Heat distribution and consumption model with continuous consumption part

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***Abstract*—**This article describes the design and preparation of discrete model for heat distribution and consumption in city agglomeration. The model takes into account the basic rules of consumption and relations in the district heating systems (centralized location for residential and commercial heating requirements) and can be applied for heat distribution from heating plant to individual heat exchange station or distribution and consumption of heat energy from exchange station to single buildings (house stations). A combination of these two parts is also allowed. Model has been introduced in the previous articles;however it is still in progress and tested in real situations. The introductory part of this article will presents the proposed model, algorithms used for the calculations, principles and practices for each step of the simulation process. This article also shows recent improvement introduces two fundamental changes. The heat consumer as an essential part of the model, were modified to work more continuously and thereby it more corresponds to real consumption equipment. Second improvement is the addition of influence of internal temperature in heated objects. Originally consumption was solely dependent on heating water temperature and outside temperature, which has its undeniable logic – colder weather means more demand for heating, however it appears to be more appropriate to consider the heat transferred as a productof mass flow and temperature difference between heating water in inlet pipe and temperature of the heated media, i.e. the desired room temperature or temperature of the inlet water in secondary part of the heat exchanger. Binding to the outdoor temperature is however still present in relation to amount of heat requirement.The final part of the article shows comparison of simulation results for original and newly introduced modifications.

***Keywords*—**Energy, distribution, heating, identification, model, prediction, simulation.

I. INTRODUCTION

THEmost of the modern world is addressing the issue of economic use of energy. The area surveyed in this article is heating energy. Especially in countries in temperate zone or even closer to polar regions, the heating is an important issue.

As mentioned in [1] energy savings are very topical, especially in the context of increases in energy prices. Also the environmental aspects support ideas of efficiency in energy use.All these constraints lead to the need for improving existing systems and building new, more economical and environmentally friendly.

The effective management of distribution of the heat energy is one of the factors that can lead to savings of energy. The “mere” saving of energy means reducing the environmental burden, because whether the renewable or fossil sources are used, the production of energy is always less or more environmental burden associated.

To talk about district heating systems, the heat energy must be transported to the place of consumption in time when it is required and in the expected quantity and quality. Quality of supplied heat energy is expressed in the temperature of heat transferring media [1].Quantity and quality of heat energy must go hand in hand with minimal distribution costs [2]. It is obvious that the heat distribution is inextricably linked to its consumption and therefore we can talk about the management of the heat distribution and consumption.

An important factor in the distribution of heat over long distances is also a traffic delay. For technical and economic reasons, the fluid is not transported at high speed and a distance of several kilometers means transport delay in hours, which is in the district heating supply system common appliances.

The previous research [3, 5] was focused on implementation of the computer model of the distribution system of heat consumption SHDC (System of Heat production, Distribution and Consumption). This model was designed as a discrete simulation model with a number of freely usable parameters. Model was further developed and were modified some of its components. The heat consumer as an essential part of the model, were modified to work more continuously and also to more correspond to real equipment.

A. System of heat production, distribution and consumption

The system of heat production, distribution and consumption (SHDC) is mostly very large and complex. Analysis and determination of the features that need to be known for its efficient management is very difficult. In addition, the values for some parameters must be known mostly in advance, i.e. must be predicted. There exist some methods for this prediction, which make it, but not always with sufficient accuracy [3].

Description of the system is shown in detail in [10] from where it is also taken a schematic fig. 1. Next chapter as well as [5] describes a simulation model developed and used for analyzes of SHDC. This model is built as a parametrical and an appropriate choice of parameters allowed using it for the analysis of the primary and also secondary network. In both distribution networks, but especially in secondary networks are usually used weather-compensation control – equithermal controlling or regulation. In such control the external temperature is the main factor influencing the input water temperature.

Prediction in these systems has different role then in primary distribution. Secondary distribution usually works with small time delay, usually tens of minutes and therefore it is preferable to apply conventional methods of system control than long-term prediction. Primary distribution networks works with longer time delay and its weather compensation curves are more sophisticated and tuned for a particular location specific. However, knowledge of system behavior is always important to design suitable control methods.

