference between the work of the hot water heating center and the heating system center is that the assigned value is constant along the outside temperature changes in the former one, while in the latter one it changes according to the regulation diagram. This means that the working conditions of the control system of hot water supply are more unfavorable than those of the central heating, since a greater change of parameters occur (smaller time variables, greater strengthening coefficients). Apart from these, the disturbances occurring in the hot water system supply are much greater than those in heating system. This effects the quality of control of these systems. It happens often that unstable work occurs in hot water systems caused by the presence of disturbances. The variability of power of hot water systems supply during 24 hours may range from 0 – 100%, while those in the central heating systems are minor and mainly dependent on outside temperature. In the solutions of hot water supply systems control, applied so far, the unstable work often occurs, due to improper structures employed. Once the systems are supplied with water distributors, water temperature fluctuations are hampered, otherwise major differences of temperature of hot water occur directly at recipients.

2. Properties of control systems of heating supply centers

In every control system two basic elements may be distinguished.

– controlled system,

– controller.

In the case of heating system centers, the process of changes of parameters caused by disturbances, as well as of the controlling values occurring in the system, are an object of regulation. It is assumed that an object is known once the dependences describing the relations between these values are known. Generally, the description of an object of control adopted for designing the systems is considerably simplified. The values appearing in that description undergo numerous changes during the heating season. That means that the quality of control in currently applied systems would also undergo changes.

Creating a proper algorithm of control enabling to obtain compatibility between the regulated volume and the assigned one is a basic task of the control. In heating systems processes, the proportional – integrating algorithms of *PI* type, and the proportional – integrating – differentiating, are applied most often.

Control of temperature of water heated up in heat exchanger is carried on via change of volume of a heating medium; it is the so-called quantitative regulation. A regulating valve is an element used for changing the flux. It is basically the sole device to be calculated in the control system.

Assignment of the control property of the system is the final stage of calculations. It is defined as a relation between the controlled and controlling value in the assigned conditions. Therefore, it is a static property. In the case of heating centers, the temperature of heated up water is a controlled volume, while a signal reaching the regulating valve, identified as a degree of its opening, is a controlling volume. Power of a heat exchanger for a given valve opening degree may be defined, with some simplification, as a controlled volume. The assignment of the property of the system of regulation requires the knowledge of both, exchanger and control volume properties.

In the case of control systems calculations, the simplified static properties of heat exchangers defined as a relation between the relative power and the relative flux of heating medium, are usually applied.

$$\frac{\dot{Q}}{\dot{Q}_N} = \frac{1}{1 + a\left(\frac{1}{\psi} - 1\right)}, \tag{2.1}$$

where: $\psi = \dfrac{v_s}{\dot{v}_{sN}}$ – the relation of the random heating medium flux to the nominal flux of heat flowing through the heat exchanger.

The parameter of the exchanger a is dependent on the mode of regulation applied in the heating system center. It is usually a quantitative control, and then this parameter is defined for nominal conditions with equation [6]

(2.2)
$$a = \left(\frac{2}{3} - \frac{1}{3} f_\varphi\right) \left| \frac{T_{11} - T_{12}}{T_{11} - T_{22}} \right|_N ,$$

f_φ = 1 for counter-current exchangers,
f_φ = 0.5 for cross – flow exchangers.

In the case a is equal to 1, the linear exchanger property is obtained. For heating centers, the a parameter has lower than 1 value, and is dependent on temperature difference between the heated and heating medium. The greater the difference, the greater nonlinearity of the static property. Diagram of the static property of heat exchanger is shown in Fig. 3.

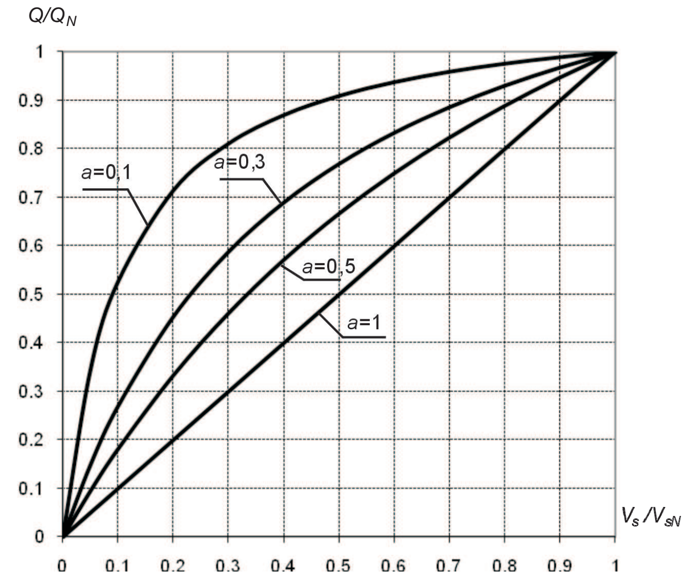

Fig. 3. Static property of heat exchanger; a – exponential parameter of heat exchanger.
Rys. 3. Charakterystyka statyczna wymiennika ciepła; a – parametr wykładniczy wymiennika ciepła

Change of the heating medium flux reaching the heat exchanger is carried out with a regulation valve being an adjusting element of impedance type. The resistance of fluxes of the valve mounted in the hydraulic system cause the pressure decrease of the through-flowing medium. If this flux is turbulent, the decrease is proportional to the square of medium velocity.

