PROCEEDINGS OF ECOS 2015 - THE 28TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
JUNE 30-JULY 3, 2015, PAU, FRANCE

Thermal fluid-dynamic model of a DHN for load prediction of thermal plants

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Abstract:

Despite district heating is a quite simple idea that has been applied for decades, it is still an important research topic, thanks to the various aspects that are continuously evolving: the use of renewable sources, innovative materials, long- and short-term storage systems, the integration of ICT solutions, etc. Detailed thermofluid-dynamic simulation tools can be of extreme importance for the optimal management of modern district heating networks. Some of the issues that simulation tools are requested to face are: peak shaving, selection of the operating temperature, operation in the case of malfunctions, storage management, etc.

This paper aims at presenting a detailed simulation approach that can be applied to large district heating networks. The main pipeline is fully modeled considering fluid flow and transient heat transfer, while the subnetworks (from the single users to the main network) are examined using two different detail levels: full model and equivalent model. The latter is directly obtained from the full model and allows one to significantly reduce the computational time.

The modeling approach is applied to the analysis of transient operation of the Turin district heating network. The main network and three subnetworks are fully modeled, while for the other subnetworks an equivalent model is used. Starting from the thermal request of the users it is possible to obtain the thermal load variation at the plants. This approach can be used to examine the effects of variations in the thermal request profiles of some of the users on the global thermal load of the network during the start-up transient.

Keywords:

District heating, Thermal modeling, Fluid-dynamic modeling, Network Model, Optimal management.

1. Introduction

District heating systems (DHS) are an efficient way for house heating in particular for densely populated areas [1]. In such systems thermal energy is produced in dedicated power plants and it is provided to the users through a district heating network (DHN). The use of decentralized power plant allows one to reach high efficiency in particular when electrical and thermal energy production are combined.

District heating systems are often analyzed in both design [2] and management stages[3], in order to obtain information that allow the reduction of primary energy consumption. In the last years the attention has been focused to the connection of district heating systems with sustainable energy sources like biomass [4], solar [5] and geothermal[6]. Recent works in literature also show a certain interest on minimization of pumping cost in district heating network [7,8,9] and prediction and analysis of the thermal loads variations of connected heat power plants [10].

Therefore the use of modeling in order to analyse different system design and particular working condition of district heating network is an important subject related to technical, economical and environmental reasons. In literature different approaches for modelling district heating networks have been proposed. They can be grouped into two main types [11], the black box approach, where the physical composition of the network is disregarded and the modeling is in form of standard transfer function models or neural networks, and the physical approach, that involves use of mathematical methods for computing flow and temperature distribution in the network. As regards the second approach different types of model have been developed. Hardy Cross [12] proposed a method built for momentum distribution in statically determinate structures in order to study network systems. In more recent period new approaches have been proposed in order to overcome problems related to convergence, computational cost and limited use that affect Hardy Cross method [13]. One of the most used approach in order to solve district heating hydraulics is the loop equation method [8].Aggregated models which use a lower number of equivalent branches in order to simplify the network have been developed [14].Furthermore anode model has been carried out; the principle of the node method is to keep trace of how long a time a water mass has been on its way from the previous node [15].Both aggregated and node models do not solve fluid-dynamic and thermal transient conservation equations within the network [16]. Stevanovic et al. [16] solve thermal fluid-dynamic problem of an existing network, neglecting heat losses; no information about computational cost are provided.

In this paper a new method is proposed in order to simulate the transient thermal fluid-dynamic behaviour of large district heating network that also involves loops. The model is applied to the Turin district heating network which is the largest in Italy. The model considers the main pipeline and the distribution pipelines (subnetworks)separately. The main pipeline is characterized by pipe with large sections while the subnetworks connect the main pipeline to the users. A fluid dynamic and a transient thermal models are developed in order to simulate the main pipelines behaviour. The first one provides the mass flow rates in all the branches of the network; mass flow rates are used in the thermal one in order to evaluate the temperature evolution in all the nodes. An equivalent model has been built in order to take into account subnetworks that connect the main network to the single users. Subnetworks model provide temperature and mass flow rate of water that exit users. This approach has been developed with the purpose of reducing the computational time required for the simulation of large networks. Using this models prediction of the thermal loads of heat power plants connected to the district heating network during the daily transient has been carried out.

2. System description

The largest district heating system in Italy has been considered in order to show the capability of the model to analyze networks with a large number of branches. The system is located in Turin and it involve about 56 million m^3 of buildings. The annual thermal request is about 2000 GWh and the maximum thermal power is about 1.4GW.A schematic of the system is shown in Figure 1.