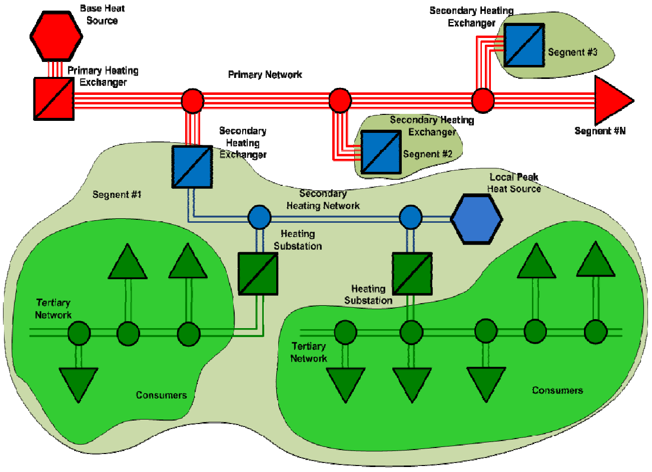


Fig. 1 Schematic diagram of SHDC [10]

B. *Description of the heat distribution network*

District heating system can be divided into three main categories: production, distribution and consumption of heat. For proper functioning of the whole system must be consistency between these elements to the network at any point system to prevent excess or deficiency [11].

Fig. 2Production, distribution and consumption of heat [10]

Heat production

Central heat sources cover 72% of the average total annual thermal energy consumption at Czech Republic. Roughly half is provided from central resources that produce heat together with electricity - industrial cogeneration. Mainly these sources: power plants, heating plants and public heating source. The total consumption of fuel contributes 65% solid fuels, 6% liquid and 29% gaseous fuels [10].

Heat distribution

Transport of heat from the source to the customer (distribution) provides heating network. The parts of this network are also heat exchanger stations. Their importance lies in the ability to effectively transfer heat from one media to another. Heat networks, with regard to the heat exchangers can be divided into primary and secondary heat distribution circuits.

1) The primary circuit is part of the thermal network between the production of heat and exchanger stance. The system of primary network according to the heat transfer medium is divided into steam and hot water.
   Steam networks have been built in recent years, according to industry requirements for use of process steam. These requirements now decreased with modifications some of the industrial production technologies.
   Hot water networks are built primarily for the supply of residential agglomerations [10].
2) The secondary circuit is part,which include the heat exchanger network between the primary and secondary distribution system,individual house stationsand necessary pipes and may include also additional source of heat for the covering of temporary failures or shortcomings of the primary circuit. Secondary distribution networks tend to be hot water systems.

Heat consumption

Heat consumption means a distribution network device that uses the supplied energyto heat buildings or prepare hot water. Larger buildings or object usually have own transfer station (house station), which controls the distribution of the heat to the building according to customer requirements. Billing is based on the consumed heat, which is calculated from the input and output temperature difference and water flow rate [10].

II. DISTRIBUTION AND CONSUMPTION MODEL

This model is capable to identify heat consumption in particular heating system based on measured data [4]. Model is designed to predict the required heat and propose the timing of the distribution. Prediction ability of the system uses weather forecast for the desired period and identification based on historical data of the day with the match in outdoor temperature. Other factors, beside outdoor temperature, affecting consumption are not yet fully considered in the model. However, their inclusion is expected in the future.Proposed simulation model were introduced in details [3, 5]. Following description shows just basic model properties linked to implementation of the new features.

A. *Model description*

The distribution network is presented as a set of sources of heat energy and heat consumers connected through piping. The pipes and heat consumers are concentrated in sections, which are connected in nodes. Section begins and ends in the node and can be divided in several elements of the distribution network basically pipe lines and heat consumers. Each element has itsown constant characteristics from the point of view flow and heat transfer. See Fig. 3.

