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Demand side management in district heating systems by innovative control

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Abstract:

Peak shaving of thermal demand plays an important role in district heating (DH) by allowing a smarter management of the plants connected. A flat demand profile causes various advantages, increasing potential of using more convenient and less pollutant sources, such as waste heat, cogeneration and heat produced through renewable sources. The flattening of the demand also allows further connections without modifying the pipelines. An option for reducing the thermal peak is the use of demand side management, also called virtual storage, i.e. the variation in the thermal request profile of the buildings. Demand side management can be applied to DH systems by changing the substation regulation strategies. This paper aims at analysing the opportunities for peak shaving with a different regulation strategy, i.e. the Differential of Return Temperatures (DRT) regulation strategy. This paper shows that use of the DRT regulation reduces the user thermal peak on average of 15% and the total request of the analysed distribution network of 24%. Furthermore, some further developments are suggested with the aim of optimally exploiting the DRT potentials for peak shaving.

Keywords:

Thermal grid; smart energy system; Demand response; thermal networks; Control strategy; Sustainability

1. Introduction

District heating infrastructures are expected to play an important role to increase energy efficiency and exploit of renewable energy sources (RES) [1-2]. These provide thermal energy produced by various types of plants and sources for space hating and domestic hot water to the buildings located in an urban area. This approach leads to a flexible use of high efficiency technologies [3-5] and renewable energy sources [6, 7] together with the utilization of waste heat from industrial sites [8, 9]. These advantages diminish when the thermal request presents significant oscillations and peaks. Particularly the presence of thermal peaks represent an important issue in DH systems. This problem especially arises in Mediterranean areas where heating systems are commonly switched off during the night and a thermal peak occurs in the morning when large temperature differences between primary and secondary side of the substation takes place.

Any reduction in thermal peak increases the possibilities of exploiting DH systems capabilities, growing the exploitation of high efficiency plants and renewable energy sources, reducing the primary energy consumption [10]. Another benefit in peak shaving is related to the possibility of connecting additional buildings to the network without modifying the existing pipelines [11]. A third advantage consist in the more effective combination of thermal and electrical energy production for increasing competitiveness on the electricity market. Furthermore, a flat request profile makes the management of DH system malfunction easier [12].

A first option that can be used for reducing the thermal peak is the installation of thermal energy storages (TES) [13-15] to limit the mismatch between supply and demand. In [16] an actual heating demand of a DH system is considered and the combination of combined heat and power (CHP) units and thermal storages that determine the theoretical maximum of flexibility is evaluated. In [17], the integration of storages in a CHP-DH system, fed also by RES, is optimized. In [18] the use of storage systems, charged at night and used during the start-up transients, is shown to be a very effective measure for shaving thermal peak and consequently reducing the boiler utilization enhancing cogeneration use. In [19] a heat storage is considered for maximising the electricity production in the CHP plants during peak-price periods and for minimizing the use of plants with higher energy costs.

A second option for smart managing mismatch between energy demand and efficient production is the exploitation of the thermal inertia of DH systems. In [20], the optimal operation for an integrated energy system combining the thermal inertia of a DH network and buildings is evaluated with the aim of enhancing the exploitation of RES (in particular wind power).

Another way of proceeding for the thermal peak reduction regards the implementation of demand side management, also called demand response or virtual storage. Demand side management allows the reduction of the thermal peak load through modification of the thermal request profiles of the buildings connected to a district heating (DH) system [21]. This can be used in place, or in addition, to TES in order to obtain a further peak reduction, by properly managing the thermal request [22]. Virtual storage requires only the installation of a substation control unit and a software infrastructure for DH energy management [23]. Once the control units are installed and the software developed, no extra investments are required. In [24] two different approaches are used for modifying the thermal request profile of some users in order to minimize the maximum peak or maximize heat production from cogeneration or renewable plants. This approach rely on the forecast of the building request profile [25, 26]. In [10], a virtual storage optimizer based on user model is used with the aim of minimizing the thermal peak without compromising the indoor temperature level. A clustering approach is proposed in [27] with the aim of quantifying the maximum request variation allowed for each building in order to increase effectiveness of peak shaving. Variation of heating system schedule is not the only approach to perform demand side management.

In the present work, a new kind of regulation strategy for the substations (DRT regulation system) is analysed in order to show its potential for thermal peak shaving. The main idea of the new regulation approach is to keep the temperature difference between the two sides of the heat exchanger low. This allows one improving the heat exchanger performances, reducing the thermal peak during the start-up phase. Clearly, a change in the regulation strategy affects not only the thermal request but also in the indoor temperature evolution. In order to test the acceptability of DRT control strategy a substation model is proposed and validated trough data collected by monitoring system installed in several substations of the Turin DH network. The monitoring system allows one detecting temperature and mass flow rate at the inlet and outlet section of the heat exchanger each 5 minutes. Furthermore, the potential for shaving the thermal peak load of the whole distribution network is estimated through a network physical model [28]. This model is applied to the substations connected to a distribution network and the effect on the reduction of the thermal demand is evaluated once acceptable settings are implemented.

The research questions this paper want to address are:

1. How to shave thermal peaks by changing regulation strategy.
2. Show a methodology to check that the regulation strategy change does not affect indoor comfort conditions.
3. Quantify the overall thermal peak shaving that can be obtained in a DH network by means of the new regulation approach.

The paper is structured as follows:

- Section 2: description of current and DRT regulation strategy.
- Section 3: methodology for the system simulation (user and network model), in order to evaluate the effects of DRT application at building level (by means of the user model) and at plant level (by mean of the network model).
- Section 4: description of the system the strategy is tested on.
- Section 5: results showing a) validation of user (building and subnetwork) model b) effect of DRT on peak reduction c) variation of the effects by changing the DRT regulation coefficient.

2. Substation regulation strategy

A DH network substation consists of a heat exchanger that transfer heat from the primary network (the DH network) to the secondary network, i.e. of the building heating system. A schematic of a substation id reported in Fig. 1, together with the current and the DRT control strategy.

