THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Development of a non-destructive field testing method for thermal assessment of district heating pipes

PETER LIDÉN

Department of Architecture and Civil Engineering

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2022

Development of a non-destructive field testing method for thermal assessment of district heating pipes

PETER LIDÉN

ISBN: 978-91-7905-641-4
ISSN 0346-718X
Ny serie nr 5107

Department of Architecture and Civil Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Chalmers Digitaltryck
Gothenburg, Sweden 2022

Development of a non-destructive field testing method for thermal assessment of district heating pipes

PETER LIDÉN
Department of Architecture and Civil Engineering
Division of Building Technology, Infrastructure Physics
Chalmers University of Technology

Abstract

The thermal state of a district heating (DH) network governs the heat losses. It is a parameter considered if a change is to be made in the network. Heat losses are costly and economic aspects are important when planning for the maintenance or replacement of DH pipes. In addition, knowledge of the DH network, and of the parts of the network that may contribute to high heat losses, is important for system control. Pre-insulated DH pipes have been in use for over 40 years. The thermal performance of these pipes decreases over time as a result of thermal aging, leading to higher heat losses. Present methods cannot assess these heat losses with high accuracy. This thesis proposes a developed non-destructive cooling method, the main purpose of which is to perform a temporary shutdown of a selected part of a network, and where temperature measurements are performed during the cooling phase.

This thesis presents the development process and the final method to use for thermally assessing pre-insulated DH pipes with high accuracy. The main research questions of this work were linked to the accessibility and measurability of the buried pipe or its connected parts. The methodology for developing the method is based on laboratory tests, field tests with several measurement points, and mathematical models of DH pipes and connected valves.

The work resulted in a method and a user guide that can be used by network owners to assess parts of a DH network. A method that by a shorter shutdown, in the range of a few hours, can be used to capture the temperature decline in a DH pipe. Results indicate that drainage valves, which are directly connected to the underlying DH network, were suitable measurement points where the temperature-decline phase of the DH pipe could be captured. The method allowed a prediction of the thermal conductivity of a buried DH pipe in operation with 2% deviation from the reference value.

Acknowledgments

This thesis summarizes my research at the Division of Building Technology, Department of Civil and Environmental Engineering, Chalmers University of Technology. The research has been funded by Energiföretagen Sverige and Energimyndigheten through the research programme Fjärrsyn and the project Livslängd och statusbedömning av fjärrvärmenät. Additional funding was provided by Energiforsk and the programme FutureHeat for the project Fältförsök för statusbedömning av fjärrvärmerör med en icke förstörande metod.

My research involved several field tests, none of which would have been possible without the very helpful energy companies and their great staff. Thanks to Borås Energi och Miljö, Mölndal Energi, Göteborg Energi, and Falu Energi och Vatten. I am also grateful to Powerpipe Systems AB for providing me with pipes for laboratory tests and for sharing their knowledge of the pipe production technique.

I would like to express a special thanks to my supervisors Bijan Adl-Zarrabi and Carl-Eric Hagentoft for having patience with and faith in my work, especially through the rather challenging time of lonely remote work during the pandemic. I am very grateful for your responsive and invaluable guidance throughout these years. To all my great colleagues at the Division of Building Technology, you will be missed, but hopefully our paths will cross in the future.

Finally, I would like to thank my family for their support and understanding – love you!

Peter Lidén

Göteborg, 2022

List of Publications

This thesis consists of an extended summary and the following appended publications, referred to in the text by the Roman numerals I–V:

Paper I Lidén, P., Adl-Zarrabi, B.: Non-destructive methods for assessment of district heating pipes: a pre-study for selection of proper method. *Energy Procedia*, 116: pp. 374–380. (2017)

Paper II Lidén, H.P., Adl-Zarrabi, B.: Non-destructive methods of district heating pipes. In *Proceedings of the 12th ECNDT*, Sweden, Gothenburg. (2018)

Paper III Lidén, H.P., Adl-Zarrabi, B.: Development of a non-destructive testing method for assessing thermal status of district heating pipes. *Journal of Non-Destructive Evaluation*, 39:22. (2020)

Paper IV Lidén, H.P., Adl-Zarrabi, B., Hagentoft, C.-E.: Diagnostic protocol for thermal performance of district heating pipes in operation. Part 1: Estimation of supply pipe temperature by measuring temperature at valves after shutdown. *Energies*, 14(16):5192. (2021)

Paper V Lidén, H.P., Adl-Zarrabi, B., Hagentoft, C.-E.: Diagnostic protocol for thermal performance of district heating pipes in operation. Part 2: Estimation of present thermal conductivity in aged pipe insulation. *Energies*, 14(17):5302. (2021)

ADDITIONAL PUBLICATIONS

The following publications are related to underground infrastructure but are not part of this thesis:

- Lidén, H.P., Adl-Zarrabi, B., Sundberg, J.: Influence of vapour diffusion on the temperature in high load transmission cables: A laboratory experiment with varying groundwater levels. *Case studies in thermal engineering*, Status: Under review.
- Lidén, P. (2020) Development of a non-destructive testing method for thermal assessment of a district heating network. Licentiate thesis. Chalmers University of Technology.
- Lidén, P. (2019) Fältförsök för statusbedömning av fjärrvärmerör [Field tests for the status assessment of district heating pipes]. Rapport 2019-590. Energiforsk.
- Adl-Zarrabi, B., et.al (2017) Livslängd och statusbedömning av fjärrvärmenät: Konventionella och högpresterande rör [Lifespan and status assessment of district heating networks: Conventional and high-performance pipes]. Rapport 2017-420. Energiforsk.
- Lidén, P., et.al. (2016) High-temperature performance for high voltage underground cables in cable sand: Laboratory experiment. Report 2016-7. Department of Civil and Environmental Engineering, Chalmers University of Technology.
- Lidén, P. & Sundberg, J. (2016) South West Link: Feedback of experience from thermal design. Report 2016-7. Department of Civil and Environmental Engineering, Chalmers University of Technology.
- Sundberg, J. & Lidén, P. (2014) Halkfria vägar – Etapp 2. Energi- och systemanalys med kostnader: Solvärme och värmelagring för miljöanpassad halkbekämpning [Skid-resistant winter roads – Stage 2. Energy and system analysis: Solar heat and heat storage for environmentally sound deicing]. Report 2014:121. Swedish Road Administration.
- Lidén, P. & Saglamoglu, S. (2012) Groundwater chemistry and its influence on the selection of construction materials: A review of four traffic tunnels in Sweden and evaluation of technical requirements. Master`s thesis 2012:108. Chalmers University of Technology.

Nomenclature

Symbols

T	Temperature (K)
ρc	Volumetric heat capacity (J/m^3K)
q	Heat flux (W/m^2)
Q	Heat flow (W)
r	Radial distance (m)
L	Length (m)
λ	Thermal conductivity (W/mK)
t	Time (s)
R	Electrical resistance (Ohm)
α	Temperature coefficient of resistivity (1/K)
V	Volume (m^3)
C	Total heat capacity (J/K)
K	Conductance (W/K)
F	Matching factor (-)
A	Cross-sectional area (m^2)

Subscripts

s	Service pipe
cp	Casing pipe
co	Copper wire
v	Valve
dv	Drainage valve
sv	Shutdown valve
a	Ambient air
w	Water
c	Intrinsic timescale
i	Polyurethane insulation

Acronyms

DH	District heating
NDT	Non-destructive testing
PUR	Polyurethane
PE	Polyethylene
HDPE	High-density polyethylene
TDR	Time-domain reflectometry
GHP	Guarded hot pipe
GHFM	Guarded heat-flow meter
TC	Thermocouple
DN	Nominal diameter
LSA	Lumped system analysis

Contents

1 Introduction

District heating (DH) networks are widely used in urban areas throughout the world, and their usage, which started to expand greatly in the 1960s in the USA and Europe, has evolved in large networks of varying ages. The main idea of DH is to deliver heat that has been produced from local heat resources, which are often residual products from other activities and therefore cheaper than other heat sources. In Sweden, energy for DH is commonly produced using excess heat from burned household waste or from industry, with low environmental impact. Internationally, fossil fuels are still the dominant heat source for DH. DH has its greatest potential in areas of high heat density, i.e., areas of high heat demand within a short distance from power plants where the DH is produced (Werner, 2017). Greater distances require multiple kilometres of pipes, thereby increasing the total heat losses from and costs of the pipes.

The pipe types used over the history of DH vary. Old networks, often referred to as second-generation DH networks, used steel pipes in concrete or asbestos boxes insulated with, for example, mineral wool or cellular concrete foam. Today we have third-generation DH networks, which are better controlled partly due to flow and temperature meters at the customers' substations, which benefit the customers since they pay only for their actual heat consumption. Pre-insulated polyurethane (PUR) single pipes are very common and came into use in the late 1960s, when third-generation DH entered the field (Fredriksen and Werner, 2013; Lund et al., 2014). Both supply and return pipes run between the heat plant and the customers, normally next to each other in a trench or as twin pipes with both supply and return within the same casing pipe (see Fig. 1). During the cold season, the supply water temperature varies between 70 and 115°C in Swedish systems, and normal casing pipe temperatures, at depths of at least 0.5 m below the ground surface, range from approximately 0 to 15°C in southern Sweden, where ground frost at these depths is rare (Trafikverket, 2021).

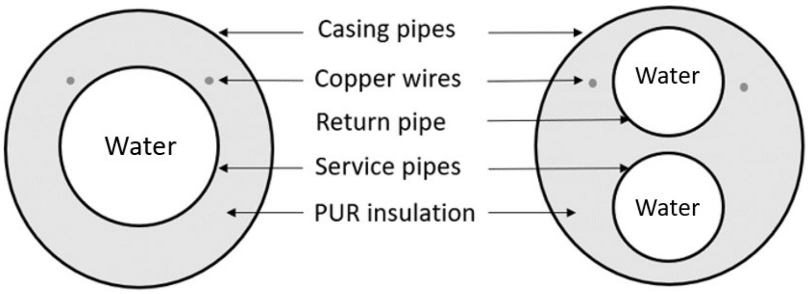


Fig. 1. Rigid pre-insulated DH pipes. A single pipe to the left and a twin pipe to the right.

A single pipe consists of an inner service pipe (i.e., water pipe), normally made of steel and surrounded with PUR foam insulation, an outer casing pipe of high-density polyethylene (HDPE), and two measurement wires for moisture surveillance embedded in the insulation. There are two types of moisture surveillance systems: the Nordic system with bare copper wires (typical in Sweden) and the NiCr system with insulated nickel-chromium wires (Brandes, 2019). A time-domain reflectometer (TDR) is connected to the copper wires in order to detect and locate water leaks. The dimensions of a pipe are given by the nominal diameter (DN) of the service pipe and the casing pipe, for example, DN50/140 (mm).

Owners of the pipe network, normally energy companies, can measure what they produce and what they deliver to customers in terms of heat energy, so the heat losses of the whole network can be determined. In Sweden, around 10% on average of the energy supplied to DH networks is lost through heat losses from the distribution pipes (Berge et al., 2015; Vesterlund et al., 2013), with aging and associated degradation of the PUR insulation being among the major reasons (Kręcielewska and Menard, 2014).

The European Standard EN 253:2009 states that pre-insulated pipes should last at least 30 years at a constant operating temperature of 120˚C, and that new pipes should have a thermal conductivity at 50˚C (λ_{50}) ≤0.029 W/mK (SS-EN253, 2009). Cyclopentane and carbon dioxide are used as the low-conductive gases in the closed cells of PUR foam. Thermal aging and degradation of the PUR insulation take place due to high temperatures in the service pipe and diffusion of gases through the casing pipe (Kręcielewska and Menard, 2014). During this process, mainly oxygen and nitrogen molecules in ambient air penetrate into the PUR and replace the blowing agent gases (Persson, 2015). This affects the thermal conductivity, which tends to increase by around 10% over 30 years (Adl-Zarrabi et al., 2017).

A clear and obvious motivation for reducing heat losses is that they may be costly. Furthermore, energy conservation is desirable for all societies in order to minimize environmental impact. It is an advantage for many energy companies to estimate the remaining service life of pre-insulated DH pipes. However, whether action should be taken, regarding, for example, pipe replacement, is not clear cut, especially regarding economic aspects (SvenskFjärrvärme, 2015). The pipe network that might need to be changed has to be long enough in order to make the excavation and replacement of the pipes economically beneficial. For DH networks that rely on an expensive heat source, pipe replacement even over shorter distances may be more beneficial than for DH networks relying on less expensive heat resources.

To inspect and assess a DH network, one can either use a destructive approach and remove the overlying soil and dismantle part of the pipe network or use a non-destructive testing (NDT) method, i.e., collecting data about a material (here, pipe) without damaging it (Berndt, 2001) and, in the present context for this purpose, preferably also without removing the soil. Estimating the remaining service life of a network is difficult, since conventional thermal NDT techniques give only rough estimations. Energy companies can use infrared thermography as an NDT method for detecting heat losses, which may indicate water leaks from DH pipes (Friman et al., 2014; Zinko et al., 1996). Thermography is conducted with a thermal camera and gives the user ground surface temperatures, with unnaturally high temperatures possibly indicating heat losses. However, the thermal state of the pipe insulation cannot be assessed with high resolution using this technique, since the surrounding soil environment and its thermal properties, as well as weather conditions, affect the resulting surface temperature of the ground.

One existing method with high accuracy for assessing the mechanical performance of the pipes is the SP plug method (Sällström et al., 2013). The method is destructive as it requires interference with the pipe network, in that small samples of the PUR insulation are taken and the mechanical and thermal properties of the sample are determined in a laboratory. This method provides a good status assessment of the removed smaller samples, although a large part of the insulation along the pipe remains unassessed.

