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Impact of network modelling in the analysis of district heating systems

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ABSTRACT

Network modelling is crucial for the simulation of district heating system responses to changes in operating conditions. Various applications, aimed at finding optimal district heating design and operations, neglect or strongly simplify the network dynamics. In this paper, the effect of including network dynamics in district heating system modelling has been analyzed. Different physical contributions have been considered separately: thermal losses, thermal transients and delay time due to the various costumer distances. This allows estimating the significance of the various phenomena in the estimation of the thermal request, in particular during demand peaks. Results shows that the thermal power required by the thermal plant is significantly different if evaluated relying on a network model or not; in case of thermal peak this is under-estimated up to 20% if the network dynamic is not taken into account. In particular, the inclusion of the thermal transient in the model is found to be crucial for considerably improving the result accuracy in the peak estimation. Effects for inclusion of thermal losses calculation have been quantified; errors reaches 4% in case of not perfectly insulated pipelines. The effect of neglecting network dynamics have also been analyzed in the context of demand side management (DSM) district heating systems. In particular, the effects are tested on a model for the best rescheduling of on-off time of the building heating device to optimally shave the thermal peak. Results show that the benefits achieved by the demand response model that include the thermal dynamics contribution increase from 1 to 18%; this is because the contribution of the different times the water trains takes to reach the plants (from the buildings) and of the water in the pipelines cooled down during night are relevant. Furthermore, different options are discussed to take into account compactly the network dynamic.

1. Introduction

In a framework of electrification of the energy supply, district heating is maintaining its importance because of the high efficiency and low costs. Low-grade heat recovered by cogeneration plants, industrial site or renewable energy technologies is a cheap resource to be used for space heating, from both economic and thermodynamic perspective. As a consequence, district heating happens to be a way for strongly reducing emissions in urban areas [1,2].

Research activity in district heating (DH) technology is greatly focused on the optimal design and management of networks [3,4]. This is aimed at reaching targets in terms of CO_2 emissions, fossil fuel consumption in a framework of economic benefits. Various works in the literature deals with improving DH performance: thermal peak reduction [5,6], pumping cost reduction [7,8], increase exploitation of waste heat [9–11], increase penetration of renewable sources [12,13], decrease use of low efficiency technologies, such as heat only boilers [14], smart inclusions of heat pumps [15–17].

Modelling of DH systems is quite complex because of a) various production/conversion/storage technologies, b) the large system domain and c) the long transients. While looking for optimal design and management solutions, it can be convenient and easier perform some simplifications. In various works in the literature, the contribution of the network dynamics is neglected.

Actually, various applications where the pipelines belongs to the control volume, the thermal and fluid-dynamic behaviour of the system significantly affects the results [18]. The dependence of the results on the network dynamics depends on various factors such as the network topology, the pipeline/network dimensions, the substation distribution, the operations and the temperature of the

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supply fluid.

Various works in the literature propose models for district heating networks [19], that can be physical-based or black box approaches. Physical models rely on the definition and solution of the physical equations, on the computational domain that is composed by the network pipelines properly discretized. Black-box approaches are data-driven models.

In the literature different types of physical models have been developed, after the pioneering Hardy Cross approach [20], specifically for DH networks. The fluid-dynamic problem of DH pipelines is non-linear and this is solved by numerical methods that are often computationally expensive. Therefore, especially in case of extended networks calculation requires significant computational resources because of the large number of pipelines. The calculation cost becomes thus a crucial characteristic of a simulation tool; this is the reason why simplifications are usually done in the network models proposed in the literature. Among the models used for the network modelling are the loop equation method [21], aggregated models [22] (applied to 20 km long network, with 1079 nodes and 10 MW of maximum heat production) and node based model [23], characteristic methods [19]. Actually, both aggregated and node-based models do not solve the fluid-dynamic and thermal transient problems in all the network nodes, while a simplification on the topology is performed [24]. The network models available in the literature are validated in entire or part of district heating systems.

This work analyses the importance of including the network thermal behaviour (by using one of these validated models) during the analysis of DH operations, and the cases the contribution of the network dynamics can be neglected. The importance of including the thermo-fluidynamic of the network is investigated trough the analysis of a real network by mean of a physical network model. DH dynamic modelling is shown to be crucial in cases of thermal transients and significant changes in mass flow rates or supply temperatures. The relevance of network dynamic analysis is specifically shown for a demand side management (DSM, i.e. modification of the thermal demand in order to make the overall profile more similar to the ideal one) application). It has been shown how results can change if the thermo-fluidynamic of the network is taken into account.

The main novelty of the present paper are 1) to show the impact of neglecting the network in the analysis of different kind of district heating 2) analyze the impact of the various phenomena (thermal losses, thermal transient, time delays) in the evaluation of the peak request.

The paper is structured as follows: section 2 describes some application very widespread in the literature, which require the network analysis, section 3 describes basic concepts for district heating networks modelling, section 4 reports the test case used for this analysis (the DH system and the model used), section 5 includes the results.

2. Applications involving DH networks

While modelling district heating systems, the network dynamic can significantly affect the results. This can happen in different applications. In different important ongoing analysis, schematized in Fig. 1, network dynamics can play a significant role:

Selection of the best plants operations (Fig. 1a). In case the thermal request of buildings is available, the optimal or smart selection of the best set of technologies to be operated to supply heat to the network allows minimizing the production costs. The selection of the best set of technologies can be done considering that the evolution of the thermal power supplied to the thermal plants is equal to the sum of the evolution of thermal power required by the costumers. This approach is based on the idea of neglecting the thermal behaviour of the network, i.e. neglecting the network pipelines as components. Actually, at some times, the total demand at plant level significantly differs to the sum of the costumer thermal request (because of the phenomena explained in Section 3). Therefore if the analysis of the network dynamics is included in an optimizer for the evaluation of the best of technologies to be operated for heat production in a certain time, results can be significantly improved respect to the cases the dynamics is neglected (because the thermal demand at the thermal plant can be significantly different than that estimated neglecting the network effects).

Localization of plants and storage units (Fig. 1b). The positioning of storage systems can affect the management of thermal peaks. As shown in the result section, the thermal demand during the peaks is strongly influenced by the network dynamics. For this reason, the inclusion of the network behaviour allows better estimation of the load that the storages can provide in the various positions.

Selection of the best pumping power at the pumping substations (Fig. 1c). Transport of water mass flow in pipelines is done by pumping groups installed in the thermal plants. The pumping power at each plant is selected to win pressure losses due to friction and altitude differences and to include in the network the prescribed amount of mass flow rate. In case of extended networks or large altitude differences, some booster pumping groups can be installed along the pipelines to achieve additional pressure increases. Selection of the best pumping power in each booster pumping group is crucial to reduce electricity consumption and increase the second law efficiency of the entire system. This can be done with proper models. In this case, inclusion of the network dynamics allows achieving a precise prediction and significantly result improvement.

Application of demand side management through heating request rescheduling (Fig. 1d). Demand side management is a technique developed for the first time in the electrical field to manage more freely the electrical load to users. Similarly for DH, it is possible slightly modify the thermal request of buildings, to make the overall demand as similar to the ideal one. This can be done by modifying the control strategy or by schedule modification. Various attempts have been done in the literature to find the optimal management, sometimes without including the effects due to the network. For this specific application, the effects of neglecting the thermal dynamics are reported in Section 5.2.