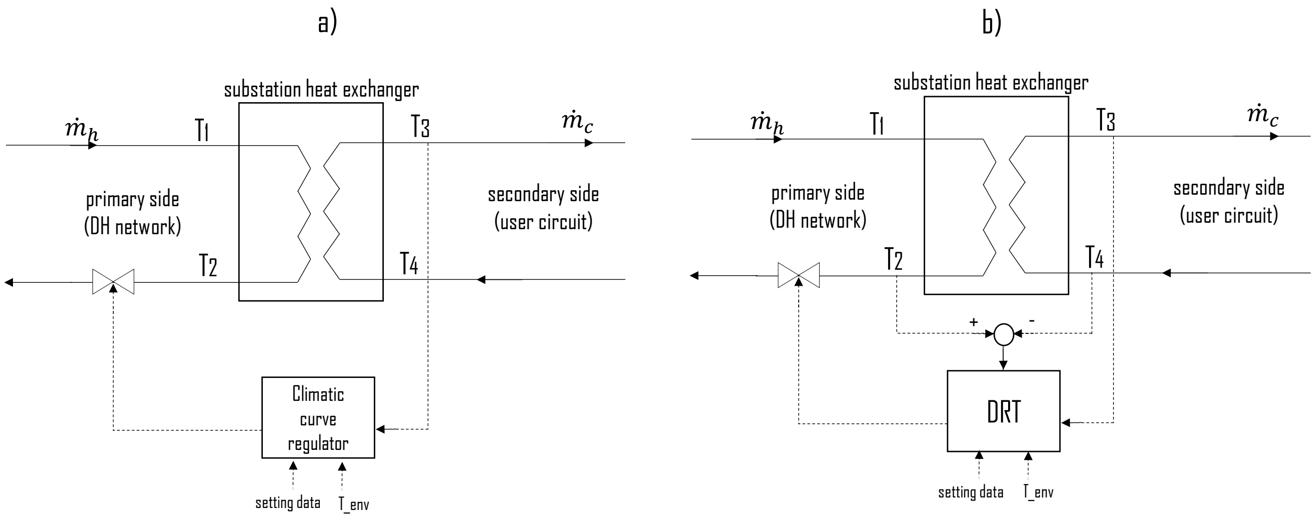

Fig. 1 Schematic of the substation a) Climatic curve strategy b) DRT regulation strategy

2.1 Conventional regulation strategy

The regulation strategy usually used in DH systems, also called climatic curve strategy, is based on a proportional-integral logic which varies the supply temperature on the secondary side as a function of the building demand. The regulation logic is reported in Eq. 1 where K_p and K_i are respectively the proportional and integral regulation constants and e is the regulation error. The mass flow rate at the primary side, G_1, is controlled through a valve; the level of opening of the valve is based on the difference between supply temperature on the secondary line, T_3, and its set-point T_{3_SP}. In fact, in each substation a control system is located for regulating the valve for the passage G, through a climatic line (Fig. 2), linking the desired T_3 with T_{env}, when the design environmental temperature, T_{env_D}, and the kind of heating devices are selected.

$$\sqrt{G(i)} = \sqrt{G(i-1)} + r_p \cdot e(i-1) + r_I \int_0^{i-1} e(t)\, dt \quad (1)$$

$$e = (T_3 - T_{3\_SP}) \quad (2)$$

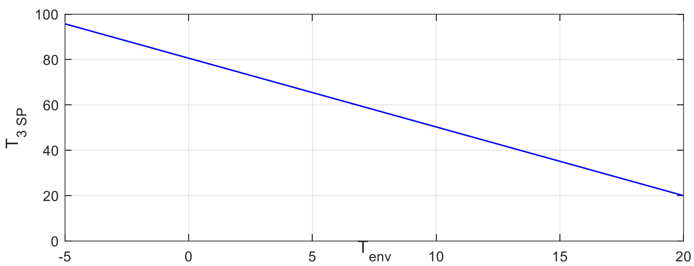

Fig. 2 Climatic temperature control

During the night shut down, temperature T3 decreases till temperature near the environmental one, since the mass flow rate in the secondary circuit is zero.
When the heating system is switched on, in the morning, temperature T3 is far from the set-point value T3_SP and therefore the error e is high. For this reason the mass flow during the start-up dramatically increases, and creates a significant peak.

2.2 Modified regulation strategy (DRT)

The second kind of regulation strategy, the DRT control strategy, is based on a proportional-integral logic but the evaluation of the error changes respect to the current regulation approach. When T_3 is lower than T_{3_SP}, if the difference between T_2 and T_4 is higher than a certain value γ, the system acts on this difference. The error evaluation is performed as described in Eq. 3.

$$e = \begin{cases} (T_3 - T_{3_{SP}}) & if\ (T_3 - T_{3_{SP}}) < 0\ \ and\ (T_2 - T_4) < \gamma \\ (T_2 - T_4) - \gamma & if\ (T_3 - T_{3_{SP}}) < 0\ \ and\ (T_2 - T_4) > \gamma \\ 0 & if\ (T_3 - T_{3_{SP}}) > 0 \end{cases} \tag{3}$$

In this case, when the difference between the temperature T2 and T4 is high the error is limited. This occurs especially during start-up when temperature T4 is very low due to the night cooling down because the mass flow rate is zero. This make the valve opening slower during the start-up. The consequence is a flatter increase of mass flow rate. The DRT regulation strategy allows thus obtaining flatter mass flow rates profile. A main advantage consist in the fact that the flattening is controllable by varying the γ coefficient. A proper selection of this value allows obtaining contemporary a) a considerable peak reduction and b) variation of the indoor temperature conditions limited. This is shown in the result section.

3. Modeling approach

The estimation of the effects of control strategy change on a) the building indoor conditions and b) the total request of the network can be done relying on proper simulation models. In order to properly visualize the whole system considered in this paper and the corresponding models used for studying the different subsystems (building, substation and distribution network), a schematic is reported in Fig. 3. The evaluation of the power required to the user with different regulation approaches, Φ_h, and the consequent indoor temperature evolution, T_{indoor}, are performed through a model of the user. The model includes both the substation and the buildings, as shown in Fig. 3. It is important to remark that knowledge of the internal temperature evolution is essential for understanding if the use of a different regulation approach causes an acceptable change in the comfort conditions inside the buildings. The effects of the regulation strategy changes in the global request of the distribution network is performed through the use of a network model, us explained in the following paragraph. The user model is largely detailed in paragraph 3.1 while the network model is described in paragraph 3.2.