Regulation valves are characterized by the presence of the strict relationship between the degree of opening and the flux. Properties of valves are defined through their properties and the flux coefficients.

In heating centers, valves of internal linear property, called proportional, are applied, as well as constant-percentage ones called logarithmic, or linear constant-percentage called proportional-logarithmic.

In case a regulation valve is built in the system, the pressure decrease at such a valve depends on tits opening degree. The relation between the relative flux through the valve and its opening degree is defined by the flux property. It is defined for the system shown in Fig. 4 where the valve is connected in series with the stable hydraulic resistance. It is assumed that the pressure difference between the supply and reflux is constant and equal to Δp.

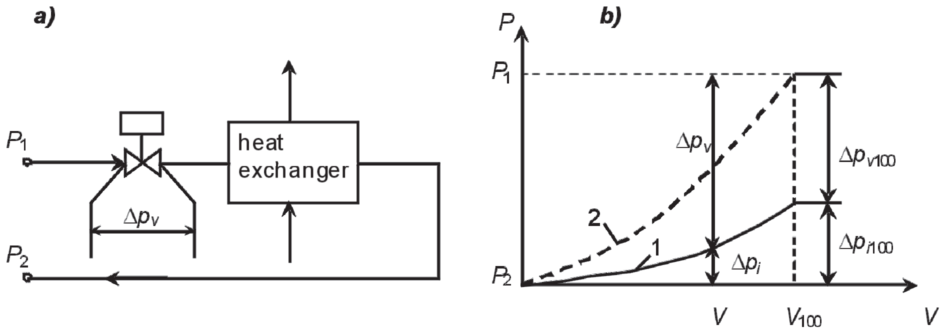

Fig. 4. Diagram of the system with regulation valve: a) hydraulic diagram of the system, b) flux property in the $p - V$ system, 1 – property with the regulation valve, 2 – property without regulation valve, Δp_i – loss of pressure in the system, Δp_v – loss of pressure at the regulation valve, V– volume of flux for random valve lift, V_{100} – volume of flux for the valve fully open.

Rys. 4. Schemat instalacji z zaworem regulacyjnym; a) schemat hydrauliczny instalacji, b) charakterystyka przepływowa w układzie $p - V$, 1– charakterystyka z zaworem regulacyjnym, 2 – charakterystyka bez zaworu regulacyjnego, Δp_i – strata ciśnienia w instalacji, Δp_v – strata ciśnienia na zaworze regulacyjnym, V – strumień objętości dla dowolnego skoku zaworu, V_{100} – strumień objętości dla pełnego skoku zaworu

The flux property of the valve is defined with the equation

$$v = \frac{1}{\sqrt{1 + k_d\,(k_v^{-2} - 1)}}. \tag{2.3}$$

Authority of valve is defined as a relationship of pressure decrease at valve fully open to the disposable pressure decrease in a given circuit, equal to the pressure decrease at the valve fully shut down.

$$k_d = \frac{\Delta p_{v100}}{\Delta p} = \frac{\Delta p_{v100}}{\Delta p_{v0}} = \frac{\Delta p_{v100}}{\Delta p_{v100} + \Delta p_{vi100}}. \tag{2.4}$$

The value of authority of valve influences the shape of flux property of the regulation valve. Kind of property and the required value authority of valve is dependent on properties of the object of regulation. The basic term to be fulfilled is to obtain a constant coefficient of control system strengthening in full range of performance. Only then the relationship between the control value and the regulating one has a linear character, and quality of control is not dependent on the point of work of the system.

Due to their great variability of loading, the district heating systems should have proper control quality secured within the entire range of the valve lift. This term is fulfilled when the control property of the system, taken as a relationship between the regulating and regulated volume, has a linear character, with the inclination equal to 1. In order to obtain this, the working property of the valve is to be a symmetric reflection of the static property of the controlled object, as shown in Fig. 5. The control property is defined by the equation

$$\frac{Q}{Q_N} = \frac{1}{1 + a\left(\sqrt{1 + k_d\left(\frac{1}{k_v^2} - 1\right)} - 1\right)}. \tag{2.5}$$

