Analysis of models applied for modelling of adaptive control for thermal energy storage system. Part 2. Models of heat pump, borehole heat exchanger and phase change material tank

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Abstract: Analysis of models applied for modelling of adaptive control for thermal energy storage system. Part 2. Models of heat pump, borehole heat exchanger and phase change material tank. The most important problem in thermal systems is long-term accumulation of heat and cold. This problem can be solve by accumulation of heat and cold in phase change materials (PCM). To solve this problem the most important is to develop an adaptive control algorithm for each system component and the system as whole. The development of adaptive control algorithm is only possible over knowledge of static and dynamic properties of each system component under exploitation conditions. This paper presents review of heat pump, borehole heat exchanger and PCM tank models focused on possibilities for simulation and implementation of these models in typical controllers, that has been applied in solar thermal system control.

Key words: ground heat exchanger, heat exchanger, heat pump, storage tank, PCM material

INTRODUCTION

Thermal energy storage system for energy efficient buildings (TESSe2b) is an intelligent system enabling long-term storage of heat and cold in phase change materials (PCM). Hot in system is generated by geothermal heat pump which cooperated with ground heat exchanger and solar thermal collectors. Cold in system is generated by geothermal heat pump with work in reverse mode. To accumulate in long term hot and cold energy, the most important part of system is hot and cold storage tank with PCM material. Long term accumulation depend at a few conditions: hydraulic construction of installation, heat loses, size of each part of system, but the most important element is smart control system. Smart control algorithm should be based on the adaptive control algorithm. To develop adaptive control system necessary are models of each part of TESSe2b. Models should possible analysis static and dynamic behavior of TESS components and implementation this models on the controller should be possible. Aim of this paper is review of models of TESS and analysis them properties.

THE MODELS APPLIED FOR MODELING THE STORAGE TANKS

In the operation of solar heating system, the buffer storage tank is very important component (Kenjo et al. 2007, Fan and Furob 2012). Both, the process of energy accumulation and transient states in operation of the whole system depend largely on the size, geometry and construction of storage tank. The system of hydraulic
connections impacts the system control algorithm. Weather conditions in central and northern Europe are the cause of an incoherence between heat demand and the available resources of solar energy (Tymiński 2001). Therefore, the hydraulic construction of the tank not only must allow connecting to a solar heating system, but also to another energy source – a heat pump. In practice, the tanks with at least two independent internal coil exchangers are used, which allows simultaneous connection of the solar heating system and a conventional energy source (Recknagel et al. 2008, Han et al. 2009).

In solar heating systems, a high level of stratification is required that in the buffer storage tank co-operating with the solar installation. Then the solar heating system, connected to the coil exchanger placed at the bottom of the tank, runs at lower temperatures. This allows to achieve higher efficiency of the collectors (Hollands and Lighstone 1989). Therefore, in the literature there is a number of theoretical work on the modelling stratification in the tank, considering the tank one-dimensional (Yoo and Pak 1996, Alizadeh 1999, Nelson and Balakrishnan 1999), two-dimensional (Cai and Stewart 1993, Roberte 1998, Van Berkel and Rindt 2002), three-dimensional object (Yee and Lai 1999, Shan and Furbo 2003, Johannes and Fraisse 2005) as well as experimental work on the subject (Kenjo et al. 2007, Fan and Furbo 2012). Analytical models (AM) are based on differential equations derived from the energy balance and combine, among others, the tank design parameters: thermal conductivity of the heat exchanger, heat loss coefficient of the storage tank, volume and heat capacity of the tank (Han et al. 2009).

In practice, due to the requirements of users and the use of internal circulation, stratification in the DHW storage tank is negligible. A small stratification can occur only in the lower parts, which are not covered by the mixing of water in the tank due to internal circulation. Regardless of the fact whether there is stratification or the water in the tank is mixed and the temperature level is fixed, the energy balance of the tank is identical to (Tytko 2010).