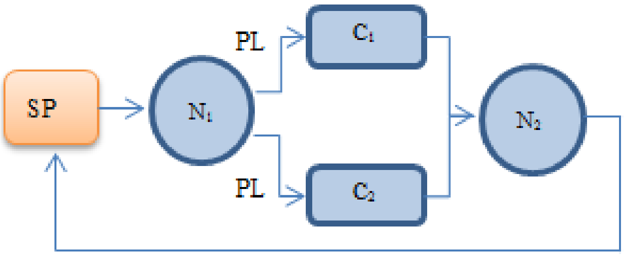


Fig. 3Schematic example of the distribution network

where:
- *C* consumer,
- *PL* pipe line,
- *N* node,
- *SP* supply

Model works in discrete intervals of constant length, signed as Δt. Time interval Δt is identical to the sampling time interval and Δt_j determine the simulation step *j*. The basic, moving element is considered "discrete flow quantum" DFQ of fluid, usually water. The DFQ flows in the network and gradually loses its heat energy, depending on the current position. The volume of the quanta is determined by the quantity of water entering into the distribution network for the time interval Δt in given step of simulation. Amount of heat energy in DFQ is based on its quantity and its temperature [4].

To monitor the flow quantum passing through the distribution network, it is necessary to respect the fundamental physical laws applicable to the fluid flow and heat energy transfer - conservation of mass and energy and the law of continuity.

Compressibility of water in the pipe is insignificant and does not need to be included in the model.In each simulation step the flow quantum, denoted $^jDFQ_i$ in the network is monitored. Shown in the following picture,

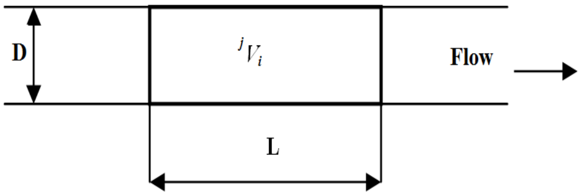


Fig.4 Discreet flow quantum

where:
- index*i* describe particular quantum,
- index*j* describe time period for $^jDFQ_i$analysis, i.e. the simulation step,
- *D* is pipe diameter in current $^jDFQ_i$location,
- *L* is current $^jDFQ_i$length,
- $^jV_i$is volume of $^jDFQ_i$

Simple terms can be applied:

$$^jV_i = \pi * D^2_i / 4 * L_i \tag{1}$$

and

$$^jV_0 = M_j * \Delta t_j \tag{2}$$

where:
- $^jV_0$ is volume of DFQ on input to distribution network
- M_j mass flow in simulation step j.

Each flow quantum in the distribution network has recalculated heat balance in each simulation step. The heat balance is based on law of the preservation of the heat energy. Equation 3 shows applied formula.

$$\frac{dT}{dt} = K \cdot (T - T_{ext}) \tag{3}$$

where
- *K* is the constant describing thermal characteristics for the particular element of the distribution network and heating medium. This constant for example for the pipe line depends on pipe wall material, its isolation, its diameter, velocity and specific capacity of the heating medium.
- *T* is the current temperature *DFQ* in the particular simulation step *j*,
- T_{ext} is the current outside temperature.

Solving the equation 1, the (2) is obtained

$$T_1 = exp\ (-K*t) * (T_0 - T_{ext}) + T_{ext} \tag{4}$$

where:
- T_0 and $T_1$are the water temperature at the beginning and end of the time interval Δt.

The amount of the ΔQ, transferred in given time interval is the function of the temperature difference T_0 and T_1, i.e.:

$$\Delta Q = m*c*(T_0 - T_{ext}) * (1 - exp\ (-K* \Delta t)) \tag{5}$$

B. Proposed modifications

As previously mentioned, method of calculating the heat transferred was modified, however the equation above still provide the basis of proposed modification.