In this schematic, all the users connected to the network are grouped with the others located in the same areas; these groups of users are called barycenters. The main pipeline, connecting the thermal plants with the barycenters, is shown on the right side of the figure. In each barycentre, a three-shaped subnetwork directly connected with the main pipeline distributes hot water to the heat exchangers located in the buildings. Three subnetworks are shown on the left side of the figure.

Five thermal plants, highlighted in green in Fig.1, provide heat to the network. The main characteristics of the plants are reported in Tab. 1. As regards the imposed start-up strategy, power plants are started up in succession with the increase of the heat request to the users. Namely, only the first plant, Moncalieri cogeneration plant, is assumed to operate when the network heat requests is lower than its maximum power. When the heat request to the network increases, the second Moncalieri is started up, then Torino Nord cogeneration plant and the storage systems are operated. As regard storage in the systems are used sensible water storage with a capacity of 2500 m^3; in the Politecnico are used three of them, in Torino Nord six of them. Boilers are used to cover large thermal request and as backup systems.

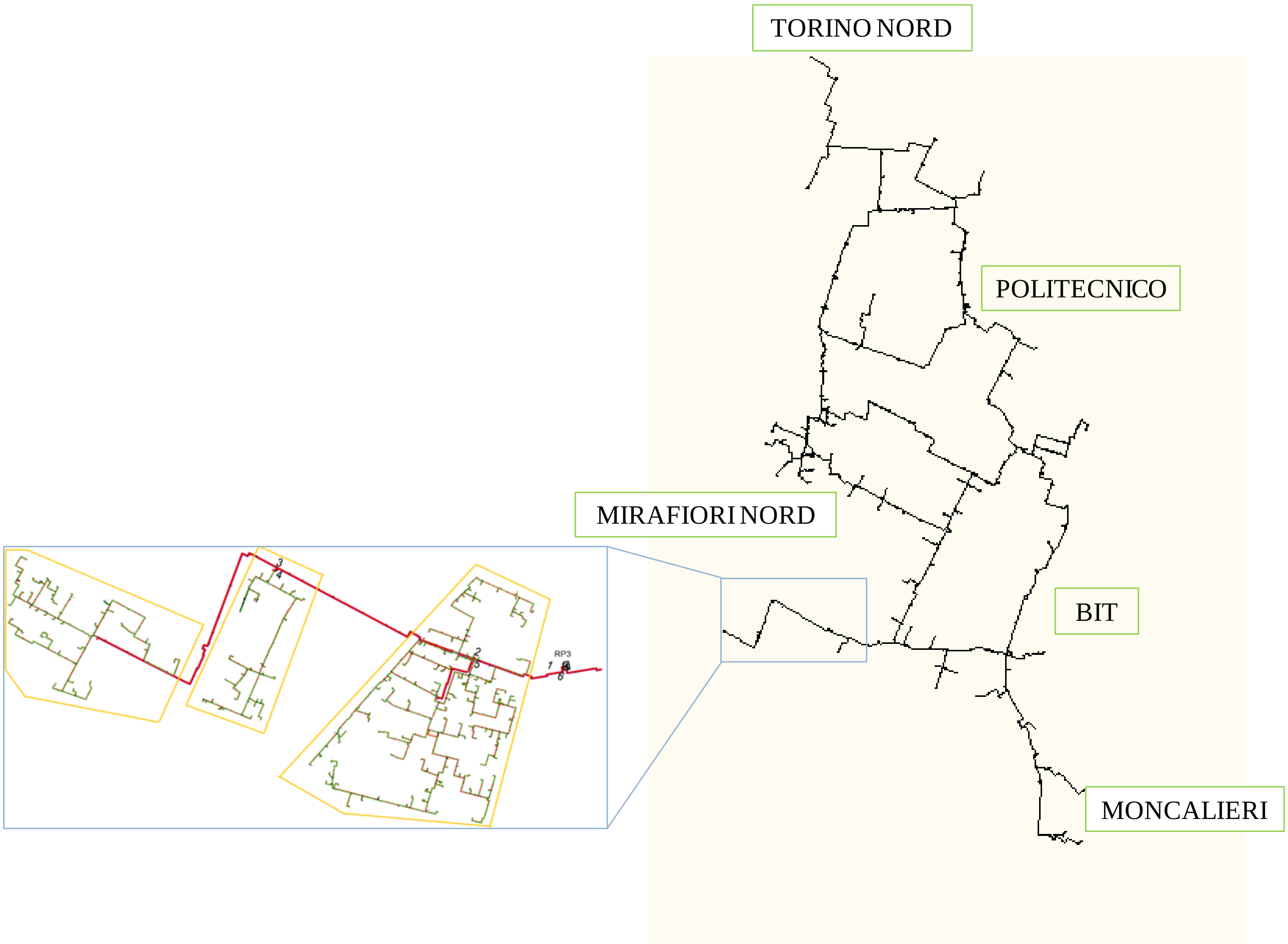

Figure 1. Schematic of Turin District Heating Network

Table 1 shows the configuration of the various plants, their nominal power, and the usual start-up order.

Table 1. Characteristics of the thermal plants

Plant	Type	NominalPower [MW]	Start-up order
Moncalieri	2 Cogeneration plants	520	1st
	Boilers	141	Back-up
BIT	Boilers	255	7th
Mirafiori Nord	Boilers	35	4th
Politecnico	Boilers	255	6th
	Storage	60	3th
Torino Nord	Cogeneration	220	2nd
	Boilers	340	Back-up
	Storage	150	5th

2. The Thermal Fluid-dynamic Model

2.1 Model description

In this section a description of the approach used in order to model the considered district heating network is reported. For simplicity in Fig. 2 a schematic of a generic power plant with the thermal fluid-dynamic variables are reported.

