Prediction of Heat Consumption Parameters in Distribution Network

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Abstract— This article analyses methods used typically for controlling the processes in the distribution system of heat energy in the urban agglomeration (SHDC - System of Heat Distribution and Consumption). The key problem in this controlling mechanism consists in transport delay of transferring heat media. Therefore the control mechanism must operate in prediction kind of mode. The two control parameters, or control variables, are temperature of heat carrier and its flow rate. Their time behavior must be predicted for efficient control of the whole heat energy supply. There are many methods used for this prediction. They are briefly described, classified and analyzed in this paper. In more details there are described the methods, developed by authors, which combined procedures for mathematical analysis of historical production data and procedures for modeling of physical features in SHDC. For modeling simulation models are used. Further the results of practical experiments reached with described methods in the concrete real heat distribution system are presented.

Keywords—Distribution, heat energy, model, prediction, simulation.

I. Introduction

PROBLEMS of consumption and distribution of heat energy in the urban agglomeration (SHDC - System of Heat Distribution and Consumption) are important and actual, especially in the context of finite worldwide energy resources and the constant increase in energy prices. There is also important ecological aspect, because obtaining and using of energy generally has mostly negative environment impact. Therefore, it is necessary to seek all paths leading to energy, including heat energy, savings [8].

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; quantity depends besides on its flow rate. The correct delivery time, quantity and quality of heat energy must go hand in hand with minimal distribution costs [1].

These two variables are also control variables for heat energy distribution process. Their values time behavior in near future (some hours) is necessary to know (predict), when whole process should be correctly controlled.

System of production, distribution and consumption of heat is very large and complex. Analysis of the features that need to be known for its efficient management is very difficult. There exist some methods for this prediction, which make it, but not always with sufficient accuracy. Unfortunately, all this inaccuracies implicate some economical losses. They are mostly not marginal because of huge amount energy mostly handled in SHDC. The development of new, more accurate methods is all the time actual and usually is connected with use of advanced methods of IT which are almost exclusively based on modeling.

This paper describes two such methods for prediction of time behavior of the distribution system of heat consumption in the urban agglomeration, designed, developed and implemented on TBU Zlin.

For our methods and their verification, the chosen city system was simplified to one model, used for subsequent experiments. The model was trained on real measured data [2]. The main aims of the experiments were to verify model itself, its ability to adapt to real process and also to proof associated potential for prediction.

Beside the methods description, this paper shows results of two days experiment on heating system of midsize city with more than hundred heat exchangers.

II. Methods classification

In this paper we speak about methods for prediction of parameters, which are important for control of production and distribution of heat energy in distribution net. The whole system for heat supply includes heat production, heat distribution and heat consumption. From the viewpoint of control this system is the hierarchy inverse – dominant is heat consumption and this amount of heat must be in appropriate time be produced and by distribution system transferred to consumer. It means, the designed method must calculate predicted heat consumption, find the parameters for distribution and check the production subsystem, whether it is able to produce required heat energy. And naturally, all these variables vary in time.

There are a lot of criterions for classification of used methods. For the purpose this paper we use the type of model. There are three types of models:

Models based on exact description of physical process by means of physical laws. This kind of model is the most accurate model in the case, when we know the correct physical laws and we are able to apply these laws exactly to real system. It's clear, that for such system as the SHDC, this kind of model is so complicated and complex that it is not soluble [12].

Models based on pure mathematical analysis of operational data from analyzed real system. These models use statistical methods, analysis of numerical series [5], but also neural networks [6].

Combined models. The base of these models is simplified parametric physical model and the parameters are identified from operational data of analyzed real system.

The below described method belongs to combined methods.

III. Procedure for prediction of heat distribution parameters

The procedure for prediction of heat distribution parameters with the use of combined model has the following main steps:

A. The parametric model design and creating

This step is for each method specific and includes:

- Definition of model structure and basic formulas for model description;
- The model parameters specification, their meaning;

B. The parametric model identification

This step usually includes parameter identification for the selected time period. Here the algorithm for parameters determination should be described and implemented, usually in the form of some SW module or application. In practical use are the concrete values of the parameters by this SW calculated.

