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Optimization of multi-source complex district heating network, a case study

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ABSTRACT

The level of complexity for a district heating network increases with the maturity of the network, and this affects the pattern of the distribution of the hot water from the heat production sites to the end users. The majority of district heating systems are also multi-source networks, typically supported with heat from one main production site and other smaller satellite sites that are activated when required. In general, local energy companies have a lack of knowledge regarding how a meshed network behaves when different production sites are operated. The schedule of heat generation at the different sites is often based on staff experience and some general rules of thumb.

In this paper a method for modeling and simulating complex district networks is further developed in order to optimize the total operating costs of a multi-source network, with constraints on the pressure and temperature levels in the user areas and on the heat generation characteristics at each production site.

The optimization results show that the usage of the cheapest resources is preferred to a distributed generation of heat, even if some of the pipes may exceed the recommended thermal load capacity. The main site water supply temperature is found to be the lowest allowed by the constraint on the temperature of the water supplied to the end users, since the decrease of the costs associated with the lower thermal losses in the network is not counterbalanced by the increase of those associated with the pumping power of a larger water mass flow rate.

1. Introduction

The evolution of district heating (DH) systems has been going on for more than 100 years, and in the beginning the first generation of DH networks used to transport steam as heat carrier. Today DH systems are at the end of the third generation, which is characterized by a water supply temperature around 100 °C, material-efficient components, pre-insulated pipes with extruded foam and plastic jacket. DH is definitely a well-developed technology that is used in most larger cities in central and northern Europe [1].

Each DH system has its own piping network in order to transport heat from the production sites to the end consumers. Fig. 1 shows that often the piping network is started as a set of small separate heating islands that successively grow together into one larger network with an increasing degree of complexity, the extent of the complexity being directly correlated with the maturity of the network. The advantage of using a meshed network (the last stage of network maturity) is that the thermal load for the single pipes is reduced and alternative paths can be used in case of pipe failure. However, the disadvantages are an increase in the thermal losses due to the larger heat dissipation area and the difficulty to determine the pattern of the water mass flow rate within the network [2].

More than often, heat generation in a DH system is planned according to the experience of the staff running the production facilities and some general rules of thumb. There is a general lack of knowledge in determining the optimal heat production plan for a system involving multiple sources (usually one main production plant supported by satellite, or just back-up, boiler plants) and a meshed piping network. The challenge is to be able to evaluate how the total heat production cost is affected by the heat output, the supply temperature, the thermal efficiency of each heat production site combined with the thermal and pressure losses in the piping

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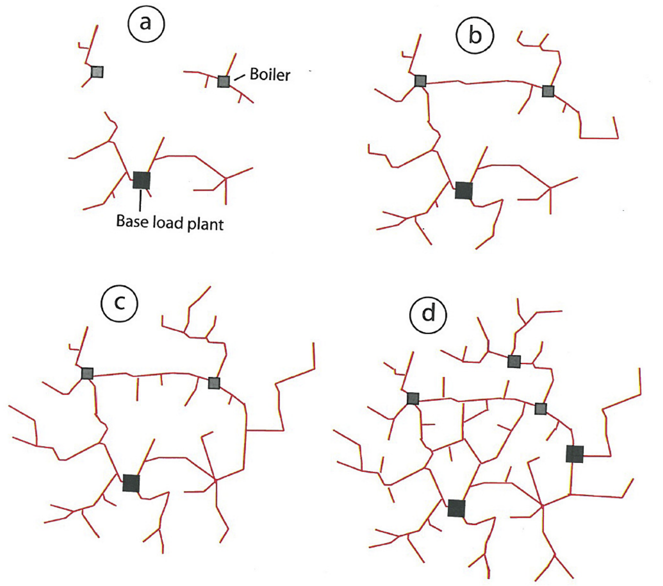

Fig. 1. Evolution of network designs, a) network with islands, b) coherent network with tree structure, c) network with ring, d) meshed network [2].

network for a given scenario characterized by the demand from the end users and the environmental conditions.

A literature review in the field of optimized heat production in meshed DH networks proves that current knowledge is still insufficient. Several studies apply optimization to simple network configurations, or the models of the DH network are built under simplified assumptions, so they do not require detailed simulation tools.