Several studies of heat loss models have been conducted over the years. This development was well described by van der Heijde et al. (2017), starting from basic equations for heat transfer in pipes presented by Carslaw and Jaeger (1986) to operational models presented by, for example, Bøhm (2000), Chicherin et al. (2020), Danielewicz et al. (2016), Fang et al. (2012), Oppelt et al. (2016), Rosa et al. (2011), and Zwierzchowski and Niemyjski (2019). A recent and thorough study was conducted by Wang et al. (2018), who modelled and assessed the thermal state of DH pipes using hourly temperature and flow measurements from customer substations as nodes in the network. This approach was shown to be a useful way of mapping weaknesses in terms of heat losses in a large system. However, this type of modelling entails approximations. A DH system consists of cyclic water flows with sometimes shifting flow directions in looped networks, which demands challenging dynamic flow modelling for accurate status analysis.

Another study in the field of DH connected to the scope of this thesis, is a cooling method introduced by Reidhav and Claesson (2010) for assessing the thermal conductivity (λ) of flexible twin pipes. In this method, flexible pipe was placed in a pool with cold tap water; warm water with a temperature of 80˚C (i.e., the service pipe temperature) was then circulated in the flexible pipe. The water circulation was then stopped and the cooling time and temperatures of the pool and supply water were measured and analysed. The temperature decline of hot stagnant water in the pipe, immersed in cool water, depends on the thermal conductivity of the pipe, which can be calculated by the transient inverse calculation of the partial differential equations of heat transfer.

The idea behind the cooling method, i.e., measuring the temperature decline in a DH pipe, was assessed to have potential for development as an NDT method in the field. However, the lack of temperature sensors on service pipes in operation is a drawback of using the cooling method without modification. Generally, implementation of the cooling method requires knowledge of two temperatures, i.e., the service pipe temperature and the temperature at an arbitrary position in the cross-section of the pipe, instead of a prescribed casing pipe temperature.

1.1 Aim

The overall and initial aim of this research was, via a broad survey inside and outside the field of DH, to search for existing NDT methods and measurement techniques that could be implemented for the status assessment of part of a DH network. This aim could be achieved either through modifying an existing method or gathering ideas with which to develop a new method.

The specific aim was to develop a non-destructive and accurate field method for thermal assessment of DH networks, based on temperature sensor readings. The hypothesis was that the thermal state of a DH pipe can be assessed during a temporary shutdown by monitoring the temperature decline in the pipe. Some research questions arose from this hypothesis:

- Where can sensors be positioned to accurately capture the temperature decline?
- How does the surrounding soil affect the use of the method?
- What is the impact of weather conditions on field measurements?
- How long should a shutdown be, and what are the consequences?
- How should measurement results be used in calculating the present thermal conductivity of the insulation in a buried DH pipe in operation?

- What are the uncertainties and total accuracy of the method?
- What will the final method be like and who can use it?

1.2 Limitations

The focus of this thesis is on rigid pre-insulated single DH pipes consisting of an inner service pipe of steel and an outer casing pipe. It is assumed that the insulation and soil material are isotropic and homogenous and that the PUR insulation is dry. Furthermore, it is assumed that a shutdown does not give rise to horizontal water movements.

1.3 Research design

The methodology for the development of the NDT method was based on a pre-study in the form of a literature review of existing methods, a choice of method to test, and laboratory and field measurements incorporating analysis and evaluations.

The pre-study was performed to identify potential NDT methods from fields other than DH, and to identify existing measurement methods within the field of DH that could be modified. This created the possibility of a choice between developing a new method and modifying an existing one. A modified cooling method was chosen and evaluated in the laboratory environment. The laboratory results were satisfactory, so field measurements were conducted, followed by analyses and evaluations. The results of the first field measurements were promising for the development of the method, so additional field measurements were carried out at different locations. The conditions regarding the accessible measurement points differed for the cooling tests throughout the method development process. Hence, different mathematical approaches were used for analysing and assessing the thermal state, ranging from analytical solutions in the laboratory test and field tests in which several measurement points were available, to numerically coding a finite difference model, which was applied in the final method using fewer measurement points. The methodology of the PhD work is illustrated in the flow chart in Fig. 2.

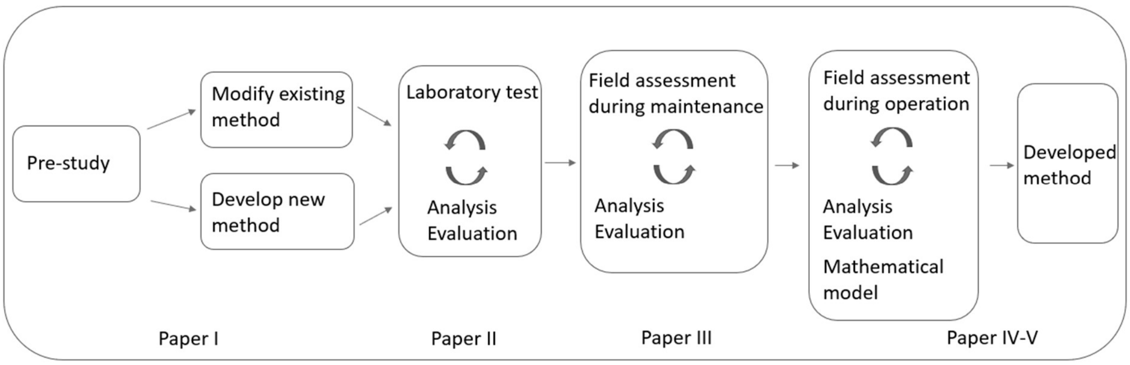


Fig. 2. PhD workflow for development of the non-destructive field testing method

The flow chart illustrates the PhD work process and addresses the aims of the thesis. Achieving these aims depends entirely on the stated hypothesis and identified research questions. The bullet points below describe the strategy and main contributions of the five constituent papers of this PhD research.

- The first identified sensor for temperature measurement was the copper wire embedded in the pipe insulation. Paper **I** addressed the utility of using copper wire as a temperature sensor by measuring the electrical resistance during temperature changes in the service pipe, work that was conducted in the laboratory.

- In parallel with further copper wire testing, the earlier identified cooling method was evaluated in Paper **II.** At this stage, the method was tested on operating mineral-wool–insulated DH pipes in a heated culvert connected to Chalmers' local DH network, with the aim of determining the thermal conductivity of the pipe insulation. During this measurement, temperature sensors were attached to the service pipe and the thin casing pipe. There was no copper wire in the pipe insulation.

- Two main conditions in the field enabled several measurement opportunities, as shown in Fig. 3. The first, covered in Paper **III,** was measurement during the maintenance of parts of the pipes exposed in an excavation. In this condition, parts of the pipes were accessible in the excavated area and DH water temperature measurements were conducted directly on the thermally conductive steel service pipe. Furthermore, the casing pipe temperature and the copper wire temperature were measured. In addition, ambient air temperature was measured in the excavated pit. Assessment of the use of copper wire was possible; however, only the part of the insulation between the service pipe and the copper wire could be assessed.

- The second condition in the field was the "normal" condition of operating and fully buried pipes; this condition was covered in papers **IV**–**V**. Here, the DH water temperature was measured at the closest customer substation. Temperatures of shutdown and drainage valves, accessible through manholes, were measured; in earlier field tests, these valves were considered parts of the system where sensors could be placed. The measured valve temperatures were then indirectly used for numerically calculating the temperature decline of the water in the DH pipe section. However, in this condition, the casing pipe temperature was theoretically assessed and calculated instead of measured.

- Finally, a proposed method for diagnosing the present thermal conductivity in operating pipes was presented in Paper **V**.

The measurement points accessible during the two main conditions in the field, i.e., during maintenance and during operation, are shown in Fig. 3. The DH water temperatures and the service pipe temperatures are assumed to be equal due to the thermally highly conductive thin steel material of the service pipe. Hence, measurements of the service pipe temperature, T_s, are also referred to as the DH water temperature, and vice versa.

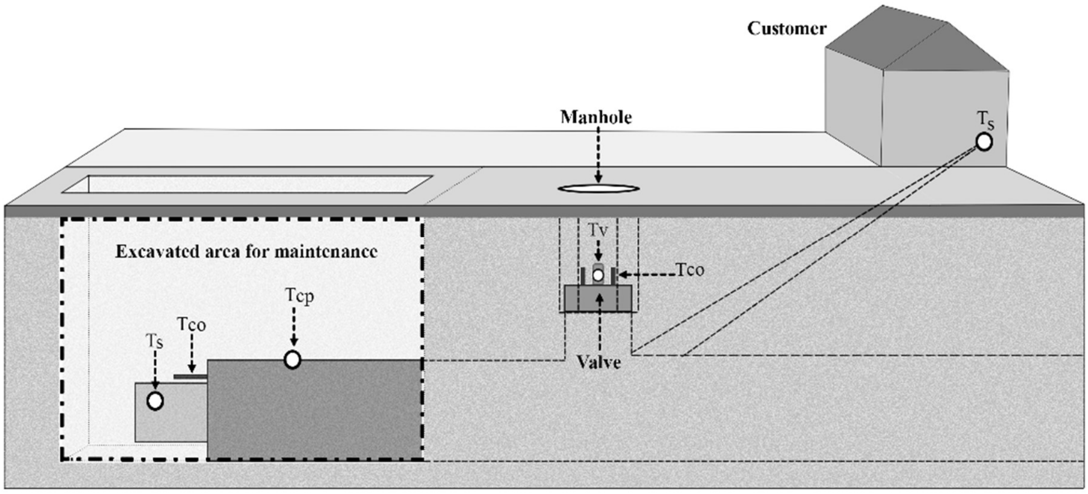


Fig. 3. Illustration of accessible measurement points for the cooling method during maintenance and during operation. T_s = service pipe temperature (called T_f in papers **IV**–**V**), T_{cp} = casing pipe temperature (called T_s in papers **IV**–**V**), T_{co} = copper wire temperature, and T_v = valve temperature (T_{dv} = drainage valve temperature and T_{sv} = shutdown valve temperature).

2 Heat transfer equations for the cooling method

Considering the cooling method as a method for further use and development calls for some general understanding of heat transfer before and during a shutdown. During normal operation and without fluctuations in DH water flow and temperature, steady-state heat transfer occurs from the inner hot region of a pipe towards the colder outside.

Three heat transfer mechanisms are involved within the pipe components, i.e., conduction, convection, and radiation. Depending on observation level, all mechanisms are involved in, for example, heat transfer in PUR insulation, which has a gas-filled closed-cell structure. However, heat transfer in the whole domain, i.e., the cross-section of the pipe, can be assumed to be pure conduction. The general equation for heat transfer by conduction is presented in Eq. (1), in which the left side is given by the product of the volumetric heat capacity ρc (J/m^{3}K) and the temperature change over time. On the right side of Eq. (1) is the net heat inflow, which is obtained by the negative divergence of the heat flux q (W/m^2). Furthermore, the heat flux can be calculated according to Fourier's law, see Eq. (2):

$$\rho c \frac{\partial T}{\partial t} = -\nabla q \qquad (1)$$

$$q = -\lambda \nabla T = -(\lambda . \frac{\partial T}{\partial x}, \lambda . \frac{\partial T}{\partial y}, \lambda . \frac{\partial T}{\partial z}) \qquad (2)$$

When calculating heat losses from a pipe, one must consider the circular geometry, meaning that cylindrical coordinates can be useful. In circular geometry there is a radial coordinate, in which the radial distance *r* is used, see Fig. 4.

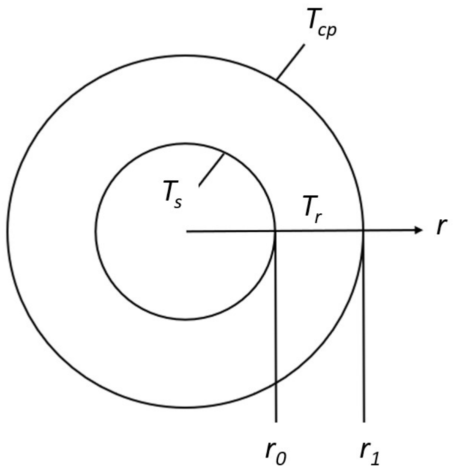


Fig. 4. A DH pipe in which T_s is the service pipe temperature, T_{cp} is the casing pipe temperature, r_0 is the service pipe radius, r_1 is the casing pipe radius, and T_r is the temperature at an arbitrary position between r_0 and r_1.

In a steady-state condition, the transient term on the left-hand side of Eq. (1) is zero, since temperatures do not change over time. Assuming constant thermal conductivity, λ (W/mK), of the insulation, the pipe can be described as an annular cylinder, i.e., the PUR insulation, with the temperature at the inner boundary, T_s (K), corresponding to the temperature of the DH water, and the temperature at the outer boundary, T_{cp} (K), corresponding to the temperature of the casing pipe. Steady-state heat conduction through a cylindrical annulus between the service pipe radius, r_0 (m), and the casing pipe radius, r_1 (m), with constant boundary conditions, is then given by Eqs. (3–5). In contrast to Eqs. (1) and (2), which are three dimensional, the heat transfer is now calculated in the radial one-dimensional direction, which is the only hot to cold direction.