C. Prediction of appropriate timing of the supplied amount of heat energy for the next period

In this step the identified model from previous step is used for calculation. The result is a time function of the course of demanded quantity of heat energy.

D. Prediction of appropriate timing of the heat distribution parameters for the next period

In this step the above mentioned parameters, i.e. temperature and flow rate of the heat transferring media are calculated. For this step the same model can be used, if it is able to also calculate those values, or another one. In experiments described below one model for both described methods was used.

For practical use there should be the following two steps added. Their detailed description is out of focus of this paper:

1. Verification from point of view of energy production, whether the predicted values of demanded heat energy, eventually heat distribution parameters are really matching reality.
2. Transfer predicted values to the control system for production and distribution of heat energy.

IV. Method based on discrete simulation model of distribution net

Detailed information about used discrete simulation model for heat transfer modeling can be found in [8], therefore here is only short description presented.

Model is discrete in time; it means we check the state values of system only in set of time points. The length of time interval determine so called Discrete Flow Quantum (DFQ), as volume of transferred heat media, which flows through defined point of distribution net in this time interval.

The distribution network can be represented by set of sources of heat energy (supply heating stations) and heat consumers which are cross connected through piping.

For the heat consumption of DFQ_i at consumer r at time interval Δt_j (simulation step j), the following equation can be used:

$$^{j}Q_{i\ consumer} = s_r(^{j}T_i, {}^{j}T_{r\ ext}, \ldots) * \Delta t_j \qquad (1)$$

where:

- $s_r(\ldots)$ is the function describing specific heat consumption for the consumer r,
- $^{j}T_i$ is water temperature for the DFQ_i
- $^{j}T_{r\ ext}$ is the outside temperature for consumer r.

Determination of this function is obviously very difficult, but for the final solution of this task, especially in terms of its accuracy for those particular parts "consumers", it is very important. There may be applied many different important factors such as:

- type of the day: workday, weekend, holiday etc.,
- part of the day: morning, afternoon, evening, night,
- type of the consumers in the particular part of the network: flats, schools, industrial companies etc.,
- other weather conditions: sun intensity, wind, air humidity

Note: To determine the functional dependences of heat consumption $s_r(\ldots)$ on these factors it is also possible to successfully use the proposed simulation model.

For example, for below described experiments is function $s_r(\ldots)$ used in simple form

$$s_r(\ldots) = k_r * (^{i}T_j - T_{ext}) * k_h \qquad (2)$$

where:

- k_r is the heat transfer coefficient, specific for current consumer r and is based on consumer structure - used material, style and material of insulation, geometric characteristic, etc;
- k_h is coefficient which corrects heat consumption oscillations during a day.

To determine searched values k_h (points of timeline) is possible to use several methods based on principles allowing us to find a function(s) which should have the best course approximating analyzed variables. One option is for example to use genetic algorithms. In the presented solution was the method PSO (Particle Swarm Optimization) used - see [5]. It was found that the results achieved in terms of accuracy and speed of convergence is comparable with other methods and PSO algorithm is simple for use.

A. Model implementation

Introduced model was implemented in the form of a software application. The program modules are written in Java, data – historical operational data, configuration and description data for distribution network, simulation results – are stored in database. Connection to database is realized through JDBC interface and all queries to database are defined by SQL statements. These chosen software tools and solution allow easy portability to different SW environments.

The basic class is class SIMULATOR, which realize separately one complete simulation experiment, i.e. one simulation run for whole simulated time period. This gives the possibility to write application as multithreaded, so that there are running in parallel several instances of the class SIMULATOR, everyone in their own thread. It gives higher performance for calculation, especially in case, when many simulation experiments must be provided.

Block diagram for the whole application can be seen in following Fig.

