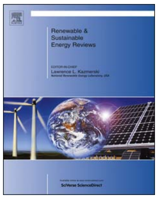
ARTICLE IN PRESS

Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Models for fast modelling of district heating and cooling networks

Itzal del Hoyo Arce[a,*], Saioa Herrero López[a], Susana López Perez[a], Miika Rämä[b], Krzysztof Klobut[b], Jesus A. Febres[a]

[a] IK4-TEKNIKER, Calle Iñaki Goenaga 5, Eibar 20600, Spain
[b] VTT Technical Research Centre of Finland, Espoo 020400, Finland

ARTICLE INFO

Keywords:
District heating modelling
Detailed physical model
Reduced model
Modelica®
Apros®
IDA-ICE®

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

---

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

[*] Corresponding author.

E-mail address: Itzal.delhoyo@tekniker.es (I. del Hoyo Arce).

http://dx.doi.org/10.1016/j.rser.2017.06.109
Received 31 January 2017; Received in revised form 23 June 2017; Accepted 24 June 2017

Please cite this article as: Hoyo Arce, I.d., Renewable and Sustainable Energy Reviews (2017), http://dx.doi.org/10.1016/j.rser.2017.06.109

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

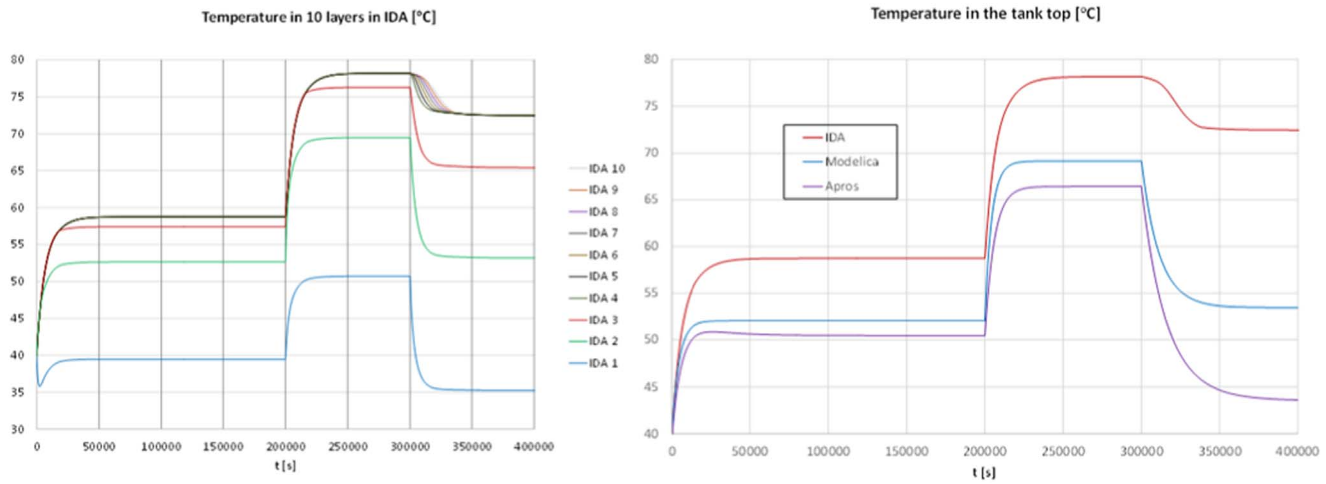


Fig. 1. Temperatures of the 10 layers in IDA (left). Temperatures in the tank top (IDA) and in the single volume tank (Apros and Modelica®) (right).

stratification phenomena to be simulated. In the model, the heating coil is located in the fourth layer starting from the bottom.

The importance of understanding temperature stratification in vertical water storage tanks was reported in [24]. As the authors stated, “it is commonly accepted that if an immersed coil is placed at the bottom of a thermal storage filled with fluid, it will promote mixing of the portion in the storage volume above the heat exchanger”. This finding is also verified in this work. In a situation where stratification takes place (Fig. 1 left-hand side), differences between the model predictions can be observed (Fig. 1 right-hand side).

It can be seen that, when there is no domestic hot water consumption, the temperature stratification gradually diminishes and almost-complete mixing takes place. However, these findings were only verified for a 1-dimensional tank model.

2.3.2. Distribution pipe model

The validation of steady state behaviour of this model is done using manufacturer's data. Heat loss results show errors less than 5%.

The dynamic validation is performed against the Apros® model due to lack of real data, using a 100 m insulated pipe. For the validation process, three different cases (found in the test site) are considered:

1. Case I: plastic pipe with insulation, buried with another insulated pipe with the same characteristics (supply and return pipes);
2. Case II: plastic single pipe open to the elements; and
3. Case III: metallic pipe with insulation open to the elements.

Simulations with identical conditions were run on both the Modelica® and Apros® models. The water outlet temperature, temperature of all the layers of the insulated pipe at different positions and heat losses are compared in Fig. 2:

The comparison of the thermal variables between Apros® and Modelica® is shown in Fig. 2. The differences seen in the results could have been caused by the modelling approaches and assumptions made:

1. No axial discretization exists in the solid structure of Apros® model, while the discretization in Modelica® model is the same for both solid and fluid parts (Fig. 3)

2. In the case of buried pipes, the Modelica®-based model takes soil into consideration by adding appropriate heat resistance in thermal calculations, while the Apros® model has heat structures for soil between, and surrounding, the pipes. The total thickness of this soil layer is defined to match the heat resistance used in the Modelica® model. The soil thickness between the pipes is defined by the set distance between the supply and return pipes, and the rest is assumed to be surrounding both pipes.
3. Nodes where temperature values are recorded in both models are slightly different due to the discretization methods.

2.3.3. Distribution network model

For the validation of the distribution network model, the AMBASSADOR test site network was modelled with a combination of both metal and plastic insulated pipes (buried or open to the ambient) arranged in eight branches (terraces) with 16 consumers each, as shown in Fig. 4.

For the simulation of the network, in addition to the distribution pipe model, the following auxiliary models are included:

- In the Modelica® model:
  - a. A pump model, based on the head and efficiency curves of the pump in the site;
  - b. An ideal heat generation model, maintaining a constant supply temperature of 80 °C; and
  - c. The individual consumers in each terrace are combined as a unique larger consumer. As a result, the network model includes just eight (big) consumers in the network. Each consumer is modelled considering; on the one hand, an instantaneous heat release for modelling the heat consumption of the terrace; and on the other hand, a balancing valve with two main objectives: (i) balancing the flow along the network, and (ii) regulating the flow in the terrace depending on the number of individual consumers connected to the network.

- The auxiliary models for Apros® model are described in Table 1

For the validation, two different scenarios are analysed, as presented in Table 2. In the first case, the disconnection of some of the users (on different terraces) is done simultaneously. In this way, the whole system is disturbed at a specific moment at different points in the system. In the second case, the disconnection of the users (on different terraces) is done at different times.

