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Modelling steady-state thermal behaviour of double thermal network pipes

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ABSTRACT

Optimal design and operation of district heating networks require accurate, but simple models to allow fast simulation. This paper describes the analytical derivation of such a model based on existing work regarding heat loss and dynamic temperature profile calculations in literature. The most important addition from this work is the incorporation and investigation of heat transfer from supply to return side in double pipes, something which is often (over)simplified in more commonly used models.

The paper presents the mathematical derivations and the assumptions made in detail for the case of steady-state heat losses in double pipes. The resulting model is carefully examined in a parameter study, from which a number of interesting conclusions can be drawn. Firstly, the heat losses are found to be nearly independent of the mass flow rate in the range of mass flow rates usually encountered in thermal network pipes. The remaining heat loss calculation is simply based on temperature levels and thermal resistance factors, determined by the pipe dimensions and materials. Furthermore, it is found that heat losses from supply to return side should be incorporated in the analysis for better accuracy of the results, even more so with the increasing popularity of twin pipes with common insulation.

1. Introduction

Fourth generation district heating and cooling networks are considered as an important technology in the effort towards a more sustainable and renewable energy system [1]. The installation of these systems has been deemed beneficial both by academia and government, see for instance the Heat Roadmap Europe 2050 [2,3] and the EU Strategy on Heating and Cooling [4,5]. The latter identifies the potential of supplying 50% of the EU heat demand with district heating. These systems are characterized by lower and fluctuating supply temperatures in order to enable the inclusion of renewable energy systems, waste heat and higher efficiency heating and cooling systems. Overall, the complexity of the thermal network increases, which calls for detailed pre-studies for design and high-performing simulation models towards improved control strategies.

The study of heat losses in buried pipes is an important subject within the research towards the operation and optimization of thermal networks. As may be seen from the literature study below, many approaches towards the calculation of the behaviour of buried pipes have been proposed already, all depending on the available computation techniques and purpose of the model. This paper aims at determining the degree of mutual influence of double district heating pipes buried underground, and at accurately calculating the outlet temperatures and heat losses. Therefore, an analytical solution to the steady-state thermal problem of buried pipes is proposed, based on existing techniques for heat loss and temperature propagation calculation in these systems.

The outline of the paper is as follows: firstly, an overview of existing literature is presented, summarizing the relevant research that has inspired this new calculation technique. In the Methodology section, the mathematical derivation of the newly proposed solution is written out. The Result section presents a study regarding the sensitivity of different parameters in the model, the outcome of which is analysed and synthesized further in the Discussion and Conclusion sections.

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Nomenclature

Subscripts

$\square_a$	Asymmetrical problem
$\square_s$	Symmetrical problem
$\square_r$	Return *(Rücklauf)*
$\square_v$	Supply *(Vorlauf)*
$\square_{in}$	Inlet
$\square_{out}$	Outlet
$\square_b$	Boundary/Undisturbed ground

Symbols

A	Area (m^2)
C	Heat capacity per meter (J/(m K))
c_p	Specific heat capacity (J/(kg K))
f_D	Darcy friction coefficient (−)
h	Shape factor (−)
k	Thermal conductivity (W/(m K))
L	Length of the pipes (m)
p	Pressure (Pa)
$\dot{q}$	Heat flow rate per meter (W/m)
$\dot{Q}$	Heat flow rate (W)
R	Thermal resistance per meter (Km/W)
S	Circumference (m)
T	Temperature ($^\circ$ C)
u	Specific internal energy (J/kg)
v	Velocity (m/s)
ξ_L	Temperature decay factor (−)
ρ	Mass density (kg/m^3)
τ	Time constant (s)
ϑ	Temperature ratio (−)

2. Previous studies

2.1. Early analytical and experimental work

Modelling the thermal behaviour of pipes in district heating systems, and in thermal networks in the broader sense, has been the subject of scientific studies for a long time already. The work of Esser and Krischer [6] is counted among the first experimental research towards steady state heat losses in pipes with insulation. The mathematical description of the heat loss partial differential equations for a single buried pipe can be found in the work of Carslaw and Jaeger [7]. The first mention of an electrical analogy for the problem is found in D'Eustachio's work [8], leading to the treatment of heat problems with equivalent thermal resistance and capacitance network models. Franz and Grigull [9] described an experimental set-up which allows the study of the heat loss from two pipes as an electrical system and thus explicated the electrical network analogy for the steady state problem in two pipe systems[2].

2.2. Mathematical derivation of steady-state losses

A more formal derivation of the steady state heat losses for dual pipe systems is presented by Wallentén [10], who applied the multipole method to define a symmetric and asymmetric thermal resistance based on the pipes' characteristics. This method has been used earlier to characterise the thermal behaviour of ground heat exchangers in borehole (underground) thermal energy storage systems, for example in the work of Eskilson [11], Bennet et al. [12], Hellström [13] and Claesson and Hellström [14]. Wallentén defined the steady state heat losses by means of a number of shape factors, depending on the configuration of the pipe system. The configuration can consist of single or double pipes, buried underground or in air, and with separate insulation layers or embedded in a common insulation tube. This method will be treated in detail in Section 3.2.

2.3. Operational modelling

The papers described above focus mainly on the description of the heat losses from a static or steady-state point of view. A more operational approach can be found in the work of Benonysson [15], who developed a novel dynamic model for district heating pipes. This model differs from the usual finite volume models in that it treats the propagation of water at a specific temperature and the heat losses separately, while including the thermal capacity of the pipe. Benonysson clearly distinguishes between the so-called *element* model and his new *node* model. The node model splits the transport phenomenon in district heating pipes in three parts:

1. the propagation of fluid with a specific temperature,
2. the thermodynamic behaviour of the pipe due to the pipe wall heat capacity and
3. the steady state heat loss, based on the instantaneous fluid velocity at the outlet.

The *propagation process* determines when the inlet temperature from some point in the past will appear at the outlet, depending on the length of the pipe and the mean fluid velocity in the pipe. This step avoids numerical diffusion that otherwise appears in the element model when the Courant number is not equal or close to one, see also [16]. The *thermodynamic behaviour* and *steady state heat loss* straightforwardly follow from heat transfer theory.

One important assumption in Benonysson's model is that it is sufficient to treat each pipe independently from other adjacent pipes. This was confirmed by Pálsson et al. [16], except for the case of cast concrete pipes. Later, Bøhm and Kristjansson revised this assumption and defined a mutual heat transfer formulation for configurations with double or triple pipes [17]. Further study was conducted by Dalla Rosa et al. [18] who compared the heat losses in detailed simulation models with experimental data and analytical solutions.

Bøhm [19] investigated the dynamic behaviour of buried district heating pipes under changing environmental conditions. The influence of the air temperature is translated to an equivalent boundary temperature at the outermost pipe layer. Comparative studies between commercial software for district heating and the node model are presented by Gabrielaitiene et al. [20], [21]. In these studies, the models were compared with measurement data from different district heating systems. The differences were small as long as the temperature changes were slow and limited, and the variations in mass flow rate were not too high.

The problems of the element model during faster inlet temperature steps and at zero mass flow are recognized by

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[2] The idea was first studied by J. Vidal, but this source is irretrievable.