Energy Conversion and Management 151 (2017) 158–169

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Dynamic equation-based thermo-hydraulic pipe model for district heating and cooling systems

B. van der Heijde[a,b,c,*], M. Fuchs[d], C. Ribas Tugores[e,1], G. Schweiger[f], K. Sartor[g], D. Basciotti[h], D. Müller[d], C. Nytsch-Geusen[e], M. Wetter[i], L. Helsen[a,b]

[a] EnergyVille, Genk, Belgium
[b] KU Leuven, Department of Mechanical Engineering, Leuven, Belgium
[c] VITO NV, Mol, Belgium
[d] RWTH Aachen University, E.ON Energy Research Center, Institute for Energy Efficient Buildings and Indoor Climate, Aachen, Germany
[e] Berlin University of the Arts, Institute for Architecture and Urban Planning, Berlin, Germany
[f] AEE – Institute for Sustainable Technologies, Gleisdorf, Austria
[g] University of Liège (ULg), Thermodynamics Laboratory (B49), Liege, Belgium
[h] Austrian Institute of Technology (AIT), Vienna, Austria
[i] Lawrence Berkeley National Laboratory, Berkeley, CA, USA

ARTICLE INFO

Keywords:
District heating and cooling
Heat loss
Dynamic thermo-hydraulic model
Modelica
District energy systems
Simulation
Thermal network

ABSTRACT

Simulation and optimisation of district heating and cooling networks requires efficient and realistic models of the individual network elements in order to correctly represent heat losses or gains, temperature propagation and pressure drops. Due to more recent thermal networks incorporating meshing decentralised heat and cold sources, the system often has to deal with variable temperatures and mass flow rates, with flow reversal occurring more frequently. This paper presents the mathematical derivation and software implementation in Modelica of a thermo-hydraulic model for thermal networks that meets the above requirements and compares it to both experimental data and a commonly used model. Good correspondence between experimental data from a controlled test set-up and simulations using the presented model was found. Compared to measurement data from a real district heating network, the simulation results led to a larger error than in the controlled test set-up, but the general trend is still approximated closely and the model yields results similar to a pipe model from the Modelica Standard Library. However, the presented model simulates 1.7 (for low number of volumes) to 68 (for highly discretized pipes) times faster than a conventional model for a realistic test case. A working implementation of the presented model is made openly available within the IBPSA Modelica Library. The model is robust in the sense that grid size and time step do not need to be adapted to the flow rate, as is the case in finite volume models.

1. Introduction

In the transition towards a sustainable energy provision, one of the proposed concepts towards higher energy efficiency and the inclusion of renewable energy sources is the new 4GDH system (4th generation district heating and cooling) [1]. These systems are characterised by lower temperature differences, but also intermittent operation, multiple supply temperatures and higher fluctuation of the supply temperature than in conventional systems. These lower temperatures for heating, or higher temperatures for cooling allow for a larger take-up of renewable heat and cold sources such as solar thermal panels, heat pumps, geothermal sources, and industrial waste heat utilisation [2,3].

The variability of local and centralised renewable heat sources alongside new concepts like Active Demand Response, multiple supply temperature levels and reversing mass flows put more requirements on accurate and fast dynamic modelling. More complex system interactions in multi-energy district or even city-wide energy systems necessitate an integrated modelling framework. Schweiger et al. [4] and Böttger et al. [5] have identified a high potential for *power-to-heat* technologies in district heating systems, which would require a more sophisticated pipe model for simulation and control as presented in this work. Not only the physical processes need to be modelled, but also the control of the system.

This brings about a need for high-performance models of all system

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* Corresponding author at: EnergyVille, Thor Park, Poort Genk 8310, 3600 Genk, Belgium.
E-mail address: Bram.vanderHeijde@kuleuven.be (B. van der Heijde).

[1] Current address: AEE – Institute for Sustainable Technologies, Gleisdorf, Austria.

http://dx.doi.org/10.1016/j.enconman.2017.08.072
Received 1 July 2017; Received in revised form 18 August 2017; Accepted 27 August 2017

Nomenclature

Subscripts

$\square_0$	initial
$\square_b$	boundary
$\square_c$	casing
$\square_g$	ground
$\square_{in}$	inlet
$\square_{mea}$	measured
$\square_{out}$	outlet
$\square_p$	pipe
$\square_{pro}$	production side
$\square_{sim}$	simulated
$\square_{sub}$	substation side