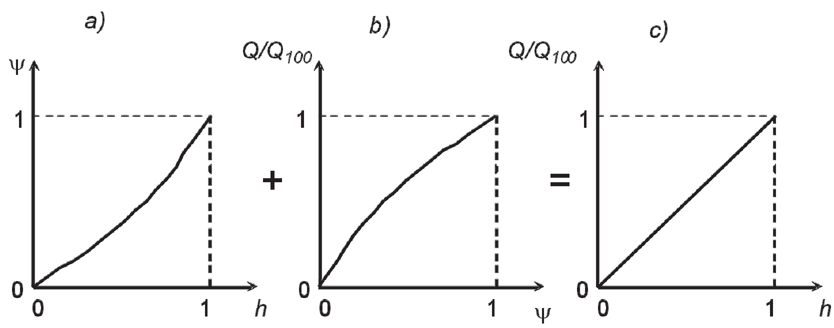

Fig. 5. An example of assignment of control property of the regulation system: a) flux property of the regulation valve, b) static property of the controlled object, c) control property of the regulation system.
Rys. 5. Przykład wyznaczania charakterystyki regulacyjnej układu regulacji: a) charakterystyka przepływowa zaworu regulacyjnego, b) charakterystyka statyczna obiektu regulacji, c) charakterystyka regulacyjna układu regulacji

Considering the cooperation of the regulation valve with the heat exchanger, a coefficient of strengthening of control property may be defined, described as a derivative of heat power related to the valve lift

$$k_{z-w} = \frac{\partial\,(Q/Q_{100})}{\partial h} \approx \frac{\Delta\,((Q/Q_{100}))}{\Delta h}. \tag{2.6}$$

The best control quality is obtained when k_{z-w} is equal to 1 in the entire range of control signal changes. In regulation systems of heating centers this condition cannot be usually fulfilled. It is assumed that the satisfactory quality of control can be obtained once the following conditions are fulfilled

$$k_{z-w\,\max} \leq 2,0,$$
$$\frac{k_{z-w\,\max}}{k_{z-w\,\min}} \leq 3,0.$$

The greatest values of the strengthening coefficient k_{z-w} occur in the initial stage of the valve work. This means that at the minor flux appearing in the case of small heat loads, a minor valve lift may cause a great change of the controlled volume, thus a significant error of the regulation. Therefore, while designing the control system, the minimal load value is to be assigned, from which an assigned precision of the regulation is required. Below that value, the quality of control is generally not sufficient.

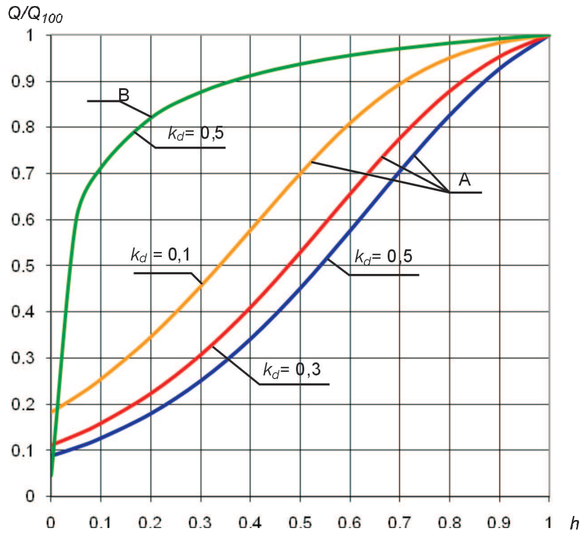

Fig. 6. Control system property for the heat exchanger parameter a =0.3. A – constant percentage valve, B – linear valve.

Rys. 6. Charakterystyka regulacyjna układu dla parametru wymiennika a = 0,3; A – zawór stało procentowy, B –zawór liniowy

In Fig. 6, the control property of the system, for the exchanger parameter a = 0.3, and for different choking criteria, is defined. The smaller this criterion is, the more this property differ from the straight line inclined by the angle of 45°, which means the strengthening coefficient changes its value along the change of the valve lift. Therefore, the control quality is not satisfactory. In the case of choking equal to 0.5, the control property has the most adequate shape. Valve of a linear property should not be employed in heating centers since the strengthening coefficient undergo major changes, which can be directly seen in Fig. 6.

3. Numerical model of the heating center control system

Control systems should secure the required static and dynamic properties for a given process. In order to obtain this, one has to:

– define a type of control algorithm based on the knowledge of object properties, design the

– structure of regulation system,

– match up the control algorithm parameters securing the required static and dynamic properties of the control system.