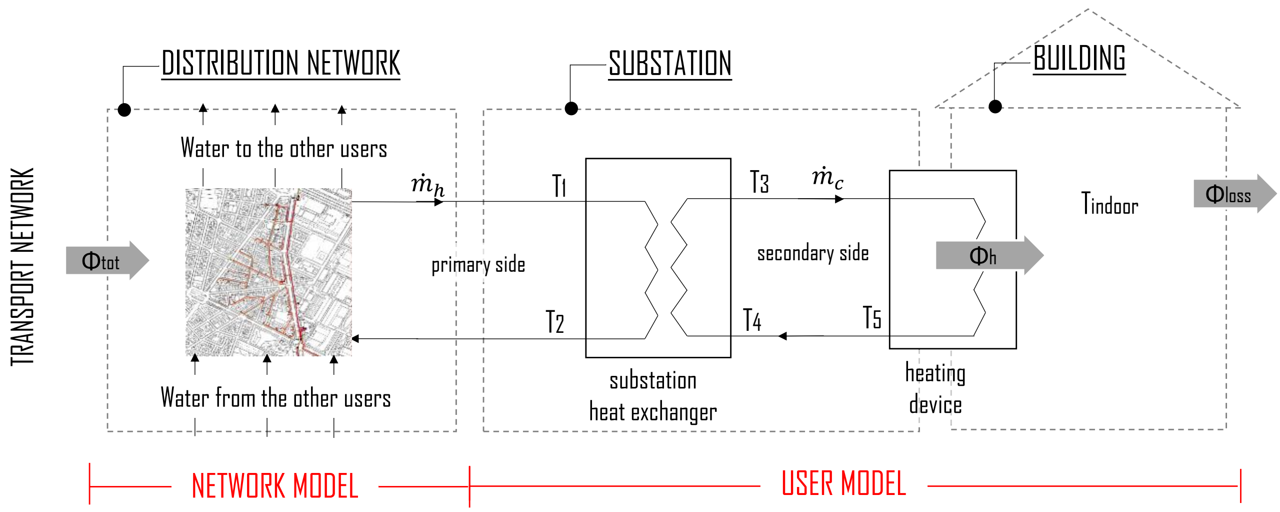

Fig. 3 Simplified scheme of the considered system.

3.1 User model (building and substation)

The substation and the heating device of each building is modelled considering two heat exchangers (Fig.5). The first is the heat exchanger installed in the substation between DH network (primary side in Fig. 5) and the user network (secondary side in Fig. 5). This is the substation heat exchanger and supplies the network bringing hot water in the heating devices (radiators, radiant floors, etc.) of each apartment of the building. The second is a fictitious heat exchanger representing the heat exchange between all the heating devices of the building and the indoor environment

The heat exchanger between the primary and secondary network is modelled using effectiveness-NTU method, both for the design and analysis of the operating conditions and evaluating the outlet temperatures. The design heat flux needed for the building is evaluated as indicated in [29]. The fictitious heating device has been solved in the same way, but an infinite thermal capacity of the cold fluid (which is the indoor air) has been considered. The difference between temperature T_5 and T_4 is due to the time delay from the outlet of the heating devices (located in the rooms) to the inlet in the heat exchanger (located in the building sub-station). It was evaluated comparing the calculated thermal request profile and the evolution obtained through the recorded data. Further details on the model are provided in [10].

This approach allows one evaluating an average building temperature T_{indoor_curr}, which is representative of the overall internal conditions (it do not coincide with the indoor temperature of a specific room). The average building temperature T_{indoor_curr} is considered as the threshold evolution for the end users comfort because it can be assumed as an acceptable profile. Therefore, when the use of virtual storages varies the indoor temperature, the change can be considered as acceptable if the new average temperature T_{indoor_new} is close enough to T_{indoor_curr}.

The heat exchanger of the sub-station is modelled applying the energy balance as show in Eq. 1:

$$C\frac{dT}{dt} - G_h c_h (T_1 - T_2) - G_c c_c (T_3 - T_4) = 0 \tag{4}$$

The model also includes the transient term in order to consider the mass heating and cooling during the switching on and the switching off. The equivalent thermal capacity of the heat exchanger, *C*, has been evaluated analysing the discrepancy between the heat flux predicted and the heat flux measured during the transient phases. The mass flow rate on the secondary circuit is usually constant in the heating systems of the buildings when it is operating while it is zero when it is not operating. The mass flow in the primary circuit is evaluated by eq. (1-3) depending on the regulation strategy.

The building has been modelled through a simple approach based on an energy balance in order to evaluate the indoor temperature T_{indoor}:

$$\phi_h - \phi_{loss} = c\ V\ \frac{d\ T_{indoor}}{d\ t} \tag{5}$$

$$\phi_{loss} = k\ V\ (T_{indoor} - T_{est}) \tag{6}$$

where Φ_h is known because it is measured, V is available from the building dataset and the parameters k and c are evaluated using the data gathered at the substation together with the external temperature. In particular, the steady state conditions (which typically occurs in the afternoon) is studied for evaluating the global heat transfer coefficient k, when it is possible to consider:

$$\phi_h = \phi_{loss} = k\ V\ (T_{indoor} - T_{est}) \tag{3}$$

The thermal capacity c is evaluated considering the transient behaviour of the building after switching off the heating system. In fact in the last three hours of transient the exponential $T_4 - T_{est}$ decades as $T_{indoor} - T_{est}$ since the temperature of the heating circuit becomes close to the indoor temperature.

In this work, the internal temperature evolution is studied for both the regulation strategies in order to estimate the acceptability for each user. A tolerance of 0.75 °C is selected and only the cases that leads to an indoor temperature reduction smaller than the tolerance, during the most critical time of the day, are considered.

3.2 Network model

The long distances involved in DH network cause significant variations in the temperature evolution. Between the thermal plants and the buildings and vice versa. This is mainly due to three causes: 1) temperature variation

within the network is not immediate, but it travels with the water flow velocity; 2) heat losses ale almost constant, especially on the supply network, while the energy transported in each pipe varies with velocity. This means that impact of losses on the local temperature varies with the thermal request; 3) water exiting a substation mixes with the streams coming from the other substations which are not all at the same temperatures because of the different distances involved and exchanged heat flux. For these reasons, a network model is used for taking into account how the pipeline affects the temperature distribution within the network.
The physical network model is based on the mass and energy conservation equations applied to all the nodes (Eq. 5 and Eq. 7) and the momentum conservation equation applied to all the branches (Eq. 6).

$$\mathbf{A} \cdot \mathbf{G} + \mathbf{G}_{\text{ext}} = 0 \tag{5}$$

$$\mathbf{G} = \mathbf{Y} \cdot \mathbf{A}^{\mathrm{T}} \cdot \mathbf{P} + \mathbf{Y} \cdot \mathbf{b} \tag{6}$$

$$\mathbf{M} \cdot \dot{\mathbf{T}} + \mathbf{K} \cdot \mathbf{T} = \mathbf{g} \tag{7}$$

Mass end momentum equation are considered in steady state, because fluid-dynamic perturbations travel significantly faster than the time step adopted for calculations (60 s), while the thermal model is expressed in transient form since thermal perturbations travel the network at the water velocity. The incidence matrix **A** describes the network topology by expressing the connections between nodes and branches, through a graph approach [30]. Further details on the method are available in [28] and [31].