Heat consumption based on outdoor temperature was expanded to include a new variable - the temperature in heated object. With regard to the type of model it could be room temperature or temperature in secondary heating circuit (output form heat exchanger). These temperatures could be almost constant – room interior temperature, generally, or dependent on the outside temperature and time – heating curves for heat exchanger.

Extended method of calculation is therefore based on the equations (5) and (6). On the one hand is available thermal energy contained into supply pipe and on the second hand represents the energy required to maintain the desired object temperature. Energy intersections can be shown in basic balance equation (4). Inlet water transmits the necessary heat quantity into heated object and the remaining heat Q_{FQR}goes back to heating source.

$$Q_{FQ} - Q_o = Q_{FQ_R} \quad (6)$$

Amount of the heat required to maintain desired interior (object) temperature:

$$\Delta Q_o = S * K_o * (T_{inter} - T_{ex}) \quad (7)$$

where:
- S cooled surface area,
- $K_o$heat transfer coefficient,
- T_{inter}desired (interior) temperature,
- T_{ex} outside temperature

The amount of the heat theoretically available in supply flow quantum:

$$\Delta Q_{FQ} = V_{FQ} * \rho * c_p * (T_{FQ} - T_{inter}) * (1 - e^{-c_1.\Delta t}) \quad (8)$$

where:
- V flow quantum volume,
- ρ density of the fluid,
- c_p specific heat capacity,
- T_{FQ} heating water temperature,
- T_{inter}desired (interior) temperature.

III. THE PROGRAM IMPLEMENTATION

In accordance with the proposed distribution and consumption model were used general modular programming environment for applications Xerusto implement test application system. The base system was created on Faculty of Applied Informatics of Tomas Bata University in Zlin. Its general basis can be adapted to the specific application of a specific application area.

A. Features programming environment Xerus

Programming environment Xerus provides functions for creating applications for the following basic areas:

1) Connectivity between applications and databasesand providing necessary security queries to the database, respectively broadcast of data structures as a result of these questions,their transfer back to the application. It is therefore possible that Xerusis considered as a data server. In its current form,Xeruscan work with databases that are able to process queries in SQL. Its functionality is tested on MS Access database products, Oracle and PostgreSQL.
2) Interpretation of functions bound to communication with the user through interactive forms. These forms can be created through the forms editor, which was described in [11] where were also described the requirements for user interface applications. This section of the Xerus was expanded to include some elements that are not located in the basic version and are specific for the heating system description, such as charts.

Further characteristics of Xerus:

- It is created in the Java programming environment, which ensures its portability to run on various platforms (Windows, Linux) and allows the use abundant of the libraries of various required functions published in Java.
- To describe the forms (dialog windows) used in the user interface is used standard XML. This allows for possible modifications to use any xml editors or even any text editor.
- Torealize application-specific functions or activities (e.g. calculate heat loss in the heated object) allows Xerus, as a modular and open system, to integrate and server modules that provide specific functionality. These modules, in the terminology Xerus called Plugins, may either be programmed in Java (the simplest case for a connection with Xerus) or in another programming language that has built up a mechanism to link Java modules.
- It is built on client-server architecture, the client ("fat" client) provides activities tied to the interpretation of forms. Server is basically a data server that provides database queries takeover, their transfer to the database and taking the resulting data structures from the database and transfer them back to the client. It is possible easy implement a multi-user system, which is usually in the industrial applications expected. For this purpose, the system provides functions such as authorization of user access to the system, selective allocation of users to a particular activity and the relevant data, administrator functions related to user management, etc.
- For the needs of applications in heating systems, the options have been expanded on the client side using user-defined threads. This greatly increased the processing speed of large-scale simulation calculations such as evolutionary algorithms, neural networks, etc.

B. Program structure

The proposed application that is part of the program implementation functions, methods and algorithms developed in the project is developed in Java programming environment. This means that work was very carefully obey the object approach, so the whole application has a structure based on objects, their classes and their instances.

