Simulation and experiments on the secondary heat distribution network system

Dolinay V., Vasek L.

***Abstract* —** This paper presents simulation model and results obtained during the practical experiments on secondary net of distribution heating system. It covers systems for urban location, typically housing estate or groups of family houses. Such systems deal with distribution between heat exchanger and individual door stations. The experiment was based on similar day identification and subsequent prediction of recommendations for system control. Predicted values were applied in real control process and later obtained results were compared with predicted courses and analyzed causes of all differences. To identify deviations caused by imperfection of the model and methods and separate them from inaccuracy of weather forecasts the simulation were repeated with ideal course – weather forecast were replaced with measured course.

***Keywords*—**secondary distribution net, heat, identification, modeling, prediction.

I. Introduction

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. The [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 now presented paper, attention is focused on its use in analysis of secondary distribution network.

In secondary distribution networks is usually used weather-compensation control – equithermal controlling or regulation. In such control the external temperature is the only 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. However, knowledge of system behavior is important to design suitable control methods.

This article will shows one of the experiments with simulation model introduced in [5]. The task will be simulating behavior of the location with one heat exchanger stance during one day in winter 2011.

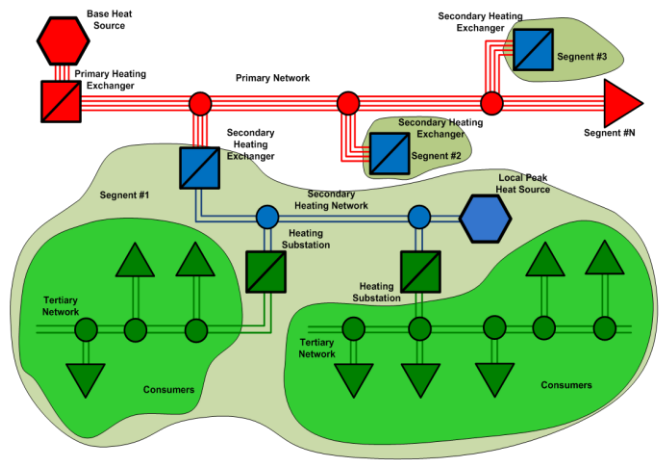

Fig. 1 Schematic diagram of SHDC [10]

A. *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. 2 Production, 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. It is 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 stance and their importance lies in changing the output values of pressure and temperature of heat carrier. Heat networks 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 stations and 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 energy to 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. Simulation Model

For the simulation is characteristic to create a model of the system, usually an abstract model and today almost exclusively a computer model. With this model are performed experiments and their results are then applied to the original system [5].

The simulation model is usually created in several steps:

1) *Analysis of the original system and the creation of a conceptual model.* Here you decide what type of model used (continuous or discrete, deterministic or stochastic, etc.), open or sealed model, what parameters that can influence and modify the properties of the model will be included in the model.
2) *Collection of data for model validation.* If the modeled and simulated system exists, it is mostly a historical operational data, where we know the values of the input data, and system behavior (output data)
3) *Programming a computer simulation model.* The model can be programmed in either a universal language, currently probably in object-oriented language, or you can use any available simulation language or a general simulation system.
4) *Verification and validation of created simulation model* using test data collected.

So created, verified and validated simulation model is prepared to subsequent using.

The use of a simulation model in this case is fundamentally twofold:

1) *offline model using*
   It is possible to analyze the properties and behavior of simulated system as a wide dynamic system
2) *online model using*
   Simulation model can be integrated into the control system simulated system as an instrument to prediction of its behavior at a certain (limited) time in the future.

Proposed model of SHDC is, in contrast to the commonly used continuous models, discretized in time - time is running in simulation discontinuous steps, with a sampling period. The size of the time period depends on the speed of change of monitored values. Therefore, if this model will be used for analysis by going to the SHDC run in normal mode and not going with great speed changes, such as surges in the piping, etc., it is possible to work with the time period of several minutes. For this kind of analysis is used concept of the simulation model justified.