3. Mainly phenomena behind network dynamics

The three main causes of the significant effects of the network dynamics on the simulation results are:

The significant presence of thermal transient. This is due to the large amount of water flowing in the pipelines at velocity usually ranging between 0.2 m/s to 4 m/s. Considering a medium size network, a typical distance between the plant and a costumer can be around 1000–2000 m. In view of these water speeds and distances, the time the water takes from the plants to reach the customers are between some minutes to more than an hour. This means that in case of plant stop (maybe for night regulation), the time necessary to completely refresh the water temperature in the network can be larger than an hour.

The thermal losses that take place along the pipelines because of the differences between the temperature of the water flowing inside and the temperature of the ground. Ground temperature is usually between 10 °C and 20 °C depending mainly on the climatic area, the depth and the external temperature. Considering the ground temperature at 15 °C, temperature

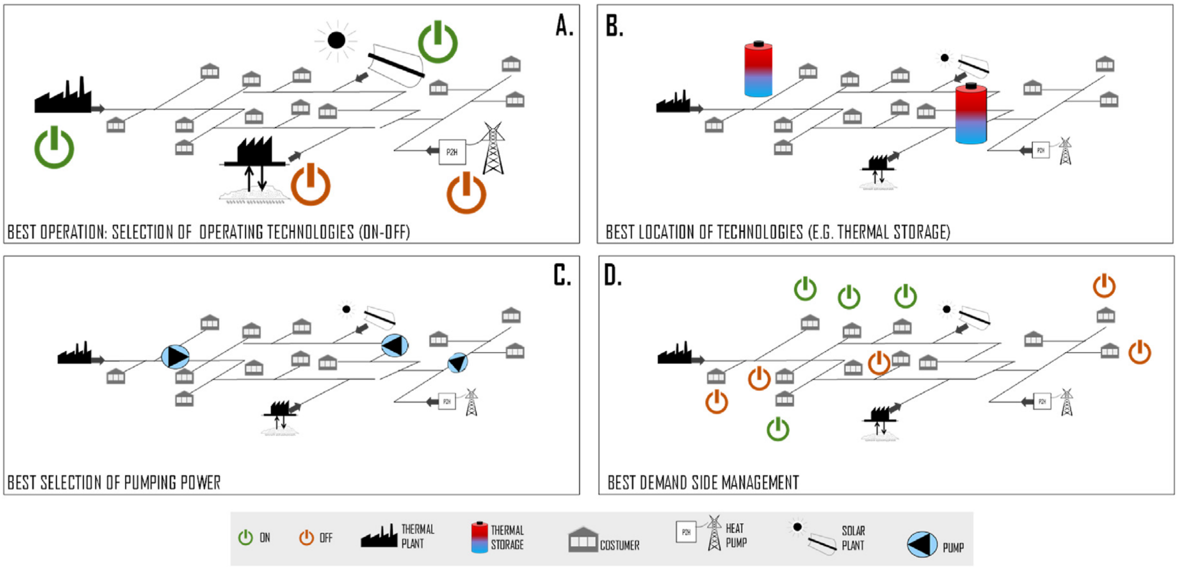

Figure. 1. Applications including the networks effect.

difference is about 100–60 °C in the supply pipeline and 50-20 °C in the return pipeline. Significant insulation layers are usually installed; these allow reducing substantially the thermal losses. Nevertheless, the aging of the insulation foam non-negligibly affects the conductivity of the pipeline. This phenomenon is particularly relevant in case of pipelines with small diameters. On average the thermal conductivity increases 7% after 10 years, 11% after 20 years and 18% after 30 years, as shown in Ref. [25]. In case of large diameters (200–800 mm), that are typically installed in transport networks, for long distances and large mass flow rates, the decrease are lower, reaching 3% after 15 years and 7% after 30 years [25]. This means that in some cases losses can affects the calculations.

The mixing of various fluids at different temperatures. Water exiting the costumer substations at different temperatures (due to different regulation status and heat exchanger areas), mixes in different pipeline junctions. Mixing alongwith thermal losses, makes the analysis of the network pipe by pipe, necessary, also in case of steady state conditions. The inclusion of various mixing in the network analysis is not straightforward to be considered because topologies are usually complex due to the localization of the domestic units and various technical constraints.

4. DH network modelling

In this section, the steps for the creation of a network model are explained. Network models can be adopted to solve various kind of networks (as detailed in Fig. 2): with or without loops, with concentrated or distributed production, large/complex or simple topologies. In this paper, a distribution network of a large district heating system is studied; this is a tree-shaped network with quite complex topology. The case study is detailed in Section 5.1.

4.1. Geometry definition

This step consists in the selection of a geometry for the definition of the problem. The network can be considered as a set of pipes interconnected among them in a certain way, depending on its topology. Because of the main propagation direction of the fluid within the pipelines, the problem is define using a one-dimensional physical description of the network. This implies that the direction considered for the problem solution is the same of the fluid within the pipelines. Actually the perfect shape of the network is not of primary important, while are mandatory the following geometry characteristics: 1) length and diameter of the pipelines 2) interconnections between the various pipelines (i.e. pipe *p2* connects pipe *p1* to pipes *p3* and *p4).* These characteristics allows identifying the water paths.

In order to take into account all the pipelines, a graph approach is used. Following the graph approach, pipelines are considered as branches, while the junctions between the pipelines are nodes. Each pipe is considered as a branch bounded by two nodes. The definition of the problem is done pipe by pipe and all the equations are solved together since the interconnections among the pipelines is known. Because of the water flowing within the pipelines, a verse must be selected as positive and another as negative. Positive verse is selected conventionally, because it is not possible to know the water flow direction in advance. Therefore the mass flow rate is positive when it flows in the same verse as the conventional positive verse and in case of opposite verse the mass flow rate is negative.

4.2. Problem definition

The thermal-fluidynamic model usually used for modelling DH networks, to analyze the thermos fluidynamic, includes:

- the mass conservation equation, used to evaluate the mass flow rate within all the pipeline of the network;
- the momentum conservation equation, used to evaluate the pressure in all the nodes of the network;
- the energy conservation equations, used to evaluate the temperature of the fluid flow in each branch of the network.

The equation must be written for each control volume of the system, therefore set of conservation equation is solved. Often the various pipelines are adopted as control volumes, but in some case smaller control volumes are required. Grid refinement in special areas and adaptive mesh can be used to enhance the precision of the solution. Mass and energy conservation equation are written at the nodes of the network (junctions) while momentum conservation equation is written for the branches (pipelines). Overall, a set

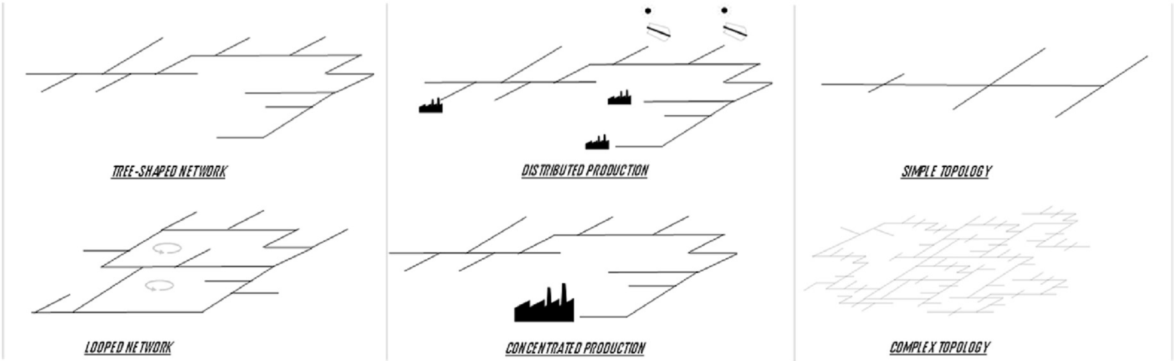

Fig. 2. Main types of district heating networks from a topology viewpoint.