**THE MODELS APPLIED FOR MODELLING THE PLATE HEAT EXCHANGERS**

Plate heat exchanger acts as a separator capable of exchanging heat between two different media. The thermal exchange process in the heat exchanger is very complex, and the thermal and hydraulic operation states of the heat exchanger in running time are strongly dependent on design parameters of the exchanger and the external parameters such as the supplied thermal power, efficiency, working medium flow resistance and the hydraulic system diameters (Gembarzhevskii 2007, Obstawski 2007, Qi et al. 2011).

There are several studies carried out in order to better understand the process of thermal exchange in the exchanger. They focus on: the impact of uneven working medium flow through the exchanger channels when the pressure of the working medium drops (Rao and Das 2004, Durmus et al. 2009), and the numerical simulations of the thermal ex-
change process with the use of IT tools (Fernandes et al. 2005, Kanaris et al. 2005, Tsai et al. 2009), including the flow visualization (Focke and Knibe 1986).

The intensity of the heat transfer process depends on the type of construction and design parameters of the heat exchanger, but mostly on the heat capacity and thermal conductivity of the heat exchanger (Roetzel and Luo 2010). Typically, the thermal conductivity is determined experimentally based on the modified Wilson’s method (Taler 2004). Research is being conducted towards the development of new methods enabling to determine the thermal conductivity of the heat exchanger in operating conditions (Ros et al. 1995, Freund and Kabalac 2010). Also numerous works are published on methods to allow optimization of the design to improve the thermal exchange process (Mazen and Abu-Khader 2012). These methods are mainly based on models created on the basis of the measurement data using artificial neural networks. Additionally they allow e.g.: to estimate the temperature of the working medium, to forecast the value of the heat loss coefficient (Rivierol and Napolitano 2005) and to develop the control algorithm of the thermal exchange process. The literature also presents models based on genetic algorithms (Peng and Ling 2008) and theoretical models developed on the basis of the energy balance (Dović et al. 2009). Moreover, innovative methods based on utilizing the properties of blocks called infinite regular polyhedra are applied to simulate the process of thermal exchange in the plate heat exchanger.

The simplest models of the plate heat exchanger (analytical models) based on differential equations of the thermal exchange process) enabling the analysis of thermal states, assume linearity of the thermal exchange process. They link together the operating parameters, regarded as specific parameters of the exchanger, i.e.: thermal capacity of the heating – \((mc)_{EW1}\) – and cooling – \((mc)_{EW2}\) – side of the heat exchanger, specific heat of the working medium on the heating and cooling side with the capacities of the circulation pumps (Selbas et al. 2009). Performance coefficient of the heat exchanger is introduced as an additional specific parameter (Duffie and Beckman 1991). These models are often based on the first order differential equation based on energy balance. It is assumed that the flow of the working medium inside the channels is even, the value of thermal exchange coefficient is constant, there is no heat loss and no thermal exchange in the direction of the working medium flow (Jorge et al. 2003). The solution of these differential equations is often approximated using a polynomial or exponential function (Setari and Venart 1972). For more advanced models, the system of differential equations is written in matrix form and for certain boundary conditions numerical problems may occur when determining a solution. Some analytical models omit the thermal conductivity of the heat exchanger rib or focus only on specific values of thermal conductivity coefficient assuming a small heat capacity of the ribs (Baguni and Chafouk 2006).

The amount of heat between the hot and cold side at a specific operating point the most important in the operation of the heat exchanger. The intensity of the heat transfer process depends on the dynamic
properties of the exchanger at a specific operating point and the applied control algorithm. It is therefore important to define the dynamic properties of the heat exchanger (Abdelghani-Idris et al. 2001). Typically, these analyses are performed by the analytical models which base on differential equations linking the design parameters. They allow determination of dynamic properties at the design stage (Adamski 2006). There are other methods based on the first order differential equations derived from the energy balance (Lachi et al. 1997). Laplace transform is often applied to solve the differential equation describing the transition state of the exchanger (Das and Murugesan 2000). The Model of the plate heat exchanger should allow the determination of the static and dynamic properties of the heat exchanger and to determine the impact of the efficiency of the primary and secondary circulation pump on the temperature rise. Such analysis is essential for the proper design of automatic control system providing intense thermal exchange in steady and transient states.