The differences in the temperature are insignificant, however, the delay time in the response to temperature changes seen in Fig. 5, shows larger differences. In the Modelica® model, the temperatures require 24 s to reach steady state, while Apros® model needs 64 s. These differences can also be seen in case II data (Table 3), the real delay time due to heat transport when a change is applied, is 72 s for the first change, 70 s for the second change, and 72 s for the last one (Fig. 6)

Several simulations show that there are two phenomena in thermo-hydraulic models, which produce a delay or advance in the response to a change in temperature. On the one hand, there is the numerical error

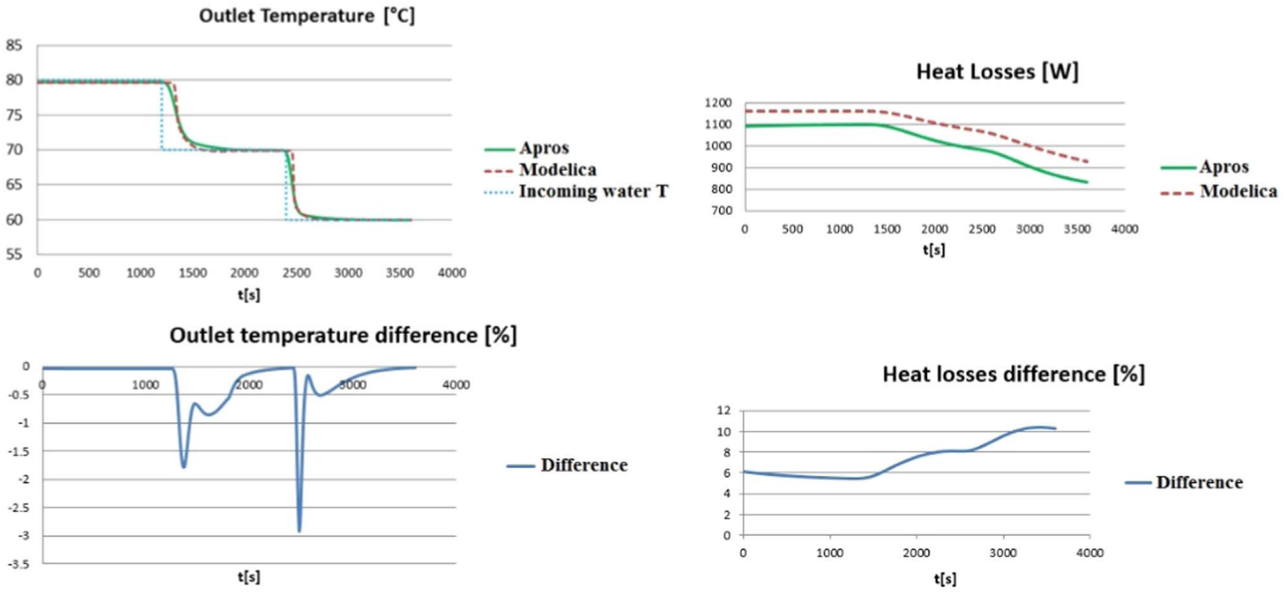


Fig. 2. For Case I: Outlet temperature of water (top-left) and heat losses in both models (top-right). The difference between the results is shown in the lower figures.

during calculation. The tolerance of the simulation is an important parameter to be chosen before running any simulation. If the tolerance is not sufficiently small, it is possible to obtain incorrect simulation results due to numerical errors. On the other hand, there is artificial diffusion introduced by the numerical integrators used in most simulation software, which results in a higher diffusivity than in a real case.

2.4. Avoiding the artificial diffusion. Development of new pipe model

One of the main issues encountered when using numerical schemes to solve differential equations is the introduction of artificial (also called numerical) diffusion. The problem becomes particularly noticeable in computer simulations of continua (such as fluids) based on the upwind-difference scheme, wherein the simulated medium exhibits a higher diffusivity (the ability regarding transport phenomena, heat transport, mass transport or momentum transport, amongst others) than the true medium [25].

One way of minimising artificial diffusion is to increase the degree of geometrical discretisation of the element under study, the pipe in this case. However, in simulations of district heating and cooling systems where pipes are usually too long compared to the distance travelled by the fluid during the simulation time step, this solution becomes non-feasible as a high degree of discretization leads to a number of equations unmanageable for most of the simulation software and hardware. Furthermore, to keep the numerical algorithm stable, the time step has to obey the Courant-Friedrichs-Lewy condition [26], where the time step must be reduced, which increases the computational cost of the simulation, and not all simulation solvers allow the user to manipulate the time step.

[27] proposed a Modelica® model of the pipe in which the energy balance equation is derived according to the method of characteristics [28]. Following this method, and without taking into account the heat capacity of the tube material, the partial differential equation becomes an ordinary differential equation, natively integrated by any implementation of Modelica®. The outlet temperature obtained from this integration is then modified to account for the heat stored in the tube material by assuming that the heat capacity of the whole tube is concentrated at the outlet of the pipe and that the fluid and tube are at the same temperature [29]. This approach speeds up the simulations, and noticeably reduces artificial diffusion. However, due to a later assumption, there is still a considerable error in the calculation of the heat losses, which becomes more relevant in simulations of district cooling.

A new model is being developed in the INDIGO project. One of the main outcomes of the project is a Modelica® library with all the components typically found in a district cooling system, including a detailed model of the piping system. The pipe model is based on the Type31 model of TRNSYS. Based on the plug-flow approach, the Type31 model represents the thermal behaviour of a fluid flowing through a pipe using variable size segments of the fluid. Entering fluid shifts the position of existing segments and the mass of the entering segments is calculated by multiplying the mass flow rate by the simulation time step. The incoming fluid temperature defines the temperature of the new segment. Finally, the outlet temperature is the mass-weighted average of the segments that are ejected by the inlet flow [30].

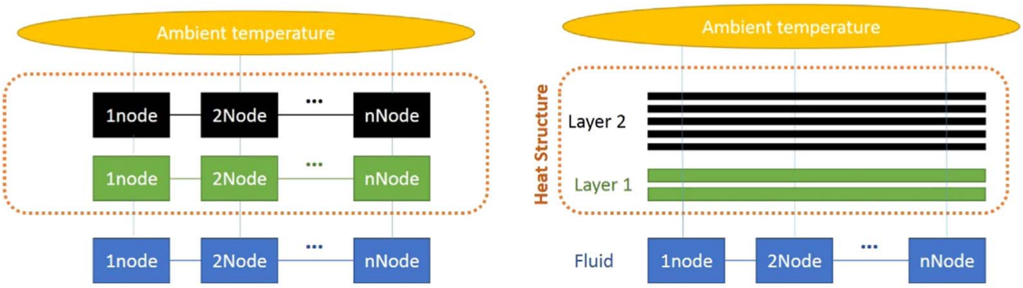


Fig. 3. Discretization approach in both models. Modelica® model (left) has implemented fluid and solid structures divided in the axial direction. The Apros® model (right)divides the fluid in the axial direction, but the solid structure of the pipe in the radial direction.