of n equation is achieved, where n is:

$$n = 2\ n_{nodes}\ n_{branches} \tag{1}$$

4.3. Assumptions

The conservation equations can be simplified in order to take into account only the terms that significantly contribute to the dynamics. Some phenomena can thus be neglected. The following assumptions are usually done for modelling district heating networks:

- Water can be considered as an incompressible fluid. This is equivalent to neglect the velocity changes in each single pipelines and the water heating due to density changes.
- The unsteady term in the momentum equation is neglected because fluid-dynamic perturbations travel at about 1500 m/s. This means that these travel an entire network (between 2 and 20 km) in a period of time of few seconds (between 1 and 13 s), that is much smaller than the time steps usually adopted for calculations (mainly larger than 60 s).
- Thermal conduction along each pipe is usually neglected.
- Adiabatic and perfect mixing is assumed, such that heat losses are ascribed to the branches.
- Viscous heating is considered as negligible.

4.4. Physical problem

In this section a general description of a physical model aimed at solving DH network problem is given.

The mass balance equation, in matrix form, is used to evaluate the array of the mass flow rates (G, nbranches x 1), as a function of the network topology and the vector of the mass flow rates exiting/entering each nodes, G_{ext} (nnodes x 1):

$$G = f(\text{topology}, G_{ext}) \tag{2}$$

G_{ext} array is usually non-zero only in the nodes corresponding to buildings and plants where a mass flow rate is entering/exiting the control volume.

The steady-state momentum conservation equation can be used to evaluate the array with the pressure in each node (P, nnodes x 1). P is a function of the pipeline characteristics (sections S, diameters D, lengths L, friction factor coefficients b, friction factors for concentrated losses β and global heat transfer coefficients U), that can be written in a sole vector C. In case some booster pumping stations are included in the system, the pressure array P also depends on Δpp, i.e. the pumping rise provided in pumping stations located along the network.

$$P = f\left(\text{topology}, G, C, \Delta p_p\right) \tag{3}$$

The energy conservation equation is used to evaluate the vector of temperature, one for each branch (T nbranches x 1), as shown in Eq. (3).

$$T(t) = f(topo\log y,\ G, T(T-1), C, T_{env}) \tag{4}$$

4.5. Problem solution

Equations (2) and (3) are not independent because the pressure vector P depends on the mass flow rate vector G. In particular, the relation between P and G is nonlinear, as pressure vector depend on the square of mass flow rate, as shown in Eq. (5):

$$P = v^2\left(b\frac{L}{D} + B\right) \tag{5}$$

In order to solve this problem, an iterative approach is required. Among them are SIMPLE (semi implicit method for pressure linked equation) or Newton algorithm, particularly suitable for solving Navier Strokes equations.

Energy equation is not coupled to mass and momentum equation, but this can be solved only after mass conservation equation since the vector G must be known. If the mesh considered is sufficiently fine the energy equation can be written as linear, considering thermal losses as constant in space in a single pipeline.

4.6. Topology inclusion

In order to include the topology in the calculations there are various ways. One of the simplest consists in using a matrix (A) with as many rows as the number of nodes and as many columns as the number of branches describes the connection between the various branches. A general element Aij is equal to 1 or -1 depending if the node represents the inlet or outlet of the branch. This can be used easily in the equations. For instance to indicate that a certain quantity R in a branch is the algebraic summation between what enters and exits the system (Eq. (5)), it is possible to use for the entire network the matrix equation (Eq (6))

$$R_{branch_j} = R_{out\_node_i} - R_{in\_node_i} \tag{6}$$

$$R_{branches} = AR_{nodes} \tag{7}$$

4.7. Control volume selection

Depending on the type of simulation required, it is possible considering different control volumes, as shown in Fig. 3.

In the case, the goal is to evaluate the temperature, given the temperature of water at the thermal plants, it make sense only considering the supply line. In such case, the boundary conditions are imposed at thermal plants for the inlet mass flows and at the costumer substations for the outlet mass flows (Fig. 3 left side).

In case the thermal load evolution at the thermal plant is expected being the goal, given the thermal request at the costumer level, it is possible considering the only return network. Boundary conditions are assigned at the costumer substations for the inlet mass flows and at the thermal plants for the outlet mass flows. Therefore, the data that should be available are a) the temperature of the outlet streams at the costumer substation and the mass flow rates and b) the mass flow rates processed by each thermal plants. These data are usually available because measurement devices are installed in the costumer substation for billing purposes and the control system in the plants allows evaluating the mass flow rate entering/exiting the system in different operating conditions. This is the approach shown in Fig. 3 (center) and that has been used in this paper, considering a distribution network instead of the entire district heating network. The approach of considering separately the supply and the return network can be useful in various applications, such as for demand side management analysis, since this allows including the study of the substation.

In the case the entire contribution of supply and return pipelines is to be considered, it can be done by imposing both inlet and outlet mass flow rate boundary conditions at the thermal plants. In this case the costumer substation should be modeled properly both fluidynamically and thermally and included in the system analysis. In this case, the network is completely modeled therefore only the mass flow rate entering/exiting the thermal plant and the supply temperature are required (Fig. 3 right). This can be particularly suitable in case of fluidynamic analysis (e.g. optimal estimation of pumping power).

5. Test case

5.1. Network

The test case used for this work is a distribution network of the Turin district heating system. Turin has almost 900.000 inhabitants; DH covers about 60% of the city thermal demand. The entire network is 800 km long and this includes a transport network made of larger diameters, to supply all the city areas, and 182 distribution networks connecting the transport network to the various users. Distribution networks are mainly long from 500 m to one km. Fig. 4 shows the entire transport network with the location of thermal plants supplying the DH and, in detail, the distribution network selected for the present analysis. In the distribution network the point connecting the transport network to the distribution network is detailed, with a red circle (BCT that stands for barycenter). In this point, only a mixing occurs, no heat exchangers are used.

The district heating in Turin is used for both space heating (mainly using radiators) and domestic hot water production purposes. The supply temperature is 120 °C (overheated water). A control system is installed in each substation in order to set the amount of mass flow rate required by the heat exchanger. The supplied temperature of the heating circuit (building side) supply temperature (while the supply temperature of the network is constant equal to 120 °C) is controlled based on the outdoor temperature compensation curve. Once the temperature required at the secondary side is set depending on the external temperature (set point temperature) the valve opens and closes to keep/reach the correct temperature value.