This relatively long sampling period is also important for the second of described ways of using the simulation model, because in the time period of several minutes we can perform numerous calculations, which are usually needed for predicting the behavior of SHDC in the near future, i.e. online model using.

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 net, basically pipe lines and heat consumers. Each element has its own constant characteristics from the point of view flow and heat transfer.

Model works in discrete time 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 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].
Proposed model has two modeling levels.

Flow modeling

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.

Heat transfer modeling level

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 (1) shows applied formula for calculation course of temperature DFQ of heating water due its cooling in pipe or consumer. We assume in this moment only direct relationship between change of temperature T and difference $T - T_{ext}$, i.e.

$$\frac{dT}{dt} = K * (T - T_{ext}) \quad (1)$$

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

$$T_1 = exp\ (-K*t) * (T_0 - T_{ext}) + T_{ext} \quad (2)$$

where:

T_0 and $T_1$are the water temperature at the beginning and end of the time intervalΔt.

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

$$\Delta Q = c_p*V*(T_0 - T_{ext}) * (1 - exp\ (-K* \Delta t)\ ) \quad (3)$$

III. Used Model

The model introduced above and described in more details in [5] 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.

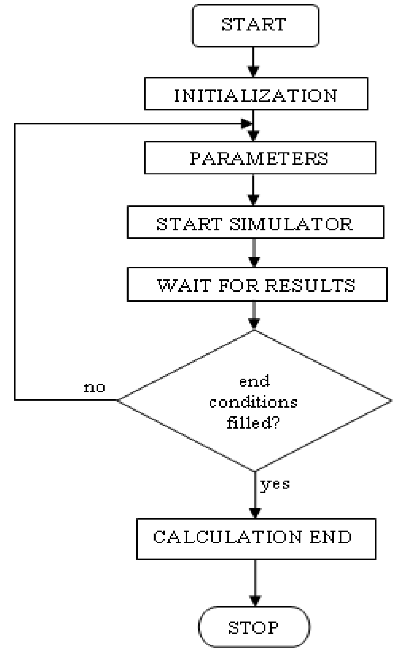

Fig. 3 Block diagram for application run

Short description of some selected block content:

INITIALIZATION:

- Read necessary data from database.
- Create and initialize internal data structures for program modules.
- Create and reset data structures for results.

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”.

START SIMULATOR:

- Create a new instance of SIMULATOR class (multithreaded application) to which given parameters are assigned.
- Define and start a new thread in which the new instance of SIMULATOR is running.

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.

CALCULATION END:

- This block is reached if the conditions for end of calculation are filled.
- The results are saved in database.
- Program ends.

