Energy Conversion and Management 173 (2018) 461–469

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Dynamic modeling for evaluation of triple-pipe configuration potential in geothermal district heating networks

Antoine Fabre*, Romain Thomas, Bruno Duplessis, Cong-Toan Tran, Pascal Stabat

MINES Paristech, PSL Research University, CES: Centre d'efficacité énergétique des systèmes, 60 boulevard St Michel, 75006 Paris, France

ARTICLE INFO

Keywords:
Triple-pipe
District heating
Low return temperature
Cascading
Network extension
Renewable energy

ABSTRACT

District Heating (DH) systems will play an important role in future sustainable energy systems. Existing networks can be optimized by lowering primary return temperatures in order to improve the use of geothermal resources. This can be done by installing triple-pipe systems. This paper defines the concept of triple-pipe configurations as it is understood in France. The objective of this paper is to demonstrate the relevance of those configurations for optimizing geothermal DH system efficiency. A dynamic thermal-hydraulic model was developed using the programming language Modelica. A generic case study is modeled considering the extension of an existing network. It is shown that triple-pipe configurations offer lower return temperatures and gas consumption, while increasing of the renewable energy share in the network energy mix.

1. Introduction

The residential and service sectors currently represent 45% of France's energy consumption, 60% of which is for space heating [1]. To face the problem of climate change, it seems crucial to tackle this end-use consumption. District Heating (DH) systems can help reducing fossil energy consumption and greenhouse gas emissions for heating by increasing the share of renewable energies in the energy mix [2]. The EU and France have enacted the development of DH systems through the European Energy Efficiency Directive and the French "Energy Transition" law [3].

In order to fulfill European and French objectives, the DH systems will have to be developed and improved in the coming years. Besides, the extension of the current DH networks must be realized as well as the improvement of actual DH system performances [4].

A key point of the DH system performances is the difference between the primary supply and return temperatures. Indeed, by increasing the temperature difference, the demand can thus be covered with a smaller water flow rate. This allows a reduction in heat loss through distribution pipes and pump's electric consumption. It can also increase the renewable energy share in the network mix by increasing the performance of production plants, in particular geothermal ones, with a limited supply temperature. Indeed, the water temperature at the outlet of the geothermal heat exchanger is limited by the temperature of the ground water, so to improve the extracted heat at a constant flow rate, the primary return temperature should be as low as possible [5]. On existing networks, large temperature differences can be obtained by the installation of triple-pipe configurations, including the cascading of heat exchangers in substations [6]. Thus this paper focuses on the improvement of performance by using triple-pipe configurations in the case of District Heating network extensions. Hence, this paper tries to determine which are the potential gains brought about by triple-pipe configurations in terms of primary return temperature, pump consumption and renewable energy rates.

1.1. Literature study

Many triple-pipe networks have been installed in the Ile de France region during these last few years, principally in the case of extensions of existing DH networks because they are supposed to lower return temperature. However, no experimental test has been carried out to prove the interest of this configuration in comparison with two-pipe configurations. Indeed, such a test would be very costly and time consuming.

Moreover, few articles relative to triple-pipe distribution are available. These articles compare the heat losses of several configurations of distribution pipes including triple pipes [7,8]. These studies come to the conclusion that triple pipes allow a significant reduction in the heat loss.

A little bit more literature about cascading substation is available. Snoek et al. [9] tried to identify the energy gain provided by cascading heat exchangers in substations within different types of heat demand,

* Corresponding author.
E-mail address: antoine.fabre@mines-paristech.fr (A. Fabre).

https://doi.org/10.1016/j.enconman.2018.07.087
Received 28 February 2018; Received in revised form 3 July 2018; Accepted 25 July 2018

network, production and climate. Furthermore another study tried to assess the techno-economic feasibility of cascading where a high return temperature is used to supply heat for low temperature networks [10]. Furthermore, Johansson et al. [11] have compared the return temperature of 4 different configurations of substation including cascading. All these studies conclude that cascading is a good way to improve the energy performances of DH systems.

It can be concluded from the previous studies that a comprehensive model for DH systems with triple-pipe configurations has not been made before. Indeed, when triple-pipe configurations have been installed, commercial simulation tools on the market were not adapted to model this kind of configuration.

Today with the emergence of new simulation tools, it is possible to model DH systems not only with two-pipe configurations but also with triple-pipe configurations The literature about the modeling of dynamic thermal-hydraulic behavior of DH systems with two-pipe configurations is widely present, even in the case of complex meshed networks [12,13]. Two main types of modeling approach have been used focusing on the modeling of pipe systems, which is the key point of the DH network model [14,15]:

– Mathematical modeling based on statistical black-box methods. These models do not require a lot of information about the physical behavior of the network but do require many historical data in order to parameterize the model.
– Physical modeling which uses a network's physical properties. These models give the flow and temperature distributions taking into account pressure drop and heat loss.