The thermal power request evolution to the ith power plant, represented in Fig. 2, is evaluated using (1).

$$\Phi_i = G_{ret\_i}\, c \left(T_{sup} - T_{ret\_i}\right), \qquad (1)$$

where T_{sup} is the temperature of water exiting the thermal plant (supply pipeline), $G_{ret_i}$is the mass flow rate that enters (and exits) the ith plant and, T_{ret_i} is the temperature of water entering the ith plant (return pipeline).The supply temperature is about 120°C.For sake of simplicity, in this work temperature is assumed as constant on the supply pipeline. An analysis for proving that the decrease of temperature in the supply main network does not widely affect the results has been performed. The analysis shows that few losses occurs and the temperature decreases only by 1-2 degrees from the power plant to the three studied barycentres. The return pipeline(line blue in Fig. 2) is considered and temperature of water entering each plant T_{ret_i} is calculated in order to determine the thermal request evolution at the plants.

Mass flow rate flowing in the network is determined by the control systems located in each substation (i.e. in each building).The mass flow rate exiting the users jth and the respective temperature (G_{us_j} and T_{us_j}in Fig. 2) are evaluated through a model of the subnetworks as described in Section 2.3.

Mass flow rate distribution among the various plants, G_{ret_i}, is a consequence of the start-up strategy previously discussed.

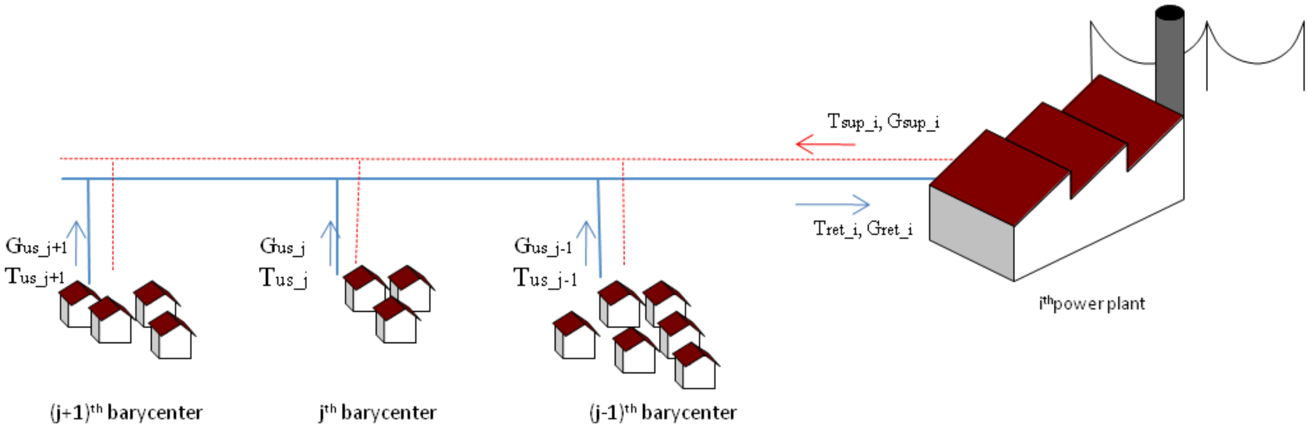

Figure 2. Schematic of inputs for the main pipeline model

The model developed in this work considers separately the main pipeline and the subnetworks. The full fluid-dynamic model only considers the main pipeline while the subnetwork are considered using an equivalent model obtained from separate application of the full model to three subnetworks. This choice was done in order to reduce the computational cost for the evaluation of transient load required to the power plants.