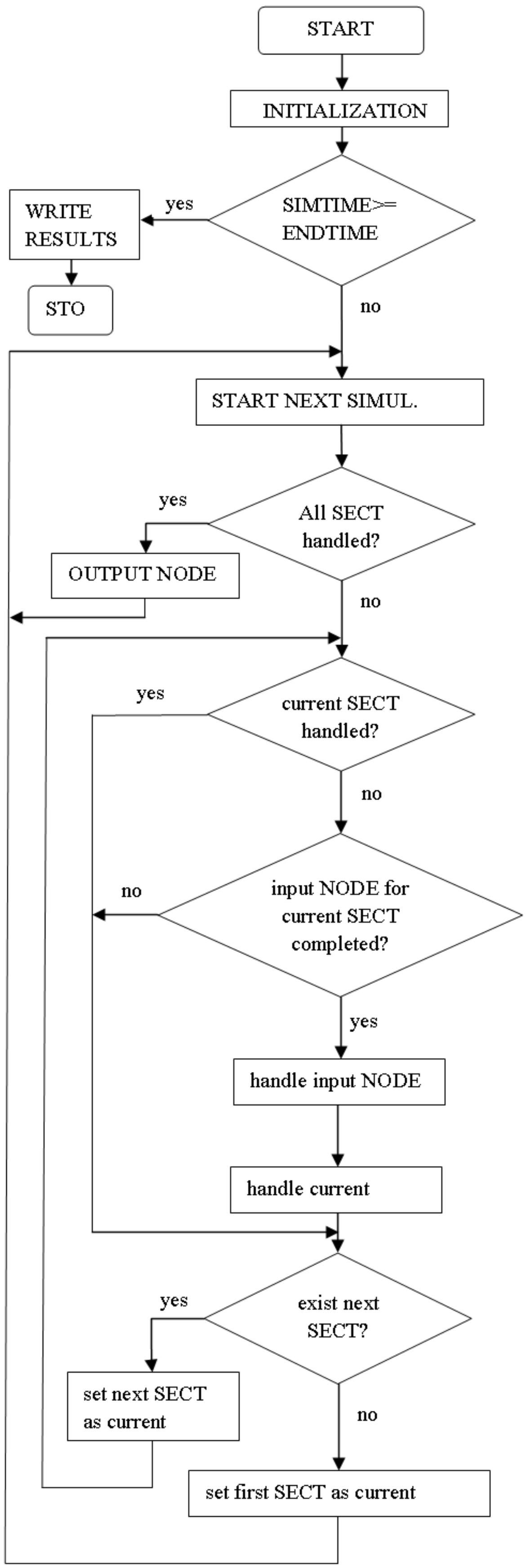

Fig. 4 Block diagram for class SIMULATOR

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:

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

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.

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.

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.

input NODE complete ?:

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

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.

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.

IV. Strategy of Using the Model

Simulation and control can be described in these steps:

1) *obtain weather forecast for day to propose,*
More frequent updates and increased accuracy for a particular location is an advantage. All presented experiments are based on public weather forecast service available on http://www.meteopress.cz/. This public service provides three day forecast for selected area with three hour resolution.

2) *seek and choose best matching day from the past*
Looking for days of ancient history has no sense, e.g. previous years, heating season, because the system is constantly changing. Days from the surrounding area should be preferred. It is also advisable to monitor the previous days, because if it is such a day following a significant change in the weather, the behavior of consumers is considerably in an unstable state. Following fig shows results obtained from the model. Based on the outside temperature forecast (green line) were found the day in the past with best matched. Days are not searched too deep in history (up to several months), because it was found that consensus on heat consumption is higher for days, located close to each other.

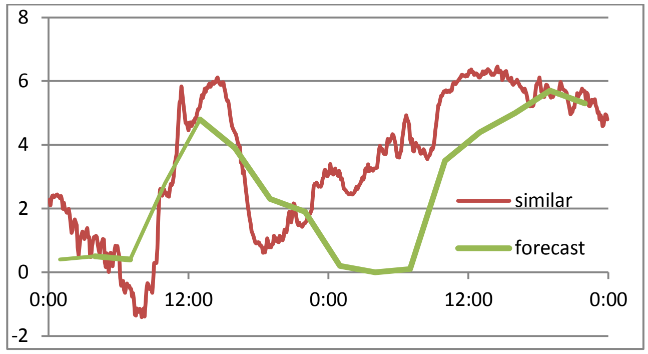

Fig. 5 Weather forecast and similar day

3) *train the model*
Behavior of consumers is highly stochastic and nonlinear – so to find a general function describing its behavior is practically impossible. Better is to identify a particular period and model optimization for a given situation. Figures below shows results from identification process.