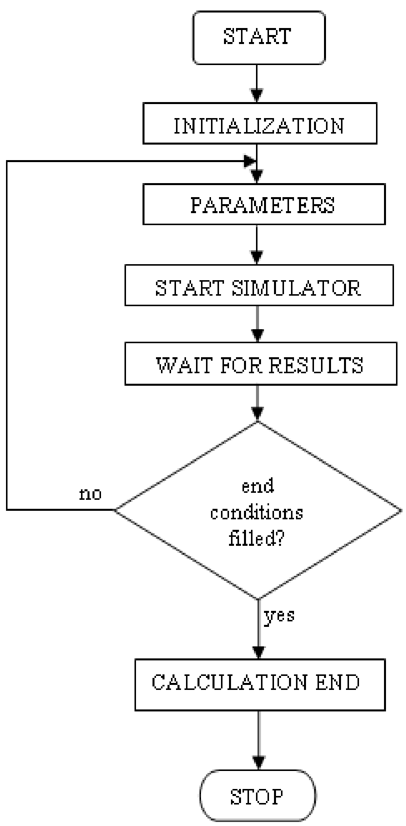

Fig. 1 Block diagram for application run

Short description of some selected block content:

Block “INITIALIZATION”:
-Read necessary data from database.
-Create and initialize internal data structures for program modules.
-Create and reset data structures for results.

Block “PARAMETERS”:
-Get set of model parameters. The set of parameters is generated by PSO algorithm. It is realized in the procedure, which has as output set of model parameters and input is value of fitness for given set of parameters. This procedure is a part of the block “PARAMETERS”.

Block “START SIMULATOR”:
-Create a new instance of SIMULATOR class to which given parameters is assigned.
-Define and start a new thread in which the new instance of SIMULATOR is running.

Block “WAIT FOT RESULTS”:
-Wait the end of simulation for each SIMULATOR instance in individual thread.
-If the end is reached, the result (the value of fitness) is put in procedure with PSO algorithm.

Block “CALCULATION END”:
-This block is reached if the conditions for end of calculation are filled.
-The results are saved in database.
Program ends.

Notations for class SIMULATOR

NODE - a mark for node object in model;
first NODE - the node on the beginning of distribution network, usually the output point from heating station;
last NODE - the node on the end of distribution network, usually the input point on heating station;
input NODE - the node in which the section begins, is defined for each SECT;
output NODE - the node in which the section ends, is defined for each SECT;
SECT - a mark for section object in model;
first SECT - first section in distribution network, usually starts in first NODE
last SECT - last section in distribution network, usually ends in last NODE
next SECT - the next section in list of SECT, it not have to be necessarily a topologic consequential SECT
SIMULTIME - simulation time

Short description of some selected block content:

Block “INITIALIZATION”:
- Set simulation time to start value.
- Create and initialize internal data structures for program modules.
- Create and reset data structures for results.

Block “start NEXT SIMUL STEP”:
- Add time interval Δt to the SIMULTIME
- Clear all marks “NODE handled” and “SECT handled”

- Create new DFQ. Its volume is calculated from current mass flow from heating station, its temperature is given by current temperature of water on output from heating station.
- Put this new DFQ into first NODE.

Block “NODE HANDLE”:

- Sum volume V_i of all DFQ’s (more exactly the parts of DFQ’s which reached the node) - volume V.
- Calculate temperature T of volume V
- Divide volume V to sections which are outputs from the node – volumes V_j
- Mark node as handled.
- Create new DFQ’s with volumes V_j, temperature T and put they into output sections for this node.

Block “LAST NODE”:

There are some similar functions as in other nodes.