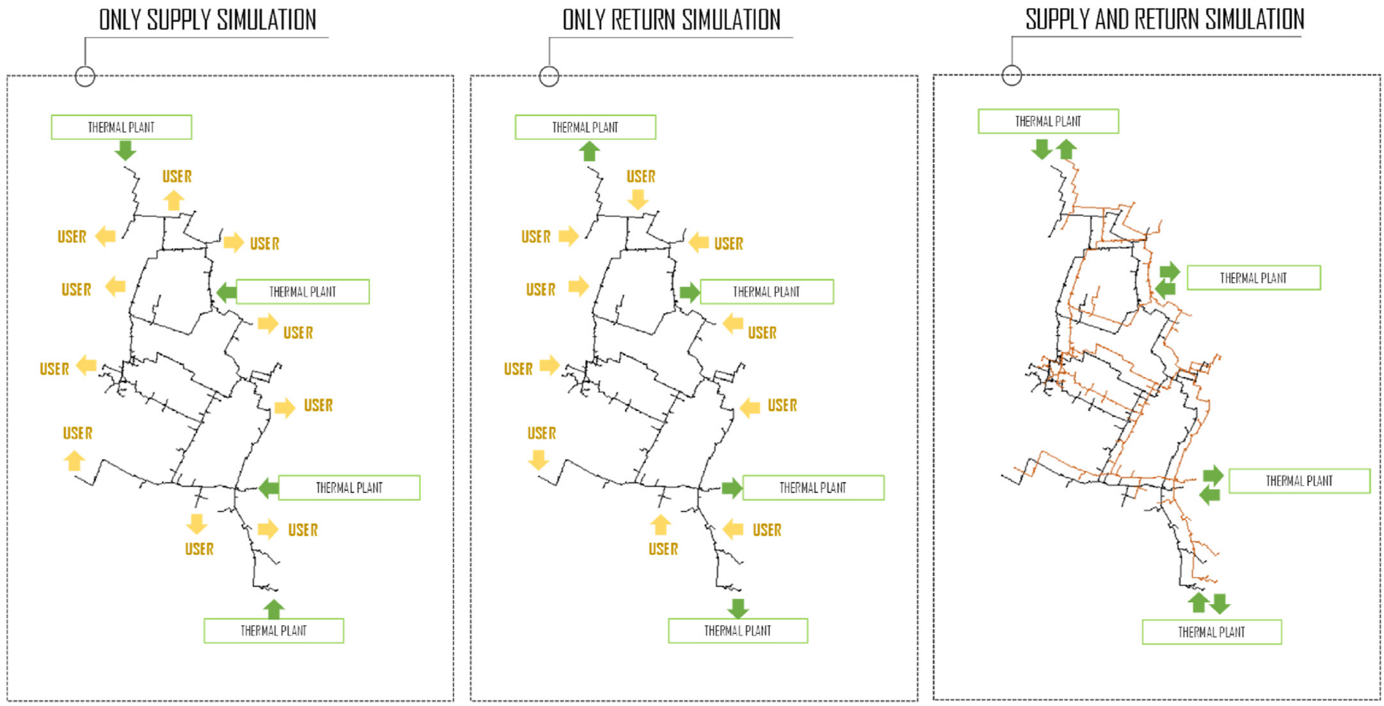

Fig. 3. Control volume and mass flow exchange for various applications.

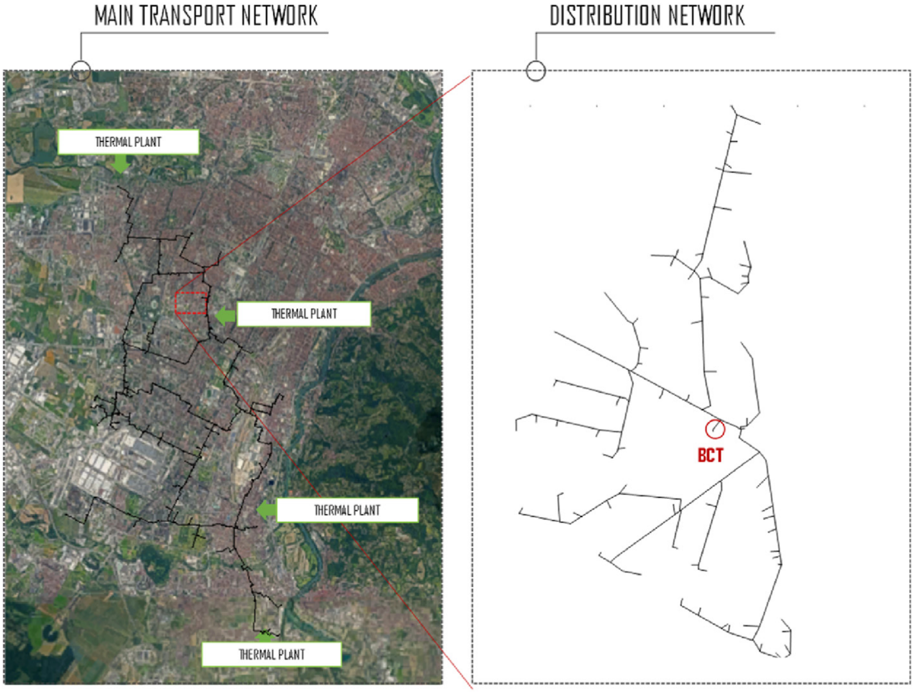

Fig. 4. Test Case. Left:The Turing district heating. Right: the distribution network considered in the analysis.

5.2. Physical model

The physical model used for the analysis is detailed in Table 1. As previously shown, this includes mass, momentum and energy conservation equations. These are written in the extended form for a single node (mass and energy equation) and for a single branch (momentum equation). When the entire network is considered the equations are rewritten in a matrix form including all the nodes for mass and energy equations and all the branches for momentum equations. The model provides in output the matrices G, P and T including respectively all the mass flow rates, pressures and temperature in the network.

The model can be applied to all kind of networks. Both tree shaped and looped networks can be solved, provided that boundary conditions are properly applied. The model works properly in case of pressure and velocities typical of district heating, regulated by mass flow variation: pressure up to 20 bar and velocities up to 5–10 m/s. Further details related to validation are reported in [26].

5.3. Applications

The physical model has here a twofold application. At first, this is applied with the aim of evaluating which are the effects of the thermos-fluidynamic in DH networks. This is done considering a period including various phases, detailed in Fig. 5. The first is, for simplicity referred to night because the time is when the systems are off or set-back. However, this is the same to all the time when the system presents a long stop. The second phase consists in the start-up, when the mass flow rates and/or temperature usually dramatically changes. The third phase consists in the steady-state condition, that is usually applied during the daily hours to the DH. In the second part of the analysis, the demand side management application has been considered and applied to the same distribution network.

6. Results

6.1. Effects of network modelling

In section, the effects of the thermo-fluidynamic in DH networks are studied. Three phases has been included in this analysis: the night-off or night setback, the starting phase (when a peak request usually occurs) and the steady state condition, as shown in Fig. 5. Fig. 6 shows the mass flow and temperature distribution at different times between 4 a.m. and 9:20 a.m. In the figure, the size of the branches reported in the graphs has been set as proportional to the mass flow rates flowing the system. The night off is considered, in order to better show the transient effects; this is typical of warmer areas, like Mediterranean zones. The color of the branches represents the temperature of the water flowing. During night the mass of water does not flow in the distribution networks. The temperature of water is about 20 °C. At 6:00 a.m. valves at some

Table 1
Equations of the physical network model used in the present analysis.