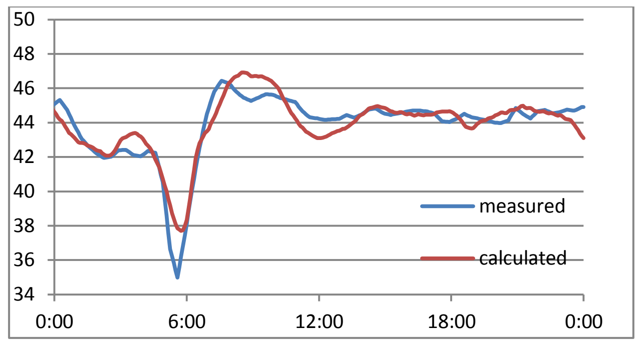

Fig. 6 Match between the input and calculated course of Tvv

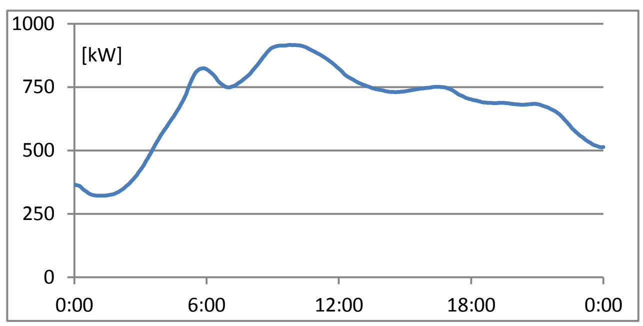

Fig. 7 Calculated course of heat for similar day

4) *predict behavior for proposing day*
Knowledge of the required amount of heat can be used with advantage in the prediction. Model trained on a similar day may in the future improve the management of individual variables to the optimal operation.

V. Experiments

Idea of the proposed simulation system [6] is to build modular structure able to model heat production and its distribution from heating plant into the city(s) followed by secondary distribution - heat from primary pipes is transferred to smaller circuits.

Described experiment, aims to verify the functionality of the simulation system in terms of identification and temperature control in secondary net.

A. *Selected location*

As a secondary network pattern, the part of Prerov town (CZ) was selected. Network contains one heat exchanger stance and fifteen house station. See fig. 8. Each house consumes heat energy for heating of dwelling and other space in house and for hot water preparation.