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} = 0 \tag{3}$$

$$T(r_0) = T_\mathrm{s} \tag{4}$$

$$T(r_1) = T_\mathrm{cp} \tag{5}$$

The temperature, T_r (K), at any position in the PUR insulation can be calculated with Eq. (6), assuming boundary conditions according to Eqs. (4–5).

$$T(r) = T_\mathrm{s} + (T_\mathrm{cp} - T_\mathrm{s})\,\frac{ln\,(\frac{r}{r_0})}{ln\,(\frac{r_1}{r_0})} \qquad r_0 \le r \le r_1 \tag{6}$$

The heat flow, Q (W), from a pipe can be calculated using Eq. (7) if the length, L (m), of the pipe is considered.

$$Q = \frac{2\pi\lambda L}{ln(\frac{r_1}{r_0})}(T_\mathrm{s} - T_\mathrm{cp}) \tag{7}$$

During a shutdown, the conditions change, and a transient heat transfer takes place, i.e., the temperature declines with time. Two different transient calculations have been used in this thesis to assess the status of the pipe insulation during a cooling process: first, assuming the pipe to be a lumped system, which was done for the condition in which an arbitrary measurement point was accessible and, second, for the condition in which no arbitrary measurement point was accessible, the transient differential heat equation was solved by superposition and numerically simulated by coding a finite difference method. This is further explained in sections 3.1–3.3 for each condition, respectively, i.e., the assessment during maintenance with excavation and assessment during normal operation.

The required shutdown time depends on the dimensions of the pipe, due to the heat capacity of the water volume in the pipe and the insulation's thicknesses and thermal properties. It was assumed that a minimum of approximately 1–2°C of temperature decline during the shutdown was required for a high-accuracy analysis, which partly depends on the use of high-precision measurement equipment. Fig. 5 shows examples of the decline in the DH water temperature. The decline is approximately exponential, with a rapid temperature change at the beginning when the temperature difference between the water pipe and casing pipe is large and a slow temperature change as the temperature gradient decreases throughout the cooling phase. The DH water temperature is assumed to be approximately constant during the time before shutdown. As seen in Fig. 5, larger-dimension pipes such as DN500, in which the nominal diameter (i.e., the actual service pipe diameter) is 508 mm, require approximately 8 h of shutdown time to reach a temperature difference of 1°C, whereas smaller-dimension pipes, such as DN100, require only 1 h to reach a temperature difference of 1°C. The optimal duration of a shutdown can be determined by balancing the consequences of the shutdown for the customers and the desired accuracy of the assessment.

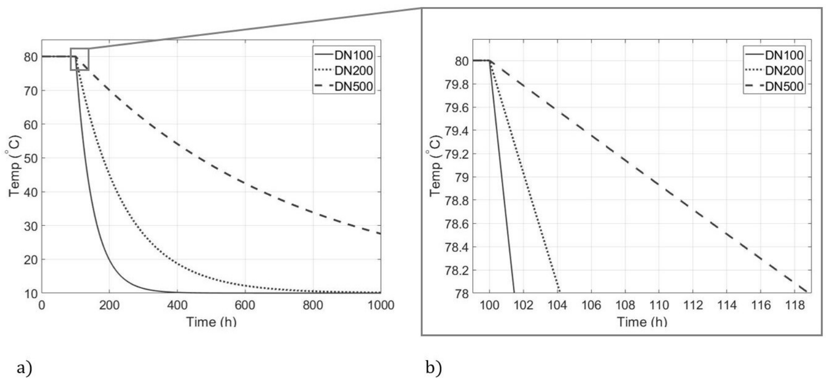


Fig. 5. a) Expected water temperature cooling process in newly produced pipes of different dimensions. A steady-state process of 100 h is followed by a shutdown. b) Close-up of the expected temperature declines during a shutdown, T_{cp} at 10°C (Paper **IV**).

3 Results: Evaluation of measurement points and lambda assessments

This chapter follows the order of the bullet points in the research design chapter, with identified possible measurement points being evaluated and further used for assessing the status of the pipe insulation. This was first done in controlled environments, then continued in the field with the condition of pipes excavated during maintenance, and finally with the condition of buried pipes during normal operation. At the end of each of the three sections 3.1–3.3 there is a subsection presenting reflections and assumptions. These also highlight considerations that were important for the method development process.

3.1 Evaluations in laboratory and controlled environments

From the pre-study, partly presented in Paper **I**, the cooling method was addressed as a method potentially meriting further evaluation. Furthermore, the copper wire was assessed as a potential arbitrary measurement point within the pipe insulation. The cooling method, previously only applied in flexible DH pipes in a unique test set-up (Reidhav and Claesson, 2010), was evaluated in Paper **II** on a pipe section of Chalmers' own operating DH network, located in an indoor culvert, which enabled the attachment of sensors in the form of thermocouples (TC) at several measurement points.

3.1.1 Utilization of the copper wire

The temperature at the position of the copper wire can be determined by measuring the electrical resistance (Ohm) of the copper wire circuit with a multimeter (Paper **I**), and by measuring the copper wire length with an ordinary TDR instrument. The electrical resistance is a linear function of the temperature, T (K), as expressed in Eq. (8) (Cutnell and Johnson, 2003). The outcome of a measurement, after converting the resistance to temperature, will be the mean value of the temperature for the total length of the pipe, at the position of the copper wire.

$$R_T = R_{T_0}(1 + \alpha(T - T_0)) \tag{8}$$

in which R_T (Ohm) is the resistance at the temperature of interest, R_{T_0} (Ohm) is the resistance at the reference temperature, T_0 (K) is the reference temperature, α (1/K) is the temperature coefficient of resistivity, and T (K) is the temperature of interest. The electrical resistivity of the soft copper wire used is 0.0113 (Ohm · m) at 20°C (T_0) (ASTM, 2018; Powerpipe, 2018), and the temperature coefficient of resistance, α_{copper}, is $3.93 \cdot 10^{-3}$ (1/K) (ASTM, 2018).

Indirect temperature measurements, calculated by measuring electric resistance, make it possible to obtain the temperature, T_r, of an arbitrary point within the PUR insulated cross-section. The copper wires run parallel to the service pipe through the PUR insulation, and their distance from the service pipe can differ. The only requirement according to the product standard is that the distance of the copper wires from the service pipe should be at least 10 mm (SS-EN14419, 2009).

The pipe production technique will have an impact on the final copper wire position within the PUR. The pipes assessed in this thesis are produced in individual sections one by one. The SS-EN14419 standard requires the mechanical tightening of the copper wires, for example, using weights, as shown in Fig. 6. Other production techniques exist, in which the pipes are produced as endless lengths and the insulation foam is cast in place or where PUR foam is sprayed onto a moving service pipe in a spiral process (Logstor, 2020). In section-based production, spacers are used. The spacers allow the service pipe to be centred within the casing pipe. The PUR foam is then inserted and fills the cavity between the service pipe and casing pipe. Spacers exist in a variety of shapes and can contain several small holes through which the copper wires can be inserted.

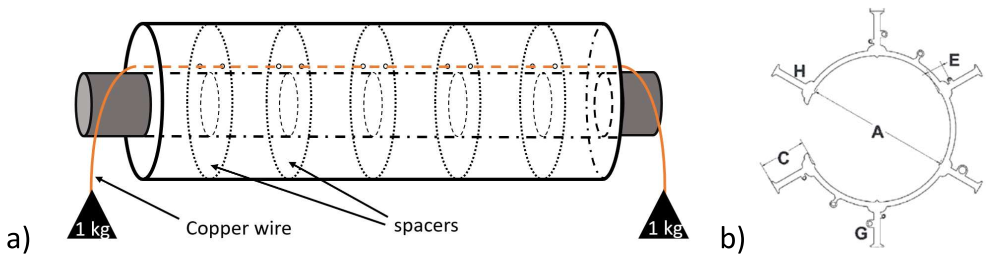


Fig. 6. a) Mechanical tightening of the copper wires during pipe production, in which pipes are produced individually in sections. The wires are threaded through holes in the spacers and tightened with weights during the insertion of PUR foam. b) Image of a spacer showing several smaller copper wire holes.

The copper wire's final distance from the service pipe is uncertain, depending on the selected hole, and can range from 15 to 40 mm (Frick, 2020). This distance may differ between manufacturers and between production techniques used in the past. In this thesis, 21 mm was used in calculations for the field tests with large-dimension pipes, based on measurements from the service pipe to the midpoint of one of the small holes in a spacer. The field tests and their results are presented in section 3.2.

Determining the temperature at the position of the copper wire was proven to be possible by laboratory measurements performed using a guarded hot pipe (GHP) device according to EN 253 (Paper **II**). The results of the measurements are presented in Fig. 7, in which measurements of the service pipe and copper wire are compared with the calculated temperature at the copper wire position. For the specific 1.2-m pipe (DN50/140) tested in the laboratory, the distance of the copper wire from the service pipe was measured to be approximately 15 mm. A clear relationship between the measured electrical resistance, converted to temperature, and the measured service pipe temperature can be seen in Fig. 7. The results also indicated that it is fully possible to measure the temperature at a position inside the PUR insulation, i.e., at the position of the copper wire.

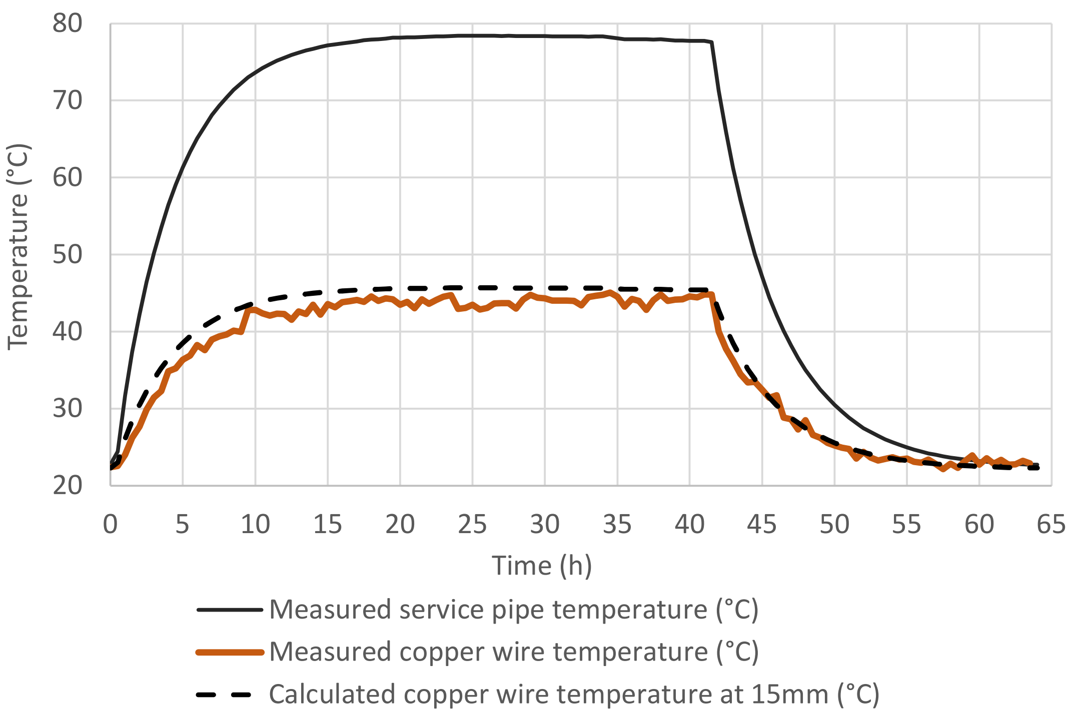


Fig. 7. Measurements of service pipe temperature and electrical resistance (presented as temperature) of the copper wire in a GHP apparatus. The copper wire is assessed to be placed 15 mm from the service pipe, and calculated temperatures at that position are included for comparison.

The resistance measurement was to some extent affected by convective heat transfer at the measurement connections, as well as by fluctuations in distance from the service pipe caused by curves in the copper wire. Before the method was further tested in the field with copper wire measurements, it was considered desirable to test the cooling method as such in a controlled environment.

3.1.2 Evaluation of the cooling method in a controlled environment

The cooling method was considered to have potential for further development and use. Hence, the hypothesis was tested on Chalmers University's own DH network, partially located in culverts at a stable temperature of 20°C. The insulating material of the pipe was mineral wool. The shutdown test was performed on a shorter 23-m section for 20 h. During this period, the service pipe temperature declined from 69°C to 53°C. The TCs were placed on the casing of the pipe, T_{cp}, freely in the air, T_a, and in an existing thermowell in the service pipe, T_s, see Fig. 8.

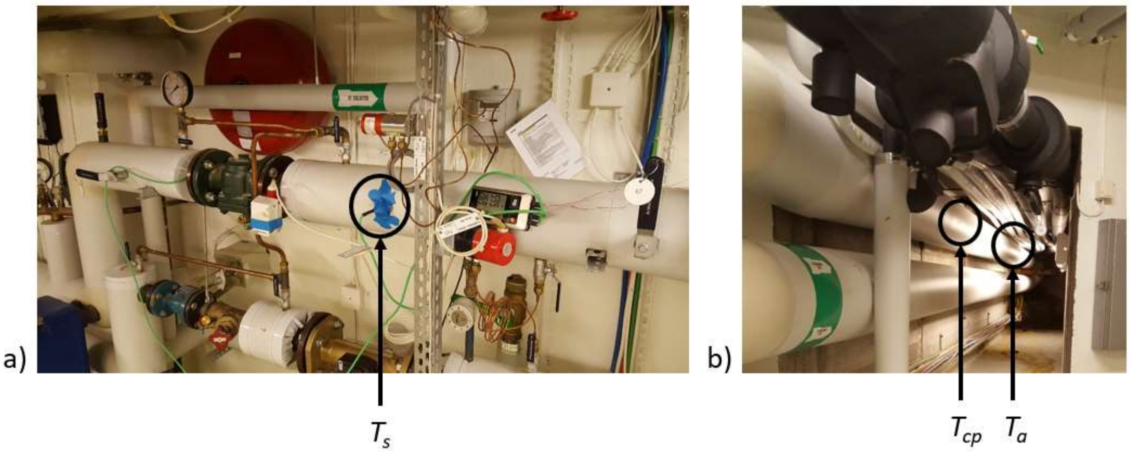


Fig. 8. a) Temperature sensors, T_s, inserted in an available temperature pocket. b) Temperature sensor T_{cp} placed on the casing pipe and temperature sensor T_a placed freely in the air.