	Mass Conservation Equation	Momentum Conservation Equation	Energy Conservation Equation
SINGLE NODE	$\sum G_{in} - \sum G_{out} = \mathrm{G}_{ext}$	–	$\frac{\partial(\rho c \Delta T)_i}{\partial t}\Delta V_i + \sum_j c G_j T_j = U_{TOT}(T_i - T_{env})$
SINGLE BRANCHrowhead	–	$(\mathrm{p_{in}} - \mathrm{p_{out}}) = \frac{1}{2}\frac{\mathrm{f}}{\mathrm{D}}\mathrm{L}\frac{\mathrm{G}^2}{\rho \mathrm{S}^2} + \frac{1}{2}\sum_{\mathrm{k}}\beta_{\mathrm{k}}\frac{\mathrm{G}^2}{\rho \mathrm{S}^2} - \Delta \mathrm{p}_{pump}$	–
ENTIRE NETWORK	$\mathbf{A}\cdot\mathbf{G} + \mathbf{G_{ext}} = 0$	$\mathbf{G} = \mathbf{Y}\cdot\mathbf{A}^{\mathrm{T}}\cdot\mathbf{P} + \mathbf{Y}\cdot\mathbf{\Delta p}_{\boldsymbol{pump}}$	$\mathbf{M\dot{T}} + \mathbf{KT} = \gamma$

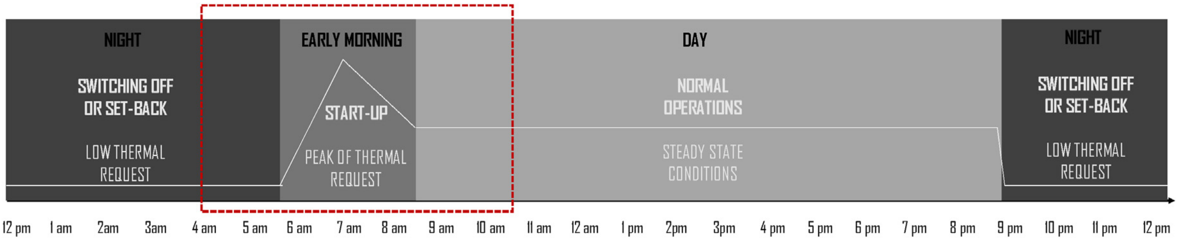

Fig. 5. Test Case: phases considered in the analysis.

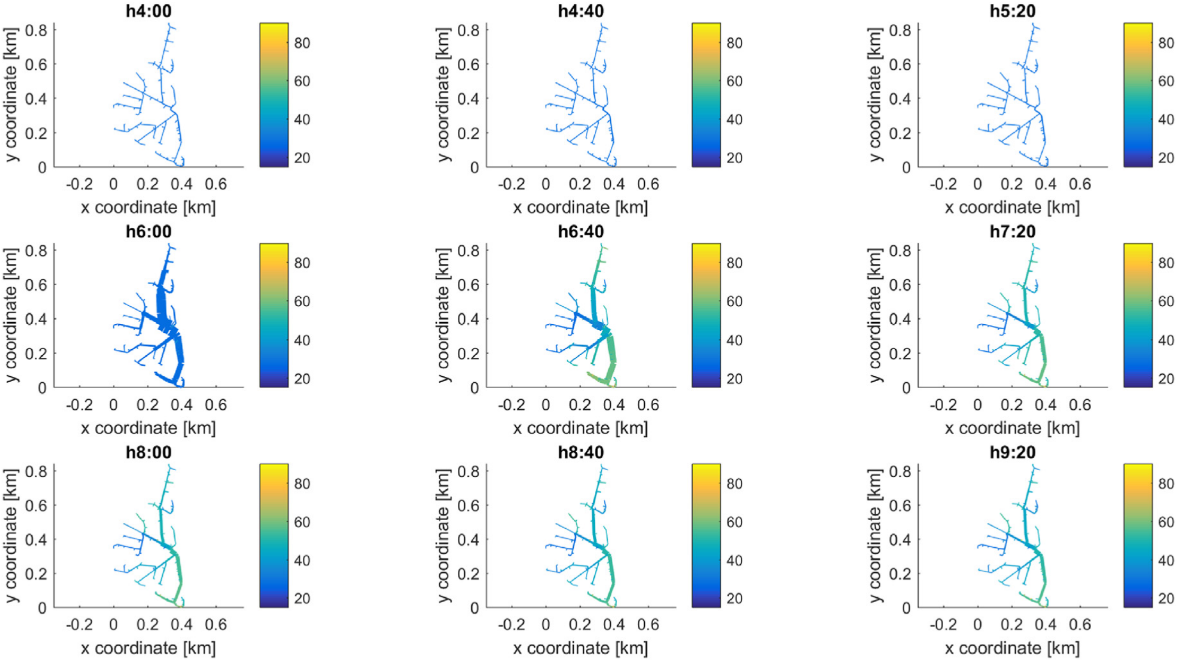

Fig. 6. Snapshots of temperature of water in the pipelines for different time. The depth of the lines is proportional to the mass flow rates flowing.

costumer substations open and mass flow rate starts flowing in the pipelines. In particular, from the figure referred to 6:00 a.m. it is possible to see that a large amount of cold mass flow rate has to be discharged. This is the water that was stopped in the return and supply lines and that cooled down during night.

Afterwards, at 6:20 a.m. the temperature of the water increases; this is the hot water that crossed the entire supply network, provided heat to the substation and that flows along the return pipelines. The mass flow rate is already reduced respect to the plot at 6:00 a.m. The temperature keep constant during the next steps, while the mass flow rates slightly decrease until the steady state condition is reached.

In general, when the thermal load at plant level is required, given the thermal request at costumer level, a this is evaluated using a network simulation. Fig. 7 reports the thermal request evolution obtained in three different ways:

- The first is the summation of the thermal requests of the buildings (as if all the buildings were located beside the thermal plants and the network does not exist). In this case, the thermal losses, the thermal transient and the time delay are all neglected (in Fig. 7 “NO TRANSIENT, NO LOSSES AND NO TIME DELAY”).
- The second is evaluated without using the fluid-dynamic model, but each building thermal request is delayed of a certain time, depending on the distance from the building to the BCT. In this case, the time delay has been considered but the thermal losses and the thermal transient have been neglected (in Fig. 7 “NO TRANSIENT AND NO LOSSES”).
- The third is the thermal request evaluated at the BCT point achieved by using the fluid-dynamic model, without considering the thermal losses. In this case, the model takes into account of both time delay and thermal transient (in Fig. 7 “NO LOSSES”).
- The fourth is the thermal request evaluated at the BCT point achieved by using the complete fluid-dynamic model. This case takes into account all the thermal losses, the thermal transient and the time delay (in Fig. 7 “MODEL”).

These series of curves are reported in Fig. 7 with two main aims:

1. Estimating the effects of not using network models to estimate thermal request profiles;
2. Evaluating the phenomena mostly affecting the discrepancy between results achieved with and without the network model.

Results show that the thermal profiles achieved with and without model are significantly different when the thermal demand changes in time (in particular at the peak). Peak amplitude in this case is under-estimated of about 20% when the network model is not used.

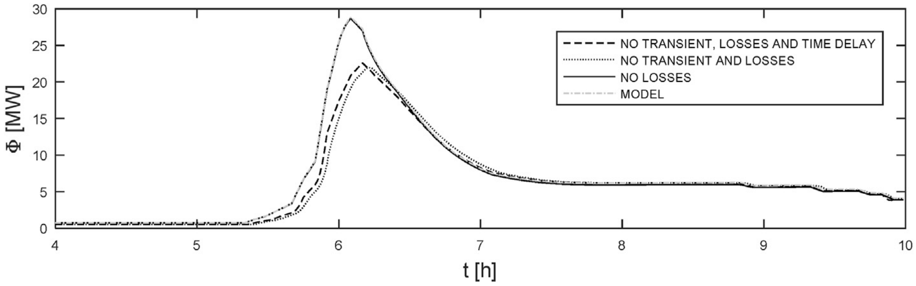

Fig. 7. Thermal load evolution evaluated with different techniques:1) as the summation of buildings thermal requests (NO TRANSIENT, NO LOSSES AND NO TIME DELAY), 2) as the summation of buildings thermal requests delayed (NO TRANSIENT AND NO LOSSES), 3) with the network physical model neglecting thermal losses (NO LOSSES), 4) with the network physical (MODEL).