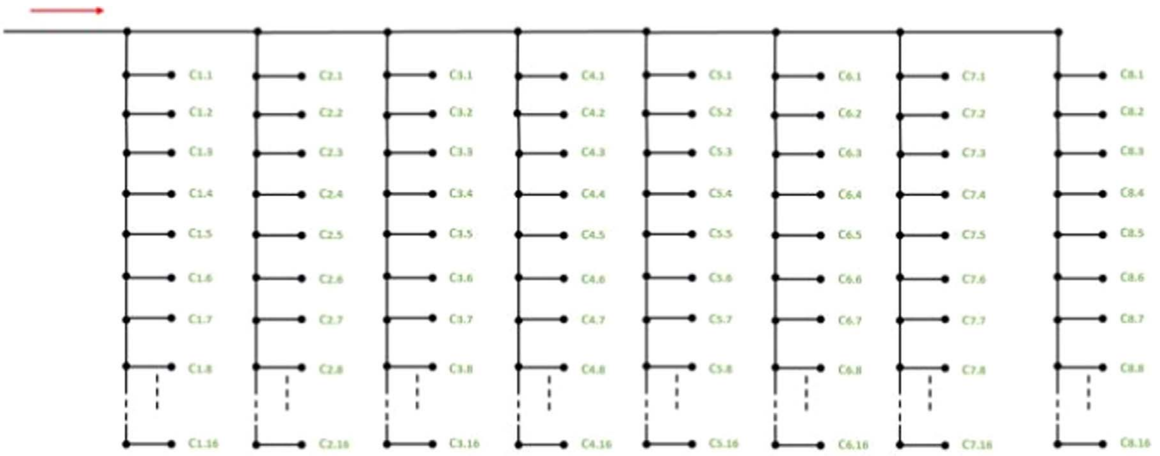


Fig. 4. DH Distribution network and Consumers Scheme (one line representation).

The TRANSYS model of the pipe has limitations, due to some of its inherent assumption. First, the energy-losses equation uses a constant overall loss conductance, which does not include the convective effect, or the heat capacity of the pipe material. Secondly, the external temperature along the entire pipe is the same, i.e. no external temperature profile may be input into the model. These assumptions make the model unsuitable for some applications, as in the case of the INDIGO approach.

The INDIGO project is proposing a global control system to be implemented at network level. The proposed global controller is based on model predictive control, and takes into account the dynamics of the piping system to take advantage of the energy the pipe may store and the response delay due to long pipes. Thus, the approach requires a detailed model that considers the dynamics of the pipe in detail, and all its inputs may be geometrically discretised along their length. As mentioned above, the TRANSYS model does not satisfy these requirements. For this reason, the INDIGO pipe model, although based on the flow-plug concept of the TRNSYS model, introduced the following modifications:

1. External temperature profile: the new model allows inputting an external temperature profile which matches the geometrical discretisation of the tube.
2. Fixed size of segments: since Modelica® allows the use of simulation events, each new segment is pulled in only when it has the size defined by a parameter of the model. This feature eases the matching of the discretisation of the pipe and the corresponding external temperature profile.
3. Convective heat transfer coefficient: the heat transfer model used by the new pipe model takes into account the convective effect.
4. Heat capacity of the pipe: the new model includes the influence of the thermal capacity of the pipe material and not just the thermal conductance effect.

As this is not the scope of this publication and due to space limitations, results regarding the INDIGO pipe model development are not detailed here and will be left for a future publication.

3. Distribution network reduced model

The DH network detailed model (comprising dozens of distribution pipe models) cannot be directly included in the DSP, not only because of the computational costs, but because, within the DSP, there are dozens of other models that must run simultaneously. For this reason, a reduced model for distribution, implemented in Simulink®, is needed. The resulting model requires less computing time, and considers the most relevant system dynamics with a simulation time step 5–15 min established by the DSP.

As described above, the distribution reduced model corresponds to a DH system with eight terraces, with 16 domestic users each (Fig. 4), and is aimed at obtaining the value of the following variables at each time step:

- Mass flow rate calculation: value of the mass flow rate supplied to each consumer.
- Temperature calculation: value of the fluid temperature supplied to each consumer, and the resulting return temperature to the generation.

3.1. General assumptions for the reduction process

1. Three different types of pipes are found in the system (types A, B, C). For each pipe type the geometry, materials, length range, and mass flow rate range (calculated based on the coincidence factor concept [31]) are established according to test site scenario.
2. The operational range is also established for the rest of system variables: supply/inlet temperature [40–100 °C], and ground temperature [5–10 °C].
3. The dynamics of the heat transfer phenomenon is considered, neglecting the flow dynamics (resulting in pseudo-dynamic models). Thus, it is assumed that mass flow rate variations are transmitted through the network instantaneously [32].

Table 1
Production and consumption models in DH network mode developed in Apros®.

	Production point model	Consumption point model
Subcomponents	● A heat node, for heating the water flow to a defined temperature ● A pump, to maintain a defined pressure difference between the measured points ● A controller ● An actuator	● Control valve. The position of the valve component is set to maintain a certain mass flow through the heat node. ● A heat node, to model heat demand by defining a heat flow out of the node component and cooling the flowing water.

Table 2
Cases used in the validation process.

	Start	Change
Case I	All users are connected to the network	At t = 10 min, disconnect from the network: 2 users in the first terrace, 3 users in the fourth terrace and 1 user in the last terrace
Case II	All users are connected to the network	Disconnect from the network in different moments: 2 users in the first terrace (t = 5 min), 3 users in the fourth terrace (t = 10 min) and 1 user in the last terrace (t = 15 min)

4. A quasi-dynamic condition between flow and temperature is assumed [1,32]. This implies that the flow can be computed independently from the temperature distribution, and the temperature is computed by assuming constant flow in the whole network.
5. The fluid is assumed to be incompressible and temperature independent (with physical properties values established at an average operation temperature).

3.2. Mass flow rate calculation

According to the abovementioned assumptions, as variations in the mass flow are transmitted instantaneously along the network, the resulting calculation is static.

Based on pressure drop tests carried out with detailed models, some additional simplifications are included:

1. In the main distribution, only pressure drop due to pipe friction is considered
2. The main pressure loss in the rest of the network is due to the balancing valves at terraces and users level (neglecting bends, pipes and immersed coils in individual consumers' storages).