The strategy for the thermal assessment of this pipe was a lumped system analysis (LSA) chosen based on the accessible measurement points. The method is based on a body of a uniform temperature with high thermal conductivity, which is surrounded by a layer of much lower conductivity, i.e., the service pipe with its surrounding PUR insulation. Eq. (9) describes the heat balance, with the heat losses on the left-hand side and the decrease in stored heat in the service pipe on the right-hand side, where $\rho c V = C_w$ (J/K) is the total heat capacity of the water (Hagentoft, 2001; Incropera et al., 2007).

$$Q = -\rho c V \frac{dT}{dt} \tag{9}$$

The heat losses are governed by the difference between the service pipe temperature, T_s, the casing pipe temperature, T_{cp}, and the conductance, *K* (W/K), of the intermediate insulation material. The heat loss, *Q*, can be written as Eq. (10):

$$Q = K(T_s(t) - T_{cp}) \tag{10}$$

From now on, both the water and the service pipe temperatures are denoted *T*. By inserting Eq. (10) into Eq. (9),

$$-\rho c V \frac{dT}{dt} = K(T(t) - T_{cp}) \tag{11}$$

which can be further rewritten as:

$$T + \frac{C_w}{K}\frac{dT}{dt} = T_{cp} \tag{12}$$

Consider that the water temperature in the service pipe is T_0 at time zero, while the casing pipe temperature is constant T_1 at $t > 0$. The solution of the ordinary differential Eq. (12) is then written as Eq. (13):

$$T(t) = T_1 + (T_0 - T_1)e^{-\frac{t}{t_c}} \qquad t \geq 0 \tag{13}$$

$$t_c = \frac{C_w}{K} \tag{14}$$

$$K = \frac{2\pi\lambda L}{ln(\frac{r_1}{r_0})} \tag{15}$$

in which t_c (s) is the intrinsic time-scale of the lumped system and *K* (W/K) is the conductance written with cylindrical coordinates as in Eq. (15). Eq. (13) can then be rewritten, and if T_0, T_1, and $T(t)$ are known for any given time, the thermal conductivity, λ (W/mK), can be calculated using Eq. (16). In Eq. (16), T_1 can represent the temperature at an arbitrary position between the service pipe and the casing pipe, for example, the copper wire within the insulation:

$$\lambda = \frac{r_0^2 \rho c \, ln(\frac{r_1}{r_0}) \, ln(\frac{T_0 - T_1}{T(t) - T_1})}{2\,t} \qquad t > 0 \tag{16}$$

in which r_1(m) is an arbitrary position in the insulation and r_0 (m) is the service pipe radius. A quasi-steady-state approximation is used for Eq. (16), since T_1 is considered unchanged during the cooling period. Furthermore, the total heat capacity of the water, C_w, is about 20 times higher than the total heat capacity of the insulation material and service pipe material (calculated for a pipe with the dimensions

DN350/560). Thus, in these equations, the influences of the total heat capacities of the insulation and steel materials are neglected.

The results of the cooling method showed that the total thermal conductivity of the pipe was 0.044 W/mK. To validate the results of the cooling method, a piece of insulation was removed from the test pipe to be tested using proven methods, namely, with the guarded heat-flow meter (GHFM) method, see Fig. 9.

a) b)

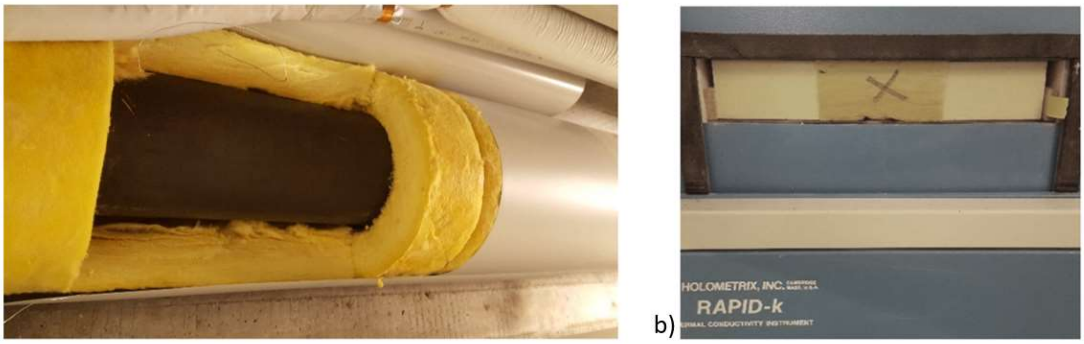


Fig. 9. a) The pipe after removing a piece of insulation. b) Part of the removed piece of insulation (x) when tested in the GHFM.

The piece tested using GHFM was exposed to 70°C on one side and 20°C on the other, i.e., λ_{45}; the result gave a lambda value of 0.034 W/mK, which can be compared with the value of 0.044 W/mK (λ_{41}) from the cooling method. The higher thermal conductivity assessed using the cooling method partly derived from existing air gaps, resulting in undesirable convective heat transfer.

3.1.3 Reflections

The results of the copper wire testing and cooling method testing in controlled environments were promising. However, shutting down the hot DH water supply for a longer time is not preferred by either energy companies or customers. Hence, finding suitable locations for field tests was not straightforward. In order not to interfere with the daily operation of DH networks, the development of the method continued with tests during maintenance or during the replacement of network sections already planned by the energy companies.

3.2 Field assessments of the cooling method during maintenance

The cooling method was tested in selected parts of the Mölndal and Falun DH networks; the results of these field tests are presented in Paper **III**. The three field tests were all of the field condition “assessment during maintenance”, i.e., measurements of the pipe during maintenance when a small end part of the pipe was excavated. One test was conducted on the Mölndal network and two tests were conducted on the Falun network. The assessed parts of the networks were of similar tree structure, i.e., a main pipe (500 m) with branching smaller secondary pipes to the customers. Three experimental field tests were performed, and the set-up was refined after each field test, i.e., by adding insulation to the exposed steel parts, including using a valve as a measurement point and slightly repositioning the TCs. The measurements were performed during the heating season, and at both locations the pipes had already been recently replaced with new PUR-insulated single pipes. In the first field test, TCs were placed on the service pipe, T_s, on the casing pipe, T_{cp}, and indirectly on the copper wire by means of electrical resistance measurements, T_{co}, see Fig. 10.

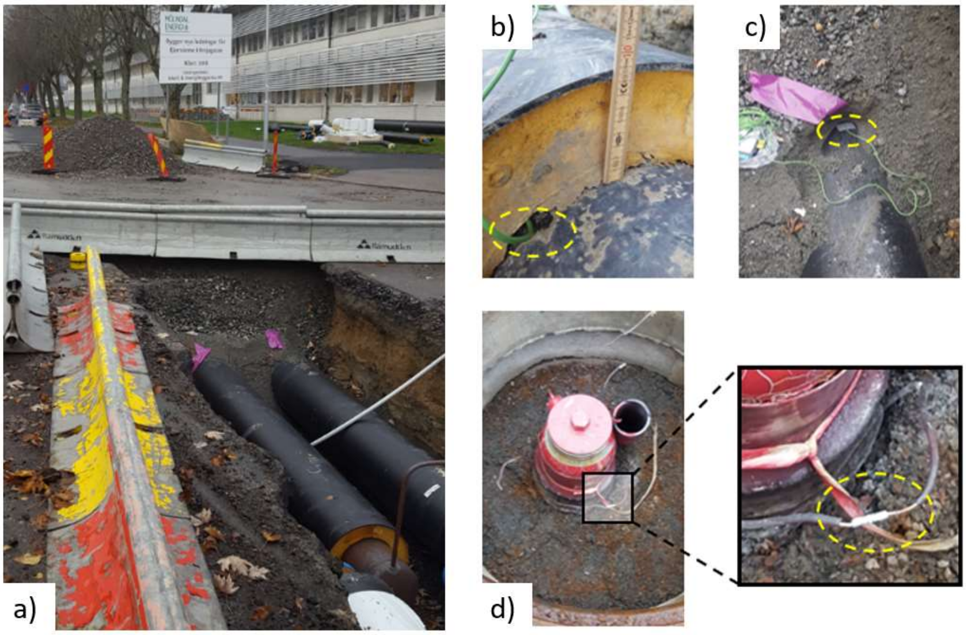


Fig. 10. a) The excavated end part of the 500-m-long pipe section in field test 1. b) TC for measuring T_s inserted under the PUR. c) TC for measuring T_{cp} attached to the casing before backfilling. d) Coupled copper wires next to a valve in a manhole.

When there is heat flow through the pipe, the temperature gradient of the exposed steel pipe is in a steady-state condition, and temperature measurements are possible and representative of the whole buried pipe under assessment. However, at shutdown, heat losses increased more than expected at the exposed end than in the pipe buried under soil, which made temperature measurements uncertain. For the following two field tests, insulation was placed on the exposed steel end to counteract this problem, see Fig. 11. Furthermore, TCs were placed on a drainage valve, T_{dv}, in an attempt to capture the temperature of DH water in the service pipe. For a more detailed explanation of the valves, see section 2.2 in Paper **IV**.

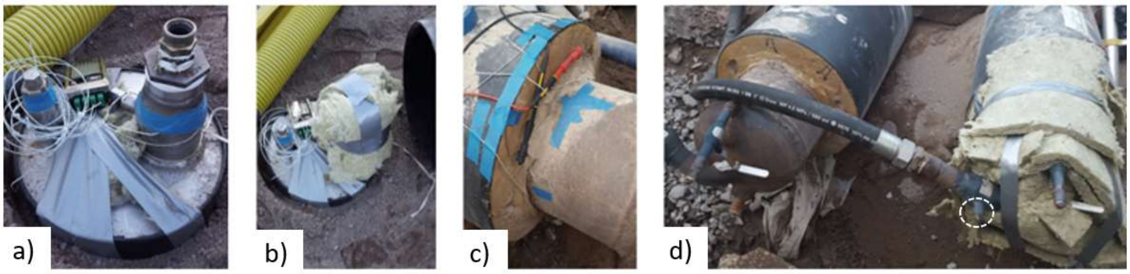


Fig. 11. a) TC attached to the drainage valve, to the right; b) the same valve after insulation with mineral wool. c) The service pipe at the excavation with TCs measuring T_s and crocodile clamps on the ends of the copper wires, connected to a multimeter; d) the same pipe, to the right, after insulation with mineral wool. White dotted circle shows the valve on the flexible pipe, which was switched off for the shutdown.

To assess the impact of insulation on the temperature level of the drainage valve, the valve was uninsulated for the second field test and insulated for the third field test.

3.2.1 Calculated thermal conductivity of the pipes

Heat losses are higher during the cooling phase at a measurement point on an excavated pipe than in the parts covered by soil. Hence, the measured service pipe temperature was lower than the temperature of the network under the soil. However, prior to shutdown and with a constant DH water flow in the pipe, the service pipe temperature, T_{s}, in the excavation was expected to be almost equal to the temperature of the rest of the assessed network. During shutdown, the temperature of the drainage valve was shown to be higher than the temperature of the excavated end part of the service pipe. Therefore, it was assumed that the measured temperature decrease of a drainage valve, T_{dv}, more accurately represents the cooling of the whole service pipe length. A matching factor, *F*, can be calculated to illustrate how well the temperatures measured on the valves correlate with the actual water temperature in the DH pipe. *F* is calculated according to Eqs. (17) and (18). A factor of zero indicates a perfect match with the DH water temperature and no impact of ambient temperature in the manhole, T_a; likewise, a factor closer to one indicates an undesirably poor match with the DH water temperature:

$$T_{\mathrm{dv}} = T_{\mathrm{s}} + F \cdot (T_{\mathrm{a}} - T_{\mathrm{s}}) \quad (17)$$

$$F = (T_{\mathrm{dv}} - T_{\mathrm{s}})/(T_{\mathrm{a}} - T_{\mathrm{s}}) \quad (18)$$

The requirements of standard SS-EN253 refer to the thermal conductivity of the PUR at 50°C, an average temperature between the service pipe and the casing pipe. Thus, the calculated thermal conductivities at temperatures other than 50°C were adjusted for according to Eq. (19) for better comparison (Adl-Zarrabi, 2005; Olsen et al., 2008):

$$\lambda_T = \lambda_{50} + 0.00016(T - 50) \tag{19}$$

in which λ_T (W/mK) is the thermal conductivity, λ_{50} is the thermal conductivity at 50°C, and T (°C) is the temperature. The thermal conductivities are calculated using LSA, as in the first cooling test in section 3.1.2, and presented as thermal conductivities for alternatives 1 and 2, see Table 1. The results for alternative 1 represent the thermal conductivity of the insulation between the copper wire, T_{co}, and the service pipe, T_s. Here, the copper wire distance was set to 21 mm from the service pipe, which has a great impact on the resulting thermal conductivity. The thermal conductivity for alternative 2 represents the entirety of the insulation, from the casing pipe, T_{cp}, to the service pipe, T_s.

Table 1. Thermal conductivity results calculated according to the LSA. The service pipe temperature, T_{s}, was adjusted by factor *F* in field tests 2 and 3.