The inclusion of time delay, shifts the thermal request ahead but this is still very different to the one achieved by the model. Comparing curve with and without thermal losses it is possible to notice that the influence of thermal losses is not significant in this simulation. The comparison of the various evolutions in Fig. 5, clarifies that the main difference between the curves occurs when the thermal transient is included in the calculation. This means that the large amount of water that is cooled down during the night has a significant effect in the thermal request when the mass flow rates strongly increases at morning.

In order to clearly show the influence of the thermal transient, two different cases are compared in Fig. 8; these are characterized by the same mass flow rate supplied to the costumers but different network diameters. The main differences between the two cases are that the first case, with smaller diameters, the mass within the pipelines is less and the water velocity in the pipelines is higher. The diameters are multiplied by a factor of 3 in the upper plot respect to the one reported in the lower plot in order to strongly show the effects of the water velocity on the thermal evolution. In case of small sections (the upper graph in Fig. 8), there is less mass cooling down in the pipelines during night (since dependence between mass and diameter is quadratic). In this case, during the start-up the thermal peak is much lower and the difference between results achieved with and without the model are significantly reduced. This is because the difference was mainly due to the amount of cold mass flow to be discharged. On the opposite, in case of large mass flow rates, the difference increases to 25%.

Fig. 9 shows the thermal evolutions for a network taking into account different level of night cooling: significant night cooling down, medium night cooling down and mild night cooling down. The level of night cool down can be due to the time the heating systems are kept stopped, the amount of thermal losses and the mass flow rate flowing the system during the night attenuation. In case of significant night, cooling down the temperature of the water inside the pipelines at the time of the start up is much lower than in case of mild cooling down. Fig. 9 shows that the thermal evolution is strongly influenced by the temperature of water inside the pipelines at the system start up. In case of significant cooling down the actual thermal request (MODEL line) is much larger than in case of mild cooling down, because at the start up a cold mass flow rate must be heated up until the supply temperature. This creates a higher thermal peak. It is interesting to notice that in case of significant cooling down the difference between the thermal evolution obtained by the model (line MODEL) and the summation of the

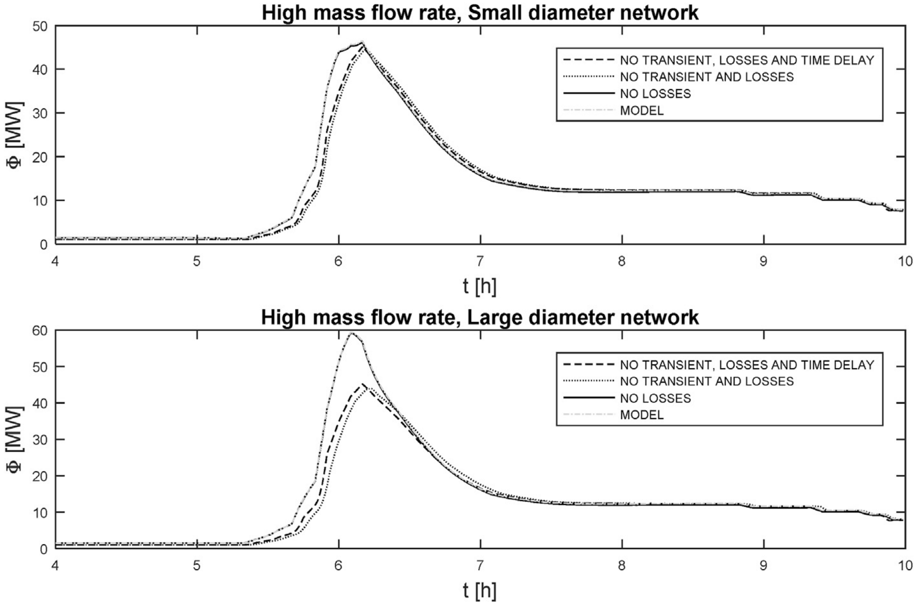

Fig. 8. Thermal load evolution evaluated with the same mass flow rate in case of small (upper figure) and large (lower figure) diameters. The various curves correspond to thermal load evaluated as:1) the summation of buildings thermal requests (NO TRANSIENT, LOSSES AND TIME DELAY), 2) the summation of buildings thermal requests delayed (NO TRANSIENT AND LOSSES), 3) with the network physical model neglecting thermal losses (NO LOSSES), 4) with the network physical (MODEL).

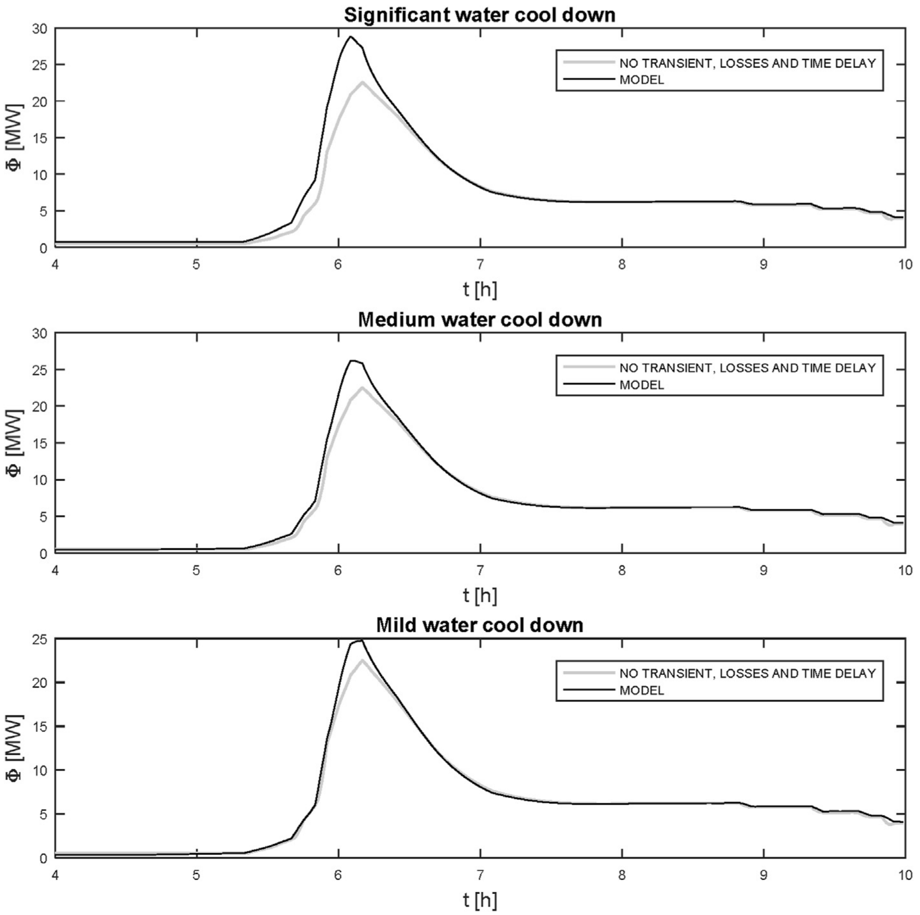

Fig. 9. Thermal load evolution evaluated with different level of night cooled down (that can be due by long switching off time or large thermal losses). The various curves correspond to the thermal loads evaluated:1) as the summation of buildings thermal requests (NO TRANSIENT, LOSSES AND TIME DELAY), 2)by the network physical (MODEL).

building thermal request (line NO TRANSIENT, LOSSES AND TIME DELAY) is much larger. In these case neglecting the thermal dynamics cause large error in the thermal request estimation.