The pressure loss in the elements under consideration is assumed proportional to the squared mass flow rate, and the proportional parameter K (obtained via detailed models), is taken as invariant with operating conditions: $\Delta P_i = K_i \cdot Q_i^2$. Once K_i values are obtained for each section of the network, the equivalent network model is generated considering the connection between sections (Fig. 4):

The expression of the total pressure loss in the network is obtained by applying, step by step, the aforementioned rule (Table 4): $\Delta P_{loss} = f(K_i)$.

Table 3
Time delay due to heat transport (CASE II).

Time delay	Real	Apros® model	Modelica® model
1st change	72	71	19
2nd change	70	65	24
3rd change	72	69	19

From this expression, the total mass flow rate is calculated by matching the pressure loss expression to the pump curve. Finally, the individual mass flow rates for each stretch of network are calculated inversely.

3.3. Temperature calculation

In the distribution network, pipes have the greatest influence on the temperature calculations. Due to this, the distribution network is assumed to be a combination of pipes of different types and lengths. As a consequence, and considering the distribution network configuration of the test site, reduced models are developed for each pipe type in the network. After that, these reduced models are linked in an appropriate way, i.e. outlet temperature of one pipe is considered equal to the inlet temperature of the next pipe/s, and so on, resulting in a complete, reduced model of the distribution network. Following, the procedure followed to obtain A, B and C pipe reduced model is described.

In order to obtain temperature dynamics, system identification techniques were applied, specifically those based on step responses. The identification process was performed over the corresponding detailed pipe models, for types A, B, and C.

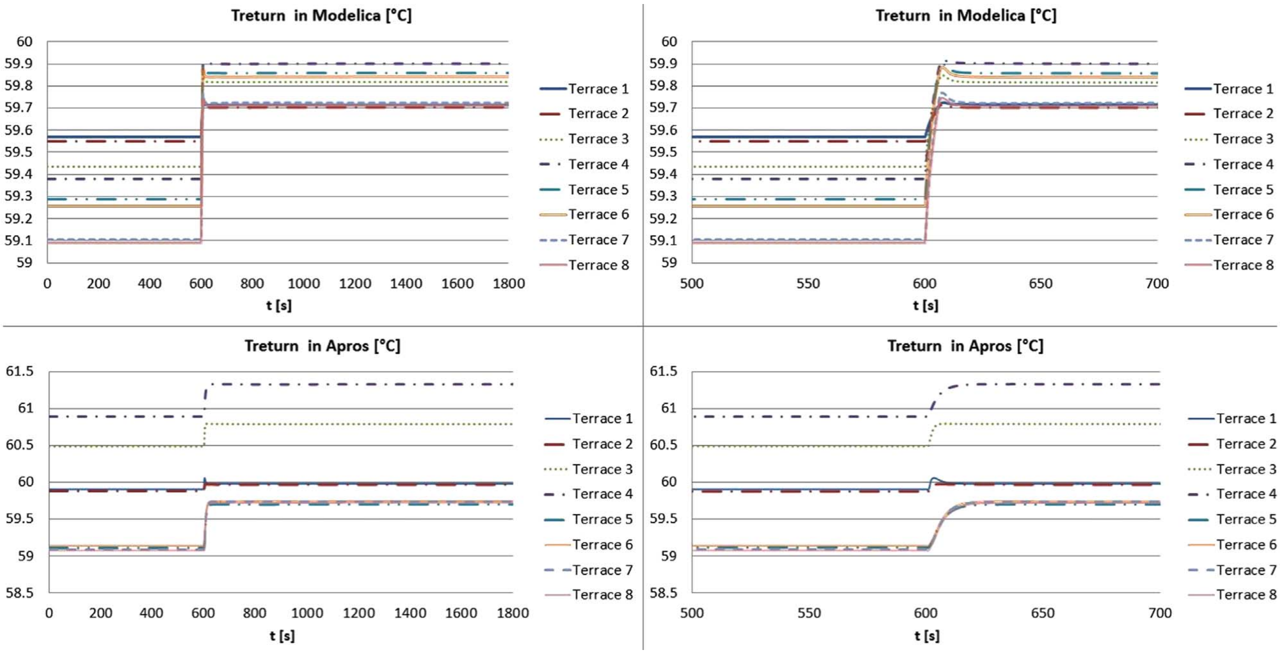


Fig. 5. Return temperature at each terrace (Case I) in Modelica® model (up left) and Apros® model (bottom left). The right side is a zoomed view of the results from left side.

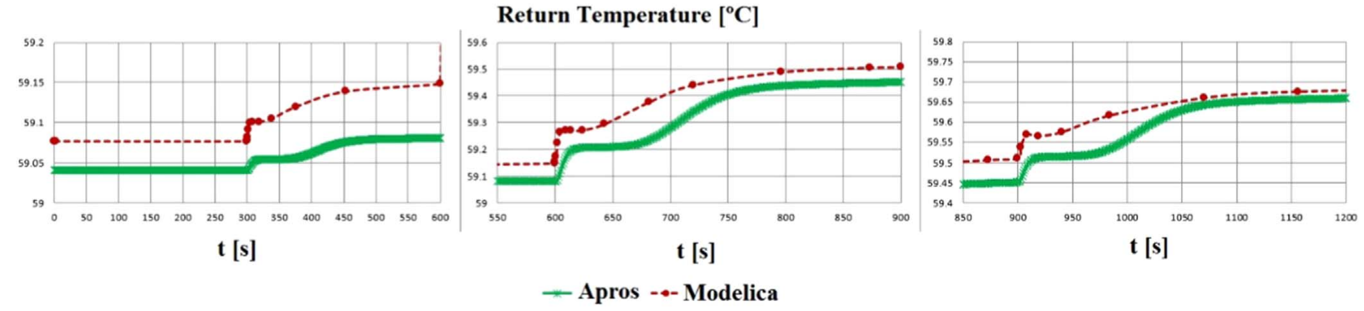


Fig. 6. Return temperature in the sixth terrace at 300 s, 600 s and 900 s (Case II).

Table 4
Proportional parameter for series and parallel arrangement.

Series arrangement	**Parallel arrangement**	
$K_{eq_s} = \sum K_i$ (1)	**[$K_1 \neq K_2$]** $K_{eq_p} = K_2\left(\frac{K_1 - \sqrt{K_1 * K_2}}{K_1 - K_2}\right)$ (2)	**[$K_1 = K_2$]** $K_{eq_p} = \frac{K_i}{4}$ (3)

Simulations of these models show that the outlet temperature of the pipe is primarily a function of the mass flow rate, inlet temperature, and ground temperature. With regard to the system dynamics, ambient temperature (ground temperature) dependence can be neglected, as its variation is very slow compared to the other two variables (mass flow rate and inlet temperature). Accordingly, system identification is performed in order to find an expression that relates the outlet temperature to the inlet temperature and mass flow rate, resulting in a multiple input simple output (MISO) system.

Results from simulations performed over this MISO system (pipe detailed models) show that the behaviour, is a combination of the system response when the inputs vary separately, and both input variables (inlet temperature, and mass flow rate) vary simultaneously (see Fig. 7).