Differences are:

- Write the output from this node into results
- Destroy input DFQ’s
- Don’t create new DFQ’s on the output from this node.
-

Block “input NODE complete ?”:

- The NODE is complete if all SECT, for which the NODE is output node, are handled

Block “SECTION HANDLE”:

- Calculate length of input DFQ from its volume and diameter of first pipe in section.
- Move all DFQ’s in section through all pipelines in section, i.e. calculate for each DFQ its new position. On calculation must be respect pass of DFQ’s over boundary lines between two consequential pipe lines and between last pipe line in section and output node – as described in chapter III.
- Calculate amount of heat and temperature change (decrease) for each DFQ in section based on heat transfer from DFQ to environment of pipe line corresponding to its current position (heating of space or energy losses).
- Mark section as handled.

Block “write results”:

- The results for each simulation step are written into internal data structures on the end of simulation step. The results contents:

- Simulation time,
- input mass flow,
- temperature of input water,
- temperature of output water and other characteristics needed for the analysis.

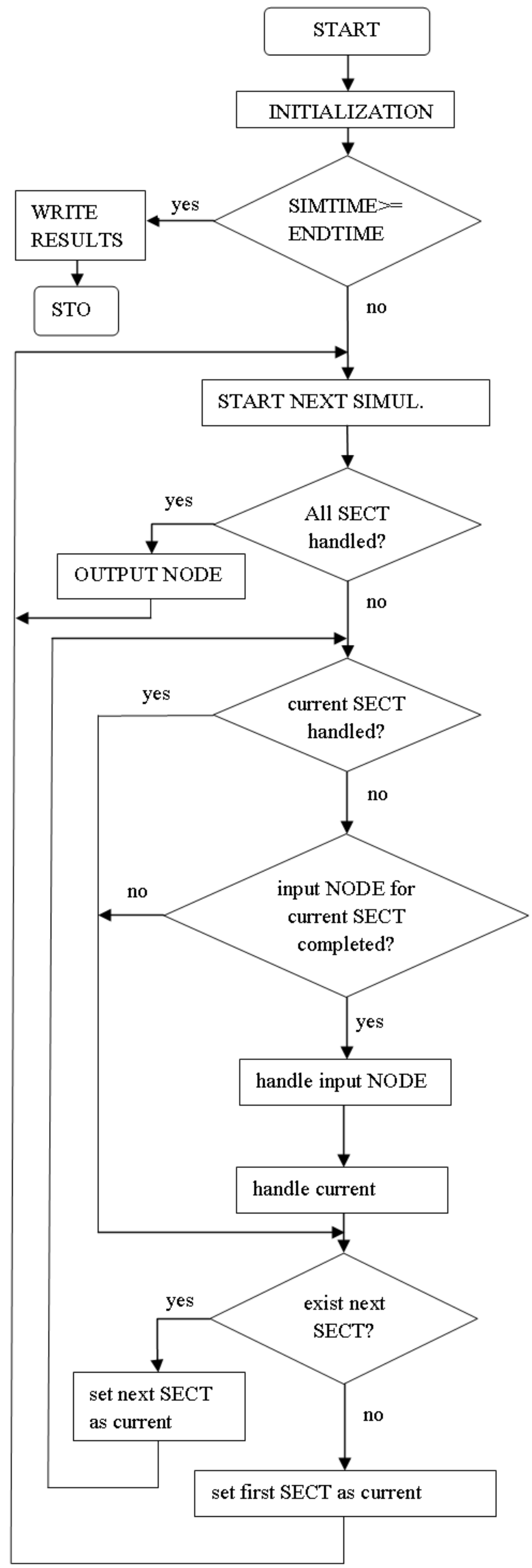

Fig. 2 Block diagram for class SIMULATOR

V. Method Based on Heat Load Modeling

We have proposed new method based on approximation of heat loading function. We suppose the dependence of this function on two variables – time of the day and external temperature. The time dependent component is approximated using sum of two peak functions. The temperature dependent component is approximated using generalized logistic function. The model parameters are estimated using evolution algorithm. This chapter presents calculation of delivered heat load and approximation model [11].