Determination of the dynamic properties of the heat exchanger becomes complicated, if performed in operating conditions, because in case of stochastic disturbances affecting the power flux on the heating and cooling side of the heat exchanger, as with solar heating systems, it is constantly in transient states. It should be noted that the operating parameters of the heat exchanger can change in transient transient, therefore the exchanger in operating conditions is a non-stationary object. This indicates that the operating parameters may be different than anticipated at the design stage. Therefore, it becomes necessary to develop a model of the plate heat exchanger in operating conditions. Such attempts undertaken in (Obstawski 2012). They only focused on determination of dynamic properties of the plate heat exchanger in operating conditions through the analysis of step response and amplitude-phase response and the impact of external functions on the nature of the transient state waveform, but for specified media velocity. The impact of circulation pumps efficiency was omitted and specific operating parameters of the heat exchanger were not determined. The method of parametric identification (PI) was applied to create the model.

In the process of identification the plate heat exchanger was treated as a dual input/dual output object (Fig. 1). Temperatures $T_1$ and $T_3$ were assumed as

![FIGURE 1. Schematic diagram of the DIDO heat exchanger and a corresponding block diagram Source: Obstawski (2007).](image-url)
input signals and temperatures $T_3$ and $T_4$ – the output signals. As a result of parametric identification the system of difference equations was obtained. The equations were then converted with Laplace transform into operational transmittance enabling the analysis of static and dynamic properties of the modelled heat exchanger in both, the time and frequency domains. Figure 2 shows the verification of the exchanger model by comparison of the actual temperature waveforms with simulated by the model. As shown in Figure 2 the exchanger model created based on actual measurement data using parametric identification (PI) captures the static and dynamic characteristics of the modelled exchanger very accurately.

FIGURE 2. Verification of the modelled plate heat exchanger
Source: Obstawski (2007).

**THE MODELS APPLIED FOR MODELLING THE GROUND HEAT EXCHANGERS**

Analytical models are based on systems of differential equations, relating to the energy balance of the heat exchanger and most often require the inclusion of certain simplifying assumptions that allow for a mathematical description of the phenomenon. These simplifications can cause discrepancies between the calculations and measurement results which is decides the quality of such modeling. The solution of the equations system is usually defined with the use of numerical
methods, e.g. the finite element method, through a discretization of the analysed area (Bernal-Augustin and Dufo-Lopez 2009).

An example of the analytical model of ground heat exchanger can be the study included by Bidarmaghz et al. (2013) and others in involved in modelling the heat exchanger rather to optimize the structure in terms of the dynamics of the work than in terms of automation. The design of ground heat exchangers (GHEs) involves the selection of detailed configuration options. However, there is limited understanding of the relative importance of different design choices on performance. This study investigates the effects of different design parameters such as pipe configuration and fluid flow rate on the heat extraction rate, and will be helpful to design a system which is energy efficient and cost effective. Different pipe configurations in vertical grouted boreholes including single U-pipe, double U-pipe, and double cross U-pipes for small diameter boreholes, and spiral and multiple U-pipes for larger diameter boreholes, are modelled in detail using state-of-the-art finite element methods. The effects of GHE configurations and fluid flow rate on system efficiency is determined and contrasted. Numerical results indicate that the thermal performance of the system is enhanced by transitioning from laminar to turbulent regime, and by increasing the volume of carrier fluid inside the pipes for a given GHE length (i.e. single versus double pipes). However, in larger diameter boreholes, GHE’s thermal performance does not change significantly for different pipe configurations with similar pipe lengths inside the borehole (i.e. spiral versus multiple U-pipes). A model of GHEs was developed from first principles, accounting for fluid flow and heat transfer through the various components of the GHE. The model represents GHEs that consist of grouted boreholes placed vertically in the ground, with water circulating within the pipes of these GHEs. Details of these models follow in Figures 3, 4, 5.