The basic step-by-step block diagram of the discrete control system is shown in Fig. 7

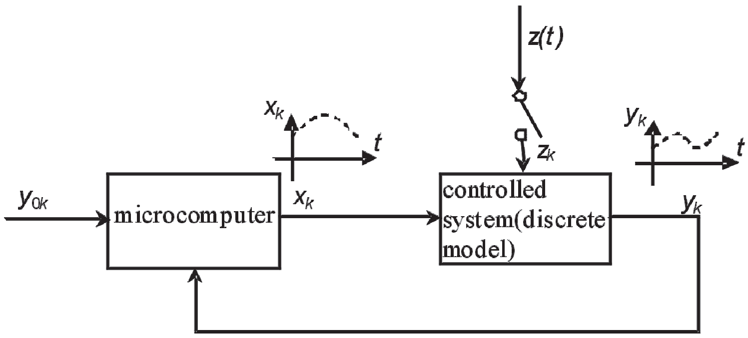

Fig. 7. Block diagram of the digital control system.
Rys. 7. Schemat blokowy cyfrowego układu regulacji

3.1. Numerical model of heat exchanger

Numerical model of heat exchanger, adopted to the research, was described in the paper [5]. Its block diagram is shown in Fig. 8. It is a model of sectional division with distributed parameters, where the whole length of the heat exchanger is divided into n elementary sections of Δx in length. In the description, a variability of parameters determining the intensity of partition heat exchange in function of spatial coordinates of heat exchanger, were considered. The adopted model of heat exchanger was verified experimentally in a real governing system.

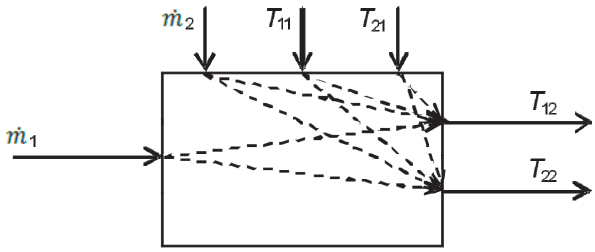

Fig. 8. Block diagram of heat exchanger: T_{11} – temperature of heating medium inflow, T_{21} – temperature of heated medium inflow, 1 – flux of mass of the heating medium, 2 – flux of mass of heated medium, T_{12} – temperature of heating medium outflow, T_{22} – temperature of heated medium outflow.
Rys. 8. Schemat blokowy wymiennika ciepła; T_{11} – temperatura dopływu czynnika grzejnego, T_{21} – temperatura dopływu czynnika ogrzewanego, $_1$ – strumień masy czynnika grzejnego, $_2$ – strumień masy czynnika ogrzewanego, T_{12} – temperatura odpływu czynnika grzejnego, T_{22} – temperatura odpływu czynnika ogrzewanego

3.2. Standard algorythms of control applied in heating centers

In the control system of heating centers, digital regulations whose digital algorithms are equivalent of analogue ones, are applied. Most often those are of proportional –integral properties - *PI* type, or proportional –integral –derivative- *PID* type.

The control signal of the discrete *PI* type regulator is described with the equation

$$x_k = k_p\left(e_k + \frac{T_p}{T_i}\sum\nolimits_{j=1}^{k} e_j\right), \tag{3.1}$$

In the case of the incremental notation, we get

$$\begin{aligned} &x_k - x_{k-1} = k_p\left(y_{k-1} - y_k\right) + k_I\left(y_{0k} - y_k\right), \\ &k_I = k_p\frac{T_p}{T_i}. \end{aligned} \tag{3.2}$$

In the case of the discrete *PID* type regulator the control signal is described by the equation

$$x_k = k_p\left(e_k + \frac{T_p}{T_i}\sum\nolimits_{j=1}^{k} e_j + T_d\frac{e_k - e_{k-1}}{T_p}\right), \tag{3.3}$$

For the incremental notation, we get

$$\begin{aligned} &x_k - x_{k-1} = k'\left(y_{k-1} - y_k\right) + k_I\left(y_{0k} - y_k\right) + k_d\left(2y_{k-1} - y_k - y_{k-2}\right), \\ &k' = k_p - \frac{k_I}{2}; k_d = \frac{k_p T_d}{T_p}. \end{aligned} \tag{3.4}$$

The sampling time T_p and parameters of adjustment $k_p,\ T_i,\ T_d$, have to be adequately selected in order to obtain the optimal run of the process of control. Parameters of the adjustment are usually defined based on Ziegler-Nichols experimental method, extended by Takahashi for numerical control. Period of sampling T_p, value of strengthening k_{kr}, and period of oscillation T_{osc} for the critical run, consist the basis for the adjustment selection. Due to the nonlinear properties of heating objects, the regulating adjustment parameters should be corrected by changing work conditions, normally dependent on outside temperature. This is to be done at least three times during the heating season: at the start, at the end, and for low outside temperature. In case of setting adjustment parameters to remain constant, the control quality depends on working conditions of the controlled system. Along with a change of heating parameters, those of the regulating object change too. This significantly influences the quality of control and on energy consumption. Application of standard algorithms of control in heating centers requires constant supervision and does not guarantee proper quality.

3.3. Application of neural networks for control of heating centers

Neural networks are more and more often applied in many fields, like biology, medicine, army, etc. Yet, they have gained no expected application in central heating systems control. The first research works on the subject [7, 8], concerning the application for the *HVAC* processes, were published in the USA at the beginning of the 90th. They brought up the problem of application of neural networks for control of simple heating and refrigerating processes in ventilation and air condition systems. Still there is a lack of research on neural networks application to control processes in heating systems.