The same analysis performed on other networks, with different topologies and load schedules, provide similar results. The thermal evolutions calculated with and without the model are reported in Fig. 10. In particular the zoom of the peak is shown for each case in the upper part of Fig. 10 while the network topology in the lower part. In all the cases, the two evolutions are different. In some cases (1st in Fig. 10) the difference between the two evolution is more significant, affecting both the shape and the peak amplitude (that reduces of about 15%). In other cases the difference is less significant in both shape and amplitude variation. Concerning the peak amplitude reduction, this is 7% and 2% respectively in the 2nd and 3rd cases in Fig. 10.

As shown in the various tests performed the importance of the network modelling is mainly related to the presence of thermal transient, due to modifications in the water temperature. In case of steady state conditions, the main contribution that the model allows to get are the thermal losses. An analysis with different values of pipeline transmittance has been performed. Results are reported in Tab. 2. Errors due neglecting the thermal losses range from 1% in case of U = 0.1 W/m2K, to 5% in case of U = 1.5 W/m2K. It is worth to mention that, although network pipelines are usually quite well insulated (well and medium), because of various reasons such as the aging of the installation, the network transmittance is much higher than the design value. Therefore it is important to use experimental data to evaluate the actual losses along the pipeline and as a consequence check the real pipe transmittance value.

6.2. Effects of network modelling on applications

As discussed in section 2, DH network modelling can be adopted to study several applications. In this section, it has been shown that the inclusion of the network dynamic can provide much more benefits while looking for the improvement of the DH performance. In particular, the demand side management application is considered. Demand side management in thermal networks is used with various aims. This is expected to shave the thermal request during the entire lifetime of the DH system. DSM allows a more free operation selection on the production side and smarter exploitation of the technologies at disposal; in particular, highest rate renewable energy sources and waste heat can be achieved. Furthermore, this allows increase the incomes from the electricity selling and use (in power to heat technologies). Another consequence is related to the possibility of reducing presence of bottlenecks that leads to an easier management of malfunctions and the possibility of having new customers by connecting new buildings without modifying the pipelines.

DSM can be done by modifying the thermal regulation or by changing the schedules of the system. In this case, schedules are modified in order to achieve the best peak reduction. Various cases are considered in the analysis, which have been reported in Table 2. Two different external temperature and two different application of DSM are considered. This allows achieving the effects of not considering the network dynamic in the research of the best DSM

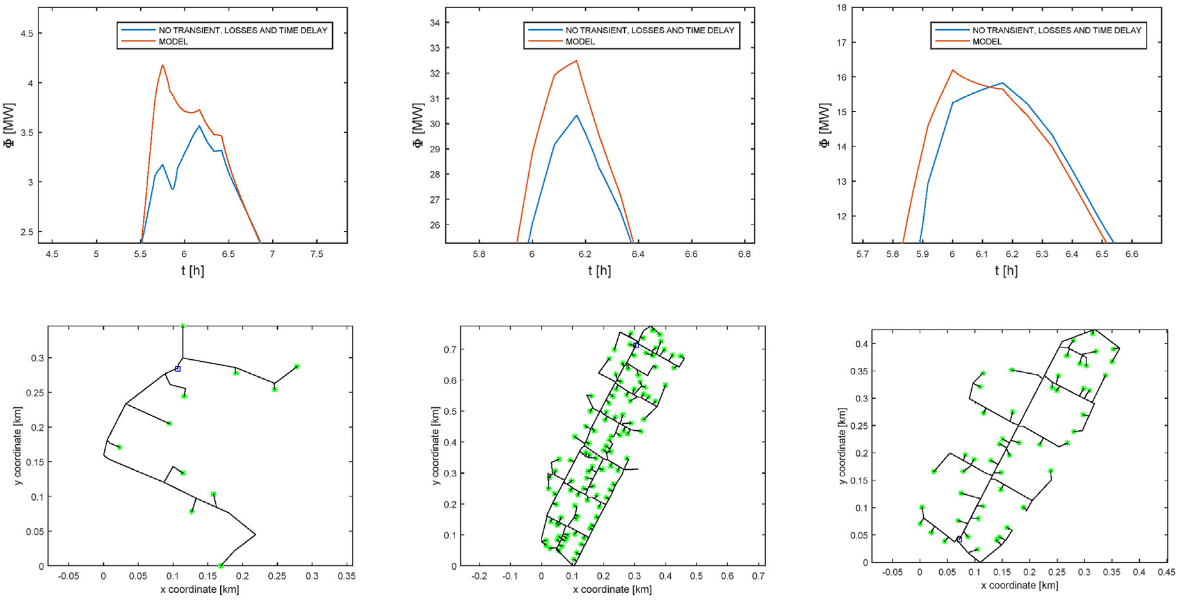

Fig. 10. Thermal load evolution evaluated for three different network topology/supply evolutions.

Table 2
Error in the evaluation of steady state thermal load for neglecting thermal losses.

	U [W/m2k]	% error in steady state estimation
Well-insulated network	0.1–0.3	0.3–0.8
Medium-insulated network	0.3–0.8	0.8–2.1
Less-insulated networks	0.8–1.5	2.1–4.3

for various types of cases.

The best DSM control is achieved by mean of an optimizer that evaluates the best change in heating schedule for each building. For the purpose of this work, the optimization is done with different objective functions. In the first case the summation of the thermal request at the buildings is minimized. In the second case it has been minimized the overall request at BCT evaluated with the physical network model. In particular, the approach described in Fig. 11 has been used for the work. The best DSM control by using the first objective function (without network modelling) is evaluated. The best DSM control is simulated by mean of the network simulator in order to evaluate the actual outcome of the DSM. This allows evaluating the actual benefits of the DSM strategy find without taking into account the network dynamic. The result obtained is compared with the one achieved with the second objective function (with network modelling).

Fig. 12 shows the peak reductions achieved for the four cases described in Table 3. In each case is reported: the profile obtained with DSM including the network model and the profile obtained with DSM without including the network model. The figure shows that the thermal peaks reduce significantly using DSM in all the considered cases. In case the network dynamics is not considered the benefits reduces in all the cases. Benefit reduction is larger in case of large networks, when (as shown in the results reported in Section 6.1) the network dynamics plays a fundamental role. Benefits in including the network dynamics significantly vary: they ranges between 1% (case 4) to about 18% (cases 1 and 2).

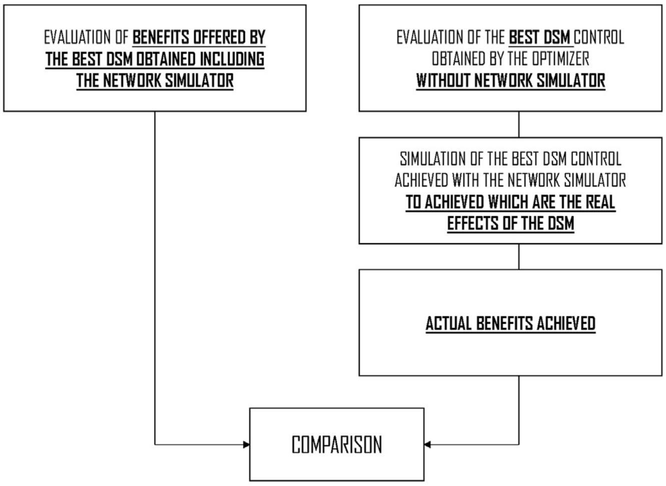

Fig. 11. Approach used for comparing DSM with and without network simulation.