A. Heat load modeling

Transport time of the supply line is estimated according to [8]:

$$R = \int_{t-T_{D1}}^{t} \dot{m}(\tau)\, d\tau \tag{3}$$

where

R – is the known mass amount [kg],

T_{D1} – is the unknown supply line transport time [s],

$m(t)$ – is the measured mass flow at time t [kg/s]

Transport time of the return line is estimated according to [9]:

$$R = \int_{t}^{t+T_{D0}} \dot{m}(\tau)\, d\tau \tag{4}$$

where

T_{D0} -is the unknown transport time of return line [s]

District heating system is approximated by load center of mass of the system [9]:

$$P(t) = \dot{m}(t)c\left(\vartheta_1\left(t - \frac{T_{D1}}{2}\right) - \vartheta_0\left(t + \frac{T_{D0}}{2}\right)\right) \tag{5}$$

where

$P(t)$ – is the heat load in time t [W],

c – is the specific heat capacity [J / kg K],

ϑ_1, ϑ_2 – the temperature of heat transferring medium on input and output of distribution line.

B. Approximation and prediction

Heat load is approximated by the sum of time dependent and temperature dependent components.

$$f_P(t, \vartheta_{ex}) = f_{time}(t) + f_{temp}(\vartheta_{ex}) \tag{6}$$

where

$f_{time}(t)$ – is the time dependent component,

t_0 – is the time offset,

ϑ_{ex} – is external temperature,

$f_{temp}(\vartheta_{ex})$ – is the external temperature dependent component. Temperature dependent component is approximated using generalized logistic function.

$$f_{temp}(\vartheta_{ex}) = A + \frac{K - A}{\left(1 + Qe^{-B(\vartheta_{ex}-M)}\right)^{\frac{1}{v}}} \tag{7}$$

where

A, B, K, M, Q and ν are model parameters, which is necessary to identify from operational data analysis.

The time dependent component is approximated by the sum of two peak functions. The Hybrid of Gaussian and truncated exponential function (EGH) [10] was selected as the most convenient function.

Hybrid of Gaussian and truncated exponential function is defined as

$$d = 2\sigma^2 + \tau(t - t_m)$$
$$f_{EGH}(t) = \begin{cases} H\,exp\left(\dfrac{-(t-t_m)^2}{d}\right), & d > 0 \\ 0, & d \leq 0 \end{cases} \tag{8}$$

where

H, σ, τ, t_m and d are again the model parameters which are to be identified by data analysis.

Function $f_{time}(t)$ is the sum of two EGH functions:

$$f_{time}(t) = f_{EGH1}(t) + f_{EGH2}(t) \tag{9}$$

The Particle swarm algorithm **Chyba! Nenalezen zdroj odkazů.** was chosen as the numeric optimization algorithm suitable for finding the unknown parameters.

VI. The Experiments

In this chapter are published results of experiments, performed with both methods. Here is shown two days experiment performed on heating system of midsize city with more than hundred heat exchangers.

A. The experiment with discrete simulation model

Its main purpose was to predict sequence of heating water temperatures *(Tv)* to control quality of heat supply [1]. The experiment was conducted from March 8th to March 10th [12].

The first step of experiment was to prepare simplified pipe model - Fig.1. Because there was not enough information about heat consumption spreading, the city for model purpose was divided into twelve heat consuming spots which represents group of heat exchangers with similar distance from the heating plant. Also all spots have the same power requirements.

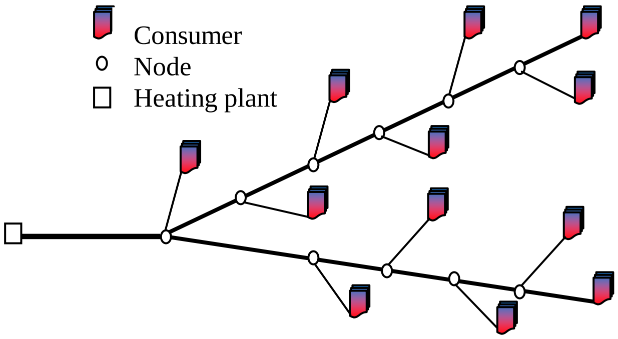

Fig. 3 Simplified diagram of the network model

Next step was to set up model for identification. According to unknown condition of day in future a day with similar outside temperature from the past was chosen to train the model [2]. From the operational data for chosen period the model parameters were identified and also expected heat consumption was calculated.