Neural networks are especially recommended for the adaptive control of non-stationary systems. Such cases occur in heating objects, since they demonstrate non-linear properties of a very wide range of variability of parameters; this especially concerns heating centers equipped in flow-through heat exchangers. Due to common application of such solutions in heating engineering, the necessity of searching for adequate control systems is extremely vital.

Intelligent calculations, defined in English literature as Computational Intelligence, include three fields of knowledge: neural networks, genetic algorithms, and broadened systems. Neural networks making use of broadened systems gain features of self-learning systems. The method of broadened systems enables the selection of genetic parameters and coefficients characterizing the pace of learning of a network.

In the case of non-algorithmic processes, or those resisting analytic description, the output signal obtained by summing up of input signals with adequate worth is given for the non-linear activating function. The matter of that model consists of summing up input signals from (?) the other elements of adequate measures and creating an output signal 1 or 0, depending on whether the resulted sum is smaller or bigger than the threshold value.

This model is described by the following equation

(3.5) $$y = f(\sum_{j=1}^{N} w_j u_j).$$

Activation functions of the model $f(\sum_{j=1}^{N} w_j u_j)$ may be different; a sigmoidal function described by the defined equation is most often used

(3.6) $$f(x) = \frac{1}{1 + \exp(-\beta\, x)}, \quad \beta > 0.$$

The theory of network teaching (learning?), concerning the adequate worth(?) *wi* selection, was worked out by Hebb [10, 11] who proposed a phenomenon of strengthening of inter-neural joints worth in the state of activity of neurons.

Theoretical basis and technological implementations of the adaptive conversion systems were worked out by Widrow [11,14]. A constant development of computer systems enables more and more broadened application of neural networks in different fields of knowledge. They may be classified in the following groups: approximation, classification and formula solutions, prediction, control and association.

In technological applications, neural networks are mainly used for prediction and control. In the case of neural network application for dynamic systems control it plays several functions simultaneously. First of all, it is used to create a model of a given process based on collecting of information by measuring particular quantities. On this basis it generates adequate control signals.

Parallel processing of information by all its links is a characteristic feature of neural network. It is very important since, as a result, a significant acceleration becomes possible which, considering huge number of neural links, is vital. A network has features of an artificial intelligence which makes it capable of learning and generalization of knowledge. If it is created based on a defined group of data, it consequently can associate the acquired knowledge and use it in the process on the data that had not taken part in the learning.

The neural network can predict future value of control output for random input quantities. It is not important what kind of object we deal with, linear or non-linear, static or non-static. The network output is treated as one of the measures, and it is considered and modified.

A good quality of non-linear processes control by applying traditional solutions is very often difficult to obtain. Benefits following the application of proper heating process control are varied and include, i.a.:

– reduction of energy usage,

– improvement of thermal comfort,

– extending the vitality of devices as a result of significant reduction of their work time.

The diagram of neural network adopted to control of heating centers is shown in Fig. 2. Based on numerous simulation research it was assumed that the best solution, and the simplest as well, is an application of multilayer unidirectional network.

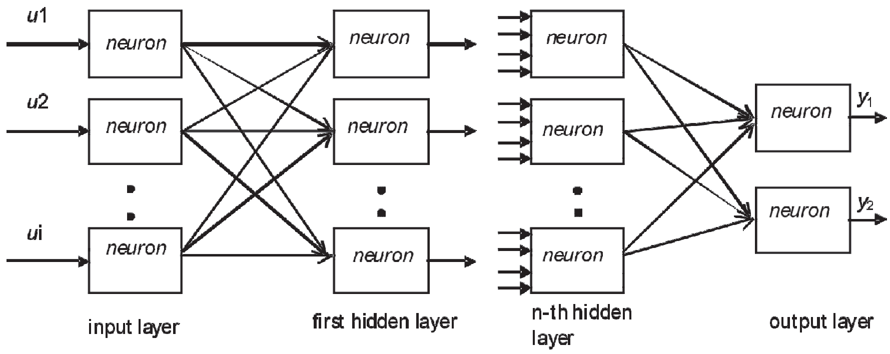

Fig. 9. Diagram of neural network for governing systems control.
Rys. 9. Schemat sieci neuronowej do sterowania węzłami ciepłowniczymi

The input volumes of the network are: temperature of heating medium inflowing and flowing out from the heat exchanger, temperature of the heated medium inflowing and flowing out from the heat exchanger, the assigned value of heated medium temperature flowing out from the exchanger, the acceptable maximum temperature of the heating medium flowing through the exchanger, position of the regulation valve head (defined on the base of the feedback signal from the servomotor). The required valve position, ensuring the assigned value of the regulated volume, is the output volume of the network.

4. Research of control in governig system

The exemplary results of simulation research are shown in the included diagrams. In Fig. 10, 12, the curves obtained in the case of digital controller with algorithm *PI* are applied. As a result of exceeding the required water temperature at the out-flow of the heating medium, significant fluctuations of the regulated volume occurred. It is noticeable that, despite optimal setting of the regulator, stabile performance was not attained. This phenomenon does not occur in the case of neural control applied (Fig. 11, 13).