2.2 Main pipeline model

A one dimensional model has been developed to detail the thermo-fluid dynamic behaviour of the main pipeline of the network. The topology of the network has been described using a graph approach [17].Namely, each pipe of the network has been considered as branch that starts from a node, the inlet node, and ends in another node, the outlet node. The main return pipeline network include 685 branches and 677 nodes, with 9 loops. The fluid-dynamic model considers the mass conservation equation applied to all the nodes and the momentum conservation equation to all the branches.

The incidence matrix **A** is used in order to describe the connection between nodes and branches. In fact the general element A_{ij} is equal to 1 or -1 if the branch j enters or exits the node i and 0 otherwise. Matrix **A** has as many rows as the number of nodes and as many columns as the number of branches. Therefore the mass balance equation written using matrix form is:

$$\mathbf{A} \cdot \mathbf{G} + \mathbf{G}_{\mathbf{ext}} = 0\,, \qquad (2)$$

where **G** is the vector that contains mass flow rates in branches and $\mathbf{G}_{\mathbf{ext}}$ the vector that contains mass flow rates exiting the nodes towards the extern. $\mathbf{G}_{\mathbf{ext}}$ terms are different than zero in the case of open networks, i.e. when only a portion of the entire closed circuit is considered. If the supply network is considered, the network results as open at the plants and at the users.

The steady-state momentum conservation equation in a branch for an incompressible fluid is considered, neglecting the velocity change between input and output sections and including the gravitational term in the static pressure:

$$(p_{in} - p_{out}) = \frac{1}{2}\frac{f}{D} L \frac{G^2}{\rho S^2} + \frac{1}{2}\sum_k \beta_k \frac{G^2}{\rho S^2} - \Delta p_{pumps}\,, \qquad (3)$$

where the first and the second terms on the right-hand side terms are respectively the distributed and the localized pressure losses, while the last term is the pressure rise due to pumps. This can be rewritten as:

$$G = Y(p_{in} - p_{out}) + Y\Delta p_{pumps}\,, \qquad (4)$$

where the term Y is the fluid dynamic conductance of the branch, expressed as:

$$Y = R^{-1} = \left[\frac{1}{2}\frac{G}{\rho S^2}\left(\frac{f}{D}L + \sum_k \beta_k\right)\right]^{-1} \qquad (5)$$

The friction factor f has been evaluated using an explicit Haaland correlation in order to reduce the computational cost of the simulations.

Therefore momentum equation rewritten in a matrix form, using the incidence matrix, becomes:

$$\boldsymbol{G} = \boldsymbol{Y} \cdot \boldsymbol{A}^T \cdot \boldsymbol{P} + \boldsymbol{Y} \cdot \Delta \boldsymbol{p}_{pumps}\,, \qquad (6)$$

where the diagonal matrix **Y** represents the fluid dynamic conductance of branches. Because of the dependence of Y on pressure, the obtained system of equation is non-linear. Equation (6) is finally modified by setting proper boundary conditions

The solution of the mass and momentum equations is performed using a SIMPLE (semi implicit method for pressure linked equation) algorithm [18].This is a guess and correction method: a pressure vector is first guessed and during the iterations it is corrected together with the mass flow rate vector obtained using (6). Further details on the method are available in [19].In order to solve the system of non-linear equations a fixed point algorithm has been used.

As regards the thermal model the energy conservation equation for the i^{th} node, neglecting conduction in the fluid along the network and volumetric heat release within the control volume is:

$$\frac{\partial(\rho c \Delta T)_i}{\partial t}\Delta V_i + \sum_j c G_j T_j = Utot(T_i - T_{env})\,, (7)$$

where the first is the unsteady term, the second regards the contribution due to all the j^{th} branches connected to the i^{th} node and the right-hand side term represents the thermal losses. In order to relate branches and nodes an Upwind Scheme, that assigns to the j^{th} branch the temperature of the upstream node, is used. Equation (6) can be written in matrix form for all nodes:

$$\mathbf{M}\dot{\mathbf{T}} + \mathbf{K}\mathbf{T} = \mathbf{g}, \qquad (8)$$

Dirichelet boundary condition have been imposed in all the barycentres. In the outlet section an outlet mass flow rate has been imposed.