Based on the heat requirements the prediction mechanisms took the place. The sequence of *Tv* were predicted, see Fig. 4. These *Tv* were than imposed into the heating plant system and real control took the place.

The next day was model updated and all steps were repeated for subsequent time period.

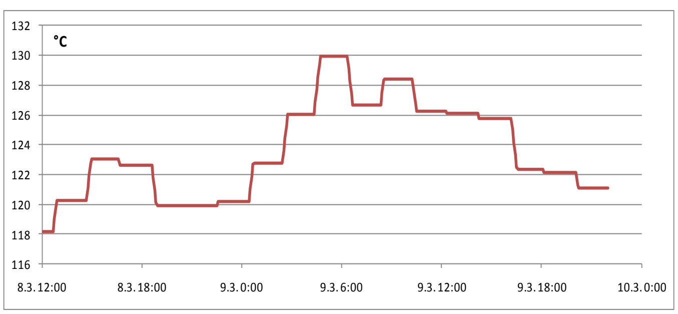

Fig. 4 Proposed values of *Tv* for first day (water in the supply line)

The proposed values were found acceptable by the heating plant and followed for both days. The measured results and its comparison with model prediction are showed in the following pictures.

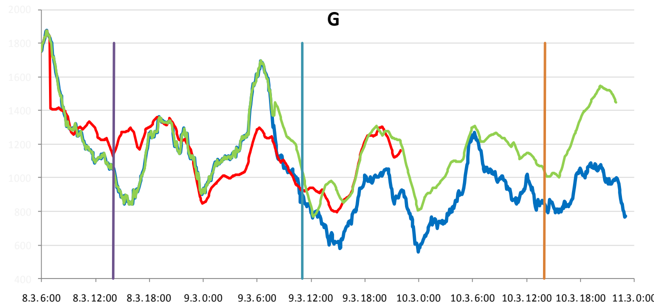

Fig. 5 Flow (transfer fluid)

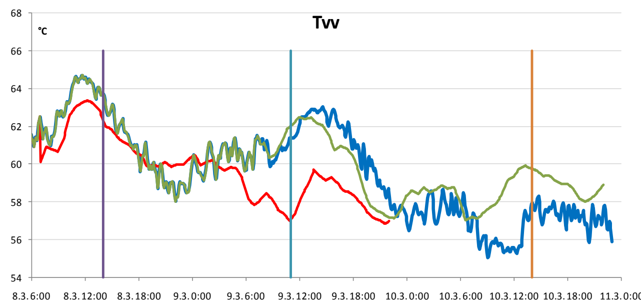

Fig. 6 Returned water temperature (water in the return line)

Graph legend:
____ first day prediction
____ second day prediction
____ measured course

B. Experiment with Heat Load Modeling

The results prove the suitability of this method. Next research will be the classification of daily patterns by means of EGH parameters.

	Date
Approximation from	9. 9. 2010 0:00
Approximation to	4. 3. 2011 23:00
Prediction from	6. 3. 2011 0:00
Prediction to	9. 3. 2011 23:00

Tab.1 Approximation and prediction intervals

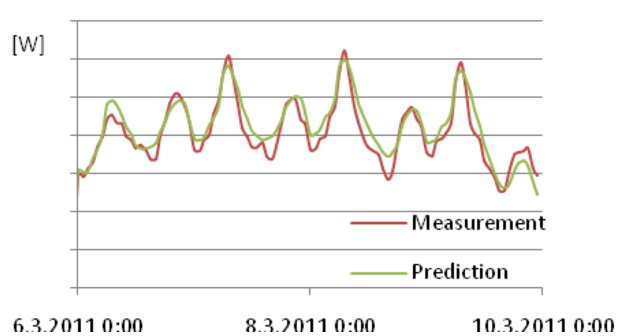

Fig. 7 Delivered load

C. Discrete simulation model used for secondary network

The proposed algorithms were also tested on secondary network. Network between one heat exchanger and several house stations (consumers). The network is schematically shown on Fig. 8. The fig. 9. shows this location satellite view.