![Figure 3](image_url)

**FIGURE 3.** Ground heat exchangers pipe configurations: a – single U-pipe, b – double cross U-pipe, c – double U-pipe

Source: Bidarmaghz et al. (2013).
Thermal non-steady processes in the ground heat exchanger system of heat pump are analysed by Hanuszkiewicz-Drapała (2009). The two-dimensional numerical model of the horizontal and U-tube vertical heat exchanger presented. The model takes into consideration characteristic of intermediate medium circulating pump and characteristic of flow system of this medium. The model allows the analysis of the hydraulic resistances influence on ground heat exchanger functioning. Heat flux taken from ground, the increase in the intermediate medium temperature and temperature of the field in the ground adjacent to the heat exchanger pipes are the main results of calculations. Exemplary results for both ground heat exchangers are also presented and analysed.

Good results in the modelling of ground heat exchanger can be obtained using the method of parametric identification. The following models were used in the process of identification of ground heat exchanger (U-pipe, length – 2 × 180 m, depth – 30 m): AMX (Auto Regressive Moving Average with Exogenous Input), OE (Output Error) and process model P1DZ. Figure 6 compares the actual waveform of the working factor heating to the simulations with the use of these models. The result of the comparison was a good correlation was between the simulated and actual outlet temperature of the ground heat exchanger working medium.

To model the ground heat exchanger operation allowing the analysis of its static and dynamic properties one can also apply the ETN method. Using analog method of equivalent thermal network (ETN) a physical model of ground heat exchanger can build with the use of wiring diagram. Figure 7 shows the basic physical model of the heat exchanger, which of course can be expanded according to its size (e.g. the number of drill-
ings). Three homogeneous components are distinguished in the construction of the heat exchanger:

- borehole filling, assigned with diagram node 1, of average temperature $T_1$, and which incorporates all the physical properties including its thermal capacity $C_1$;
- exchanger tube, assigned with the diagram node 2, of average temperature $T_2$, and which incorporates all the physical properties including its thermal capacity $C_2$;
- working medium, assigned with the diagram node 3, of average temperature $T_3$, and which incorporates all the physical properties including its thermal capacity $C_3$;

In physical sense, the thermal resistances presented in the diagram are:

- $R_{gr}$ – equivalent thermal resistance of the ground with temperature of $T_{gr}$;
- $R$ – thermal resistance of the borehole filling;
- $R_p$ – the thermal resistance of the conduction through the exchanger pipe wall;
- $R_{w}$ – thermal resistance of the heat transfer from the inner wall pipe of the heat exchanger to working medium;
- $R_f$ – thermal resistance associated with heating of the working medium.

Using the diagram in Figure 7 one can determine the operational transmittance of the exchanger based on the theory of electrical circuits. Its character is compatible with the ones described above, obtained in discrete. However, its advantage is that it can be used to study the impact of design and operating parameters on the dynamics of the heat exchanger (as in the solar collector).

The exchanger modelling with the use of artificial neural networks (ANN) is also described in the literature. Diaz creates neural models of the exchanger for the prediction of output signals and applies them in the control systems (Diaz 2000).
MODELS APPLIED FOR MODELLING THE HEAT PUMPS

The heat pump is a heating device that allows changing the temperature level of the refrigerant from low to high with the use of additional source of energy (in compressor heat pump – electric energy). This means that the heat pump using thermodynamic medium undergoing phase changes as a working medium enables the change of the low temperature level heat source to a higher temperature level of the receiver. The COP coefficient determined normatively was assumed as a quality parameter that allows the comparison of heat pumps supplied by different manufacturers. Seasonal SCOP coefficient was assumed as a parameter characterizing the heat pump operating in a particular installation. Modelling of the heat pump operation successfully utilizes analytical models based on the properties of the thermodynamic medium used in the heat pump (its physical parameters are shown in the $p$–$h$ graph) and the parametric models (PI) generated by the parametric identification as well as the models in the form of artificial neural networks (ANN).