For the current application, only the return line of the distribution network has been considered for the sake of simplicity since the network is managed keeping the network supply temperature as constant. Mass flow rate and water temperature at the outlet section of the user heat exchangers are imposed as boundary condition in the return model. The network model provides the temperature evolution of the water entering the transport pipeline. This allows evaluating the effect of the application of DRT control strategy to the whole distribution network.

4. System description

4.1 *Network description*

The DRT control strategy is applied to one of the distribution networks of the Turin DH system, which is one the largest in Italy and one of the largest in Europe (Fig. 4a). The Turin DH system is fed by three cogeneration plants, which provide the base heat, and by several boilers, for covering the thermal peaks. The Turin total thermal request presents a significant peak during the morning, about 1400 MW, which can be three times higher than the thermal request during the afternoon. The morning peak is due to the fact that heating systems are usually switched off at night and switched on when occupants wake-up.

The network can be considered as composed of two interconnected parts: a transport network, including the pipes with larger diameter, which distribute water in all the areas of the city, and several distribution networks, including the pipeline with smaller diameters, which link the transport network to the users. The node that links the transport network and the distribution network is called barycentre. The Turin DH system includes 182 distribution networks. In this work, a distribution network where several users were monitored has been considered. This network connects 62 buildings, which are mainly residential buildings, to the DH system. The selected distribution network is depicted in the red tringle in Figure 4a and it is detailed in Figure 4b.

(a) (b)

Fig. 4. a) Turin DH system b) distribution network analysed

4.2 Monitoring system

The substations considered in are equipped with a monitoring system composed of four temperature sensors (for measuring T_1, T_2, T_3 and T_4) and a mass flow meter form measuring the water mass flow rate at the primary side. Fig. 5 shows the general trend of the data collected in the substations of the users located in the distribution network considered in this work (BCT as detailed in paragraph 2.2); these data are used in the validation stage, as shown in paragraph 5.1. The figure shows that the various profiles significantly differ. The evolutions of the thermal request are dissimilar, due to the different building dimensions, shape factors, occupant habits and building insulation. Some of the heating systems stop up to three times per day while others operates continuously from the morning until the evening. This causes a different number of peaks in the profiles. Most of the mass flow rate profiles (and consequently heat flux profiles) present a peak between 5 am and 7 am. Temperature values at the secondary side are comprise between 50 and 80 °C, which are typical operating temperatures of radiators. The model described in the next section allows predicting the evolution of these quantities once the characteristics of the system are known (such as heat exchanger characteristics, temperature of the water entering the primary side, T_1).

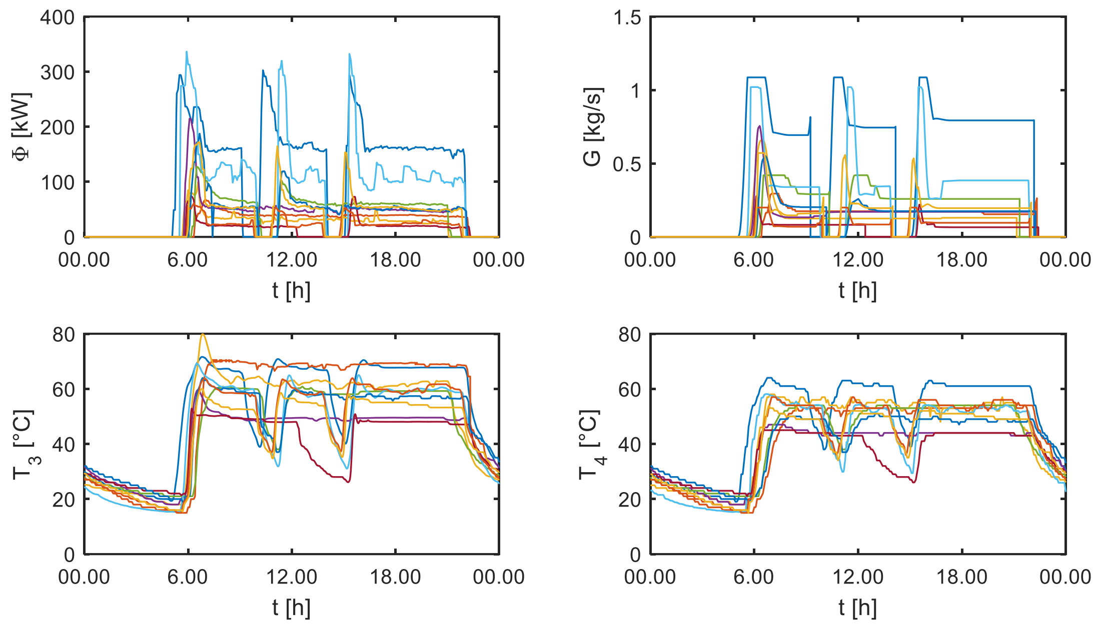

Fig. 5. Data collected at the heat exchangers of users located in the same distribution network

4. Results

4.1 Model Validation

The building model has been validated as reported in [10]. The current control system model has been compared with experimental data in order to test its capability to reproduce the correct behaviour of the heat exchanger. This has been done by comparing data gathered by the monitoring system and the value predicted by the model for a certain day, given the outdoor conditions and the heating device schedule (when the devices are switched on). The thermal power transferred at the heat exchanger is reported (black continuous line) in Fig. 6. These evolutions are compared with the evolutions obtained using the model (red dashed line). Results show that the model predicts thermal power evolutions with a good level of approximation. Both peak amplitude and steady state condition are well detected in all the case. The mean error is around 5%. It can be noticed from Fig. 6 that the mean value of the steady state thermal request is detected with a mean error lower than 10 % in all the cases. As regards the thermal peak, this is optimally detected in most of the cases. In some cases, the maximum value predicted appears to be slightly different to experimental data. Differences between model and experimental data have various causes, such as a) different time step used for simulation and instrument data collection b) metering or communication error c) changes in user behaviour or building characteristics.