Consequently, it is decided to represent the MISO system via two different transfer functions (Laplace domain) depending on the control variable (Fig. 8).

The procedure to develop the transfer functions representing the MISO system (G1(s) and G2(s) in Fig. 8) is to obtain the structure and parameters for both of them. For establishing the transfer function structure for mass flow rate variations, several simulations were run with the pipe detailed model, fixing inlet and ambient temperatures and applying several mass flow rate step inputs. The results show that no pure delay or overshoot are present at the response, therefore 1st and 2nd order systems (Smith method, Ho method and Harriot approximation) are considered. In this case, the structure that best fits the pipe detailed model response is the 2nd order system determined by the Ho method (Fig. 9).

Once the transfer function structure is obtained, the value of the corresponding parameters (T_1 and T_2), and their variation within the operation ranges, has to be established:

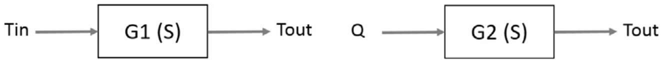


Fig. 8. Transfer functions in the pipe reduced model.

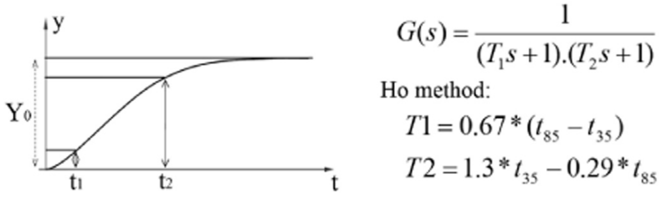


Fig. 9. Overdamped/critically damped second order system.

- Mass flow rate value influence: several simulations are performed by applying mass flow rate step inputs with different initial values and different step amplitudes. Results show that the Ho systems parameters depend on the final value of the mass flow rate reached with the step simulations, but not on the initial value or the step size. Besides, in all cases the relation between T1, T2, and the mass flow rate is a negative exponential function, although the curves differ (Fig. 10).

- Inlet temperature (Tin) influence: the simulations carried out (constant mass flow rate step and constant ambient temperature for different Tin) show that the influence of inlet temperature on T1 and T2 is negligible.
- Ambient temperature (Tamb) influence: as in the previous case, the simulation results show very little influence of the ambient temperature on T1 and T2 values.
- Pipe length (L) influence: the simulation results show that the dependence of Ho parameters on pipe length is almost linear (Fig. 11), with different slope values depending on the pipe type.

For determining the **transfer function structure for inlet temperature variations**, several simulations of the pipe detailed model were run, but this time, fixing the mass flow rate and ambient

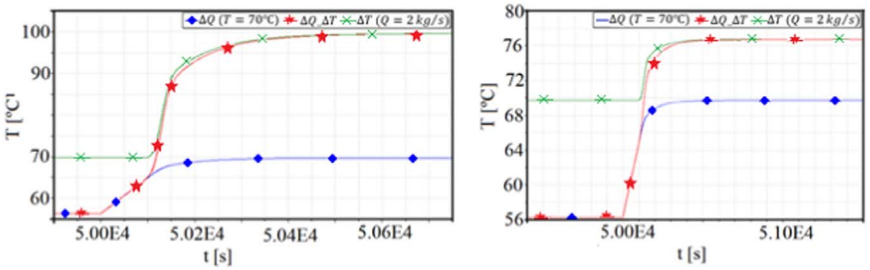


Fig. 7. Type A pipe simulation results. Mass flow rate step variation from 0.03 to 2 kg/s (both); inlet temperature step variation from 70 to 100 °C (left) and inlet temperature step variation from 70°–77 °C (right).

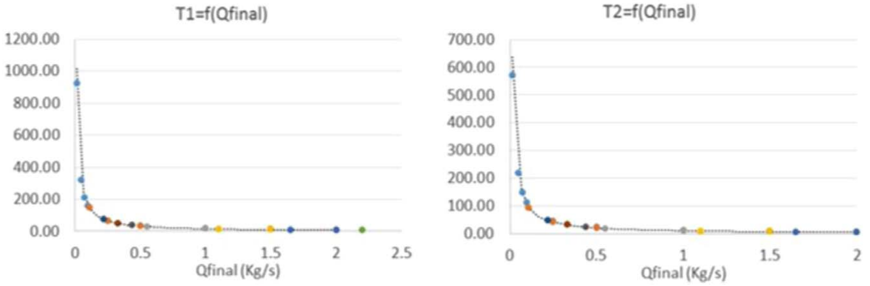


Fig. 10. T1 and T2 as a function of mass flow rate for a type C pipe.

temperature, and applying several inlet temperature steps. The results show a pure delay at the outlet temperature variation, but no overshoot. According to this, 1st order systems with a delay, and 2nd order systems (overdamped) with delay are considered (Smith method, Ho method, and Stark method). In this case, the Ho system (2nd order system with delay) is used for the structure definition (Fig. 12).

The pure delay (t_d) is clearly a result of the transport effect: the time the fluid takes to go from the pipe inlet to the outlet according to its velocity (mass flow rate). Therefore, its calculation can be carried out analytically:

$$t_d = \frac{A\rho L}{Q}$$

where A is the pipe inner transverse area, ρ the fluid density, L the pipe length, and Q the mass flow rate. Despite the Ho 2nd order system and the delay approach calculating the delay from the simulation results, it was decided to calculate it according to the previous formula, since it is an analytical method instead of experimental.

Once again, according to the transfer function structure, the value of the corresponding parameter ω_n, and its variation within the operation ranges, have to be established:

- Inlet temperature influence: depending on the pipe type, different results are obtained. While type C simulations show no influence of this temperature, the type A and B relationship between ω_n and inlet temperature fits a negative exponential function (Fig. 13)

- Mass flow rate influence: for all cases, the results show a linear dependence between ω_n and mass flow rate (Fig. 14). The slope depends on the pipe type.

- No influence of the ambient temperature is observed.
- Pipe length influence: in all cases, the dependence of ω_n on pipe length results in a negative potential function (Fig. 15). The parameters of this function differ depending on the pipe type.

Once the dynamic part of the system response is determined (transfer functions structure and parameter identification), the steady state response is determined. Due to the dual character of the dynamic response (two transfer functions) and in order to simplify the process, it is decided that **the stationary value of the outlet temperature** is directly established (identified via simulations), instead of using a gain.

Therefore, for each pipe type and via stationary simulations, the dependence of the stationary outlet temperature value on the operation variables is determined:

- Mass flow rate: the stationary value of outlet temperature depends on this variable, the higher the mass flow rate, the higher the outlet temperature value (Fig. 16).

- Ambient temperature: negligible variation.
- Inlet temperature: linear dependence of the temperature (Fig. 17), with slope value depending on pipe type.