For instance, Åberg and Widén [3] present a study on the cost optimization of heat generation in DH systems considering different fossil and renewable fuels and different types of conversion units for heat generation, but in their method, the DH network is described as a black box characterized only by the overall heat demand of the users (a similar approach was also used by Chinese and Meneghetti [4]). Sartor et al. [5] concentrate on the optimal operation of combined heat and power plant connected to DH networks, and their modelling is far more detailed on the plant side than on the network side of the simulated system.

Pirouti et al. [6] aim at minimizing the capital costs and energy consumption in a DH network by varying the flow rates and supply temperatures. However, their case study, the DH network of Ebbw Vale in Wales, UK, consists of a simple tree structure including just one heat production site and seven user clusters. An in-house software has been developed by Ancona et al. [7] for the design, analysis and optimization [8] of DH networks, which are described with a matricial representation of mass and enthalpy balances at network nodes. The mass and heat flows in the pipes are obtained by solving the matricial system of equations with an iterative procedure (the Todini-Pilati algorithm). The case study shown in the two references features a network with a tree structure supplied by a single heat production site.

A group search optimizer (GSO) algorithm is used by Jiang et al. [9] to optimize the daily operation of the DH station of a small-scale system integrating different energy sources such as wind, solar, electricity and natural gas. Koiv et al. [10] propose a new method for optimizing the size of DH network pipes based on a probabilistic estimation of user consumption. The application of the method is shown for a network with a tree structure comprising ten users and one heat production site.

A mixed-integer linear optimization problem is formulated in Haikarainen et al. [11] for optimizing the structure and the operation of a DH network. The decision variables considered are the types of fuels, the technology and the location of the heat production sites, the layout of the distribution pipes, the capacity and the location of heat storage utilities, in order to obtain optimal conditions from an economic or environmental perspective. A hypothetical urban area in southern Finland is used a test case, the network layout (and its expansion options) having essentially a tree structure. The methodology may not be easily applicable to problems of more realistic size, due to the use of binary variables to represent network structure alternatives and the linearization of some key physical relationships to make the optimization problem a mixed integer linear one.

Fazlollahi et al. [12] demonstrate that the annual operating cost can be reduced by almost 30% and a higher thermal efficiency can be obtained with an optimization procedure that selects the resources, decentralized vs. centralized heat production technologies and the configuration of the piping network. Wang et al. [13] find that the optimal location for a peak load boiler is a peripheral position within the network (i.e. far away from the main plant) close to an area that is dense of end users. On the other hand, the peak load boiler should be placed within the main plant if the electricity from combined heat and power generation can be used on site. Fang and Risto [14] perform the optimization for a multi-source system with two heat production sites, the DH network being simply represented as a sink. It is concluded that in sparse networks thermal losses represent the dominating term in the total cost, which results in a lower supply temperature from the heat production sites and higher water mass flow rates in the pipes.

Bordin et al. [15] highlight a general need for further development of DH models including meshed networks and multi-source heat production, and present preliminary results showing the potential to solve realistically sized networks.

Mertz et al. [16] proposed a mixed-integer nonlinear formulation for the optimization of the structure and the technologies involved in the design of a DH network, minimizing the total costs evaluated over multiple reference periods for the heat demand in the system. They emphasize the importance of the roles of heat losses and pressure drops in the compromise that decides the water supply temperature in the optimal network Their method is however tested for a series of very simple academic cases characterized by two heat generation sites and 4 consumer areas. Morvaj et al. [17] use a mixed-integer linear approach to the multi-objective (economic and environmental) optimization of the topology, design and operation of an urban distributed energy system including a heating network. Different scenarios about the available technologies, layout limitations and operating constraints are investigated, but some fundamental hypotheses (e.g., the constant supply and return temperatures in the heating network) show that the focus of the work is not on a detailed simulation of DH network behaviour.

Recently, Guelpa et al. [18] have published a work on the optimal operating conditions of DH networks with a special focus on the role played by the power required for pumping the hot water from the heat production sites to the end user. Assessing this contribution to the overall primary energy usage requires detailed simulation tools to evaluate the flow distribution and the pressure losses in network having a complex meshed topology, so a reduced model based on proper orthogonal decomposition and radial basis functions is proposed to cut down the computational time while maintaining an acceptable accuracy. The test case proposed is the large meshed DH network of the city of Turin, the largest network in Italy, and the reduction in computation time compared to a full fluid-dynamic model indicates that this approach could be used as