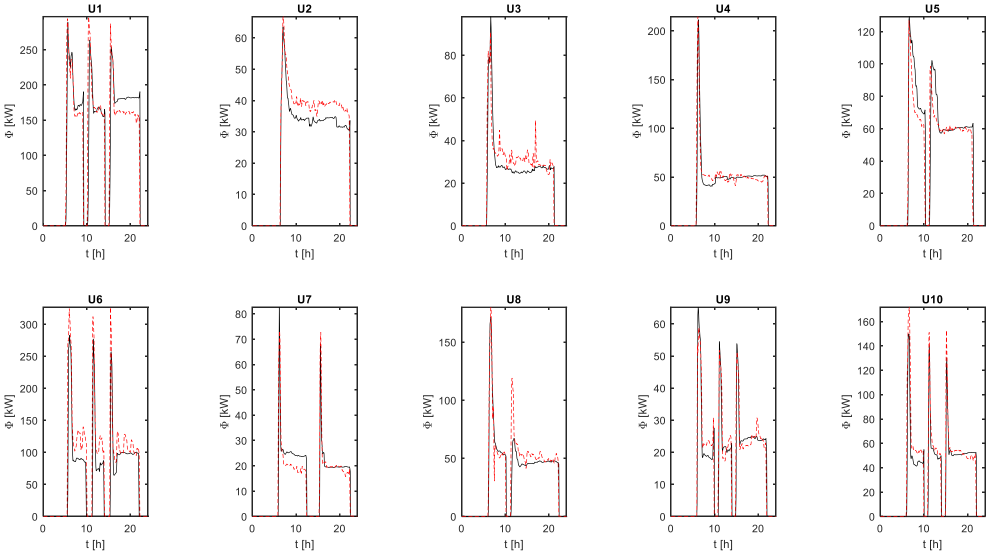

Fig. 6 Regulation model validation (red dashed=experimental, black=model)

4.2 DRT effect at user level

In this section, the effects of the DRT control strategy are analysed at user level. In particular, these are investigated in terms of modification of the user thermal request. At first, the DRT control strategy is set by a γ constant equal to 3 °C. This means that the target temperature difference between the two return flows is set to 3°C. The thermal profile evolutions obtained through the climatic curve strategy and the DRT strategy are both reported in Fig. 7.

Results show three main types of results:

- Buildings where the DRT use does not affect both the steady state conditions and the thermal peak (building U1). In this case, the DRT installation does not cause any effect on the thermal request evolution. This is because the DRT constant γ is set to a value that is too low for the particular building. This means that for these kind of building the constant γ should be increased in order to get some benefits from DRT installation.
- Buildings where the DRT use affects the peak but not the steady state conditions (buildings U4,U6-U10). This is the expected effect of DRT. This means that DRT constant γ is selected in a proper range. However the acceptability of the γ value must rely also on the check on the indoor conditions.
- Buildings where the DRT use affects both the peak and the steady state request (buildings U2, U3, U5). In this case, the γ value selected could be too high, because it causes significant effects on the thermal request. Also in this case it is necessary check the effects on the indoor temperature.

The maximum peak reduction obtained is about 50% while the average peak reduction is 15%. In general, as expected, the DRT installation never causes an increase in the maximum peak value.

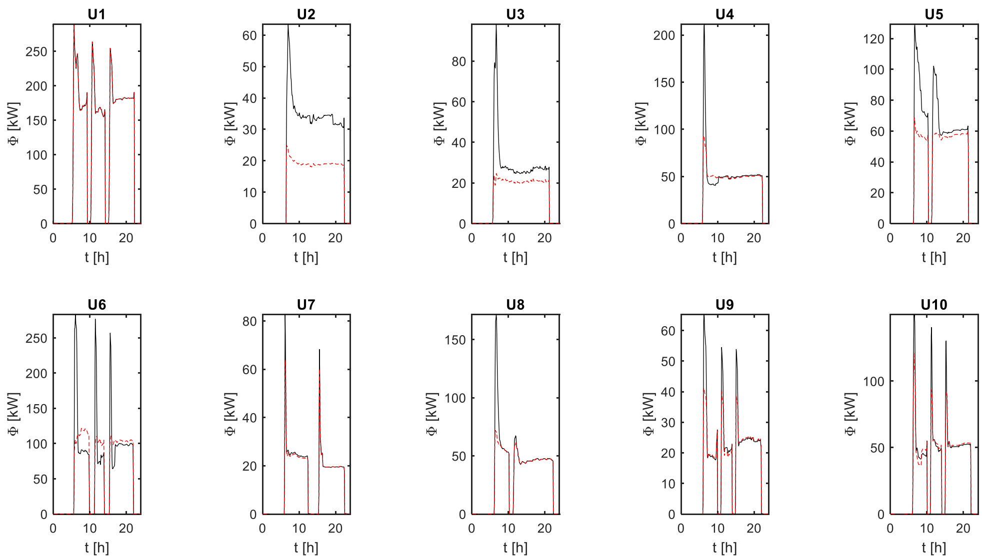

Fig. 7 Thermal request profiles a) Climatic curve strategy b) DRT regulation strategy

The effects of the control strategy change on the indoor temperature evolution are analysed in order to assure that the comfort level inside the building is acceptable. This check is fundamental to prevent complaints of the users of DH system. Fig. 8 shows the temperature evolutions with the two regulation strategies. In all the considered cases, the indoor temperature is lower when DRT is used. This is because, as shown in Fig. 7 the use of DRT limits the heat flux provided to the user and this causes lower indoor temperature values respect to the current regulation strategy. DRT causes various kind of effects:

- An undetectable temperature change occurs for the building where no particular changes in thermal demand could be noticed from Fig. 7 (U1)
- A small temperature change occurs for the building where the selection of γ was done in a proper range (U4, U6-U10)
- A significant temperature change occurs for the buildings where variation where detected in both the steady state condition and peak (U2, U3, U5).