- Length: linear dependence (Fig. 18), with slope value depending on pipe type.

At this point, a pipe reduced model was achieved for the three types of pipe in the selected scenario. Additionally, a pipe reduction procedure was developed, which uses, in a generic way, all of the calculation steps described above.

3.4. Pipe Reduced Model validation

Validation was carried out by comparison with results obtained with the corresponding detailed model. Four simulation cases are considered:

1. Case1: step in the inlet temperature and mass flow rate simultaneously.
2. Case2: mass flow rate step first and step in the inlet temperature before the end of the transient due to the mass flow rate step.
3. Case3: step in the inlet temperature first and mass flow rate step before the end of the transport delay (inlet temperature variation).
4. Case4: step in the inlet temperature first and mass flow rate after the end of the transport delay and before the end of the transient due to inlet temperature step.

The following figures (Fig. 19 and 20) show the results obtained from these simulations

It should be noted that the detailed model simulation uses a variable time step solver, while the reduced model is run under a DSP solver (fixed time step = 300 s). Taking this into account, the

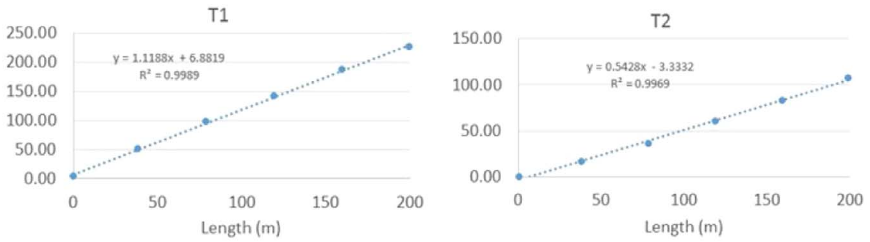
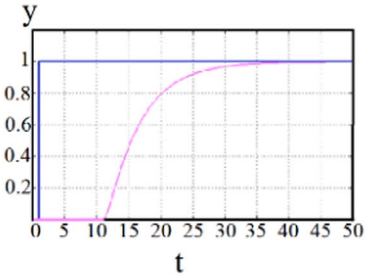


Fig. 11. T1 and T2 as a function of L (mFlow=0.55 kg/s) for type A pipe.



$$G(s) = \frac{e^{t_d s}}{s^2 + 2\varsigma\omega_n + \omega_n^2}$$

Ho method (2nd order system + delay):

$$\omega_n = \frac{1}{0.463 * (t_{85} - t_{35})}$$

$$\varsigma = 1$$

$$t_d = 1.574 t_{35} - 0.574 t_{85}$$

Fig. 12. Step response of 2nd order system with delay.

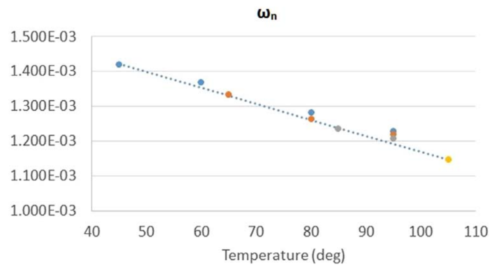


Fig. 13. ωn as a function of inlet temperature (mFlow = 0.054 kg/s) for type B pipe.

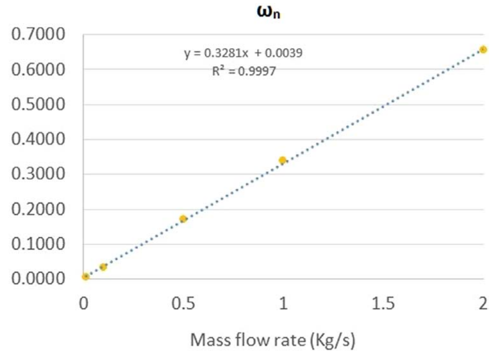


Fig. 14. ωn as a function of mass flow rate (initial T = 343 K) for type C pipe.

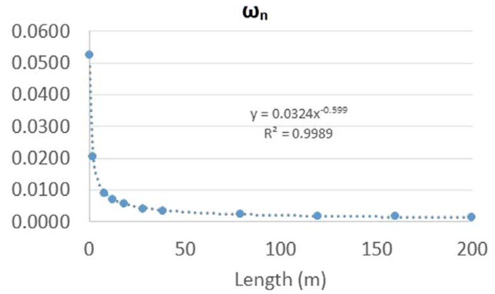


Fig. 15. ωn as a function of pipe length (mFlow = 0.054 kg/s) for type A pipe.

results obtained are considered suitable for the required application.

3.5. Distribution reduced model validation

From the mass flow rate calculation (Section 3.2), and the developed pipe reduced model, the distribution reduced model is worked out, structured as follows:

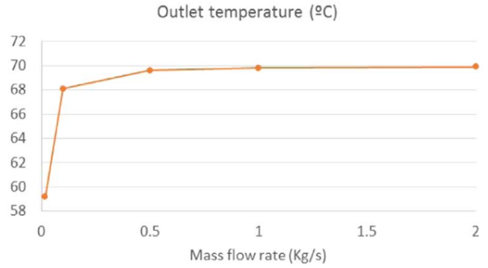


Fig. 16. Stationary value depending on mass flow rate for type C pipe.

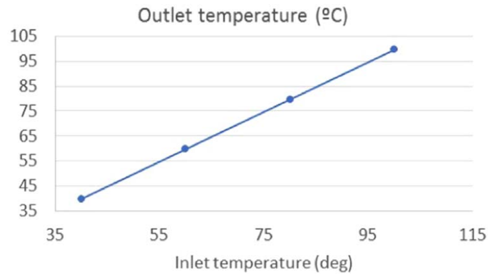


Fig. 17. Stationary value depending on inlet temperature (type A pipe).

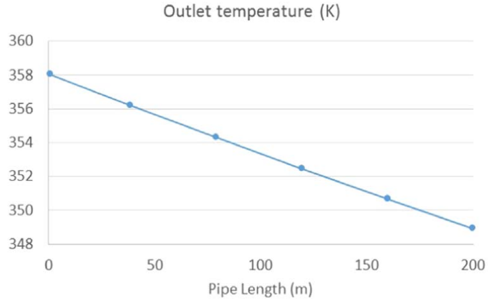


Fig. 18. Stationary value depending on pipe length (type A pipe).