In accordance with the above features of the program environment Xerus, it is possible to specify the structure of the proposed applications as follows:

1) Each user function or activity has created form that serves as a user interface that allows users to:
   - insert, or edit designed parameters specifying the desired function or activity;
   - control of the assembly process - start, pause, stop, etc.;

- get results from the implementation of particular function or activity, and these results visualize in an appropriate form - tables, charts;
- save selected data into a database for further use.

2) The form functions can be divided in relation to the possibilities of Xerus into two categories - standard and specific functions. The functions are then under the affiliation of one of these categories realized in one of two ways:
   - standard set of system events in Xerus;
   - with specific objects, known as PluginXY that are objects of classes that implement the interface IPlugin. Implementation of this interface provides links to other classes and items of Xerus environment.
3) Individual plugins use other objects, which implement their own methods, procedures and algorithms from the application area, in our case from the production, distribution and consumption of heat and its management in the urban agglomeration.

C. *User description of the program*

Working with developed application will be shown on the example of practical use to support supervisory control of heat supply to the distribution network of urban agglomeration.

The main intention is to preparation of the draft sequence of time-control interventions for the management of basic parameters of hot water (Tv), so that the response of the system would be in the pre-defined limits. This is an illustrative example and some explanation, not directly related to user control will be simplified.

Data preparation

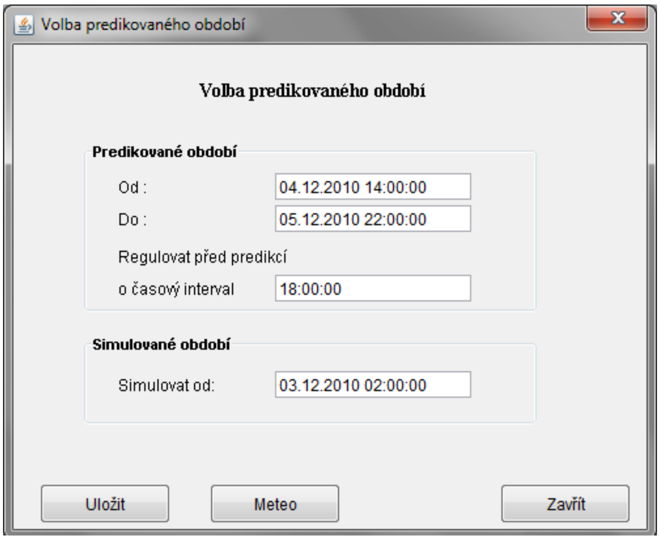
The following figure shows the form initiating the process of identification and subsequent control.

It is necessary to identify a few basic questions, which are the basis of follow-up used solution algorithms.

Solution algorithms:

- "From"and "to" timestamp to perform control: An example task of regulating Tv is from 2:00 p.m. to 2:00 p.m. the next day. Due to traffic delays throughout the system should choose the end time of a few hours later than we want in the result. This provides an opportunity toidentify the model parameters over the entire time with regard to traffic delays.
- "Regulate before prediction in time intervals":Identification apparatus of the model seeks internal model parameters from the two time intervals. The first is the time interval immediately preceding the required regulatory and other desired interval deals with the data from similar period for such regulation. The parameter "Regulate before …" determines the length of the first interval
- Simulate from
- Simulation model for its initialization needs sufficient time to stabilize. This time depends on the properties of the real system, which is represented by the model. In the case of selected heating plant, the time was experimentally determined to 20 hours. Shorter time causes inaccuracies in the beginning of the simulation andtime too long would bring unnecessarily slowing of the algorithm.

After selecting the necessary data, the form is closed by *Save*button. The temporary database tables are automatically prepared data for further processing.
Weather button is used to update a table with a weather forecast. The user must ensure that this table contains the forecast for the predicted time period (regulated) period.