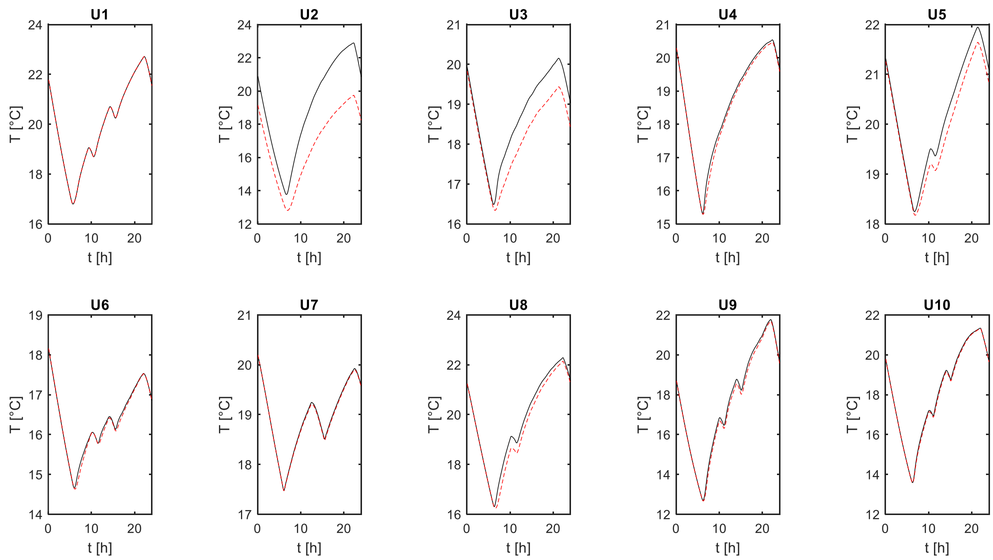

Fig. 8 Indoor temperature evolutions (continuous line=current, dashed line=DRT)

In order to better visualize the effects of the two regulation strategies on the indoor temperature, the difference between the current strategy and the DRT is computed. Results are reported for each analysed building in Fig. 9. It is possible to notice that the indoor temperature obtained through the DRT strategy is always lower than the current one. In Fig. 9 also the horizontal line corresponding to a temperature difference of 0.75 °C is reported; such value is considered in this work as the threshold for the acceptability of the change in the regulation strategy. When the maximum change in the indoor temperature is lower than 0.75 °C in the strategy can thus be considered as acceptable. It is possible to notice that in case of building U1, the temperature change is always zero. This means that the DRT use, with γ=3 °C, has no influence on both thermal request and indoor temperature evolution. This is because in this building the temperature difference between T2 and T4 never exceed 3 °C.

In all the cases except for building U2, a temperature reduction occurs without exceeding the limitation. Altrough in case of building U3 the steady state request is reduced, the indoor temperature reach a stationary difference respect to the conventional regulation of -0.7 °C. In building U2 the indoor temperature is never acceptable. For this case it is interesting analyzing the effects of the DRT coefficient variation on the indoor conditions and therefore on the acceptability of the new regulation strategy.

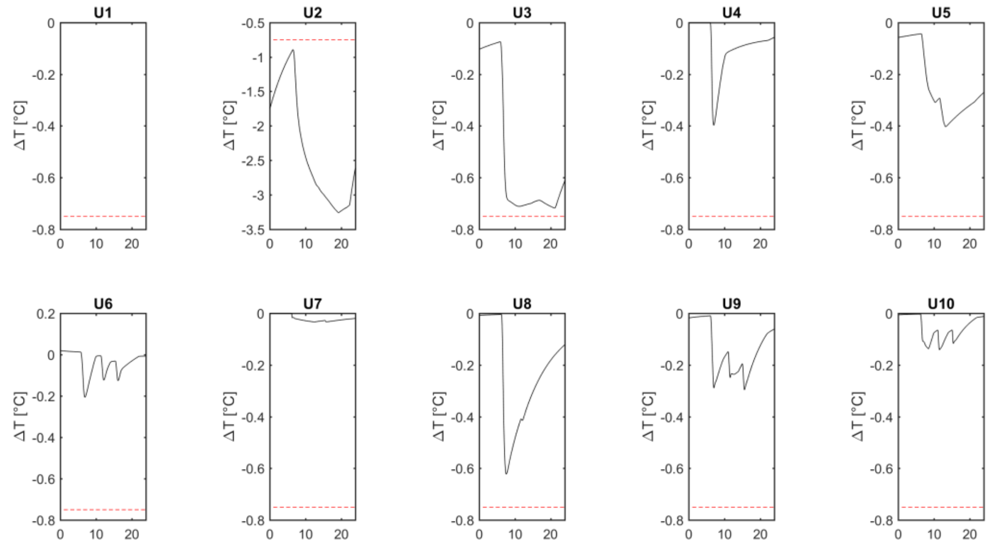

Fig. 9 Indoor temperature difference between DRT and conventional regulation strategy.

In this work building U2 is taken as an example for showing efforts corresponding to changes in the regulation coefficient γ, in terms of the peak shaving and indoor temperature evolution. This has been done because of the evident unacceptability of the profile obtained by using DRT regulation strategy with γ=3°C. For this purpose, the thermal request and indoor temperature are evalauted for U9, with different γ values. Fig. 10 depicts the evolution of the thermal request, the evolution of the indoor temperature and the evolution of the temperature variation respect to the current regulation strategy. Results reported in Fig. 10 also show that a large range of thermal request evolution can be obtained acting on the γ coefficient. Its variation significantly affects the thermal request and indoor temperature evolution. The higer the γ value, the lower the thermal peak and the larger the temperature variation. In such case γ has to be selected higher than 15 °C in order to keep the maximum temperature difference above 0.75 °C. This selection causes a reduction of the morning peak of about 35 % with respect to the current strategy.

