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Optimal operation of large district heating networks through fast fluid-dynamic simulation

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ABSTRACT

Optimization of the operating conditions of district heating networks is usually performed limiting the analysis to the primary energy related with heat production. An additional aspect that should be considered is the role played by the pumping system. Pumping may contribute to about 10% of the total primary energy consumption, especially in large networks or when small temperature levels are applied. Furthermore, the increasing share of waste heat or renewable energy sources from distributed producers requires a flexible and efficient pumping system. A further aspect which pumping strategy should face is system operation when malfunctions in the plants, pumps or pipes occur.

Optimization of the pumping system requires the use of detailed simulation tools, which may need significant computational resources, especially in the case of large networks. A reduced model, based on Proper Orthogonal Decomposition combined with Radial basis functions (POD-RBF model) is proposed in this paper. This approach allows maintaining high level of accuracy despite reductions of more than 80% in the computational time. This make the approach effective tool for control strategy operations. An application to a large district heating network shows that reductions of about 20% in the pumping request and effective management of failures are possible.

1. Introduction

DH (District heating) is considered a very efficient option for providing heating and domestic hot water to buildings, particularly when they are located in densely populated areas [1]. The main advantage of DH systems consists in the possibility of utilizing the waste heat from industries or waste-to-energy plants or the heat generated by a number of efficient/low carbon thermal plants, such as cogeneration plants, and biomass [2], solar [3] and geothermal [4] systems.

An important aspect to achieve high efficiency in DH is the optimization of the operating conditions the system has to face in order to comply with the household thermal request. In the literature, various papers deal with the analysis of supply temperature during daily [5] and seasonal [6] operations or with the selection of the optimal supply and return temperatures [7]. In Ref. [8] a control approach is proposed in order to increase the temperature difference across the substations with a consequent increase of overall performances. In Ref. [9], the operating conditions of a district heating system are optimized acting both on the set-point temperature of the boilers and on the water flow of the pumps; the total fuel consumption is considered as the objective function to be minimized. In Refs. [10] and [11] the opportunities to modify the thermal request profile of some users are investigated to maximize the heat production from cogeneration or renewable plants.

An important aspect of optimal strategy analysis refers to pumping systems. Pumping systems are used to fulfill the desired heat flux to users facing the issues related to variations in friction losses. They include a set of pumps located along the network to provide consumers with hot water from the heat generation plants. The energy consumed for pumping operations is not negligible, in particular in large district heating networks, when distances

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involved are long. This aspect is further stressed in the case of low temperature district heating systems, typically operating with small temperature differences between supply and return networks and large mass flow rates [12]. Moreover, pumps work continuously during the heating season, even when heat demand is low.

For instance, the DH system of the city of Turin, which is considered in this work as a case study, requires up to about 6 MW of power transferred to the fluid, depending on the thermal load. This means that pumping represents about 2% of the primary energy consumption at peak request and increases to about 6–8% at night.

This aspect is also highlighted by various papers in literature, proposing the implementation of fluid dynamic models of the network for design purpose or the analysis of the effects of the control strategy on the energy consumption. A method for district heating network dimensioning, based on the probabilistic determination of the flow rate for hot water heating was carried out in Ref. [13]. Network costs, pumping energy consumption, and power of boilers were considered. In Ref. [14] a multi-objective optimization model is performed for the best network design considering both initial investment for pipes and pumping cost for water distribution. The best pipe diameters that reduce the total cost have been evaluated. A technical-economical optimization with the aim of minimizing both the pumping energy consumption and the thermal energy losses while maximizing the yearly annual revenue is performed in Ref. [15]. In Ref. [16] a fluid dynamic model solved with the Hardy Cross method [17] is used in order to compare hydraulic performances of distributed variable speed pumps and conventional central circulating pump. Stevanovic et al. [18] solve the fluid dynamic model with a loop method in order to show the potential for energy savings in pumping operations; the loop method is shown to be more effective with respect to the Hardy Cross method that is affected by problems related to convergence, computational cost and limited use [19]. In Ref. [20] a fluid dynamic model of the network based on conservation was built and a genetic algorithm used in order to minimize the energy required by the system. Most works available in literature are focused on small district heating networks. When a large district heating network is considered, the computational cost to solve a physical based model becomes very high; this excludes the use of full physical models for fast multi-scenario and fast optimization applications.