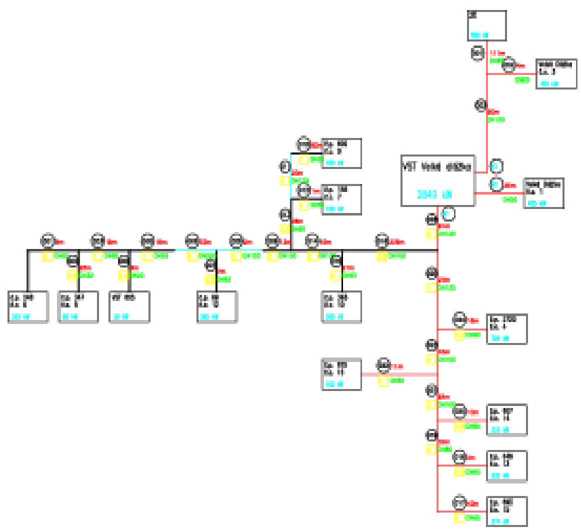

Fig. 8 Schematic consumers lay-out

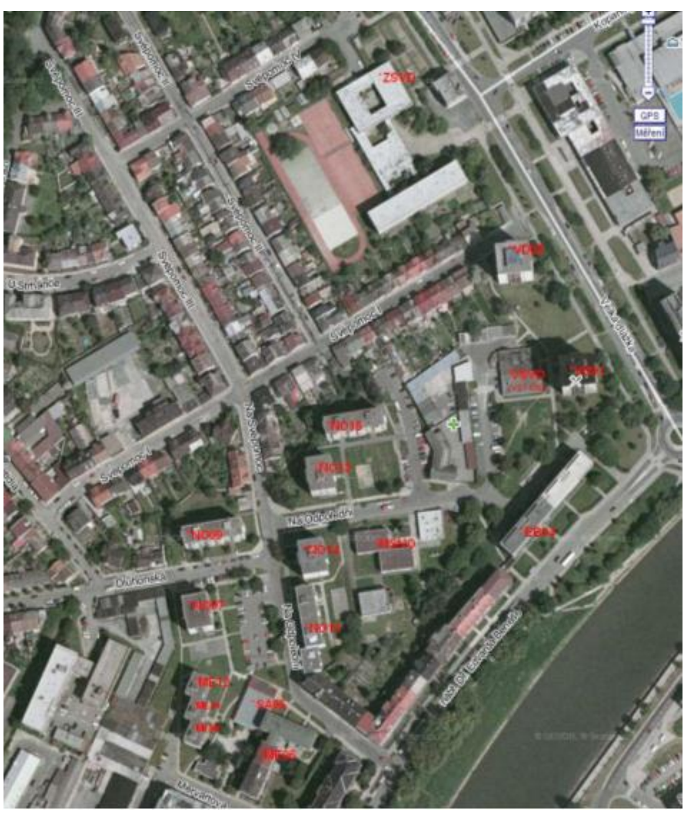

Fig. 9 Station layout in city area

B. *System identification*

The practical experiment had the task to propose temperature for heating water and predict mass flow time behavior. One of the goals for the temperature proposal was to avoid rapid changes, peak and other inappropriate behavior of mass flow. Base on the strategy above, the particular steps were:

1) select day with similar outside temperature time course (similar day),
2) similar day identification (means to find variable parameters of the model that have the best fitness for the similar day). Fig. 10 shows identification results from the prepared software. Blue curve symbolize the measured course (return water temperature), red is identified course.

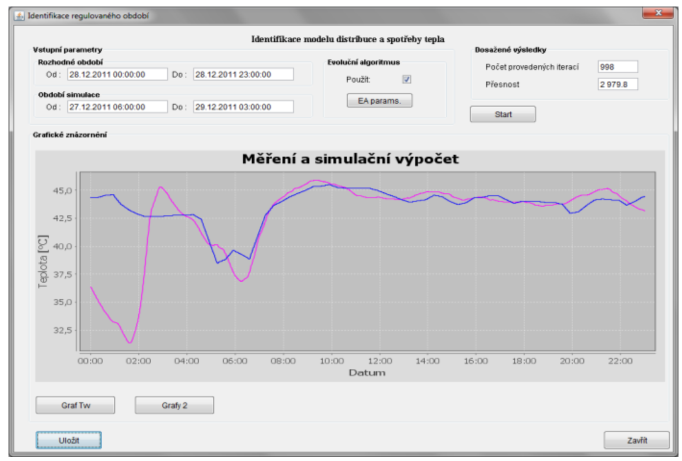

Fig. 10 Identification results

Proposed temperature of heating water is shown in Fig. 11. This temperature information were passed to heat distribution system and applied on the real system.

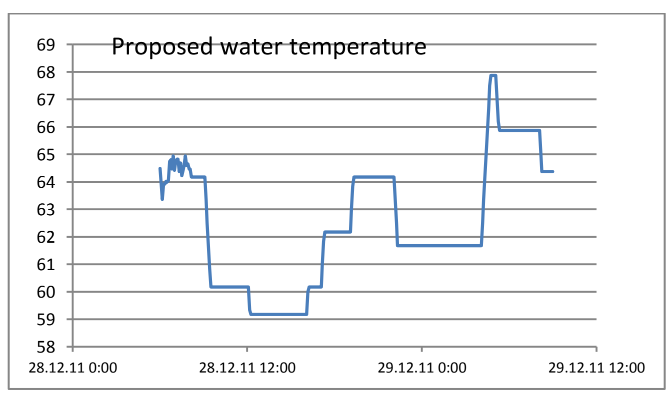

Fig. 11 Proposed water temperature

The system response can be seen in Fig. 12 and 13. Blue curves show predicted course and red color belongs to measured data.