These models allow the calculation of both the COP, SCOP coefficients and temperature level of the thermodynamic medium powering the condenser of the heat pump at a specific temperature of the ground heat source. The analytical models usually require the use of complex mathematical apparatus and thorough theoretical and practical knowledge. On the other hand, creating a model of the heat pump in the form of neural network requires a large operating database, which significantly complicates the process of modelling. However, by observing certain regularities in the work of a compression heat pump, the modelling process can be greatly simplified through narrowing down to the simplest models.

ADVANTAGES AND DISADVANTAGES OF APPLIED MODELS

The models most commonly used for modelling static and dynamic properties of individual TESSe2b are the follow-
ing: analytical (AM) based on the laws of physics, numerical which include parametric models (IP) and artificial neural networks (ANN), and thermoelectric analogy based models in the form of equivalent thermal network (ETN). Each models have advantages, disadvantages and limitations.

Analytical models in the form of an equation or system of linear differential/difference equations based on the laws of physics allow you to create a model of all key TESSe2b components, namely: solar collector, buffer tanks, ground heat exchanger, heat pump and plate heat exchanger. Disadvantages, advantages and limitations of analytical models are presented in the following table.

The main advantages of analytical models include the capability to perform the analysis of the static and dynamic characteristics of the TESSe2b modelled components. In case of distributed-parameter analytical models it is also possible to perform the analysis of the thermal exchange process between homogeneous elements of the modelled component, taken into account in the model. The advantage of analytical models is also possibility of steady and transient state analysis and the implementation in certain types of controllers e.g.: microcircuits and PLCs. The main disadvantages of analytical models based on the laws of physics include the necessity to calculate the parameter values of the difference equation(s) coefficients, which is difficult to carry out in operating conditions. Moreover, the model of a given component is in the form of differential equation or a system of differential equations, which enables modelling in entire range of changes in input and output signals, yet only for linear objects or systems. In case of non-linear or non-stationary objects or systems the linearization around specific operating point is required, which is a significant limitation of this type of models.

Parametric models (PI) developed as a result of parametric identification – as well as analytical models – allow to create models of individual key components of the TESSe2b. Parametric models can be divided into two groups: linear models and non-linear models, which should be considered one the advantages of this model group. Linear models developed in the parametric identification process can be in the form of difference equations, state variables, operational transmittance and polynomials. Non-linear models are in the form of a non-linear autoregressive functions.

The main advantages of linear parametric models include the capability of the analysis of static and dynamic properties of the modelled object or system, the analysis of steady and transient states and the possibility of implementation in certain types of hardware, e.g.: microcircuits and PLCs. The main disadvantages include the possibility of modelling in the entire range of variability of input and output signals of the linear static characteristics. In case of modelling the object of non-linear static characteristics, the linearization around the selected operating point is necessary, which restricts the use of such models. Certain limitation of this type of models is the modelling of non-stationary objects or systems.

The main advantage of applying the non-linear parametric models is the possibility of modelling over the full range of variability of input and output signals.
for the objects of linear and non-linear static characteristics as well as for stationary and non-stationary objects. The main disadvantage and at the same time the limitation of this type of models are limited possibilities of hardware implementations.

The main disadvantages and at the same time the advantages of both linear and non-linear parametric models include the requirement of having the operating data available in the form of time series, and that it is impossible to analyze the thermal exchange process in case of modelling distributed-parameter objects or systems.