Symbols

A	area (m^2)
C	heat capacity per meter (J/m K)
c_v	specific heat capacity (J/kg K)
f	Darcy friction coefficient (–)
k	thermal conductivity (W/m K)
L	length of the pipes (m)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (Pa)
$\dot{q}$	heat loss rate per meter (W/m)
R	thermal resistance per meter (K m/W)
S	circumference (m)
T	temperature (°C)
U	heat loss coefficient (W/m K)
v	velocity (m/s)
ρ	mass density (kg/m^3)
τ	time constant (s)
ε	relative error (–)

components involved. The goal is threefold: namely high accuracy, low calculation time and high numerical robustness. This paper presents a physical model for district heating and cooling pipes that is able to cope with fluctuating inlet temperatures, varying (even stopping or reversing) mass-flows and arbitrary network lay-outs, including both branching and meshed systems.

This work is done collaboratively within the development of the Annex 60 Modelica Library [6] and the IBPSA Project 1 Modelica Library, which the presented model is contained within. In these international collaborations, the efforts of various research institutes in separate Modelica libraries have been bundled into one free, open-source, validated and well-documented library.

The main contribution of this paper is a novel, open-source, dynamic thermo-hydraulic pipe model for district energy systems.

The aim is to accurately model the thermo-hydraulic behaviour in district heating and cooling pipes. After the derivation of the thermal propagation equations, the model is implemented in Modelica [7] and validated experimentally. Modelica is an equation-based, object-oriented modelling language that allows simulation of complex dynamic processes in multiple physical domains, including their control. The proposed model is validated against two experimental cases. Furthermore, performance of the model is compared to that of a commonly used model in the Modelica Standard Library [7]. The models are compiled and simulated with Dymola [8].

To the authors' knowledge, there exists no freely available open-source models able to handle this degree of complexity with sufficient accuracy. The presented model intends to fill this gap. Available libraries struggle with accuracy or with applicability to larger multi-domain systems [9,10].

1.1. Literature study

This section provides an overview of previous literature on the topic of dynamic simulation of district heating and cooling pipe systems. The literature survey is organised chronologically and based on modelling strategy.

1.1.1. Early steady-state computational models

One of the first scientific reports about modelling heat losses for pipes buried underground can be found in Franz and Grigull [11]. Using an experimental set-up involving an electrically charged plate to represent the temperature field around a supply and return pipe, they effectively linked the thermal problem to its electrical equivalent. Menyhárt and Homonnay [12] described the steady-state heat loss equations for buried pipes in a concrete casing with a supply and return pipe. The mutual influence of supply and return was not taken into account.

In the late 1980s and early 1990s, scientific progress in the field of geothermal borefields and borehole heat exchangers (Eskilson [13], Bennet et al. [14], Hellström [15] and Claesson and Hellström [16]) was applied to the steady state heat loss calculation of district heating pipe systems in different configurations (Wallentén [17]). Configurations considered were pipes buried in the ground or surrounded by air, and pipes insulated separately and jointly. Wallentén described the accuracy of the results of different multipole expansions with increasing order. The simplest method (i.e. the zero-order multipole expansion) introduced an error of up to 5%, while higher order solutions quickly increased the accuracy.

1.1.2. First dynamic models and operational optimisation

With the development of stronger and cheaper computers, dynamic models for the operation of district heating systems started to be investigated. For dynamic simulations, mostly finite element models (so-called *element models*) were used, where the pipe is spatially discretized in order to compute the temperature propagation and heat losses. The physical process of the flow of water through a pipe can be approached as an advection-diffusion equation with a source or loss term. This equation can efficiently be solved with the QUICK discretization scheme [18]. Notice that in regular operation conditions, the diffusive term in the equation is negligible.

On the other hand, the propagation of water can be modelled by only considering the in- and outlet of the pipe and calculating the output based on the propagation delay. This is the so-called *node method* and was described, together with the element method, by Benonysson [19]. Benonysson et al. [20] presented a case study of an operational optimisation of the supply temperature to a district heating system, with operating cost as the objective function. In this study, the node model was not used, but Benonysson et al. expected that the optimisation would be faster if the node model were used.

A general overview of different modelling approaches for district heating pipes and the errors induced by them was presented by Pálsson et al. [21]. They concluded that the number of floating point operations per time step for the element method scales linearly with the number of discretization elements for the pipe. The node method does not use a discretisation and hence the number of floating point operations remains the same for every pipe. The accuracy of the element method is inversely proportional to the square of the element length, while for the node method it depends only on the Courant number.