- Hydraulic model: collects the calculation of the mass flow rates depending on the user's valve position. It also calculates the electric power consumed by the distribution pumps, from the corresponding efficiency curve.
- Temperature model: calculation of outlet temperature depending on the inlet temperature and mass flow rate, by appropriately linking the corresponding pipe reduced models:

a. Supply: inlet temperature corresponds to fluid temperature coming from generation plant, and outlet temperature to the fluid temperature reaching the users.
b. Return: inlet temperature corresponds to fluid temperature from each user, and outlet temperature to the fluid temperature at generation return, following the reduction process described as

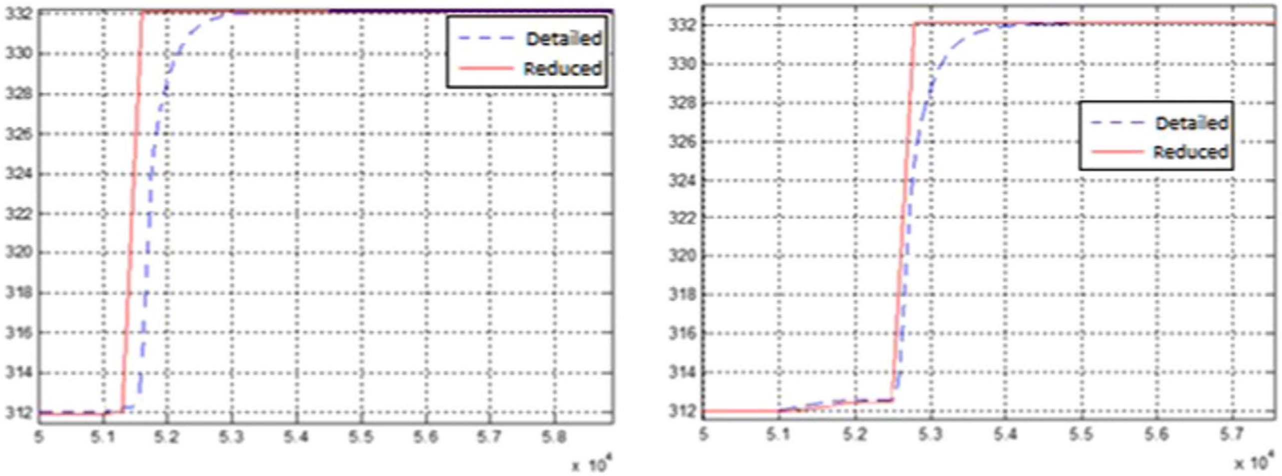


Fig. 19. Results obtained for type A pipe, detailed model result vs. reduced model result. Case1 (left). Case2 (right).

follows:

Regarding the distribution reduced model validation, it is carried out by simply comparing simulation results obtained with both the reduced and the detailed distribution models. The stationary analysis results show relative errors less than 5% in the mass flow rate, and 0.02% in the temperature. The transitory analysis results show differences in the pure delay in temperatures within the network. In Table 5, the corresponding delay values at the terraces inlet are presented.

As mentioned before, the DSP requires a discrete solver with a fixed sample time of 300 s. As a result, delays calculated with the reduced model are always multiples of that number. For its part, the detailed model run in Modelica® uses a variable step solver, which shows a more accurate delay.

Conclusion and further work

In the AMBASSADOR project, a specific application of DH system component models was required, aiming at real-time control design and optimization of the whole DH system. The challenge was to develop models that properly represent slow dynamics such as those coming from thermal phenomena, as well as fast dynamics for control purposes. In addition, models must be detailed enough to allow the implementation of a control based on model predictive control (MPC) but simple enough to be used in real-time applications because based on reviewed literature, other existing models did not fulfil such requirements.

Table 5
Delay values for each terrace.

Detailed model	10 s	18 s	50 s	68 s	100 s	117 s	166 s	177 s
Reduced model	0 s	0 s	0 s	0 s	0 s	300 s	300 s	300 s

Detailed models of the components commonly found in a DH network are developed in a Modelica®-Dymola simulation environment. A distribution pipe model, distribution network model and hot water storage model are described and validated with models implemented in other software (Apros® and IDA-ICE®), also described in this work.

The validation of steady state heat losses of distribution pipe detailed model against manufacturer data showed an error less than 5%. The comparisons between Apros® and Modelica® models showed differences in the dynamics in the range of 6–10%.

In addition, the comparison of the detailed models developed in Modelica®, Apros®, and IDA-ICE® show that, while most of the models performed similarly, they do not reproduce the dynamics in the same way. The relevant causes are analysed, and procedures to control them developed. However, the validation of the hot water storage detailed model revealed significant differences, therefore, modifications were

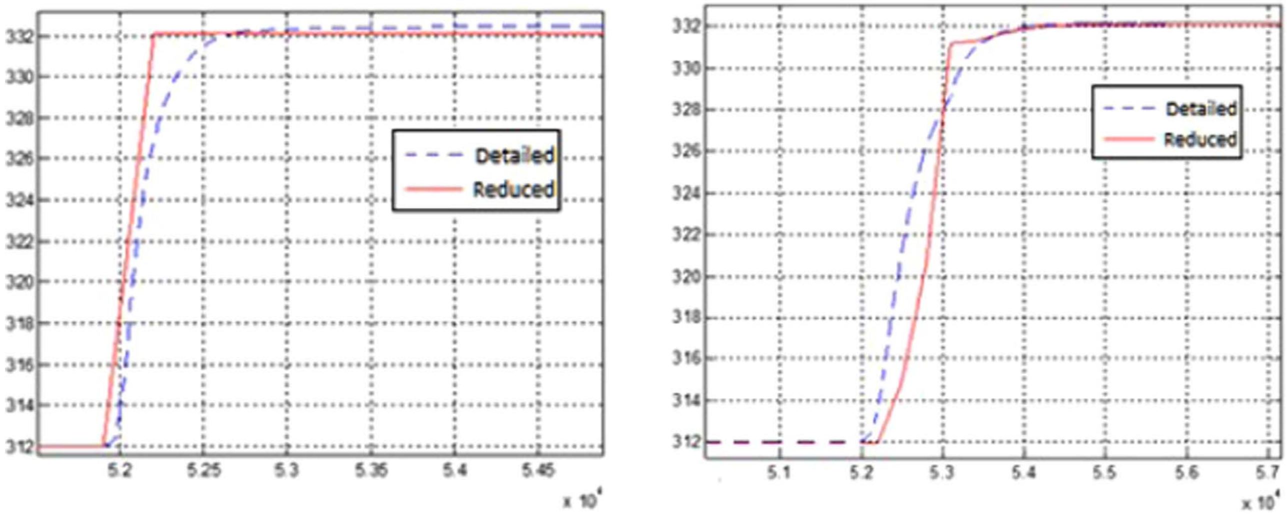


Fig. 20. Results obtained for type A pipe, detailed model result vs. reduced model result. Case 3 (left). Case4 (right).

introduced in cases where stratification could not be neglected. Nevertheless, all developed models capture the related phenomena with a reasonable degree of accuracy, and could be used for analysis of complex systems.

