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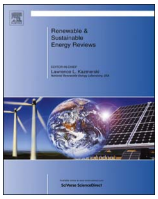

Models for fast modelling of district heating and cooling networks

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ABSTRACT

Within the framework of AMBASSADOR, a collaborative project funded by European Commission under FP7, a Modelica® library for the modelling of thermal-energy transport in district heating systems has been developed. This library comprises detailed models of the distribution and consumption components commonly found in district heating systems. In this paper, the detailed models are discussed, along with their validation against Apros® and IDA-ICE® Software. The results show that, although most of the models perform similarly, they do not equally reproduce the dynamics. Some of the limitations detected from the simulation results are currently being solved in new developments within the EU-funded INDIGO project.

Furthermore, with the aim of avoiding problems derived from the simulation of large models, the methodology for developing reduced mathematical models, implemented in Simulink®, is also presented in this research work. This methodology includes identifying the relevant model dynamics. During the procedure, additional information about the models can be obtained. For instance, the mass flow rate and the temperature can be assumed to be decoupled, without losing accuracy in the case of the distribution pipe model.

1. Introduction

Modelling of district heating (DH) networks tends to be computationally intensive, especially in the simulation of large DH systems. Larsen et al. [1] presented a method in which a fully described model of a DH network was replaced by a simplified one, in order to reduce the simulation time. Two methods of simplifying model representations of DH networks were discussed in [2]. These simplifications addressed the transient temperatures in DH networks, but their ultimate aim was the subsequent calculation of the operational costs of running DH systems [2]. A contribution to increasing numerical efficiency for simulation of complex pipeline networks was presented in [3] and [4], aimed at optimising operational regimes of DH systems. Based on a loop model of the network, and the square roots method for solving a system of linear equations, the numerical simulation of a DH system, focused on thermal and hydraulic transient regimes, is discussed in [5], with particular emphasis on temperature waves combined with temperature fluctuations. However, considerable differences were observed between the results obtained during large- and sudden- flow rate variations, and relatively small- and slow- temperature increases. Comparison against measured data from actual DH systems, also showed deviations from the simulated results during periods with low velocities.

A relatively new software discussed in [6], attempts to overcome limitations of previous models by using a specialised algorithm. This was done to study the main characteristics of the DH network using graphic visualisation of numerical simulations.

In the near future, as energy consumption in buildings is expected to decrease due to improving energy efficiency measures, heat losses in DH networks will also need to be reduced. Thus, methods, such as reported in [7] to simulate heat transfer between water and the surroundings through pipes become even more relevant. In addition, a viable option is to reduce the supply temperature of DH as much as possible, which requires reviewing and improving existing DH networks, including the connections to substations and domestic hot water supply systems. Solutions, based on the preceding numerical simulations of low temperature DH, are already being demonstrated and implemented [8].

One of the primary interests when modelling DH networks, is the simulation of the rate of energy transport through the system. This transport is not only dependent on the mass flow rate of the water flowing through the system, but also on the temperature level in the DH network. The flow, which is driven by pressure differences within the network, is responsible for most of the energy transport. For

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Abbreviations: DH, District Heating; DSP, District Simulation Platform; MISO, Multiple Input Simple Output; MPC, Model Predictive Control; MSL, Modelica® Standard Library; TES, Thermal Energy Storage

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example, the so-called steady state physical pipe model [9] was used for simulating variable flows in DH networks. The study showed that the model is considerably faster than the transient model, but is highly sensitive to the variation of the time step size in simulations. [10] shows that there is an important difference between flow and temperature dynamics. Changes in the flow are quickly transferred to the whole network as pressure waves, typically in seconds. On the other hand, the temperature is related to the mass of water in the system; consequently, effects from changes in temperature within the DH network are transferred relatively slowly. Based on this, dynamic models can be classified in two groups. The first group is represented by the fully dynamic models, where both the temperature and the flow are simulated dynamically, i.e. heat transfer and hydraulic phenomena are dynamic variables. The second group comprises the pseudo dynamic models, where only the heat transfer phenomenon is simulated dynamically.

Some of the features of DH systems are also valid in district cooling. A dynamic thermo-hydraulic model for district cooling networks is presented in [11]. The network model comprises a quasi-static hydraulic model, and a transient thermal model, based on tracking water segments through the whole network.

Since district energy systems may have storage facilities, the most relevant modelling methods in this regard are presented in [12]. The authors compared the methods with respect to computational limitations, level of precision, as well as the degree of certainty in the output level.