2.3 Subnetwork model

In this section the equivalent model of the subnetworks is analyzed. Three of the barycentres have been chosen for detailed study. The considered barycentres are characterized by different values of volume of buildings connected and therefore different maximum required heat power; these are the three barycentres highlighted in Fig. 1.They are modelled using the same approach described in 2.2 Section in order to obtain the temperature and the mass flow rate living them.

The same thermo fluid-dynamic model considered in the previous section is considered for full modelling. The only difference consists in the boundary conditions that are set. The mass flow rate supplied to each user is obtained by adjusting the valves in order to achieve the set point temperature on the heating system of each building. In the case the heating system is based on radiators, the set point is considered as a linear function of the external temperature (supply temperature is 80 °C when the external temperature is -8 °C and 20 °C when the external temperature is 20 °C).

As already discussed the total volume of buildings fed by these barycentres is different in the three cases. Therefore a relation between mass flow rates(and temperature) of water that enters the network from the users and the maximum required heat power is obtained using 2D linear interpolation. Using this relationship it is possible to set the values of mass flow rates G_{us_j} and the temperature, T_{us_j} of water that comes from all the users.

3. Results

In the first part of this section results regarding the subnetwork model are analyzed. Only three barycentres have been considered. Fig. 3 shows the evolution of the temperature and mass flow rate in the three barycentres during the transient between 8 p.m. and 10 a.m.

Due to users regulation strategy discussed before, mass flow rate required to the three users, is constant during the last hours of the evening, then it dramatically decreases at 11 p.m and it remains constant during all night. Early morning the mass flow rate gradually increases between 5 a.m. and 6 a.m then it remains constant.

Temperature values change during all the considered time. Temperature is 335 K at 8 p.m., it decreases until 6 a.m. then it increases and reaches a value of about 330 K in each considered case.

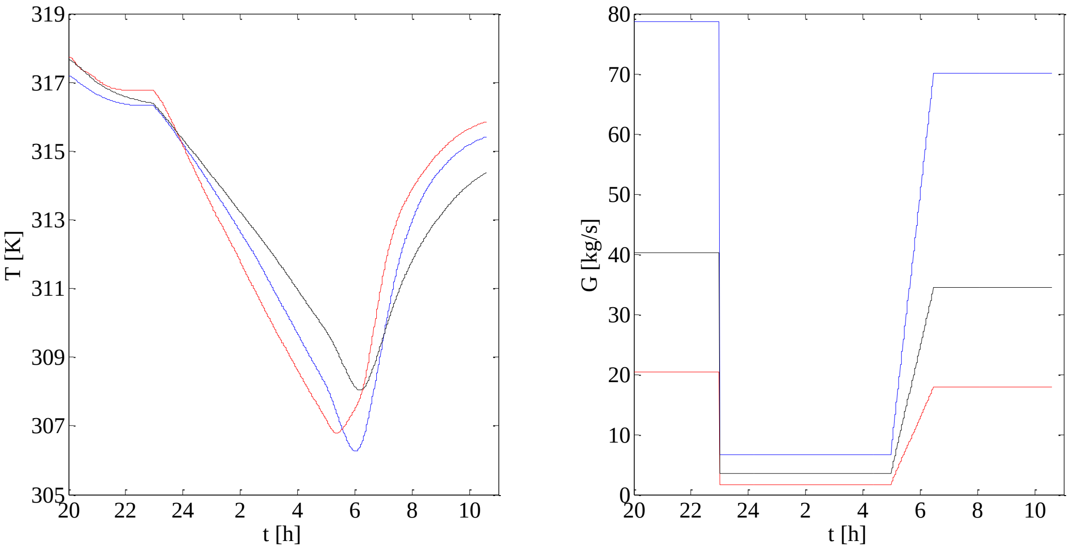

Figure 3. Temperature and mass flow evolutions rate of water exiting the analyzed barycentres

The relation between the barycentres temperature evolution and the maximum load of users has been evaluated and reported in Fig.4. Temperature of water that exits the users is lower when the heat power required by the users is higher.