Volba predikovaného období

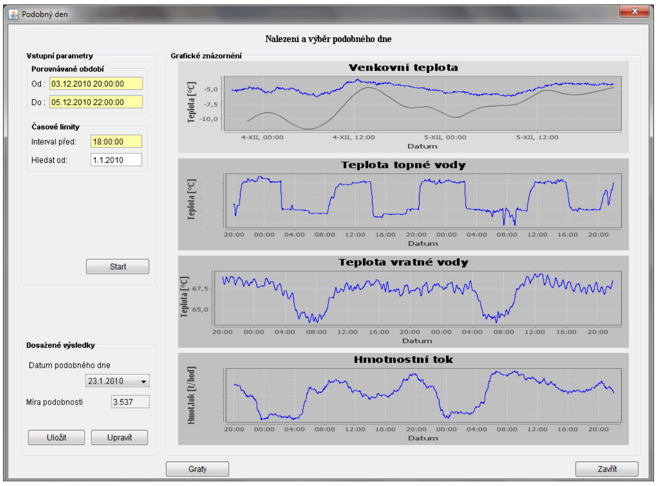
Predikované období
Od : 04.12.2010 14:00:00
Do : 05.12.2010 22:00:00
Regulovat před predikcí
o časový interval 18:00:00

Simulované období
Simulovat od: 03.12.2010 02:00:00

Fig. 5Form for data preparation

Similar period search

In this step, the similar period from the past is sought, Fig. 6



Nalezení a výběr podobného dne

Vstupní parametry
Porovnávané období
Od : 03.12.2010 20:00:00
Do : 05.12.2010 22:00:00
Časové limity
Interval před: 18:00:00
Hledat od: 1.1.2010

Dosažené výsledky
Datum podobného dne 23.1.2010
Míra podobnosti 3.537

Fig. 6Form for similar period search

The requirement was to regulate the period from 4.12.2010 14:00 to 22:00 December 5, 2010. From the meteorological database were selected outdoor temperature forecast for this period and found a group of database records withsimilar temperature.

After pressing the Save button relevant data from similar period are added to the database table. This is a link to data from the previous period.Data linked together form the bases for subsequent identification. The Edit button will smooth the return water temperature (*Tvv*) of the predicted period.


Podobný den

Nalezení a výběr podobného dne

Vstupní parametry

Porovnávané období

Od : 03.12.2010 20:00:00

Do : 05.12.2010 22:00:00

Časové limity

Interval před: 18:00:00

Hledat od: 1.1.2010

Dosažené výsledky

Datum podobného dne 23.1.2010

Míra podobnosti 3.537

Fig. 7Form for similar period searchafter the application of the selected day

Specific period identification

The actual identification for each period is invoked from the forms "Identification of a similar period" and "Identification of the previous period", see figure 8. These forms already have all necessary information and user only choose whether to start a new identification or only recalculate model with previously found parameters. Selection is made through "evolutionary algorithm" check box.

The process of identification, which is triggered by clicking "Start" takes about ten minutes (depending on the length of the identified period and computing capacity of the computer). After complete identification, the user have available graph comparing the measured values of *Tvv* and values calculated with the identified model. Another criterion for assessing the quality of identification is the fitness value, displayed in the upper right corner of the form.

If the user is satisfied with the results of identification, the form closes pressing "Save" button and thus save the identified parameters, including prediction of the heat, into the appropriate tables in the database.


Identifikace podobného dne

Identifikace modelu distribuce a spotřeby tepla

Vstupní parametry

Rozhodné období

Od : 23.01.2010 20:00:00 Do : 25.01.2010 22:00:00

Počátek simulace

Od : 22.01.2010 08:00:00

Evoluční algoritmus ☑

Dosažené výsledky

Počet provedených iterací 1251

Přesnost 760.7

Fig. 8Form for similar period identification

The output of the identification process is an estimate of heat over time, see figure 9. These values are then applied in the control.