Calculations applied to the evaluation of quality of control, defined with the Root Mean Square *RMS* and the Mean-Absolute Percentage Error *MAPE,* are shown in the legend to the diagrams. The calculations carried out are a good measure of evaluation

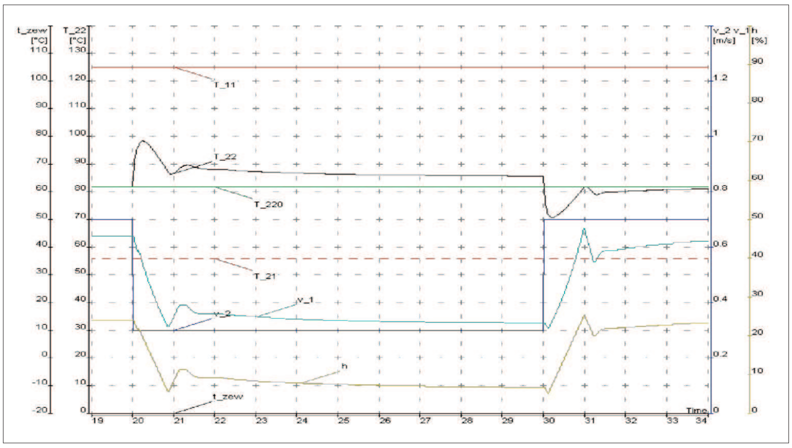

Fig. 10. Step-by-step regulator PI (the optimum regulator adjustments according to the Ziegler-Nichols-Takahashi method). The response of the of hot water supply control system to the disturbance caused by the flux change of the heated medium v-2 (research for computational terms), ***RMS*=9,6879, *MAPE*=10,8751**.

Rys. 10. Regulacja z regulatorem krokowym PI (optymalne nastawy regulatora wg metody Zieglera-Nicholsa-Takahashi). Przebieg odpowiedzi układu regulacji ciepłej wody użytkowej na zakłócenie spowodowane zmianą przepływu czynnika ogrzewanego v_2 (badania dla warunków obliczeniowych), ***RMS*=9,6879, *MAPE*=10,8751**

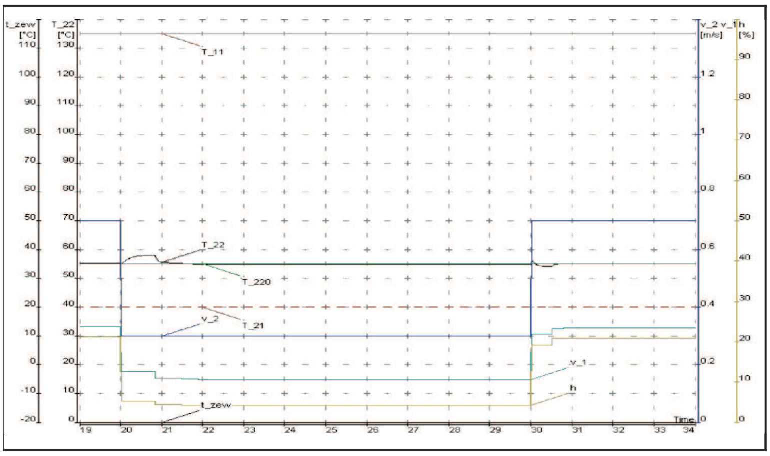

Fig. 11. Regulation NN. The response of hot water supply control system to the disturbance caused by the flux change of the heated medium v-2 (research for computational terms), ***RMS*=0,1862, *MAPE*=0,1660**.

Rys. 11. Regulacja NN. Przebieg odpowiedzi układu regulacji ciepłej wody użytkowej na zakłócenie spowodowane zmianą przepływu czynnika ogrzewanego v_2 (badania dla warunków obliczeniowych), ***RMS*=0,1862, *MAPE*=0,1660**