In this study, the aim is to model a generic DH network, so very few data are available. Hence, the physical modeling approach has been used.

Several methods are described in the literature to compute the physical model. Two methods are mainly used: the element method and the node method. According to [14,16] the node method is superior to the element method with respect to accuracy and computational cost. Indeed, on the one hand the node method needs less equations to be solved than with the element method; on the other hand the accuracy of node methods only depends on the Courant number whereas element method's accuracy depends on the discretization scheme [17]. Both methods have been widely validated by comparison with experimental data.

Comparative studies have been made in order to test the two methods mentioned before. The node method generally shows good accuracy with measured data except for substations far from the production site [18–21]. Regarding the element method, its accuracy has been proved against experimental data by using three order discretization schemes [22,23]. Hence the element method seems to be more appropriate to our project since its accuracy validated whatever the distance between the generation plant and the substation.

1.2. Research motivations

It can be seen from the previous section that even if DH networks with triple-pipe configurations have been installed as a solution to lower the return temperature, the potential brought about by this type of configuration has not been quantified. Therefore, this paper focuses on the modeling of a DH system as mentioned before for the purpose of assessing the potential of triple-pipe configurations on existing networks. The potential of triple-pipe distribution and cascading in substations are compared to a classical double-pipe distribution in terms of return temperature, energy consumption and renewable energy share.

2. Methodology

2.1. Model

2.1.1. Simulation environment

Several software and simulation languages are used to model a DH system using the element method. For this study, the model has been developed with Dymola [24], which is a commercial simulation environment based on the Modelica language [25]. It allows the numerical simulation of dynamic behaviors and complex physical interactions between different physical phenomena (mechanics, hydraulics, thermodynamics, electrical, etc.). Modelica is an open object-oriented language, whose advantages are extensively explained in [26]. It allows users to freely create and share libraries of components.

The user puts components (which are blocks of Modelica code) on a grid, and the simulation environment (in this case Dymola) translates them into an equation system to be solved. The main characteristic of the Modelica language is its acausal nature, which means that no equation sequence has to be given by the user for numerical solving. This makes the creation of a model fast and easy, yet it can imply solving problems which are a bit more difficult to debug.

Moreover, the element method has been validated in several studies using Modelica [17,21,27,28].

The global model used in this study is an assembly of validated components coming from the Modelica Standard Library 3.2.1 (build 4) and the Buildings Library 3.0 [26]. Some of those models have been combined and adapted to fit our needs. The relevance of global model answers to unitary tests has been checked.

2.1.2. Component modeling

The model is separated into three parts: heating demand, control and DH network (see Fig. 2). Controls and DH network are modeled by Modelica/Dymola whereas consumer's behavior (DHW, LT and HT heating demands) is obtained from another model described in [29] and based on the model of Da Silva [30]. Hence HT and LT load curves are assessed by modeling several multi-zone buildings. Each zone is considered as a cube with 4 walls: a vertical wall in contact with the outside, a floor, a ceiling and an inside wall. On each wall element, the energy conservation equation is applied thanks to an electric analogy and the temperature inside a zone is considered as homogeneous (see Fig. 1). The model takes into account solar and internal gains, and a simplified model of a radiator has been used. The internal nominal gains are supposed to be equal to 11.5 W/m^2 including equipment and sensible heat of inhabitants during occupancy [30].

Thanks to measured hot domestic water demands on substations at hourly time steps, a statistical model has been made to generate realistic DHW demand curves. From these measured data, one can calculate hour by hour the mean of all the measured demand and the standard deviation. Then, at each time step a random sampling according to a normal law is carried out to generate DHW demand curves. DH network and its strategy of control are described in Fig. 2

2.1.2.1. Heat generation. The heat generation plant is centralized and composed of a renewable energy source (geothermal) and a gas boiler for peak demand. These energy sources are of in-series configuration. As observed in a typical French DH system, the supply temperature is set through an outdoor temperature reset control (see Fig. 3). The thresholds of supply temperature law are determined by observations on a real DH system.

The gas boiler is only used when the outlet temperature from the geothermal plant is inferior to the temperature set by the outdoor reset control. The gas boiler efficiency and the geothermal heat exchanger effectiveness are considered as constant values.

2.1.2.2. Pump. The pump is ideally controlled. The prescribed pressure head is given by a very similar law to the one controlling the network