	λ (W/mK)	λ_{50} (W/mK)
Field test 1 – Alternative 1	λ_{58} (0.110)	(0.109)
Field test 2 – Alternative 1	λ_{80} 0.027	0.023
Field test 3 – Alternative 1	λ_{81} 0.026	0.021
Field test 1 – Alternative 2	λ_{38} (0.090)	(0.092)
Field test 2 – Alternative 2	λ_{48} 0.025	0.026
Field test 3 – Alternative 2	λ_{49} 0.024	0.024

A reference value that can be used for comparison is the manufacturer's declared value for new pipes, 0.026 W/mK. The results indicated high thermal conductivities for field test 1 (within parentheses), because the service pipe temperature was unadjusted due to the lack of valve measurements in that test. The results of field tests 2 and 3 are comparable to the reference value. The accuracy of these results are here defined as the measurement error, the ratio of the average measurement error to the reference value multiplied by 100. The results of alternative 1 in field tests 2 and 3, which are related to the copper wire, showed an error of 15.4%. The results of alternative 2 in field tests 2 and 3, which are related to the casing pipe, showed an error of 3.8%.

3.2.2 Reflections

The results indicated that assessment during maintenance was feasible and quite accurate, if the drainage valve measurements were used for determining the DH water temperature. The bullet points below are reflections on the tests considered in the next step of the development, i.e., when assessing a pipe network during operation.

- The distance of the copper wire from the service pipe has a great impact on the measured temperature. A difference of 1 mm will result in a temperature difference of approximately 1°C. When calculating the thermal conductivity in the three field tests, the copper wire was assumed to be positioned 21 mm from the service pipe, based on measuring the distance on a spacer. As described in section 3.1.2, this distance is uncertain and can differ between spacers. In field test 2, this resulted in a thermal conductivity of 0.0230 W/mK, which is 12% below the manufacturer's declared value for new pipes (0.026 W/mK). However, the mean position of the copper wires, r, within the insulation can be calculated for steady-state conditions using Eq. (6) if the temperatures T_s, T_{co} (T_r), and T_{cp} are measured and known. It should be noted that an assessment based on the copper wire and service pipe temperatures only allows for an evaluation of the insulation state between these measurement points.

- The idea of using the valves as measurement points arose after the first field test. However, as for the excavated pipe end, high convective heat losses were also expected at the valves. Insulating a valve affects the temperature level and the accuracy of the measurement. The valve measurements from field test 2 (uninsulated) and field test 3 (insulated) showed large differences in R-squared values, implying that high fluctuations, due to heat convection, took place at the valve surface and made the uninsulated valve measurements uncertain, see Fig. 12.

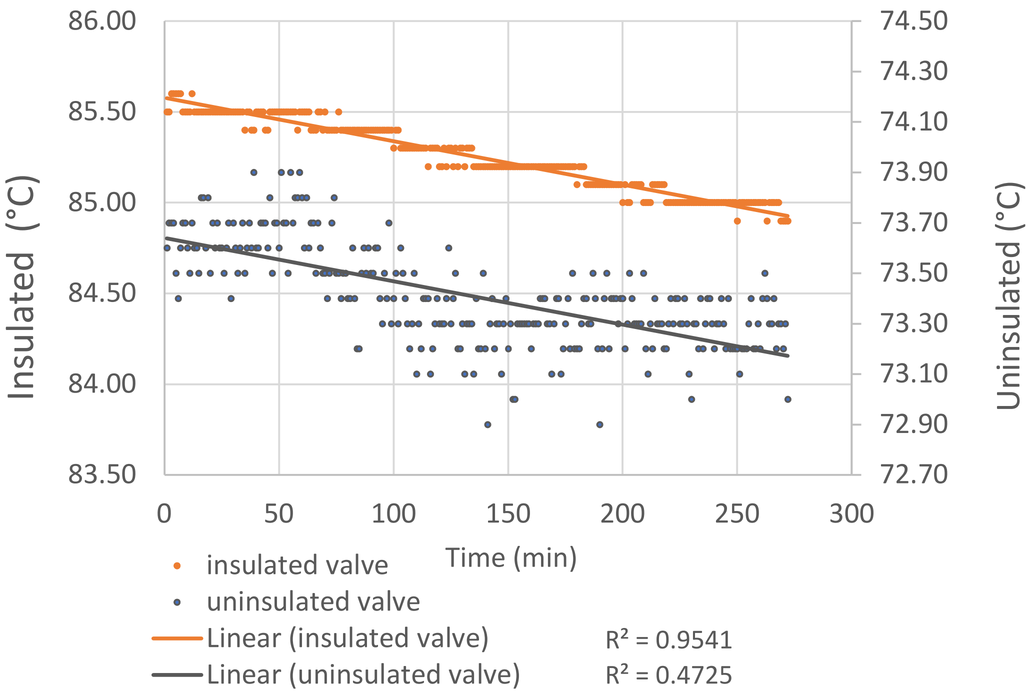


Fig. 12. Comparison of insulated and uninsulated valve temperature measurements.

Insulating the TCs, and also insulating the crocodile clamps at the copper wire connections, reduced the spread in measurement data, i.e., provided higher accuracy. Thus, for the following measurements, this issue was to be considered. Both the drainage valves and the so-far-untested shutdown valves were considered interesting to proceed with, since there are fewer measurement opportunities during the assessment of pipes in operation. However, using the valve temperatures merits further evaluation.

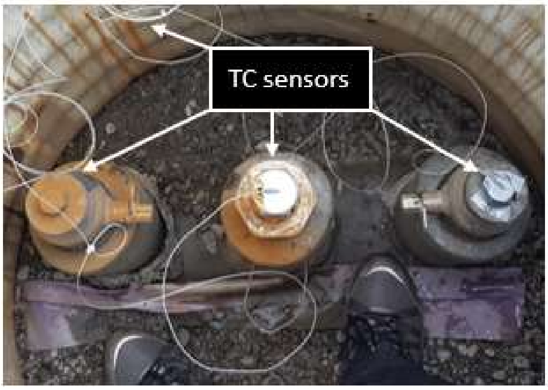
- During a DH pipe shutdown, the temperature declines of the different pipe components do not start simultaneously. The start time of the temperature decline at the measurement point at the top part of the valve is governed by the thermal diffusivity and length of the valve and by the heat convection in the water within the valve. Results of the field test showed that the response time was approximately 75 min. This response time had to be considered for calculations of the matching factor *F*. Further evaluations regarding the response time were also assessed to be important in the next step of the method development.

- The shutdowns for the field tests were prompted by discussions and planning with the energy companies and their subcontractors regarding the specific planned maintenance. The involved field workers were, for example, operational staff of the energy company (for shutdown, TDR measurements, and sometimes traffic closures) and welders for pipe repair/replacement. A maintenance intervention is planned and announced to the customers weeks ahead of the actual work; likewise, a shutdown for maintenance is performed efficiently so as not to affect the customers more than necessary. Performing a field test under such conditions demands clear communication among the involved workers regarding what to do and not to do. Unfortunately, two field tests at other locations (chronologically the first and third of five in total) resulted in what turned out to be insufficient or uncertain measurement data, due to various factors and unclear communication. Although additional field tests at supplementary locations and with other pipe dimensions would have been useful, the encountered problems provided great knowledge for the method development, especially regarding preparation and instructions to the involved workers.

The next step in the method development was to test the method on fully buried pipes in normal operation, i.e., with a reduced number of measurement opportunities. Measuring the temperature of the valves was an obvious path for the further evaluation/development of the method. A mathematically different approach was needed to deal with the absence of temperature measurements at the casing pipe.

3.3 Field assessments of the cooling method during operation

The prerequisites for capturing the actual temperature in the service pipe are now limited to measurements of DH water temperature, T_s, at the customers' substations and indirectly from accessible valve temperatures, T_{sv} and T_{dv}. Valves are normally installed and accessed through traditional manholes, as in Fig. 13; likewise, the network used for evaluating the cooling method during operation was also accessed through manholes. The assessed network was loop shaped, with a 500-m section used for the evaluation. Two separate field tests were conducted at the same location, including three shutdowns each. The first test is covered in Paper **IV** and the second in Paper **V**.



a)


b)

Fig. 13. a) Measurement set-up in the manhole, showing TCs attached to three valves and one to the side of the manhole to capture the air temperature. The valve in the centre of the photo is a shutdown valve, and the two on the left and right are drainage valves. b) The valves insulated with mineral wool "hats".

The valves situated in manholes covered by a lid were assessed to be usable from an accuracy perspective, due to their sheltered environment. For the field tests during maintenance, measurements of the service pipe temperature were assessed to be accurate prior to shutdown. Similarly, the DH water temperature measured (by the energy company) at a nearby customer's substation was assessed to be useful prior to a shutdown, as was the use of the matching factor *F*.

During operation, the casing pipe temperature cannot be accessed or measured due to the overlying soil (and often asphalt). However, this temperature is still required in order to determine the magnitude of the temperature gradient between the service pipe and casing pipe. The casing pipe temperature is governed by the annual average temperature of the DH water and the annual average outdoor temperature, resulting in an average annual soil temperature. Overlying this is the seasonal variation in the soil temperature, the amplitude of which is much less than that of the outdoor temperature due to the dampening of the soil layer (Hagentoft, 1988). The principle of calculating soil temperatures outside the casing pipe in regard to seasonal temperatures was presented by Hagentoft (2001). Using that principle, numerical calculations were conducted to assess the impact on the casing pipe temperature of seasonal variations in service pipe temperature and outdoor air temperature, see Fig. 14.

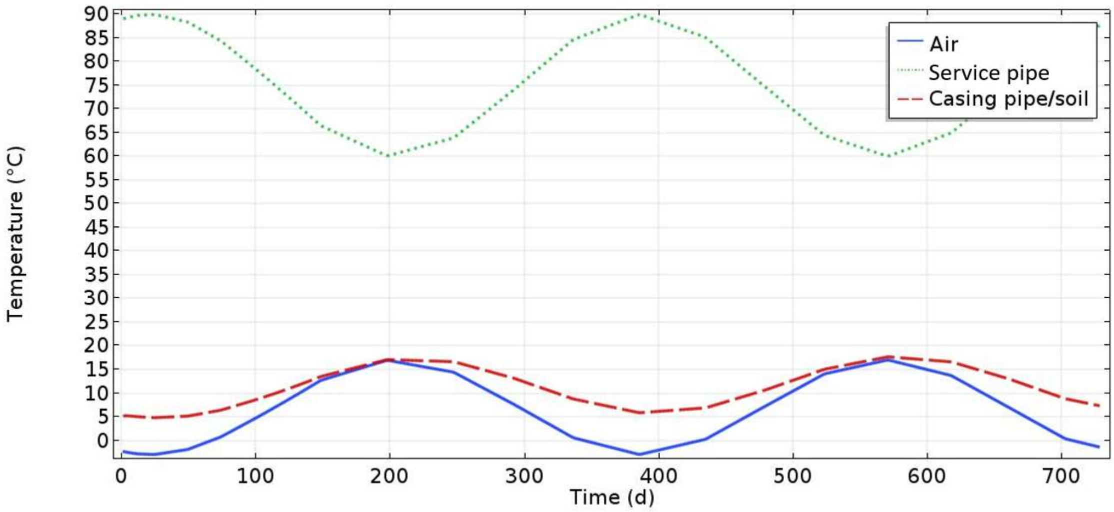


Fig. 14. Seasonal variations in casing pipe/soil temperature over two years; numerical calculations conducted in COMSOL Multiphysics.

The dampening effect of both the soil and insulation can be seen in the casing pipe temperature. The temperature variations over a shorter time frame, such as hours and days, have an even smaller effect on the resulting casing temperature. The boundary conditions of the model and the thermal properties of the involved materials are further explained in Paper **V**, where a simplified method of calculating the casing pipe temperature was used, taking account of soil and insulation resistances and of the monthly average soil surface temperature and DH water temperature.

Due to the dampening effect of insulation and soil, the casing pipe temperature is expected to be fairly stable over time (regardless of any shutdown). The heat transfer from the DH pipe can therefore be considered a quasi-steady-state condition.

The mathematical approach, presented in Paper **IV**, for assessing the thermal state of a network in operation is based on the superposition of two elementary processes: first, the steady-state condition throughout the pipe domain during normal operation with a constant heat-flow rate in the radial direction, which is constantly balanced by ongoing heat supply from the DH water flow; second, the temperature decline induced by the shutdown, seen as a heat flow withdrawn from the water starting at time zero.

The heat transfer between the service pipe and the insulation can be neglected over the first short period, since these temperatures are approximately the same as at the time of the shutdown. The temperature drop, i.e., the slope of the DH water temperature, $\frac{dT_s}{dt}$ (K/h), over short periods, is therefore directly given by the following heat balance, Eq. (20):

$$\rho c A_\mathrm{s} \frac{dT_\mathrm{s}}{dt}\bigg|_{t\approx 0} = -q \tag{20}$$

in which ρc (J/m^{3}K) is the volumetric heat capacity of the DH water and A_s (m^2) is the cross-sectional area of the water in the service pipe.

The estimated thermal conductivity, λ_i (W/mK), of the pipe insulation can then be calculated using Eq. (21):

$$\rho c A_\mathrm{s} \frac{dT_\mathrm{s}}{dt}\bigg|_{t\approx 0} = -q = -\frac{2\pi\lambda_i}{ln(r_1/r_0)}(T_{\mathrm{s},0} - T_{\mathrm{cp}}) \tag{21}$$

$$\Rightarrow$$

$$\lambda_i \approx \frac{\rho c A_\mathrm{s}}{2\pi(T_{\mathrm{s},0} - T_{\mathrm{cp}})} ln\left(\frac{r_1}{r_0}\right)\left|\frac{dT_\mathrm{s}}{dt}\right|_{t\approx 0}$$

3.3.1 Evaluation of valves as measurement points for DH water temperature

During the development of the strategy for using the cooling method, both the drainage and shutdown valves were deemed interesting to evaluate as measurement points. The drainage valve was identified early on as the measurement point with the highest temperature. However, compared with the shutdown valve, which is directly connected to the DH water in the horizontal DH pipe via a vertical steel rod, the drainage valve is connected via both water and a vertical steel pipe, see Fig. 6 in Paper **IV**.