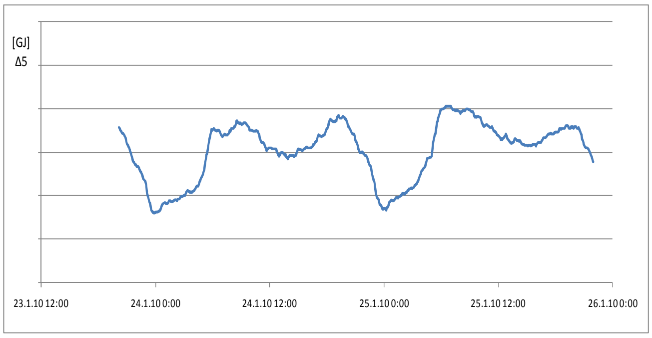
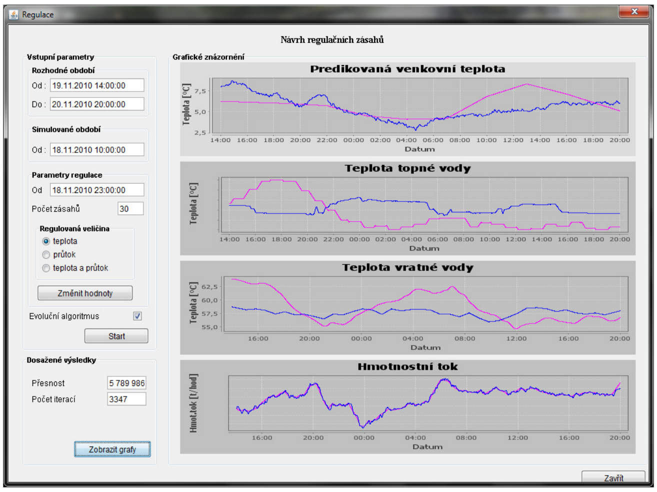


Fig. 9Estimation of heat

Proposal of the control actions

The model is designed so that in addition to tools for identifying heat also includes a prediction of individual variables in the system. Everything is in relation to the desired course of the remaining variables or optimization over a similar period. The model is currently being tested to optimize over a similar period with the additional conditions and smoothing the mass flow and *Tvv*. The output of the model, in this configuration, is the recommended temperature of heating water *Tv*. Prediction tools are available to the user through the form "Control", see figure 10.



Návrh regulačních zásahů

Vstupní parametry

Rozhodné období

Od : 19.11.2010 14:00:00

Do : 20.11.2010 20:00:00

Simulované období

Od : 18.11.2010 10:00:00

Parametry regulace

Od 18.11.2010 23:00:00

Počet zásahů 30

Regulovaná veličina

● teplota

○ průtok

○ teplota a průtok

Evoluční algoritmus ☑

Dosažené výsledky

Přesnost 5 789 986

Počet iterací 3347

Fig. 10Form for control

IV. IDENTIFICATION AND COMPARISON OF METHODS

Two simulation experiments were carried out to show possible improvements in the quality of the identification process. The objective was to identify the behavior of the particular time period by the original method and repeat identification using new method. To take any conclusion, the experiment was performed on independent data samples.

The experiments were performed on data from primary distribution - the area between the heating plant and the exchanger stations in the supply area.

For subsequent experiments constant temperature 20 °C were used as T_{inter}. The data used are from January 2013, it was the middle of the heating season with average outdoor temperature about +5 °C.

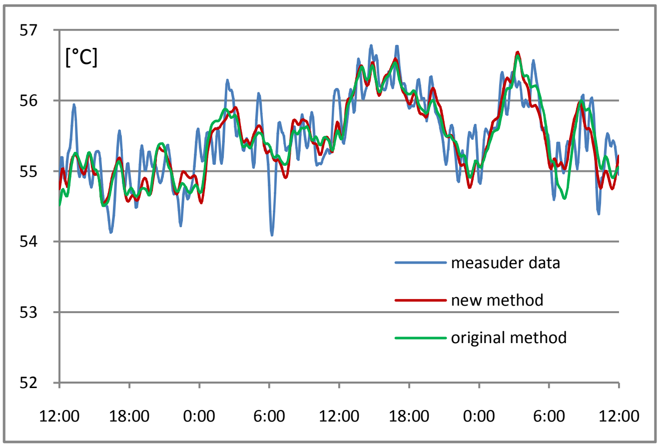


Fig. 11 Identification results – water temperature on return (first experiment)