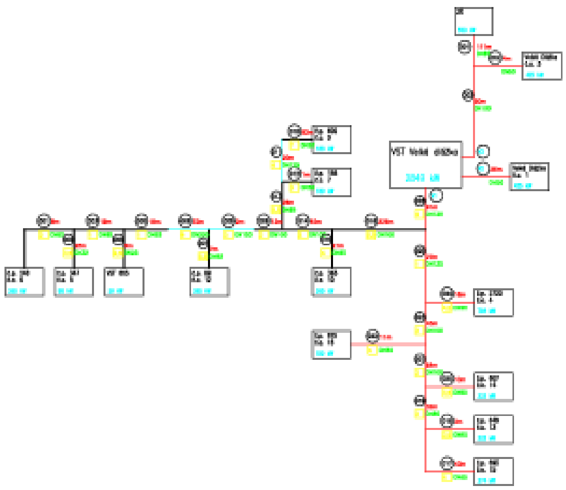

Fig. 8 Schematic consumers lay-out

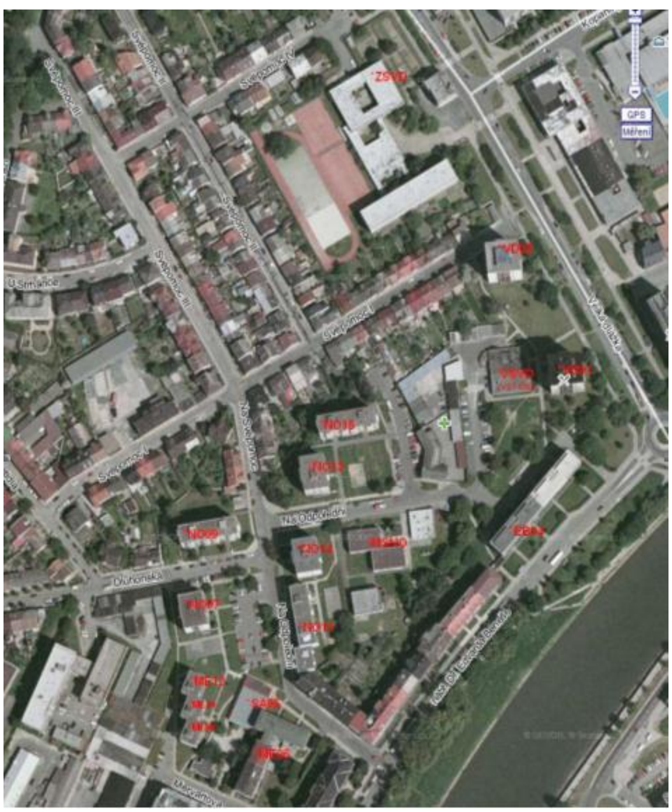

Fig. 9 Chosen location in satellite view

First at all, with regard to proposed model requirements, the similar period were identified. Compliance between measured and output data after model identification is shown in fig. 10.

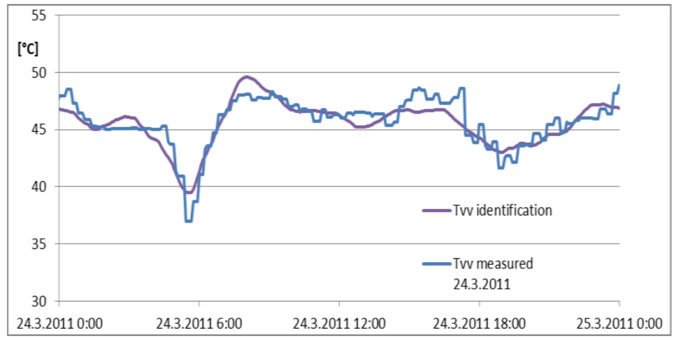

Fig. 10 Identification results

Successfully identified model were after that used for real system behavior prediction. The temperature of T_v were taken from real control actions. The result from the model was compared with the real system responses. Obtained results are shown on following pictures. The mass flow and temperature of water in return line were observed.