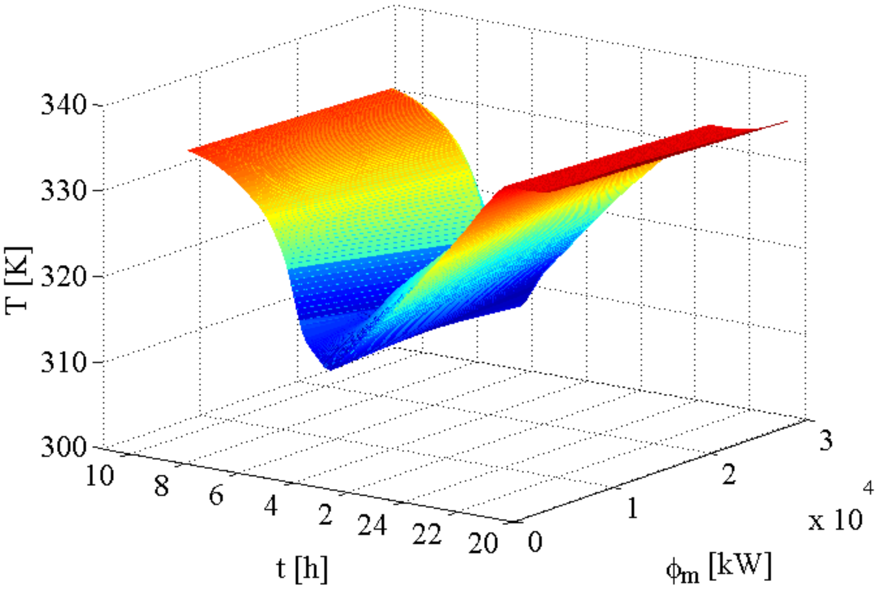

Figure 4. 2D interpolation for boundaries condition evaluation

As mentioned previously results reported in Fig.4havebeen used to find temperatures and mass flow rates of fluid that exits each barycenter; they have been used as boundary conditions in the main pipeline model. The main pipeline model provides values of pressure and temperature in each node and mass flow rate in each branch. The temperature evolution in some particular points of the network has been monitored and reported in Fig. 5.