In the present paper, the authors present two different model approaches for the simulation of large networks and the analysis of the optimal control strategy for the pumping system. The two models are built in order to find the set of pumping pressures that should be applied to the pumps located along the network so as to minimize the total electricity consumption for a given operating scenario. The first model is a fluid dynamic model based on mass and momentum conservation equations which consider the network topology through a graph approach. The second method is a reduced model, which has been derived from the fluid dynamic model. Model reduction is obtained through the combination of POD (proper orthogonal decomposition) and RBF (radial basis functions). POD is a reduction technique which is able to decrease the computational cost of full physical models without losing the most relevant information. POD is able to capture the main features of a complex problem using a smaller degree of information (eigenfunctions) than the full model. This method has received much attention for the reduction of complex physical systems and it has been used in different fields of science and engineering, such as the analysis of turbulent fluid flows [21,22], unsteady thermal systems [23], image processing [24] and many other fields.

Both the full physical model and the POD-RBF model are used in order to find the optimal set of pumping pressures that minimize the mechanical power that should be applied to the working fluid (i.e. the efficiency of the pump and the efficiency in the overall energy supply chain from primary energy to electricity production have not been considered) to fulfill the thermal requests of the various users, once the heat production of each plant is fixed. In the following, this objective function has been indicated as pumping cost, which should be intended as a cost expressed in energy units. An analysis with different thermal loads was performed because of the peculiar characteristics of district heating networks to work for a large number of operating hours in off-design conditions. Therefore a careful analysis of optimal operating conditions, with different thermal requests, is necessary to achieve high levels of the annual efficiency. The heat flow supplied by each thermal plant is provided as an input of the model by setting the water mass flow rates exiting the various plants.

Results obtained with the two models are compared in terms of both minimum energy consumption and computational time for each thermal load. The POD-RBF model allows us to obtain optimal costs that differ from the cost provided by the full physical model of less than5%. The full physical model is extremely time-consuming especially if applied to large district heating networks. The POD-RBF method is much faster than the full physical model and allows us to perform multiple simulations and optimizations using small computational resources. The POD-RBF approach is shown to be very effective for the optimal management of complex district heating systems reducing computational cost by more than 90% with respect to the full physical model. This allows the optimization process for a much larger number of scenarios. Results of the optimization are then compared with the current pumping strategy used for the district heating system of the city of Turin; the comparison shows that a change in the policy of pumping operations can reduce the energy consumption for pumping by about 20%.

2. System description

The Turin district heating network is the largest network in Italy. It currently connects about 55,000 buildings with an annual thermal request of about 2000 GWh. The maximum thermal power is about 1.2 GW. An expansion of the system, to reach about 72 million cubic meters of buildings is already planned [25]. The water supply temperature is constant and its value is 120 °C while the return temperature varies with mass flow rate in the network and thermal load; the mean value is 65 °C.

The complete network can be considered as composed of two parts: a transport network and a distribution network. The transport network, consists in large diameter pipes, usually larger than 200 mm, and connects the thermal plants to the thermal barycentres. Each barycentre is a subnetwork that reaches a group of buildings that are located in the same area. In the Turin network there are 182 barycentres. The ensemble of these sub-networks constitutes the distribution network. The transport network is a loop network, while the sub-networks are tree-shaped networks. Fig. 1 depicts the transport pipeline network and, in detail, 3 barycentres with their corresponding tree-shaped networks.

The model developed in this work only considers the main transport network. The total length is about 515 km. Five thermal plants, which are highlighted in green (in the web version) in Fig. 1, provide heat to the network. The main characteristics of the plants are reported in Table 1. The most usual start-up strategy of the thermal plants is the following: the two cogeneration plants in Moncalieri are started-up first (when the thermal request is below 260 MW one plant is operating, while the second one is operating when the request is below 520 MW), then the cogeneration plant in Torino Nord is started up and then the storage units in Politecnico and in Torino Nord. Larger thermal requests are covered using the boilers in Politecnico, Torino Nord, Mirafiori Nord, BIT, Moncalieri.