The drainage valve and shutdown valve were evaluated for their usability as measurement points, in both theory and practice. A thermal simulation model of the convective heat transfer in the water in the drainage valve is presented in Paper **V**, section 4.1. Results of the simulation indicate that a linear temperature decline can be expected, similar to that experienced in the horizontal main pipe. Since it is the slope of the temperature decline in the DH pipe that reveals the state of the insulation, the same slope needs to be identified from the valve measurements. When analysing the slope of the measurements from the valves, the start time of the temperature decline must equal the start time of the main shutdown. Since the measurement points are located on the accessible steel parts of the valves, they are at a certain distance from the heat source (i.e., the DH water). Hence, the thermal diffusivity and thickness of the material govern the response time, i.e., the time it takes before a temperature change in the DH water causes a temperature change at the measurement point. The response times of both valve types were evaluated in Paper **IV**. Results indicate that the response time was approximately seven times longer for the shutdown valve than the drainage valve, which had a response time of 50 $\pm$ 20 minutes, see Table 4 in Paper **V**. The long response time of the shutdown valve was confirmed by calculations based on one- dimensional transient heat transfer, see Fig. 7 in Paper **IV**.

Adding an insulating "hat" of mineral wool on the drainage valve was shown to be beneficial in terms of reducing undesirable heat losses and ensuring high measurement accuracy, see Fig. 12. The same set-up was also used in the field tests on an operating DH network, where it also included the shutdown valve. However, even though the shutdown valve was fully insulated, see Fig. 2 in Paper **V**, the temperature did not rise to desirable levels. The impact of the ambient temperature, T_a, in the manhole is described by the matching factor, F, with the most desirable being F equal to zero, i.e., fully decoupled from the ambient temperature. Results of the field tests on the operating DH network can be seen in Table 2.

Table 2. Calculated average matching factors for the drainage valve measurements: three different insulation conditions.

	Drainage valve uninsulated	Drainage valve "hat" insulated	Drainage valve fully insulated
Matching factor	0.28	0.12	0.05
Standard deviation	0.04	0.06	0.03

The impact of the ambient temperature decreased with increased insulation. Fig. 12 in Paper **IV** shows how the drainage valve measurements were matched with DH water temperature data from a nearby customer's substation, using the matching factor. Furthermore, drainage valve measurements showed good repeatability between shutdowns, with a slope of temperature decline of 0.43–0.46°C/h for all six shutdowns, see Table 4 in Paper **V**.

In theory, there is a relationship between the slope of the temperature decline in the shutdown valve and in the water in the horizontal DH pipe, which is shown by the mathematical model presented in section 3.1 in Paper **V**. However, the great influence of the ambient manhole temperature, together with the long response time, reduced the accuracy of the shutdown valve measurements. Hence, the shutdown valve needed to be dismissed as a measurement point.

Now, knowing the service pipe temperature, T_s, and casing pipe temperature, T_{cp}, assessment of the pipe's thermal insulation is possible.

3.3.2 Calculated thermal conductivity of the pipes

A more dynamic mathematical approach, taking account of the pipe surroundings, was assessed to be preferred to the LSA due to the moved boundary condition from casing pipe to ambient outdoor temperature.

As the drainage valve was shown to represent, with high accuracy, the actual temperature decline in the DH pipe, the mean temperature decline was calculated from the drainage valve measurements during the three shutdowns in the field test. The mean decline was then compared with numerical simulations of the temperature decline in the DH pipe according to the finite difference model described in section 2.1.1 of Paper **IV**.

The results indicated that with a thermal conductivity of 0.026–0.027 W/mK for the PUR in the DH pipe, a good match is found between the simulated and measured temperature decline, i.e., the actual status of the evaluated two-year-old operating DH pipe, see Fig. 11 in Paper **V.** This can be compared with newly produced pipes, which, according to the manufacturer, should have a thermal conductivity of 0.026 W/mK (Powerpipe, 2018), resulting in a slope of 0.44°C/h.

This work has also resulted in a convenient user guide that allows the network owners to assess the thermal conductivity of their pipes (see Appendix).

The uncertainties related to the cooling method, when used on an operating DH network, are the following:

- The casing pipe temperature could be assessed either by including seasonal variations in outdoor temperature and DH water temperature, or by a simpler approach using the average monthly outdoor and DH water temperatures. Results presented in section 5.2 in Paper **V** indicate that misjudging the soil temperature would lead to an error in the final assessed thermal conductivity of the PUR of approximately 1.4% per degree Celsius of soil temperature. When comparing the two approaches, the resulting casing pipe temperature differed by 1°C.

- The accuracy of the temperature measured by a TC is ±0.4°C. However, for calculating the thermal conductivity, the governing variable is the temperature difference during cooling and not the temperature level. Thus, the error of the temperature sensors is of minor importance.

- The temperature decline slopes were 0.43–0.46°C/h for the drainage valve, as determined using the cooling method on two-year-old pipes. Comparing these slopes with the expected slope of 0.44°C/h for a newly produced pipe results in an error of 1.9% (ratio of average slope error to expected slope). Furthermore, similar temperature decline slopes could be seen throughout all six shutdowns, even though TCs were relocated and additional insulation was tested, showing little impact on the repeatability of the method. The accuracy of the method can also be described by the 95% confidence interval, which is 0.445±0.017°C/h.

3.3.3 Reflections

The drainage valve measurements were improved by adding a “hat” of mineral wool insulation. Measurements also improved, in terms of the matching factor, when a manhole was completely filled with mineral wool; however, the slope of decline was almost unaffected by full insulation. This implies that “hat” insulation is sufficient for accurate measurements. Furthermore, since the slope of decline was unaffected by completely filling the manhole with mineral wool, the measured heat losses in the horizontal pipe during shutdown are considered not to derive from the manhole itself. The thermal response time of the drainage valve was assessed to mainly derive from the convective heat transfer in the water within the vertical drainage valve. This convective heat transfer would theoretically be higher for an uninsulated valve, since it is driven by the temperature difference between the hotter DH water in the horizontal pipe and the colder DH water in the top part of the drainage valve. However, no significant difference could be seen in terms of the response time between an uninsulated and an insulated drainage valve, see Table 4 in Paper **V**.

The numerical model, used for the cooling method, was considered validated since the slope of temperature decline in the model matched the slope from the field measurements when a thermal conductivity of 0.026 (W/mK) was used, as also expected in the assessed newly produced pipes.

The operating network used for assessing the cooling method had a loop structure, i.e., allowing the flow to shift direction due to the consumption pattern. This affected the manhole where the shutdown took place (see the decline phase [drainage valve D] in Fig. 9 in Paper **V**). If the network had a tree structure, the manhole used for the shutdown could also have been used, due to the stagnant water on both sides of the shutdown valve.

4 Conclusion

The aim of this thesis was to develop a non-destructive field testing method for thermal assessment of part of a DH network, thereby contributing a method that could be used by network owners. The thesis is based on field measurements at several measurement points and on mathematical models of a DH pipe and its connected valves. The main conclusions of the thesis are as follows:

- A cooling method has successfully been developed and tested on DH networks during maintenance and during normal operation. Results indicate that, to use the method with high accuracy, it is crucial to accurately capture the temperature decline of the DH water as well as the temperature at an arbitrary position within the insulation or at the casing pipe.

- The moisture surveillance system, i.e., the measurable copper wire, was proven to be serviceable as an arbitrary measurement point within the insulation. By measuring the electrical resistance in the copper wire, and converting it into temperature, it was possible to thermally assess the insulation between the service pipe and copper wire. The measurement error with respect to the reference value was approximately 15%.

- The use of valves as measurement points for assessing the water temperature in the DH pipe has been thoroughly investigated, in theory using mathematical models and in practice using repeated field tests. The results indicate that measurements of the drainage valve can, after adjustment with a matching factor, represent the water temperature in the pipe. This matching factor decouples the impact of the ambient air temperature in a manhole.

- Results indicate that the thermal properties of the soil surrounding a DH pipe have minimal effect on assessment with the method.

- A sufficiently long shutdown for the cooling method is assessed to be in the range of two to eight hours, depending on the pipe dimensions.

- If the casing pipe is inaccessible as a measurement point, its temperature can be assessed through simple calculations, with miscalculation of the actual soil temperature affecting the final assessed thermal conductivity by only 1.4% per miscalculated degree Celsius in soil temperature.

- The method allowed a prediction of the thermal conductivity of a buried DH pipe in operation with 2% deviation from the reference value. This result was obtained by coding a numerical simulation model, with superposition and the finite difference method being applied for the heat transfer problem.

- Finally, a user guide is presented in the Appendix of this thesis. It provides the network owners with simple instructions for using the method, and convenient graphs for evaluating the thermal state of the examined network part.

5 Future research

A newly developed cooling method is presented in this thesis. However, as is usual, there is always room for further development and fine-tuning. Some suggestions for further research are presented here:

- The thermal response time of the drainage valve was in the range of 30–70 min, whereupon a linear temperature decline took place. The reason for the variation in response time is judged to depend on the convective water movement within the drainage valve. A thorough analysis of the phenomenon would be desirable, especially since the drainage valves are of different heights, which may affect their response times.

- The pipes assessed during the field tests presented here were all new and recently installed in the network. It would be of great interest to further validate the method by assessing an old pipe in the field using the cooling method, and then removing part of the pipe to the laboratory for further GHP analysis.

- In this thesis, the assessments using valves were conducted in one manhole, located approximately in the midpoint of the assessed pipes. Further research could involve several manholes, allowing the comparison of multiple measurements of the same pipe. Furthermore, if copper wire measurements are also included, additional information would be gathered regarding the status of the insulation throughout the length of the assessed pipe.

References

ADL-ZARRABI, B. 2005. Ny metod för att bestämma fjärrvärmerörs isoleringsförmåga. *rapport 2005:122.* Svensk fjärrvärme.

ADL-ZARRABI, B., BERGE, A., LIDÉN, P., DOMHAGEN, F. & RAMNÄS, O. 2017. Livslängd och statusbedömning av fjärrvärmenät - Konventionella och högpresterande rör, Rapport 2017:420. Energiforsk AB.

ASTM 2018. Standard Specification for Soft or Annealed Copper Wire, ASTM International, Designation: B3-13.

BERGE, A., ADL-ZARRABI, B. & HAGENTOFT, C.-E. 2015. Assessing the Thermal Performance of District Heating Twin Pipes with Vacuum Insulation Panels. *Energy Procedia,* 78**,** 382-387.

BERNDT, M. L. 2001. NON-DESTRUCTIVE TESTING METHODS FOR GEOTHERMAL PIPING. United States.

BRANDES 2019. Product brochure - Early detecting and precise location systems for moisture and leakages.

BØHM, B. 2000. On transient heat losses from buried district heating pipes. *International Journal of Energy Research,* 24**,** 1311-1334.

CARSLAW, H. S. & JAEGER, J. C. 1986. *Conduction of Heat in Solids*, Clarendon Press.

CHICHERIN, S., MAŠATIN, V., SIIRDE, A. & VOLKOVA, A. 2020. Method for Assessing Heat Loss in A District Heating Network with A Focus on the State of Insulation and Actual Demand for Useful Energy. *Energies,* 13**,** 4505.

CUTNELL, J. D. & JOHNSON, K. W. 2003. *Physics*, Wiley.

DANIELEWICZ, J., ŚNIECHOWSKA, B., SAYEGH, M. A., FIDORÓW, N. & JOUHARA, H. 2016. Three-dimensional numerical model of heat losses from district heating network pre-insulated pipes buried in the ground. *Energy,* 108**,** 172-184.

FANG, T., KONTU, K. & LAHDELMA, R. 2012. Estimation of the State of a District Heating Network based on Consumption Measurements. *Proceedings of the IASTED International Conference on Power and Energy Systems and Applications, PESA 2012*.

FREDRIKSEN, S. & WERNER, S. 2013. *District Heating and Cooling*, Studentliteratur AB.

FRICK, J. 2020. *RE: Powerpipe AB.*

FRIMAN, O., FOLLO, P., AHLBERG, J. & SJÖKVIST, S. 2014. Methods for Large-Scale Monitoring of District Heating Systems Using Airborne Thermography. *IEEE Transactions on Geoscience and Remote Sensing,* 52**,** 5175-5182.

HAGENTOFT, C. E. 1988. *Heat loss to the ground from a building. Slab on the ground and cellar, LTH/TVBH-1004.* doctoral thesis, Building Physics, Lund.

HAGENTOFT, C. E. 2001. *Introduction to Building Physics*, Ligthning Source.

INCROPERA, F. P., DEWITT, D. P., BERGMAN, T. L. & LAVINE, A. S. 2007. *Fundamentals of Heat and Mass Transfer*, Wiley.

KRĘCIELEWSKA, E. & MENARD, D. 2014. Thermal conductivity coefficient of PUR insulation material from pre-insulated pipes after real operation on district heating networks and after artificial ageing process in heat chamber. *The 14th International Symposium on District Heating and Cooling, September 7th to September 9th, 2014.* Stockholm, Sweden.

LOGSTOR. 2020. *Production* [Online]. Available: www.Logstor.com [Accessed 02/01 2020].

LUND, H., WERNER, S., WILTSHIRE, R., SVENDSEN, S., THORSEN, J. E., HVELPLUND, F. & MATHIESEN, B. V. 2014. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy,* 68**,** 1-11.

OLSEN, P. K., LAMBERTSEN, H., HUMMELSHØJ, R., BØHM, B., CHRISTIANSEN, C. H., SVENDSEN, S., LARSEN, C. T. & WORM, J. A New Low-Temperature District Heating System for Low-Energy Buildings. The 11th International Symposium on District Heating and Cooling, 2008 Reykjavik, ICELAND.