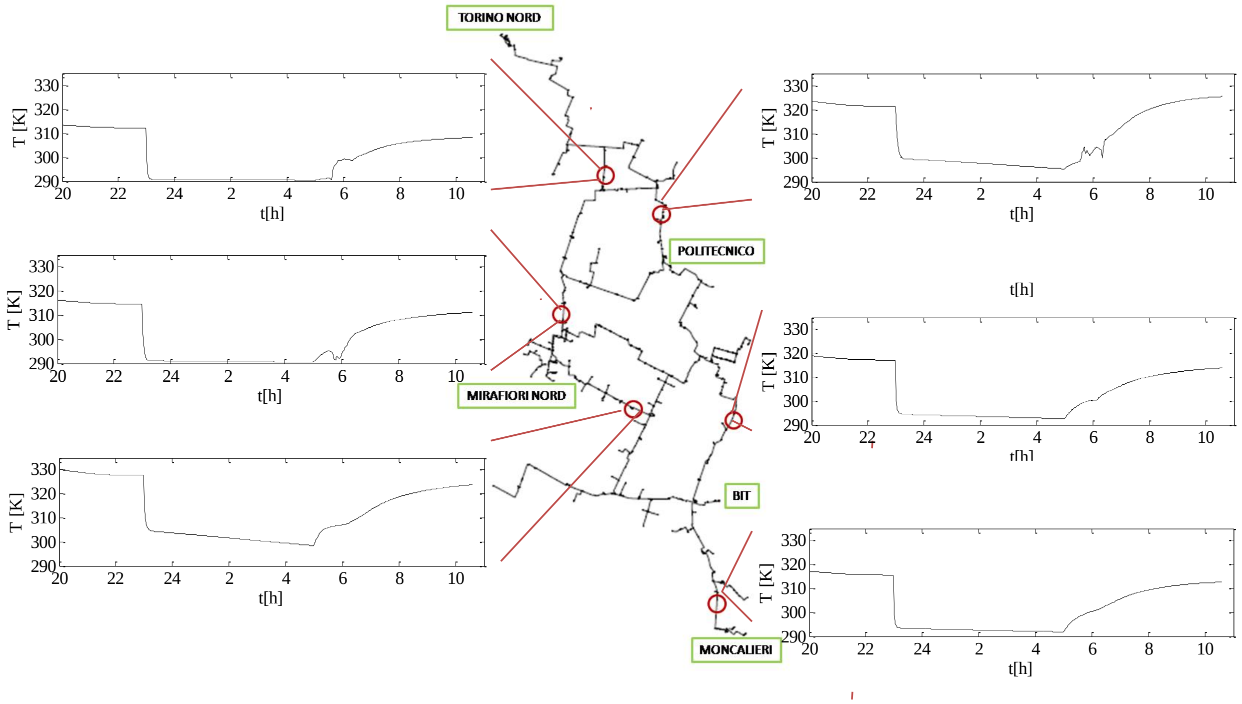

Figure 5. Schematic of inputs for the main pipeline model

The shape of temperature evolution is similar to the evolution of water mass flow rate for the users, displayed in Fig. 3.Temperaturesare constant until 11 p.m. with a values included between 315 K and 330 K, then drastically decrease to values between 290 K and 300 K. After 5 a.m. temperatures rise slowly due to some different reasons: the large distances involved from users to the other nodes of the network, the gradually increase of mass flow rates exiting the users (Fig. 3) and the thermal inertia of pipes.

As detailed in Fig. 5 temperature values in two of the considered nodes, c) and d), do not decrease below290 K as in the other monitored nodes. This is due to the fact that they are placed close to a high number of users and the global request is not negligible even at night.

The thermal heat power evolution during the transient in the all the plants is reported in Fig. 6.It appears that at 5 a.m. the maximum power load is verified in all the power plants. Moncalieri is the only power plant where the thermal request does not become zero. All the other plants are started up at 5 a.m. except for boilers located in the Bit plant.

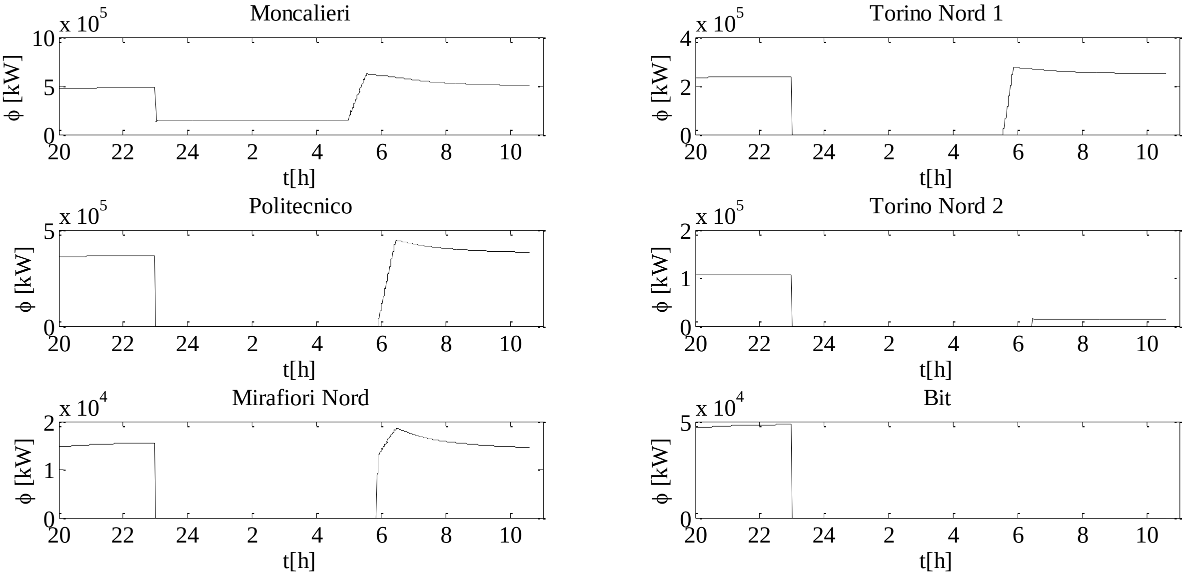

Figure 6. Heat power required to the power plants during all the night transient

In Fig. 7 the total amount of thermal energy required during the considered transient has been represented. The energy demand reaches the maximum value of about 1350 MW during the start-up period after 6 a.m. After that the heat required slightly decreases until a value of about 1250 MW. This is the same heat power quantity required during the evening, before 11 p.m. All the data provided in Fig. 6 and 7 might be used to forecast the thermal power demand in all the power plants with different load conditions in order to implements primary energy saving plans.