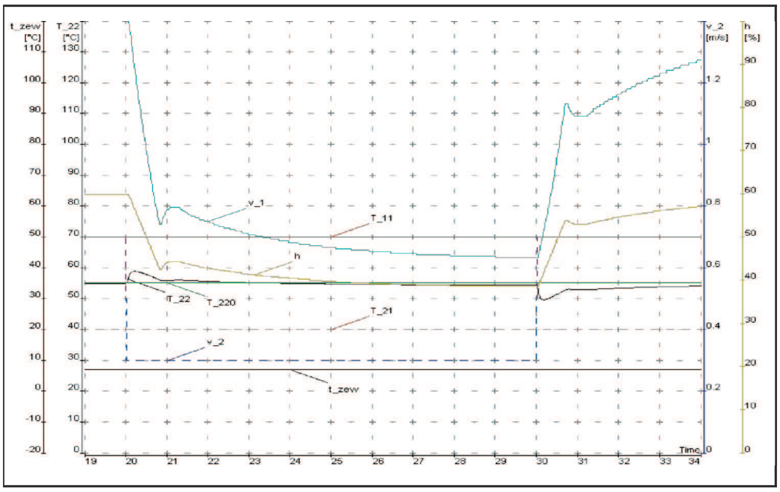

Fig. 12. Step-by-step regulator control PI (adjustments of the regulator k_p=6%/K, T_i=100s). The response of the hot water supply system to the disturbance caused by flux change of heated medium v_2 (research for transient period), ***RMS*=1,9168, *MAPE*=2,8394**.
Rys. 12. Regulacja z regulatorem krokowym PI (nastawy regulatora k_p=6%/K, T_i=100s). Przebieg odpowiedzi układu regulacji ciepłej wody użytkowej na zakłócenie spowodowane zmianą przepływu czynnika ogrzewanego v_2 (badania dla okresu przejściowego), ***RMS*=1,9168, *MAPE*=2,8394**

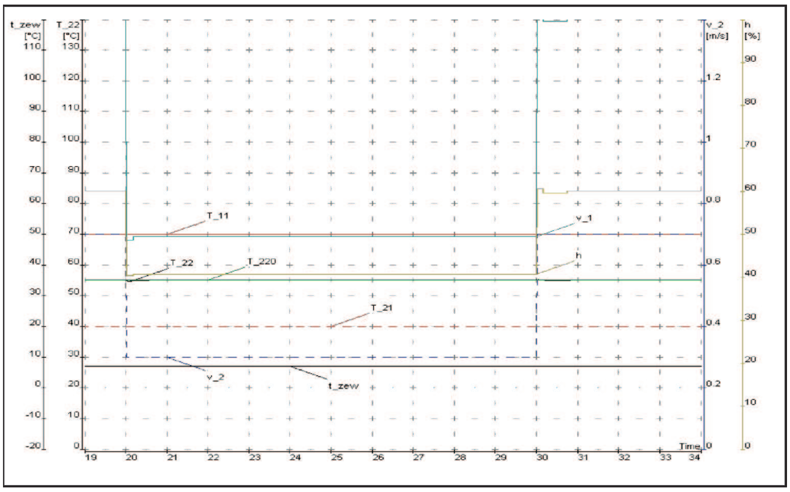

Fig. 13. Regulation NN. The response of the hot water supply control system to the disturbance caused by change of flux of the heated medium v-2 (research for transient period), ***RMS*=0,0827, *MAPE*=0,0628**.
Rys. 13. Regulacja NN. Przebieg odpowiedzi układu regulacji ciepłej wody użytkowej na zakłócenie spowodowane zmianą przepływu czynnika ogrzewanego v_2 (badania dla okresu przejściowego), ***RMS*=0,0827, *MAPE*=0,0628**

of the research accuracy and picture fully the obtained control quality which in linear systems is defined by some indicators (time of regulation, maximum deviation, number of oscillation while regulating, etc.). While analyzing the obtained characteristics it is to state that in the case of neural control application, the final value of the performance was attained as a result of a single-time adjustment of the regulation valve. All the typical regulation indicators were definitely better than those with traditional control applied.

The following symbols were adopted in the included diagrams: $\dot{v}_2$– velocity of water heated up in the heat exchanger, T_{220} – setpoint temperature of the heated medium at the outflow of the heat exchanger, T_{21} – temperature of heated water flowing into the heat exchanger, T_{11} – temperature of heating medium flowing into the heat exchanger (as a function of the outsider temperature, defined with the regulation diagram of the given heating system), T_{22} – temperature of the heated medium at the outflow of the heat exchanger as a regulated volume, T_{12} – temperature of the heating medium at the outlet of the heat exchanger, limited by the bottom regulation diagram of the given heating system.

5. Summary

Application of neural networks is the latest innovation in the control system *HVAC*. The main target of the searched solutions is an improvement of control quality within the wide range of work of the installations, with no need of control of the work and necessity of adjustment. The work of neural networks is self-serviced which is particularly important in heating systems supplying big cities agglomerations.

At present, there is a lack of neural networks solutions able to be installed for heating systems control. The solutions applied so far [7,8], concerning the *HVAC* systems, are simulation tests in nature and have not been implemented in real systems. The neural networks applied there usually cooperate with traditional *PID* regulators. For that reason, the final result of control is worse than in the case of “pure” networks application. The aim of the described neural networks [7,8,11]was an adaptation of *PIT* regulator outlet to the static nonlinear and dynamic *HVAC* processes. Yet, the final effect of the control resulted from the activity of *PID* regulator. As it stems from(follows) the research carried out, the application of neural networks contributes to the significant improvement of control within the whole range of heating systems performance.