Artificial neural networks – as the two previous groups of discussed models – are applied to model all the major components of the TESSe2b. The main advantages include the capability to model stationary and non-stationary objects and systems of linear or non-linear static characteristics. The models in the form of artificial neural networks also allow the analysis of steady and transient states. The main disadvantages of this type of models include a very large amount of operating data in the form of time series required to develop the model and the incapability to analyse the process of heat exchange between different homogeneous components when modelling distributed-parameter objects. Impossibility or limited possibility of hardware implementation should be considered the main limitation.

Equivalent thermal networks belong to the group of analytical models based on the thermoelectric analogy and utilizing the Beuken’s model. These models are used to model the key TESSe2b components except compressor heat pumps. The main advantages – as in case of the analytical models (AM) – include capability to perform the analysis of static and dynamic properties of the modelled object or system and the analysis of the steady and transient state. For modelling of the distributed-parameter objects or systems, these models also allow the analysis of the thermal exchange process between homogeneous components included in thermal network. The advantages of this group of models include the possibility to implement in certain types of controllers, e.g. PLCs and MCs. The main disadvantages of ETN models include the necessity to calculate the values of individual thermal network components and the possibility of modelling in the entire range of changes in input and output signals, yet only for objects of linear static characteristics. In case of modelling non-linear objects or systems linearization around the operating point is necessary, which should be considered a limitation.

The main disadvantages, advantages and limitations of different types of models applied to model the key TESSe2b components are shown in the table. It should be noted that any type of model does not fully meet the set requirements. The best solution would be to develop a model capable of modelling the key TESSe2b components, which would combine the properties of an analytical (AM) and parametric (PI) model.

**CONCLUSIONS**

In this paper has been done review of most often used models for modelling of some particular components (heat
pump, borehole heat exchanger and tank) of thermal system with possibility of long-term accumulation of heat and cold. Models have been divided into four groups, advantages and disadvantages of each group of models were described. Possibilities for simulation and implementation over exploitation conditions of these models in typical controllers were listed. Based on presented analysis, the most appropriate group of models for implementation in adaptive controller are analytical models.

| Model | Used in analysis of | Data measured in | Implementation into controllers | Disadvantages / Restrictions |
|-------|---------------------|------------------|--------------------------------|-----------------------------|
|       | Static properties   | Dynamic properties | Heat exchange process | Steady state | Transient state | Laboratory condition | Exploitation condition | PLC, IPC, PAC, MC |
| AM    | x                   | x                | x                             | x | x               | x                  | x                    | calculation values of parameters of differential equation is needed |
|       |                     |                  |                               |               |                 |                    |                      | in case modeling object with nonlinear static characteristic, linearisation around of point of work is needed |
| ANN   | X                   | X                | –                             | X | X               | –                  | X                    | many empirical data is needed |
|       |                     |                  |                               |               |                 |                    |                      | implementation in controllers is very difficult – possible only in IPC |
| PI    | L                   | X                | X                             | – | X               | –                  | X                    | calculation values of parameters of differential equation |
|       |                     |                  |                               |               |                 |                    |                      | in case of object modeling with nonlinear static characteristic, linearisation around of point of work is needed |
|       |                     |                  |                               |               |                 |                    |                      | many measurement data is needed |
| NL    | X                   | X                | –                             | X | X               | –                  | X                    | – |
|       |                     |                  |                               |               |                 |                    |                      | it is not possible to implementation in controllers |
|       |                     |                  |                               |               |                 |                    |                      | many empirical data is needed |
| ETN   | X                   | X                | X                             | X | X               | X                  | X                    | – |
|       |                     |                  |                               |               |                 |                    |                      | calculation values of parameters of differential equation is needed |
|       |                     |                  |                               |               |                 |                    |                      | in case modeling object with nonlinear static characteristic, linearisation around of point of work is needed |
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