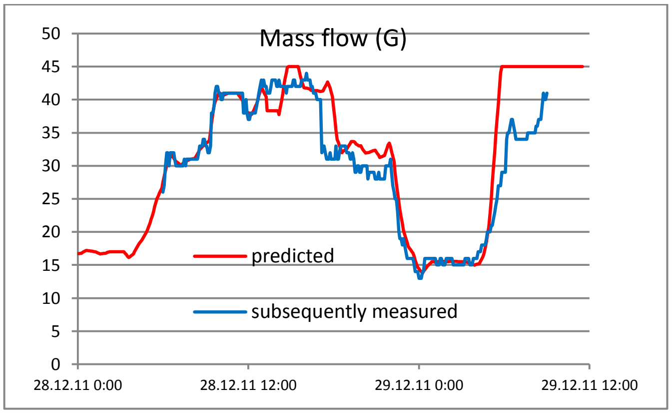

Fig. 12 Comparison of the mass flow

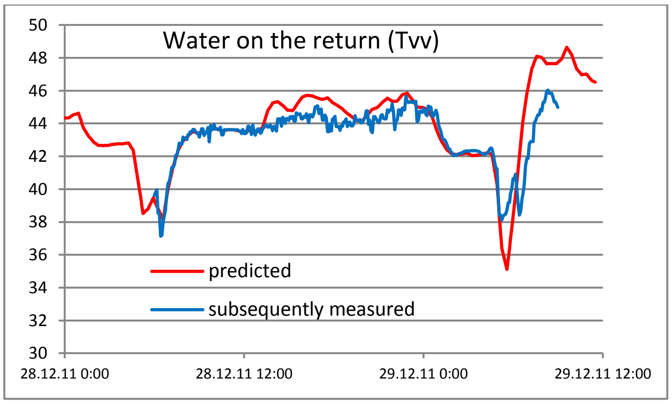

Fig. 13 Comparison of the Tvv temperature

Obtained results can be declared as good according to previous pictures, but there is always chance to cut some inaccuracies. Even though the results are good, most disturbing is the temperature precision of weather forecasts. See Fig. 14. Even the forecast came from one day before the particular day, the biggest error in obtained results is caused by the forecast for the entire area. Our location is in the city center and therefore the temperatures often vary from the general predictions for the whole city.

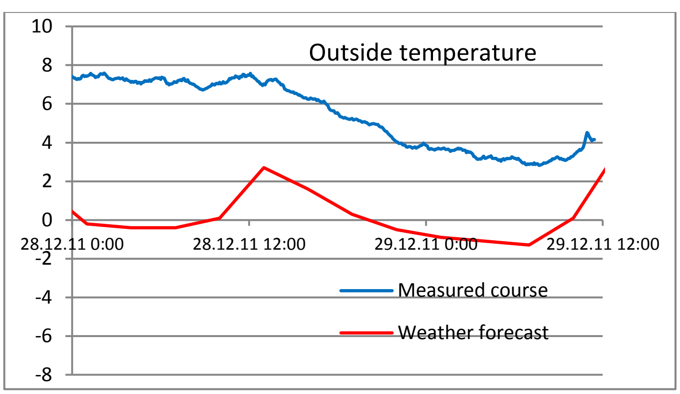

Fig. 14 Outside temperature

For the second part of our experiment we pretend ideal forecast. We moved back in time and instead of forecast used measured outside temperature. The heating water temperature was known from the first part of the experiment, so the task was just to retrieve model response describing course of the temperature of water on the return and behavior of the mass flow. Following figure shows obtained results.

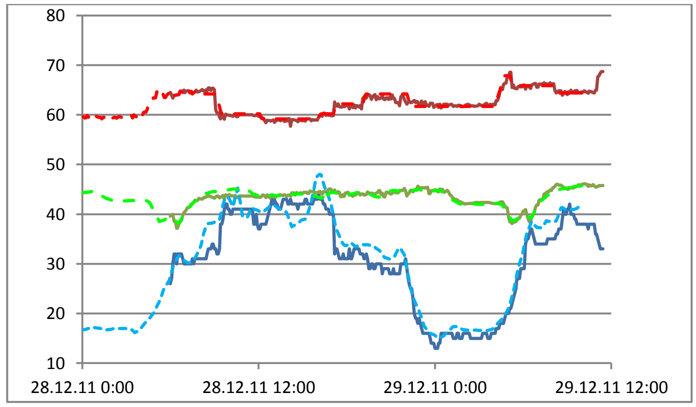

Fig. 15 Ideal course simulation

where:

G denotes the mass flow,
Tv denotes the input water temperature and
Tvv denotes temperature of the returned water

As can be seen in previous fig., the simulation model using ideal temperature forecast gives course with really good accordance to the real system response.