Due to the computational cost of detailed models, the DSP in AMBASSADOR required reduced models, which take the most relevant system dynamics into account but do not include all the possible terms. The reduced models presented in this paper met this aim. The most relevant dynamics in the pipes were identified assuming some simplifications, such as the decoupling of the mass flow rate calculation from temperature calculation. In this way, the temperature calculation of the reduced model was implemented by combining the corresponding pipes' transfer functions. For the mass flow rate calculation, an analytical calculation of the whole network was implemented using a Matlab® function. Both pipe (temperature calculation) and distribution network reduced models were validated against the corresponding detailed physical models. Results from the stationary validation of the distribution network reduced model with the detailed model, showed an error less than 5% in the mass flow rate, and 0.02% in the temperature, while the transient analysis showed differences in the pure delay in temperatures within the network.

In conclusion, it has been demonstrated, via simulation results of newly developed models that both detailed and reduced developed models are performing sufficiently well for the application at hand. Nevertheless, although the reduced models showed good performance in the simulations (where the simulation environment uses a variable step solver), they give a less accurate delay once they are implemented in the DSP, due to the fixed sample time imposed by the platform. Hence, further improvements are required when larger systems are simulated.

Consequently, a new pipe model based on the "plug-flow" approach is being developed in the INDIGO project. This development will improve the results obtained in AMBASSADOR regarding the distribution network model, presented in this publication. Furthermore, the model will be validated against real data gathered from a district cooling network. The validation results and a comparison between the actual and the INDIGO pipe models will be presented in future publications. In addition, the improved model is to be included in an open source library by the end of the INDIGO project.

Acknowledgement

Part of this work was carried out within the AMBASSADOR project that received funding from the European Union Seventh Framework Programme (FP7/2007–2013) under grant agreement No 314175.

The newest research leading to the results presented in this paper is undertaken in the framework of project INDIGO, which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 696098.

References

[1] Larsen H, Pálsson H, Bøhm B, Ravn H. Aggregated dynamic simulation model of district heating networks, Journal of Energy Conversion Management; 43:995-1019; 2002.
[2] Larsen HV, Bøhm B, Wigbels M. A comparison of aggregated models for simulation and operational optimisation of district heating networks. J Energy Convers Manag 2004;45:1119–39.
[3] Stevanovic V, Prica S, Maslovaric B, Zivkovic B, Nikodijevic S. Efficient numerical method for district heating system hydraulics. J Energy Convers Manag 2007;48:1536–43.
[4] Stevanovic VD, Zivkovic B, Prica S, Maslovaric B, Karamarkovic V, Trkulja V. Prediction of thermal transients in district heating systems. Energy Convers Manag 2009;50:2167–73.
[5] Gabrielaitiene I. Numerical simulation of a district heating system with emphases on transient temperature behaviour. In: Proceedings of the 8th International Conference Environmental Engineering, Vilnius, Lithuania; 2011.
[6] Ancona M, Bianchi M, Branchini L, Melino F. District heating network design and analysis. Energy Procedia 2014;45:1225–34.
[7] Zhou S, Tian M, Zhao Y, Guo M. Dynamic modeling of thermal conditions for hot-water district-heating networks. J Hydrodyn 2014;4:531–7.
[8] Brand M, Thorsen JE, Svendsen S. Numerical modelling and experimental measurements for a low-temperature district heating substation for instantaneous preparation of DHW with respect to service pipes. Energy 2012;41:392–400.
[9] Duquette J, Rowe A, Wild P. Thermal performance of a steady state physical pipe model for simulating district heating grids with variable flow. Appl Energy 2016;178:383–93.
[10] Frederiksen S, Werner S. District heating and cooling, 1st ed.. Lund: Studentlitteratur AB; 2013.
[11] Oppelt T, Urbaneck T, Gross U, Platzer B. Dynamic thermo-hydraulic model of district cooling networks. Appl Therm Eng 2016;102:336–45.
[12] Olsthoorn D, Haghighat F, Mirzaei PA. Integration of storage and renewable energy into district heating systems: a review of modelling and optimization. Sol Energy 2016;136:49–64. http://dx.doi.org/10.1016/j.solener.2016.06.054.
[13] Autonomous Management System Developed for Building and District level. FP7 European project, ⟨http://ambassador-fp7.eu/⟩.
[14] Bourry F, et al. District energy management and information model. Deliv D2 6 AMBASSADOR Proj 2015, [February 2015].
[15] INDIGO consortium. INDIGO project; 2016. ⟨http://www.indigo-project.eu/⟩ [Accessed 25 January 2017].
[16] Modelica® Association. A Unified Object-Oriented Language for Physical System Modeling. Language specification. Version 3.3 Revision1; 2014.
[17] Apros® Process Simulation Software, ⟨http://www.apros.fi/en/⟩.
[18] Equa Simulation AB. IDA Indoor Climate and Energy, User Manual, version 4.5. Stockholm; 2013.
[19] Cruickshank CA. Evaluation of a stratified multi-tank thermal storage for solar heating applications. Ontario, Canada: Queen´s University of Kingston; 2009.
[20] Feiereisen T. An experimental study of immersed coil heat exchangers. University of Wisconsin; 1982.
[21] Logie W. Immersed Coil Heat Exchanger. Inst für Sol 2007.
[22] Incropera FP, DeWitt DP. Fundamentals of Heat and Mass Transfer. 4th ed; 1999.
[23] del Hoyo Arce I, López Perez S. et al., Proceeding Proceedings of the 11th International Modelica® Conference, Palais des Congrès de Versailles, France. September 21–25.
[24] del Hoyo I, Herrero S, Mesonero I, López S, Rämä H, Heikkinen J. Modelling of the thermal energy transport network at district level. Deliverable D4.4. Ambassador project; 2015.
[25] Leonard BP. A stable and accurate convective modelling procedure based on quadratic upstream interpolation. Comput Methods Appl Mech Eng 1979;19:59–98. http://dx.doi.org/10.1016/0045-7825(79)90034-3.
[26] Courant R, Friedrichs K, Lewy H. On the partial difference equations of mathematical physics. IBM J Res Dev 1967;2:215–34.
[27] Giraud L, Bavière R, Paulus C, Vallée M, Robin J. Dynamic Modelling. Exp Valid Simul a Virtual Dist Heat Netw 2015.
[28] Wylie EB, Streeter VL. Fluid transients. McGraw-Hill International; 1978.
[29] Giraud L, Bavière R, Vallée Paulus M, Presentation C. Validation and application of the district heating Modelica® library. In: Proceedings of the 11th modelling conference; 2015. p. 79–88 ⟨http://dx.doi.org/10.3384/ecp1511879⟩.
[30] Solar Energy Laboratory . Trnsys 17 mathematical reference, 4. Madison: Wisconsin; 2009.
[31] EN 806–3 . Specifications for installations inside buildings conveying water for human consumption. Pipe Sizing Simpl Method 2006.
[32] Bohm B, et al. Simple model for operational optirnization. IEA Dist Heat Cool 2002, [Annex VI: Report 2002:S1].