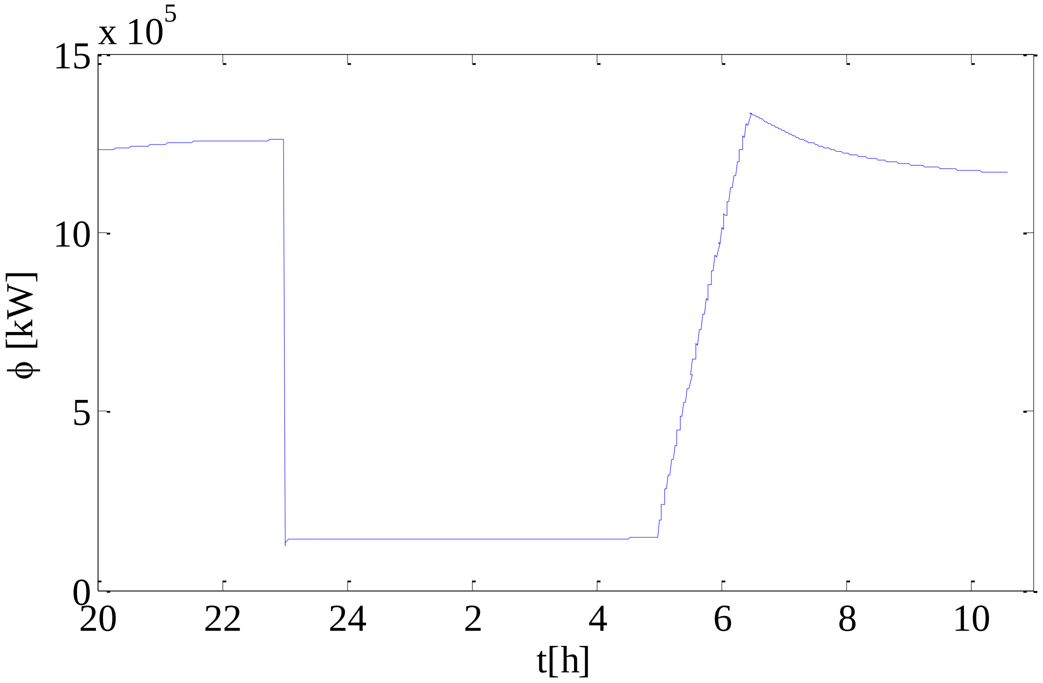

Figure 7. Total heat power required evolution during all the night transient

The computational time needed to solve the thermal fluid-dynamic model for the entire transient on a single 3.3 GHz CPU is about300 s. Therefore this model can be used in order to simulate behavior of large district heating network with an appreciably low computational cost.

4. Conclusions

In the present work a thermal fluid dynamic model for the unsteady simulation of large district heating network, based on the conservation equations, has been proposed. The model has been applied to the Turin district heating network, the largest in Italy, in order to analyze the start-up transient.

The main pipeline has been simulated while an equivalent model has been used in order to study the behaviour of subnetworks. A fluid dynamic and a transient thermal model has been built; the fluid dynamic model provides the mass flow rates in branches. Mass flow rates are used in order to evaluate, with the thermal model, the temperature evolution in the nodes. A SIMPLE algorithm is used in order to solve the fluid-dynamic problem. As regards the thermal problem an Upwind scheme is used. Three subnetworks are also studied using the models previously discussed in order to evaluate mass flow rate and temperature of water that enters the main pipelines as function of total volume of connected buildings.

The computational time to solve the thermal fluid-dynamic model to simulate the network behavior for 10 hours is about300 s.Therefore this model might be considered an useful toll in order to simulate thermal fluid-dynamic behaviour of large district heating networks with low computational cost.

Temperature in all the nodes and mass flow rates in all the branches are obtained. Using these data the thermal power evolution in all the plants connected to the network has been evaluated. Results clearly report the value of heat power peak and how it is shared among the power plants. It is also reported the time when the peak occurs, that is different for all the plants connected to the users, due to the large extension of the network. Furthermore it is shown the evolution of the total thermal request with its peak and the time it occurs. The prediction of all these information can be useful as decisional support in strategies for primary energy saving and thermal peak shaving.

Nomenclature

A	incidence matrix
c	specific heat, J/(kg K)
D	pipe diameter, m
f	distributed friction factor
G	mass flow rate, kg/s
K	stiffness matrix
L	pipe length, m
M	mass matrix, kg
p	pressure, Pa
P	pressure matrix
S	pipe section, m^2
T	temperature, °C
U	pipe transmittance W/kg K
Y	fluid dynamic conductance

Greek symbols

β	localized friction factor

ρ density

Φ Heat power

Subscripts and superscripts

ext external

in inlet

out output

ret return

sup supply

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