VI. Conclusion

Presented experiment shows proposed simulation model in practical use. The model was used for prediction of heating system behavior, also in the secondary distribution net. It's using proved that its ability to predict is sufficiently accurate. Also was shown, that the better outside temperature prediction can further improve the final results.

The temperature difference between observed values on consumer side and general forecast will be further studied and sought a suitable compensation procedure, which would be able properly prepare the data for the model.

The prediction mechanism seems to be well prepared, however the main task still remains - the task to propose control actions (in form of appropriate temperature of heating water). As an option to achieve better result, may be searching for the "intelligent compensation curves" which will reflect the time in day or more factors.

Complex system for secondary heat distribution must be able to find the optimum among all parameters to make quality heating for consumers but also for the best prices. Good prediction is however important starting point.

ACKNOWLEDGMENT

The work was performed with financial support of research project NPVII-2C06007, by the Ministry of Education of the Czech Republic and is also supported by the European Regional Development Fund under the Project CEBIA-Tech No. CZ.1.05/2.1.00/03.0089.

REFERENCES

[1] Balate, J. “Automatic Control”, 2nd edition, BEN - technical literature, ISBN 80-7300-148-9, Prague, 2004.
[2] Balate J., Chramcov B., Navratil P. ”Strategy evolution of control of extensive district heating systems”, Powereng 2007: International Conference on power engineering – energy and electrical drives proceedings, vols 1 & 2 Pages: 678-683 Published: 2007.
[3] Incropera, F. P.; DeWitt, D. P. & Bergman, T. L. “Introduction to Heat Transfer”, Wiley, ISBN: 978-0471457275, London, 2006.
[4] Chramcov B.” Identification of time series model of heat demand using Mathematica environment”. In Recent Researches in Automatic Control: Proceedings of 13th WSEAS Int. Conference on Automatic Control, Modelling& Simulation. Lanzarote: WSEAS Press, 2011. pp. 346-351. ISBN 978-1-61804-004-6.
[5] Vasek L., Dolinay V. “Simulation Model of Heat Distribution and Consumption in Municipal Heating Network”. International journal of mathematical models in applied sciences, <http://www.naun.org/journals/m3as/>. ISSN 1998-0140, 2010.
[6] Saarinen, Linn. “Modelling and control of a district heating system”. Uppsala, 2008. 67 s. Uppsala University. ISSN 1650-8300.
[7] Vasek L., Dolinay V. “Simulation Model of Heat Distribution and Consumption in Practical Use”. Proceedings of the 13th WSEAS International Conference on Automatic Control, Modeling and Simulation, Lanzarote, WSEAS Press 2011, pp. 321-324, ISBN 978-1-61804-004-6.
[8] Vasek L., Dolinay V., Kral E. “Methods for Prediction of Heat Distribution Parameters”. Mathematical Methods and Techniques in Engineering and Environmental Science, Catania, Sicily, Italy, WSEAS Press 2011, pp. 335-340, ISBN 978-1-61804-046-6.
[9] Varacha P., Jasek R. ANN Synthesis for an Agglomeration Heating Power Consumption Approximation. In Recent Researches in Automatic Control. Montreux : WSEAS Press, 2011, s. 239-244. ISBN 978-1-61804-004-6.
[10] Vargovcik L., Kvapil D. “Research report on project 2C06007”, UNIS Ltd. June 2010.