It can be summarised, that, in terms of simulation, a reasonable compromise between the level of considered detail and calculation effort is necessary for practical applications of DH modelling. Where the simplifications can be employed and greater accuracy is required, greatly depends on the ultimate purpose of the approach at hand.

During the AMBASSADOR project [13], a dedicated tool, District Simulation Platform (DSP), was developed with the aim of conducting simulations of complex DH systems, including real-time control and optimization [14]. For this reason, models able to reproduce both fast and slow dynamics correctly (e.g. local loop control and district heating network energy storage, respectively), sufficiently detailed to allow application of advanced control based on Model Predictive Control (MPC), but simple enough to be used in real-time applications, are needed. From reviewed literature [1–12], other existing models do not meet these requirements; therefore, specific models of the subsystems usually found in a DH network were developed. To make it possible with a reasonable effort, and to assure access to the source code for swift modifications, detailed models of mentioned subsystems were first created using Modelica®. After validating them against other existing sophisticated software, detailed models are simplified and reduced models are derived for inclusion in the abovementioned DSP. This paper presents this, for a number of specific elements of a DH system (distribution network, and thermal energy storage (TES)).

Further development, tuning and implementation for applying the modelling approach to district cooling are taking place within the INDIGO project, an EU-funded project that aims to develop a more efficient, intelligent and economical generation of district cooling systems by improving system planning, control, and management [15].

2. Detailed models

The detailed models developed in Modelica® [16] are described in this section. The models can be used for simulating the operation of networks and storage of DH systems, and offer a reasonable degree of accuracy to assist in deriving smart control decisions.

These models are compared with the equivalent models developed in Apros® [17] (distribution) and IDA-ICE® [18] software (storage).

2.1. Hot water storage detailed model

The storage tank at the test site comprises a cylindrical container for water storage, and an immersed coil through which the water flows from the DH system. Cold water is pumped into the container, and, after being heated, is extracted for use as domestic hot water. In addition, the tank has an immersed electrical heater as a backup if the DH system is not able to meet the demand.

In the hot water storage model developed in Modelica®, three subsystems are considered: (i) a hot water storage containing domestic hot water, (ii) an immersed coil, and (iii) an immersed electrical heater. All subsystems are thermally linked but are implemented independently. Moreover, as suggested by some authors, the water in the tank is assumed to be fully mixed during the heat exchange [19,20]. In general, the modelling strategy described in [21] is followed. However, for the natural convection between the immersed coil and water in the tank, the well-known Churchill and Chu [22] correlation is implemented. For the modelling of forced convection inside the coil, the correlation of Sieder-Tate and Gnielinski [22] has been used, dependent on the flow type (laminar or turbulent).

The hot water storage model developed in Apros® also considers the hot water inside the tank as a single volume, with the coil submerged inside. The model is built using components from the Apros® library, and a tank component (HEAT_TANK) and coil model (consisting of several HEAT_PIPES) constitute the model. In addition, a heat node (modelling a point of consumption) and several point- and pipe-components are used for connecting the components, and as a method for defining pressure levels for the storage tank. In order to stabilise the pressure in the tank, a pressure level correction point is needed. Heat losses into the environment are also considered.

2.2. District heating network detailed model

The base model for the network representation is the distribution pipe model, and the network model is constructed as a succession of spliced distribution pipe models.

At the AMBASSADOR test site, the insulated pipes are made of either plastic or metal; and are buried (singly or with other pipes) or open to the elements. A detailed pipe model has been developed for each type of pipe.

The distribution pipe models in Modelica® are based on the Modelica® Standard Library (MSL). These models describe the hydraulic and thermal behaviour of pipes, which makes it suitable for modelling pipes with one or more solid layers. In the case of buried pipe, an additional sub-model considering heat exchange with the surrounding soil and pipes is added to the general insulated pipe model. The models are described in detail in [23].

The detailed pipe models developed in Apros® are also specific for the test site, and comprise mainly Apros® Library components, such as HEAT_PIPE and HEAT_STRUCTURE. In these models, the heat storage capacity within the pipe material is taken into account, as well as the thermal losses to the outside. In addition, in the case of buried pipe model, the surrounding soil and the thermal interaction with nearby pipes are also considered.

2.3. Validation of detailed models

The Modelica® hot water storage model is validated against IDA-ICE® software results, and the distribution pipe and network detailed models are validated against the Apros® software results.

2.3.1. Hot water storage model

The changing of the water temperature inside the tank is compared with the Apros® model, and the IDA simulation results (using the 1-dimensional storage tank model in IDA-ICE® 4.5 software [18]). In the IDA model, the tank is divided into ten layers, in order for the