7. Discussion

In general, it is impossible to define a-priory both the evolution and the peak amplitude. In fact, it is not possible to define if the sum of the thermal request at costumer level is higher or lower than that at the plant level. This is affected by various phenomena:

- The thermal losses (low influence).

Table 3
Test Cases considered for demand side management.

	Large network	Small network
Light DSM (maximum 20 min schedule change)	CASE 1	CASE 3
Significant DSM (maximum 60 min schedule change)	CASE 2	CASE 4

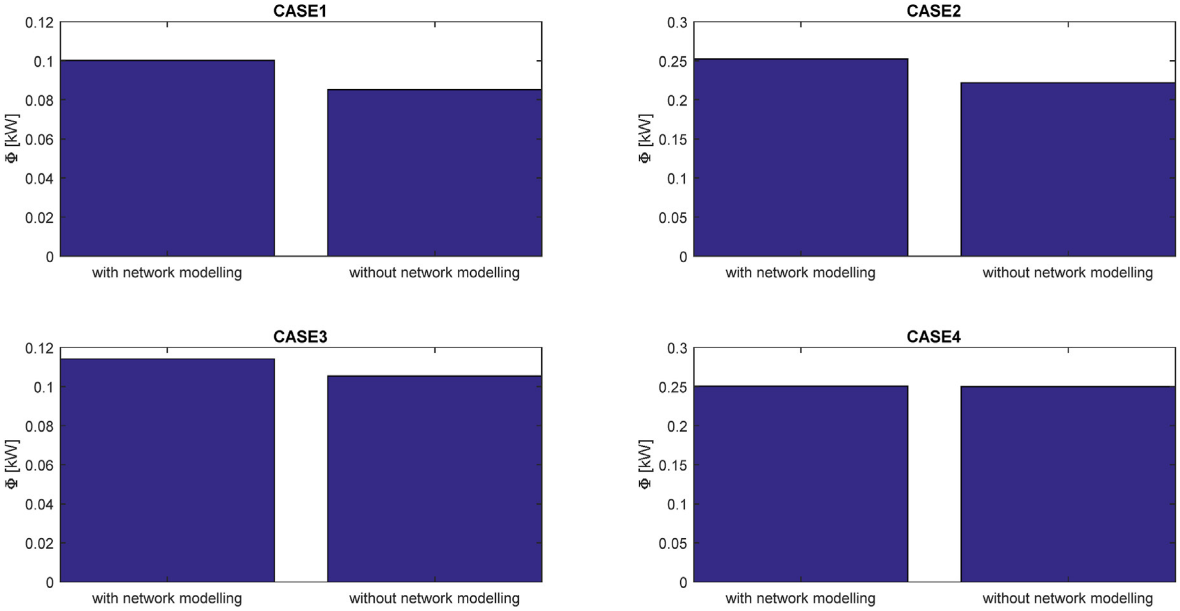

Fig. 12. Maximum peak reduction achieved by DSM in various cases in case the network is considered or neglected.

- The temperature of water within the pipelines between the costumers and the plants.
- The time the peaks occur at the buildings; if peaks occur at the same time, in case costumers and the plant are located at various distances, the peak at the plant could be reduced by the distance of the various users.
- The time the peak request takes to reach the plant. This is mainly due
  - The distances between the costumers and the plants, because if costumers were all located at the same distances from the plant and the peak at the costumers peaks occur at the same time, in case water velocity within the pipelines was similar, the global peak at the plant could be significant.
  - The mass flow rate, and therefore the water velocity, in each branch.

Actually, all these phenomena cannot be easily included without a proper network model. Results show that the network dynamics should be considered in the following two main cases:

1) In case of large networks
2) In case of significant fluid cooling down in some parts of the network

Inclusion of the network model in more complex analysis could create various problems, not the least the computational time required but also the nonlinearity of the problem. This can be particularly not trivial in case of optimizations or when multiple scenarios are taken into account. An interesting option consists using techniques that can be used to reduce the problem complexity and as a consequence the computational cost. Some of these are:

1) Running the simulation of the fluid dynamics problem (which is non-linear) only when a significant amount in mass flow rates occurs, while running the simulation of the thermal problem (which is linear) in all the time steps.
2) When pressure distribution is not required, use approaches to consider looped networks as tree-shaped networks, as shown in [20].
3) Use of compact model or equivalent black box approaches to solve the dynamic problem with a simpler model.

All these types of approaches can be used to make modelling simpler to be included in more complex model, optimizer and simulation tool without losing the result precision.

8. Conclusions

In this work, the effects and the relevance of including network dynamics in district heating system modelling are studied. The final aim is to provide insight on the impact and possibility of neglecting the thermal dynamics in the analysis of district heating networks. A district heating network has been analyzed during thermal transients and steady state condition. Various simulations have been performed to find the physical phenomenon (e.g. thermal losses, time delay, thermal transient) which significantly affect the results.

Results show that the energy requested by district heating during peak after relevant changes in network operations is significantly larger if considering the effects of the thermal mass of water within the pipelines. This means that in case of changes in network operations (i.e. night shut-off or setback) the network dynamics should not be neglected. In particular, the most significant phenomenon is the thermal transient, while time delay and especially thermal losses plays minor roles; the thermal transient is due to the large amount of water that cool down during night. The differences in thermal request range between 2 and 20%. This depends on a combination of network topology/dimension and building heating system schedules In particular, the network dynamic is relevant in case of large amount of water (large diameters and large thermal masses) and significant variations in supply mass flow rates and temperatures.

Concerning the cases of constant supply (no variation of mass flow rates and temperatures), the use of network physical models makes sense only in case of not perfectly insulated networks, for instance due to network aging (relative errors up to 4% in the thermal request evaluation).

Effects of neglecting network dynamics while looking for optimal district heating management are also analyzed considering a specific application. This is demand side management and in particular the adoption of proper model to find the best rescheduling of building demand. . Inclusion of network dynamics in optimal demand response evaluation can produce a large range of outcomes; in some cases benefits increases up to 18%, in other cases reduction are less significant. As expected larger benefits are obtained in case of large networks, where the network dynamics plays a significant role.

Declaration of competing interest

I hereby declare that are no financial interests and personal relationships with other people or organizations that could inappropriately influence (bias) their work.

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NOMENCLATURE

A: Incidence matrix, [−]
b: distributed fluidynamic losses coefficient
C: array with pipeline characteristics
c: thermal capacity [J/kgK]
D: diameters [m]
G: mass flow rate, [kg.s-1]
K: Stiffness matrix
L: Length [m]
M: Mass matrix
P: Pressure [bar]
T: Temperature, [K]
T: Time [s]
V: Volume [m3]
v: Velocity [m.s-1]
U: Global heat exchange coefficient, [W.m-2. K-1]

Greek symbols

φ: Thermal power, Kw
B: Concentrated fluidynamic losses coefficient
ρ: Density

Subscripts

env: environmental
ext: From the extern