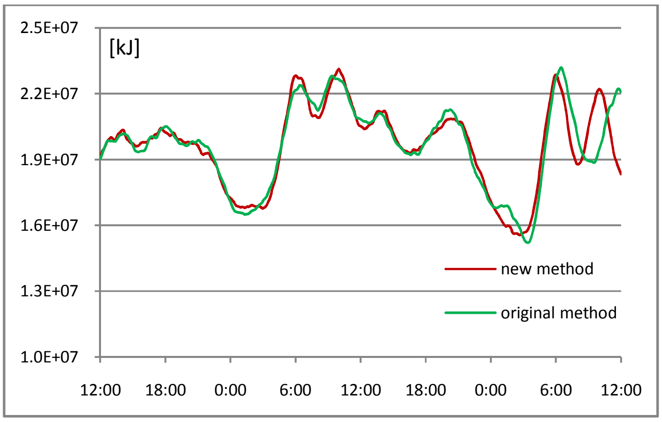


Fig. 12 Heat gained from identification (first experiment)

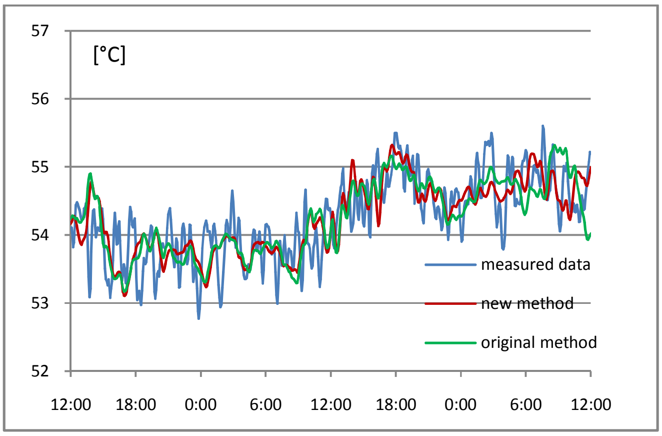


Fig. 13 Identification results – water temperature on return (second experiment)

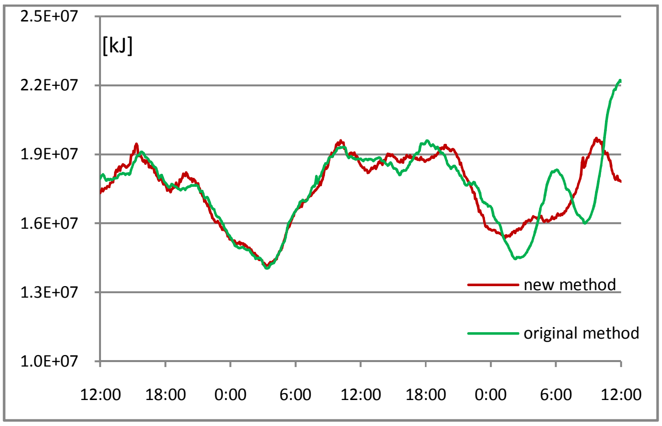


Fig. 14 Heat gained from identification (second experiment)

As can be seen in figures above, both methods have fairly consistent results. There is hardly noticeable difference in return water. To express this difference numerically, the average error between measured and identified results decreased from 0,262 (original method) to 0,258 °C per sample (modified method), for first experiment, and from 0,354 decreased to 0,345 °C per sample in second experiment.

V. CONCLUSION

Despite the fact that the presented modification does not yielded substantial improvements in identification process, it is obvious that an improved model, which clues to the real heating system behavior is an important move in its development. The modified model may continue to be developedand incorporate other fundamentals of the real system, such as the accumulation of heat in the buildings, non-natural cooling during night setback in a heating, include additional meteorological influences such as sunlight, wind, humidity, etc.

ACKNOWLEDGMENT

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