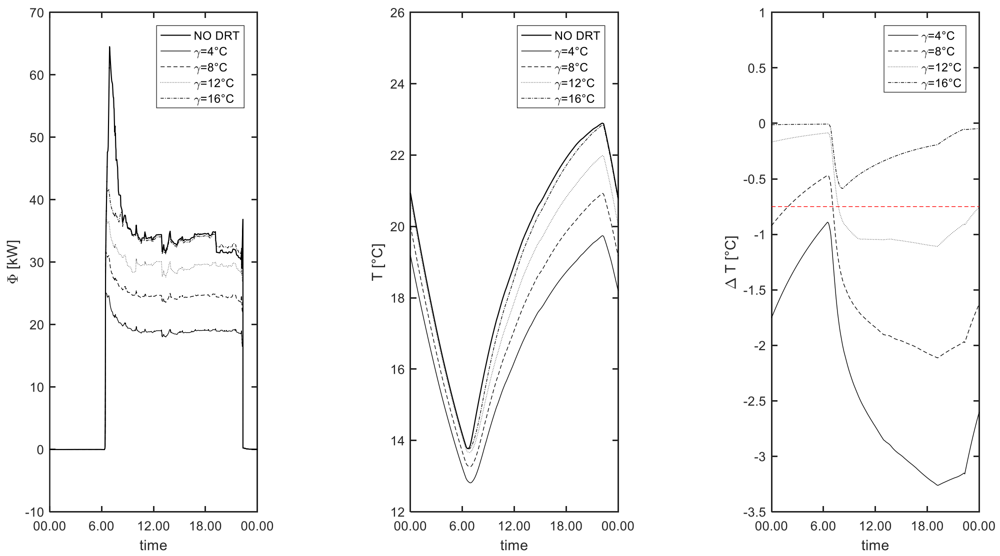

Fig. 10 Thermal request, indoor temperature and temperature variation for different values of DRT coefficient in building U2.

The same approach of varying coefficient γ can be used in order to increase the benefits offered by the DRT control strategy:

- in case of building U1, the DRT coefficient can be properly decreased in order to obtain non negligible request modification
- it should be possible to create a proper tool with the aim of optimally selecting the DRT coefficient for each user. This should provide the best value to obtain the most significant peak reduction without violating the indoor condition limitations.

Potentials of DRT are deeply examined in section 5.

4.3 DRT effect at network level

The effects of the DRT regulation strategy on the heat load of the entire distribution network are evaluated through application of the thermo-fluid dynamic model of the network. Fig. 11 reports the thermal load occurring before and after the DRT installation considering a typical cold winter day with an average temperature of about 3 °C. The continuous line represents the heat flux required with the current regulation strategy; the dashed line represents the heat flux required to the distribution network when the DRT regulation system is used in all the buildings installed in the distribution network. Results show that the application of DRT yields a considerable peak reduction (24 %). The thermal peak in the current conditions reaches 12.4 MW, while DRT produces a maximum peak of about 9.4 MW. The peak duration is higher in case of DRT use; this is because DRT allows flattening and widening the thermal peak, These are promising result encouraging research on potential of different regulation approaches for the thermal peak shaving.

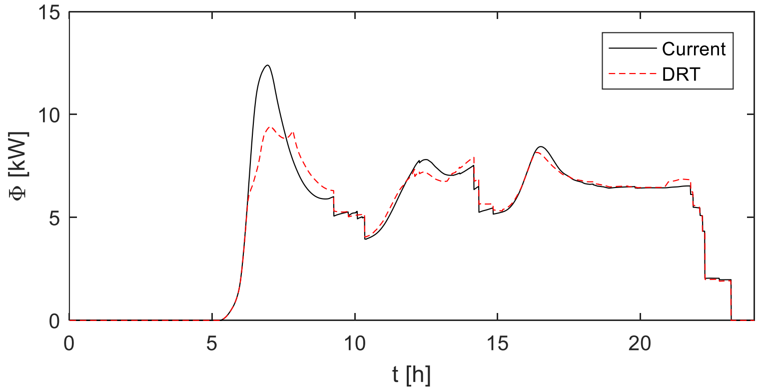

Fig. 11 Peak shaving of the entire distribution network request

4.4 Discussion

There are many potentials for the application of the DRT control strategy for improving and optimizing the thermal peak shaving. At first, the choice of the coefficient γ is an important aspect and it should be carefully considered. In fact, results show that, when the γ is high, the thermal peak does not go through a significant shaving but the indoor comfort level is preserved. On the other hand, when γ is small the peak is greatly shaved but the indoor temperature suffers for a large decrease in some periods of the day. A compromise has thus to be find in order to obtain a peak reduction with a lot of attention paid to the indoor conditions, as has been done in this paper for building U2. In particular, the DRT system potentials could be fully exploited through the use of more accurate control systems. Some examples are:

- A system able of evaluating the best value for γ in order to minimize the maximum peak request for each users, once the maximum allowed temperature variation is set.
- A global optimizer, including the network model, for the selection of the best set of coefficient γ for the best peak reduction for the whole distribution network.

The change in the regulation strategy can be also associated with the adoption of the anticipation or delay of the time the heating systems are switched on. This approach has already been shown to be very effective for the peak reduction and its potential can be increased through the addition of the DRT control strategy. In this case, an optimization tool able to select the best combination of both the γ coefficient and the amount of anticipation of switching on time can be used.

All these approaches can be applied not only to the morning thermal peak but also for reducing the oscillations of the request that occur during the day or for shaving profiles that presents more than one peak.
The analysis can be also extended to the transportation pipeline together with all the other distribution networks. In such case, a complete optimization could be performed; the effects are expected to be larger in terms of peak reduction because the distances involved when the overall network is considered are very large and the modification of the load for each building, or distribution network, can leads to a considerable peak shaving.
It is important to remind that the change in the regulation strategy leads also to a reduction of the mass flow rates in the pipelines during the peak request time and therefore to the possibility of connecting new users to the DH system without changing the pipes dimensions or adding new pipes.

5. Conclusions

The paper presents an analysis for the potential of the DRT regulation strategy for the substation control with the aim of reducing the thermal peak in DH system. The DRT control system is based on the idea of keeping the temperature difference between the inlet of the cold side and the outlet of the hot side low. This approach allows one reducing low the thermal power exchanged, especially during the start-up time, when the temperature difference between the two sides of the heat exchanger is high. This control strategy is shown to have great peak shaving potentials when applied to a DH substation. A compact model able to simulate the substation and the building has been used, together with a control strategy model. The test has been performed on one of the distribution networks of the Turin DH system. The substations of the considered distribution network were all equipped with a measuring system able of gathering mass flow rates and temperature data. The data are used with the aim of validating the entire model.

The potential of the DRT control system for the thermal peak shaving are shown at a building level. The effects of the DRT control system on the users are evaluated in terms of thermal peak shaving and changes in the indoor temperature. The indoor temperature is used to check that the standard of comfort are guaranteed. Furthermore, the effects of the DRT control system on the overall request of the distribution network have been evaluated. This step is conducted through the use of a physical network model for taking into account the different distance of the users from the junction with the transportation network. Results show that a peak reduction until 26% (on average 15%) can be reached at user level, while a reduction of 24% can be reached on the overall distribution network request.