OPPELT, T., URBANECK, T., GROSS, U. & PLATZER, B. 2016. Dynamic thermo-hydraulic model of district cooling networks. *Applied Thermal Engineering,* 102**,** 336-345.

PERSSON, C. 2015. *Predicting the Long-Term Insulation Performance of District Heating Pipes.* Dissertation, Chalmers University of Technology.

POWERPIPE 2018. Product catalog.

REIDHAV, C. & CLAESSON, J. Transient thermal conductivity of flexible district heating twin pipes. 12th International Symposium on District Heating and Cooling, 2010. 90-95.

ROSA, A., LI, H. & SVENDSEN, S. 2011. Method for optimal design of pipes for low-energy district heating, with focus on heat losses. *Fuel and Energy Abstracts,* 36**,** 2407-2418.

SS-EN253 2009. District heating pipes – Pre insulated bonded pipe systems for directly buried hot water networks - Pipe assembly of steel service pipe, polyurethane thermal insulation and outer casing of polyethylene. Swedish standards institute.

SS-EN14419 2009. District heating pipes – Preinsulated bonded pipe systems for directly buried hot water networks – Surveillance systems. Swedish Standards Institute.

SVENSKFJÄRRVÄRME 2015. Underhållshandboken För Fjärrvärmedistribution [Maintenance book for district heating distribution].

SÄLLSTRÖM, J. H., RAMNÄS, O. & SÄLLBERG, S.-E. Status assessments of district heating pipes. DHC13, 2013 Copenhagen.

TRAFIKVERKET. 2021. *Trafikverket tjäldjup/ ground frost depth* [Online]. Swedish Road Administration. Available: https://tjaldjup.trafikverket.se/ [Accessed November 29 2021].

VAN DER HEIJDE, B., AERTGEERTS, A. & HELSEN, L. 2017. Modelling steady-state thermal behaviour of double thermal network pipes. *International Journal of Thermal Sciences,* 117**,** 316-327.

VESTERLUND, M., SANDBERG, J., LINDBLOM, B. & DAHL, J. 2013. Evaluation of losses in district heating system, a case study. *International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems : 16/07/2013 - 19/07/2013.*

WANG, H., MENG, H. & ZHU, T. 2018. New model for onsite heat loss state estimation of general district heating network with hourly measurements. *Energy Conversion and Management,* 157**,** 71-85.

WERNER, S. 2017. International review of district heating and cooling. *Energy,* 137**,** 617-631.

ZINKO, H., BJÄRKLEV, J., BJURSTRÖM, H., BORGSTRÖM, M., BOHM, B., KOSKELAINEN, L. & PHETTEPLACE, G. 1996. Quantitative Heat Loss Determination by means of Infrared Thermography -The TX model. Paris, France, Tech. Rep.,: International Energy Agency.

ZWIERZCHOWSKI, R. & NIEMYJSKI, O. 2019. Simulation of Heat Losses of a Distribution Network with Different Technical Structure and Under Different Operating Conditions for a District Heating and Cooling System. *IOP Conference Series: Materials Science and Engineering,* 603**,** 032091.

Appendix: Proposed cooling method – Prerequisites and user guide

The cooling method, a non-destructive field testing method for estimating the mean thermal conductivity of a DH pipe in operation, can be conducted given the following prerequisites:

- An accessible manhole with a shutdown valve for turning the flow off and on.
- At least one measurable drainage valve accessible through a manhole in the assessed part of the network. The drainage valve should be insulated with at least “hat” insulation. Installing the manhole set-up and starting recording with the temperature logger should be performed at least 2 h before the shutdown.
- The DH network under assessment should be shut down for at least 2 h for pipe dimensions up to DN200 and for at least 8 h for pipe dimensions up to DN500. As a rule of thumb, the required shutdown time can be adequately estimated by dividing the nominal diameter (DN) by 60, i.e., DN500/60 = 8.3 h.
- The cooling method is assessed to have an error of less than 2% of the estimated thermal conductivity if estimates of the following parameters are known: thermal conductivity of the soil (rough estimate), DH water temperature data from nearby customers, pipe depth from soil surface, and seasonal air temperature variations on location.

Prior to using this cooling method, it is recommended that ordinary TDR measurements are performed to ensure that no major DH water leakage is present, which otherwise would give misleading results.

A measured temperature decline gives an associated thermal conductivity, which can be read from the graph in this appendix. Five pipe dimensions are presented in Fig. A1, A2, A3, A4, and A5, in which the pre-shutdown temperature differences between the service and casing pipes are 100°C, 90°C, 80°C, 70°C, and 60°C, respectively.

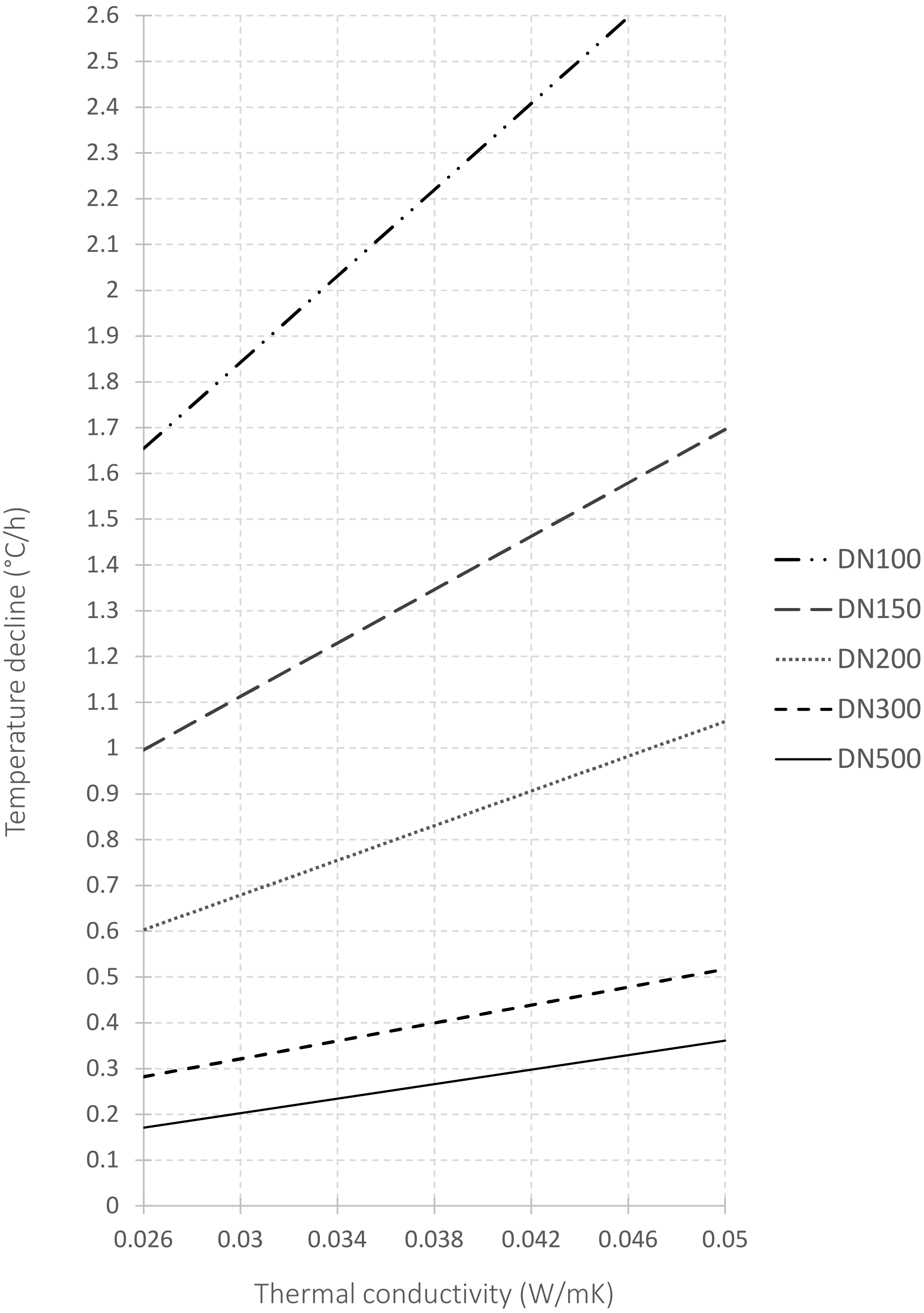


Fig. A1. Example of the resulting thermal conductivities for various pipe dimensions, with respect to declines in drainage valves. The temperature difference between the service and casing pipes is 100°C.

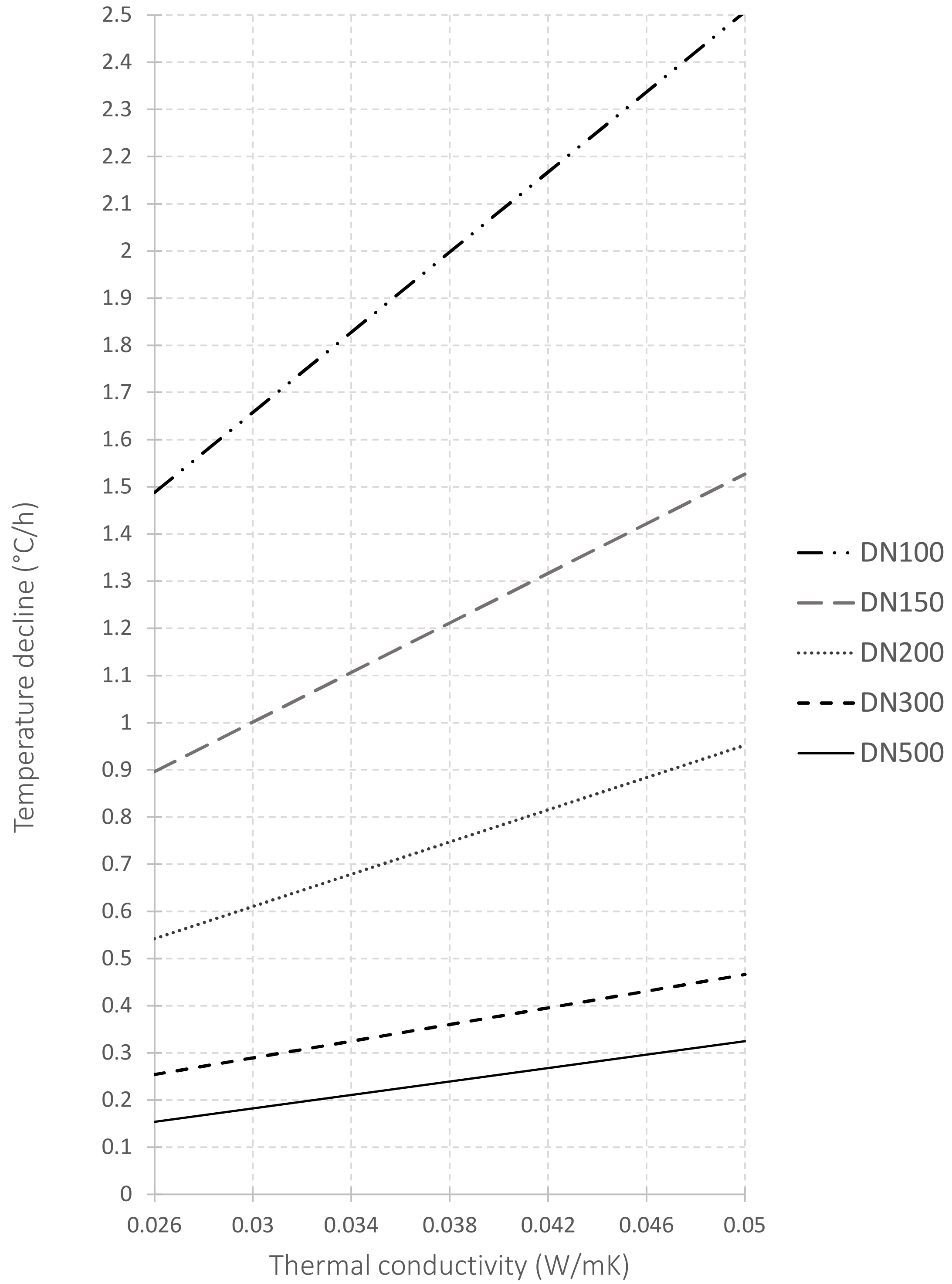


Fig. A2. Example of the resulting thermal conductivities for various pipe dimensions, with respect to declines in drainage valves. The temperature difference between the service and casing pipes is 90°C.