The neural network application ensures better control conditions and a broader range of applications than the previous *PID* regulators. Phenomenon of instability of the control system caused by activity of disturbances does not appear. Restricted to minimum transient runs ensure the users’ satisfaction and enable the implementation of algorithms allowing major energy savings, in comparison to the previous systems furnished with traditional *PID* type controls. The neural network enables application of system control without introduction of special adjustments, both at the time of system initiation, as well as during the change of work conditions.

The worked out model of neural regulation may be put in operation for control of multifunctional heating centers.

REFERENCES

1. *ASHRAE 2001 Handbook. Fundamentals,* American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.
2. *ASHRAE 2001 Handbook. HVAC Systems and Applications,* American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.
3. W. J. CHMIELNICKI, *Sterowanie mocą w budynkach zasilanych z centralnych źródeł ciepła* [In Polish], PAN. Studia z zakresu inżynierii nr 41, Warszawa 1996.
4. W. J. CHMIELNICKI, *Sterowanie mocą cieplną w budynkach na potrzeby ciepłownicze z wykorzystaniem sieci neuronowych* [In Polish], Raport KBN, Projekt badawczy Nr 7 T07E 001 14, Warszawa 2001.
5. W. J. CHMIELNICKI, *Model of flow-through heat exchanger for heating systems*, Arch. Civ. Eng. 44,2, Warszawa 1998.
6. W. J. CHMIELNICKI, *Regulacja automatyczna urządzeń ciepłowniczych* [in Polish], Unia Ciepłownictwa, Warszawa 2001.
7. P.S. CURTIS, J.F. KREIDER, M.J. BRANDEMUCHL, *Adaptive control of HVAC processes using predictive neural networks,* ASHRAE Transactions part 2, volume 99(1) 1993.
8. P.S. CURTIS, G. SHAVIT, J.F. KREIDER, *Neural Networks Applied to Buildings–A Tutorial and Case Studies in Prediction and Adaptive Control,* ASHRAE Transactions part 2, volume 100(1) 1996.
9. R. ISERMAN, *Identifikation dynamischer Systeme,* Springer–Verlag, Berlin, Heidelberg, New York, London, Tokyo 1988.
10. MacArthur J.W., Grald E.W., Konar A.F.: *An effective approach for dynamically compensated adaptive control,* ASHRAE Transactions 1989, volume 95(2).
11. S. Osowski, *Sieci neuronowe,* WNT, Warszawa 1996.
12. Poradnik Recknagel Springer: *Ogrzewanie i klimatyzacja* [In Polish], Warszawa 2007.
13. Rietschel: *Raumklimatechnik,* Springer–Verlag, Berlin, New York 2005.
14. J. Żurada, M. Barski, W. Jędruch, *Sztuczne sieci neuronowe podstawy teorii i zastosowania* [In Polish], Wydawnictwo Naukowe PWN, Warszawa 1996.

WYKORZYSTANIE SIECI NEURONOWYCH DO REGULACJI W CIEPŁOWNICTWIE

Streszczenie

Roczne zużycie ciepła na potrzeby ciepłownicze w Polsce w sektorze komunalno-bytowym, szacowane jest na około 650PJ. W znacznej części przeznaczone ono jest na potrzeby centralnego ogrzewania i ciepłej wody użytkowej. Istotny wpływ na jego zużycie ma rodzaj przyjętych rozwiązań dotyczących regulacji i sterowania oraz systemów zarządzania energia. W przypadku budynków mieszkalnych koszty energii

stanowią największy udział w stosunku do całkowitych kosztów związanych z eksploatacją budynku. Podstawowym warunkiem umożliwiającym racjonalne jej zużycie jest wyposażenie budynku w nowoczesne cyfrowe systemy do regulacji i sterowania instalacji ciepłowniczych. W stosowanych obecnie rozwiązaniach wykorzystuje się zwykle algorytmy *PI* lub *PID*. Jednak ze względu na nieliniowe właściwości ciepłowniczych obiektów regulacji, nie zapewniają one odpowiedniej jakości. Często przebiegi mają charakter niestabilny i dochodzi do znacznych odchyłek regulacji. Alternatywą do stosowanych obecnie rozwiązań jest wykorzystanie sieci neuronowych. Są one szczególnie zalecane do sterowania adaptacyjnego układów niestacjonarnych. Takie przypadki występują w obiektach cieplnych, gdyż mają one właściwości nieliniowe o bardzo dużym zakresie zmienności parametrów, dotyczy to zwłaszcza węzłów ciepłowniczych wyposażonych w przepływowe wymienniki ciepła. W pracy przedstawiono opracowany model sterowania węzłów ciepłowniczych za pomocą sieci neuronowych. Wyniki badań wyraźnie wskazują na celowość takich rozwiązań, gdyż jakość regulacji jest znacznie lepsza aniżeli w przypadku stosowania układów tradycyjnych. Aktualnie trwają prace nad wdrożeniem zaproponowanych rozwiązań.

Remarks on the paper should be sent to the Editorial Office no later than December 30, 2010

Received June 10, 2010 revised version September 15, 2010