Furthermore, the effects of the regulation coefficient γ have been analysed on the users thermal request and on the indoor temperature. In particular, an option trade-off between primary energy savings and comfort of the end-users can be obtained through proper selection of γ. This value strictly depends on the characteristics of the building the control is applied to.

Nomenclature

A	incidence matrix
b	pumping vector
c	specific thermal capacity, J/(m^{3}K)
C	thermal capacity J/K
e	regulation error
g	constant term in energy equation
G	mass flow rate, kg/s
k	global heat transfer coefficient, W/(m^{3}K)
K	stiffness matrix
M	mass matrix
P	pressure matrix
t	time, s
T	temperature, K
V	volume, m^3
Y	fluid dynamic conductance
Greek letters	
γ	DRT regulation coefficient
ϕ	heat flux W
Subscript/Superscript	
c	cold
env	environmental
h	hot

References

[1] Rezaie, B., & Rosen, M. A. (2012). District heating and cooling: Review of technology and potential enhancements. *Applied Energy*, 93, 2-10.
[2] Persson, U., & Werner, S. (2011). Heat distribution and the future competitiveness of district heating. Applied Energy, 88(3), 568-576.
[3] Lindenberger, D., Bruckner, T., Groscurth, H. M., & Kümmel, R. (2000). Optimization of solar district heating systems: seasonal storage, heat pumps, and cogeneration. Energy, 25(7), 591-608.
[4] Casisi, M., Pinamonti, P., & Reini, M. (2009). Optimal lay-out and operation of combined heat & power (CHP) distributed generation systems. Energy, 34(12), 2175-2183.
[5] Sciacovelli, A., Guelpa, E., & Verda, V. (2014). Multi-scale modeling of the environmental impact and energy performance of open-loop groundwater heat pumps in urban areas. Applied Thermal Engineering, 71(2), 780-789.
[6] Lund, H., & Mathiesen, B. V. (2009). Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. Energy, 34(5), 524-531.
[7] Lund, H. (2005). Large-scale integration of wind power into different energy systems. Energy, 30(13), 2402-2412.
[8] Sun, F., Fu, L., Sun, J., & Zhang, S. (2014). A new waste heat district heating system with combined heat and power (CHP) based on ejector heat exchangers and absorption heat pumps. Energy, 69, 516-524.
[9] Fang, H., Xia, J., & Jiang, Y. (2015). Key issues and solutions in a district heating system using low-grade industrial waste heat. Energy, 86, 589-602.
[10] Verda, V., E. Guelpa, A. Sciacovelli, E. Patti, A. Aquaviva (2016). Thermal peak load shaving through users request variations. *International Journal of Thermodynamics*, *19*(3), 168-176.
[11] Guelpa, E., Mutani, G., Todeschi, V., & Verda, V. (2018). Reduction of CO2 emissions in urban areas through optimal expansion of existing district heating networks. Journal of Cleaner Production, 204, 117-129.
[12] Guelpa, E., & Verda, V. (2018). Model for optimal malfunction management in extended district heating networks. Applied energy, 230, 519-530.
[13] Hasnain, S. M. (1998). Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques. *Energy conversion and management*, *39*(11), 1127-1138.
[14] Zhou, D., Zhao, C. Y., & Tian, Y. (2012). Review on thermal energy storage with phase change materials (PCMs) in building applications. *Applied energy*, *92*, 593-605.
[15] Sciacovelli, A., Guelpa, E., & Verda, V. (2014). Second law optimization of a PCM based latent heat thermal energy storage system with tree shaped fins. Int. J. Thermodyn, 17(3), 127-136.
[16] Wang, H., Yin, W., Abdollahi, E., Lahdelma, R., & Jiao, W. (2015). Modelling and optimization of CHP based district heating system with renewable energy production and energy storage. *Applied Energy*, *159*, 401-421.
[17] Nuytten, T., Claessens, B., Paredis, K., Van Bael, J., & Six, D. (2013). Flexibility of a combined heat and power system with thermal energy storage for district heating. *Applied energy*, *104*, 583-591.
[18] V. Verda, & F. Colella, "Primary energy savings through thermal storage in district heating networks," *Energy*, *36*, 4278-4286, 2011.
[19] Rolfsman, B. (2004). Combined heat-and-power plants and district heating in a deregulated electricity market. *Applied energy*, *78*(1), 37-52.
[20] Gu, W., Wang, J., Lu, S., Luo, Z., & Wu, C. (2017). Optimal operation for integrated energy system considering thermal inertia of district heating network and buildings. *Applied Energy*, 199, 234-246.
[21] Wernstedt, F., Davidsson, P., & Johansson, C. (2007, May). Demand side management in district heating systems. In Proceedings of the 6th international joint conference on Autonomous agents and multiagent systems (p. 272). ACM.
[22] Verrilli, F., Srinivasan, S., Gambino, G., Canelli, M., Himanka, M., Del Vecchio, C., ... & Glielmo, L. (2017). Model predictive control-based optimal operations of district heating system with thermal energy storage and flexible loads. IEEE Transactions on Automation Science and Engineering, 14(2), 547-557.
[23] Capone, M., Guelpa, E., & Verda, V. (2019). Optimal operation of district heating networks through demand response. International Journal of Thermodynamics (IJoT), 22(1), 35-43. .

[24] Guelpa, E., Barbero, G., Sciacovelli, A., & Verda, V. (2017). Peak-shaving in district heating systems through optimal management of the thermal request of buildings. *Energy*.
[25] Guelpa, E., Marincioni, L., & Verda, V. (2019). Towards 4th generation district heating: Prediction of building thermal load for optimal management. Energy.
[26] Guelpa, E., Marincioni, L., Capone, M., Deputato, S., & Verda, V. (2019). Thermal load prediction in district heating systems. Energy. In Press.
[27] Guelpa, E., Deputato, S., & Verda, V. (2018). Thermal request optimization in district heating networks using a clustering approach. Applied Energy, 228, 608-617.
[28] Guelpa, E., Sciacovelli, A., Verda, V. (2017). Thermo-fluid dynamic model of large district heating networks for the analysis of primary energy savings. *Energy*. In press.
[29] F. Orecchini, V.Naso., Energy Systems in the Era of Energy Vectors. Springer 2011
[30] Harary, F. Graph Theory, New Delhi: Narosa Publishing House ,1995.
[31] Guelpa, E., & Verda, V. (2019). Compact physical model for simulation of thermal networks. *Energy*. In Press.