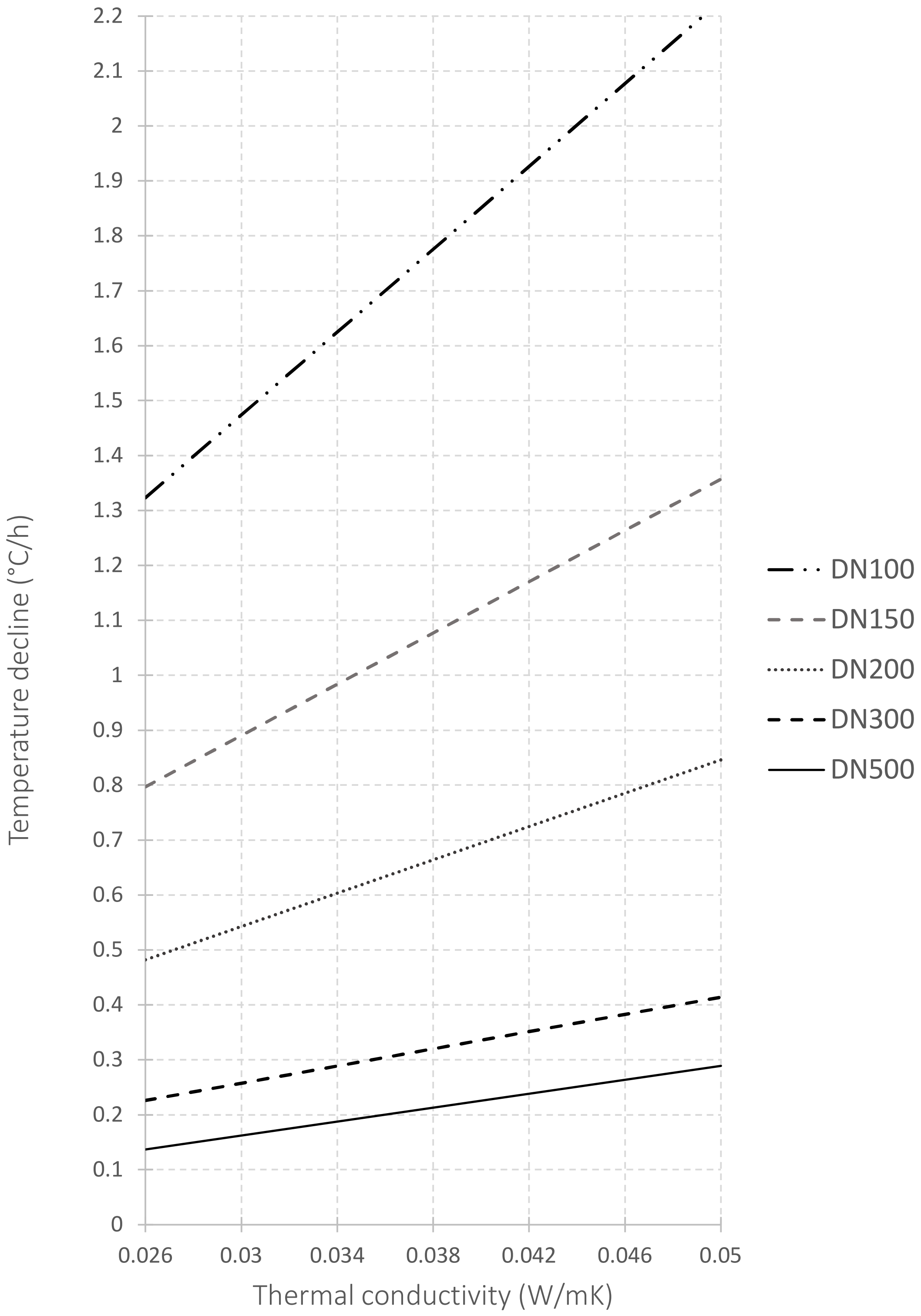


Fig. A3. Example of the resulting thermal conductivities for various pipe dimensions, with respect to declines in drainage valves. The temperature difference between the service and casing pipes is 80°C.

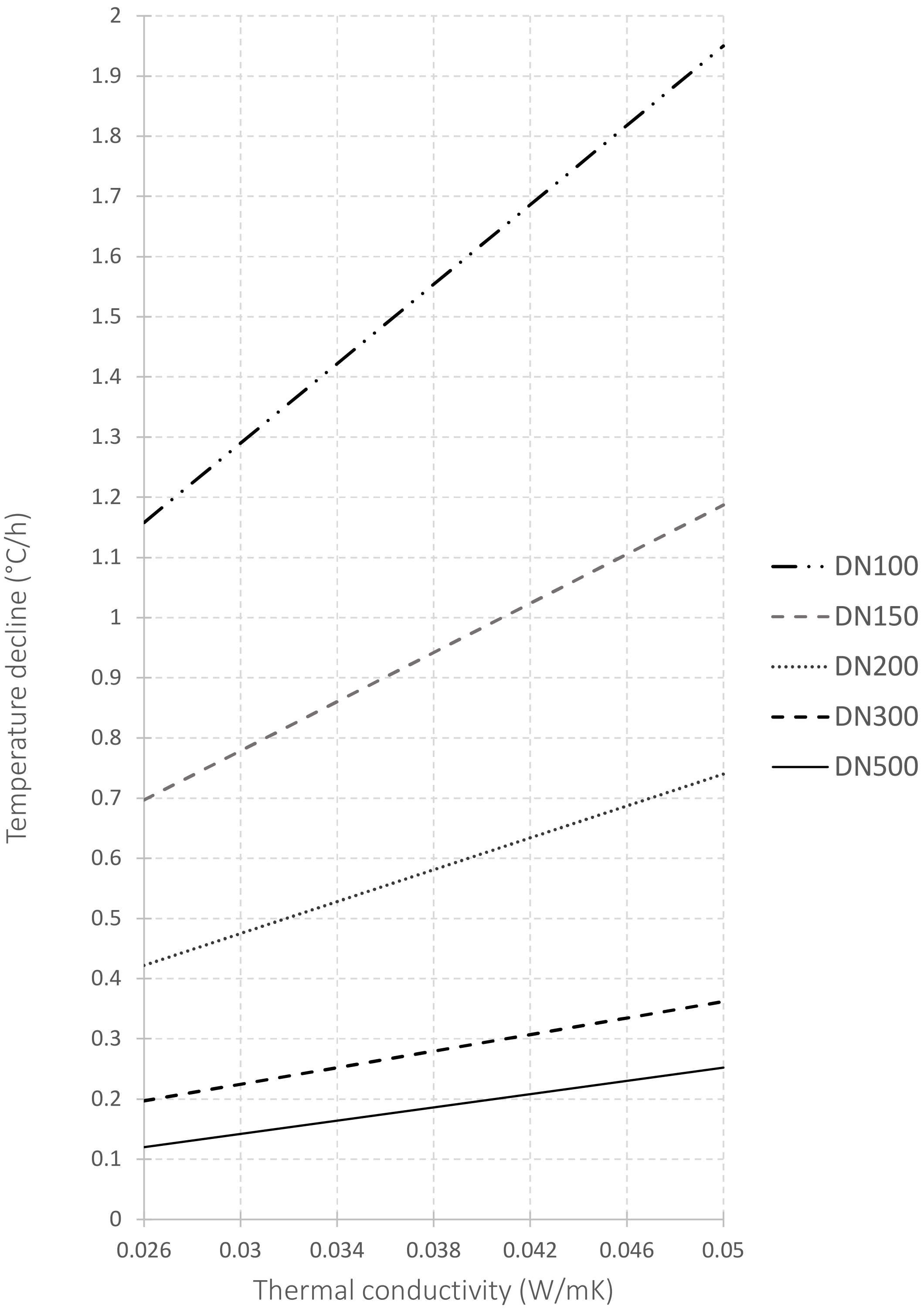


Fig. A4. Example of the resulting thermal conductivities for various pipe dimensions, with respect to declines in drainage valves. The temperature difference between the service and casing pipes is 70°C.

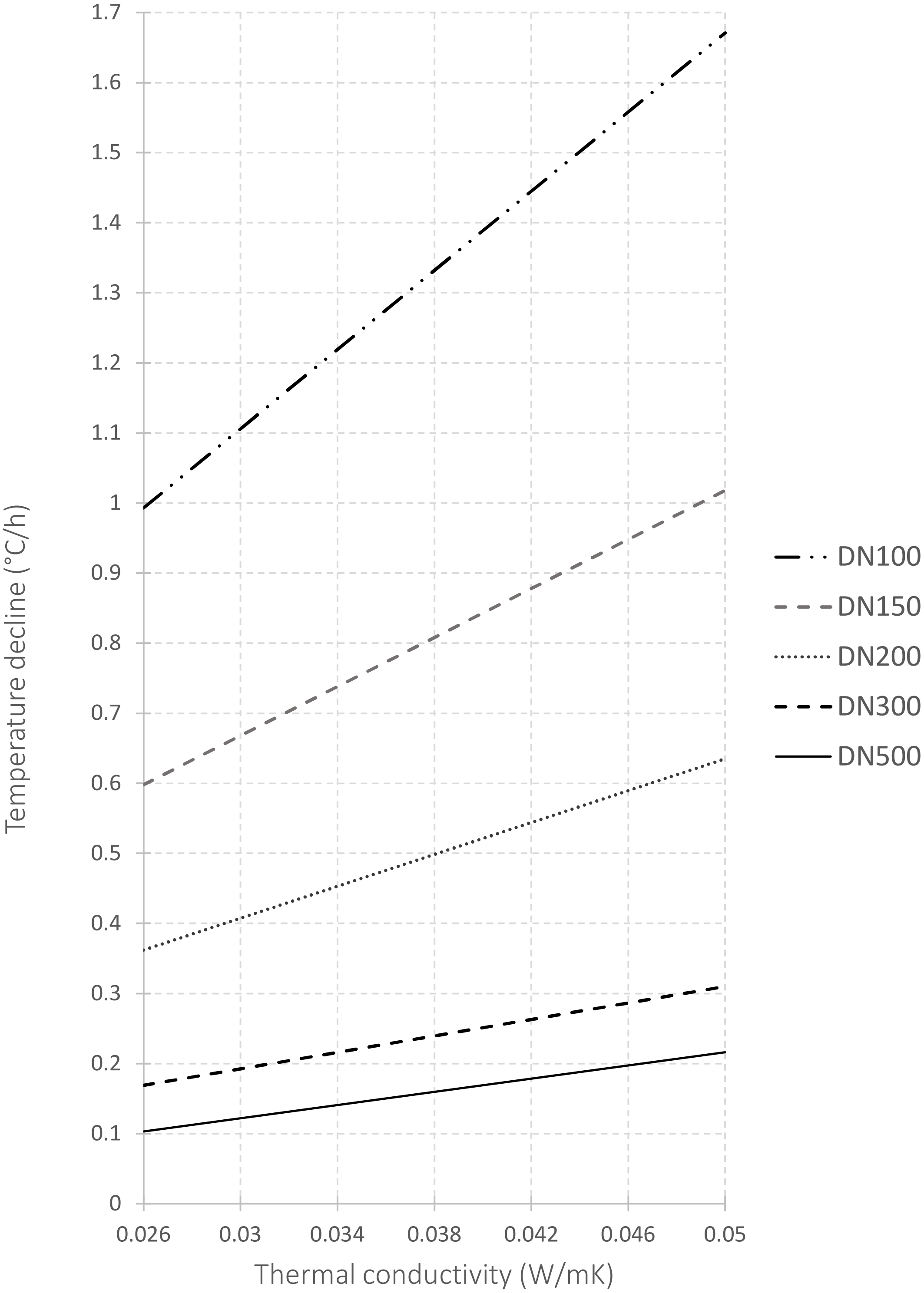


Fig. A5. Example of the resulting thermal conductivities for various pipe dimensions, with respect to declines in drainage valves. The temperature difference between the service and casing pipes is 60°C.

Papers I to V

Errata

Paper, page, paragraph, or location	Error	Correction
1, 377, Eq. (3) 2, 2, Eq. (2)	$\Delta\lambda \approx \Delta R$	$\Delta\lambda \propto \Delta R$
2, 3, Fig. 2	The graph shows a clear connection…	The graph shows a clear **relation**…
2, 4, Eq. (5)	$Q = \rho c * A * L * \triangle T$	$Q = \boldsymbol{C} \triangle T$
2, 4, Eq. (6)	$K = \frac{-C * ln\left(\frac{\triangle T_{start}}{\triangle T_{slut}}\right)}{t_{tot}}$	$K = \frac{\boldsymbol{C}\, ln\left(\frac{\triangle T_{start}}{\triangle T_{end}}\right)}{t_{tot}}$
2, 4, Eq. (7)	$\lambda = \frac{K * ln(\frac{r_2}{r_1})}{2 * \pi}$	$\lambda = \frac{K\, ln(\frac{r_2}{r_1})}{2\pi \boldsymbol{L}}$
2, 4, 2	ρc gives C [J/K]	$\rho c \boldsymbol{AL}$ gives C (J/K)
3,2, Eq. (2)	$t_c = \frac{C}{G}$	$t_c = \frac{\boldsymbol{C_{water}}}{G}$
3, 2, section 2.1	(350 mm in diameter of steel pipe/560 mm in diameter of casing pipe)	(**355.6**-mm-diameter steel pipe/560-mm-diameter casing pipe)
3, 6, 5	and T (K) is temperature.	and T (**°C**) is temperature.
3, 7, 3	can be included in regular drift stops during…	can be included in regular **operational** stops during…
4, 4, 1	$\frac{dT_f}{dt}$ (K/m)	$\frac{dT_f}{dt}$ (K/**h**)
4, 4, Eq. (2)	$\rho c_f A_f \left.\frac{dT_f}{dt}\right\|_{t\approx 0} = -q_s = -\frac{2\pi\lambda_i}{ln(R_{out}/R_{int})} T_{f,0} - T_s$	$\rho c_f A_f \left.\frac{dT_f}{dt}\right\|_{t\approx 0} = -\boldsymbol{q_f} = -\frac{2\pi\lambda_i}{ln(R_{out}/R_{int})} (\boldsymbol{T_{f,0}} - \boldsymbol{T_s})$
4, 4, Eq. (3)	$\lambda_i \approx \frac{\rho c_f A_f}{2\pi T_{f,0} - T_s} ln\left(\frac{R_{out}}{R_{int}}\right) \left\|\frac{dT_f}{dt}\right\|_{t\approx 0}$	$\lambda_i \approx \frac{\rho c_f A_f}{2\pi(\boldsymbol{T_{f,0}} - \boldsymbol{T_s})} ln\left(\frac{R_{out}}{R_{int}}\right) \left\|\frac{dT_f}{dt}\right\|_{t\approx 0}$
4, 7, 5	(see Table 1).	(See Table **2**).
5, 5, Fig.4	versus the dimensionless time	versus the **dimensional length**
5, 11, 5	density of 2500 m^3/kg	density of 2500 **kg/m³**