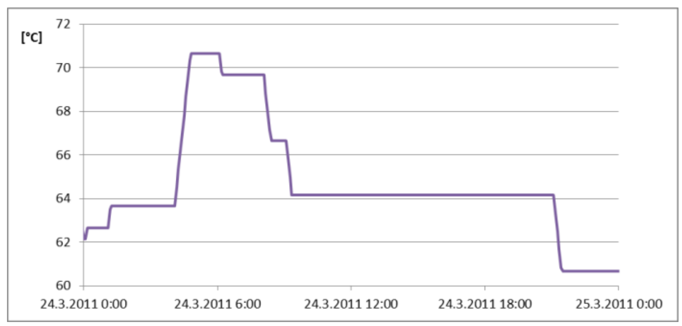

Fig. 11 Heating water temperature T_v

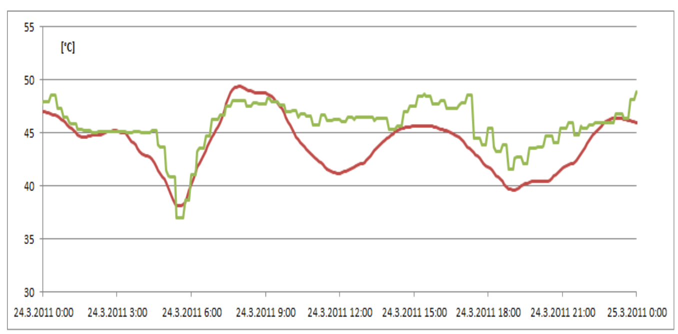

Fig. 12 Predicted and measured values T_{vv}

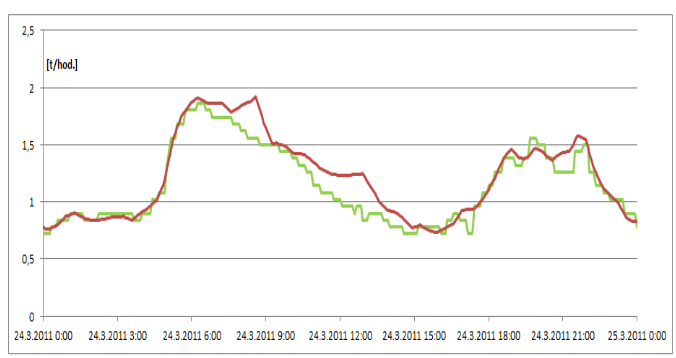

Fig. 13 Predicted and measured values G (mass flow)

VII. Conclusion

The results obtained during the verification of both methods on real measured data show that the proposed methods are well suited tools for analyzing the properties and behavior of SHDC.

The principal difference between two described methods is in structure of the model used. In first method, which uses the simulation model, the model is more detailed, composed from individual parts – heat sources, heat consumers, connecting pipes – and the time interval for identification is always found as a similar interval. In second method, based on heat load, the model has simple structure – there is only one heat consumer and time interval for identification is one longer period. It means that second method works more with average values of variables. This fact brings an advantage – it is not necessary to every time perform the identification of model parameters and the calculations are faster than for the first method. On the other side, if a predicted day will differ from an average day, the accuracy will be lower.

For first method also some inaccuracies remain. As can be seen in Fig. 4 the flow predicted and measured course have considerable deviation. This is probably due to inappropriate binding between similar and examined days. To eliminate this insufficiency, the current research focuses on possible combination of both developed methods.

Nevertheless, used methods and algorithms appear to be leading to improved performance of existing heating systems.

Acknowledgment

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