THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

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

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Abstract

This thesis presents the development of a non-destructive testing (NDT) method for thermal assessment of pre-insulated district heating (DH) pipes with high accuracy, in which the development process from literature review to its present stage is presented and discussed.

Pre-insulated DH pipes have been in use for more than 40 years. The thermal performance of these pipes decreases over time as a result of thermal aging, which leads to higher heat losses. Present methods are unable to assess these heat losses with a high accuracy.

The main idea with the method is to perform a temporary shutdown of a selected part of a network for less than two hours, which enables temperature measurements during the cooling phase. Measured temperatures are then used for analyzing the thermal performance of the pipes. The accessibility for temperature measurements on the pipes depend on the conditions in field. Thus, the methodology for the development of this cooling method involves different measuring points during different conditions in field.

This thesis covers three conducted field tests during maintenance, which allowed for temperature measurements on the service pipe, the casing pipe, and connected valves. Furthermore, the method utilizes the copper wire, which is already embedded in the polyurethane insulation for detection of water leakage, as a sensor for measuring the mean temperature at copper wire position along the pipe under assessment.

This thesis presents the possibilities and uncertainties with the cooling method at its present stage. The method shows good potential to meet the aim as an NDT method with high accuracy, and to be a future tool for the network owners.

Key words: District heating pipes, NDT, Cooling method, Polyurethane, Copper wires, Shutdown

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Sammanfattning

Denna licentiatuppsats presenterar utvecklingen av en icke förstörande metod med hög noggrannhet för termisk utvärdering av förisolerade fjärrvärmerör, i vilken utvecklingsprocessen från litteraturstudie till dess nuvarande form presenteras och diskuteras.

Förisolerade fjärrvärmerör har använts i mer än 40 år. Dessa rörs termiska prestanda minskar med tiden till följd av termisk åldring, vilket leder till högre värmeförluster. Nuvarande metoder kan inte bedöma dessa värmeförluster med hög noggrannhet. Idén med metoden utgår från att en utvald del av nätverket tillfälligt stängs ner i mindre än 2 timmar, vilket möjliggör för temperaturmätningar på rören under avsvalningsprocessen. Uppmätta temperaturer används sedan för att analysera rörens termiska prestanda. Tillgängligheten för temperaturmätningar på rören beror på fältförhållandena. Därmed involverar metodiken för att utveckla en avsvalningsmetod olika mätpunkter vid olika förhållanden i fält.

Denna licentiatuppsats omfattar tre genomförda fältförsök där underhållsarbete förekom, vilket möjliggjorde temperaturmätningar på mediaröret, manteln och anslutna ventiler. Dessutom kunde elektrisk resistansmätning utföras på kopparträden, vilken redan är inbäddad i polyuretanisoleringen som en sensor för vattenläckage. Genom dessa mätningar kunde därmed medeltemperaturen vid kopparträdens position längs röret beräknas.

Licentiatuppsatsen presenterar möjligheterna och osäkerheterna med avsvalningsmetoden i dess nuvarande form. Metoden visar god potential att uppfylla målet som en icke förstörande metod med hög noggrannhet, vilken i framtiden kan vara ett verktyg för nätägaren som vill statusutvärdera sitt ledningsnät avseende termisk prestanda.

Nyckelord: Fjärrvärmerör, Icke förstörande metod, Avsvalningsmetod, Polyuretan, Koppartråd, Avstängning.

List of Publications

This thesis consists of an extended summary and the following appended publications:

Paper 1 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 2 Lidén, H.P., Adl-Zarrabi, B.: Non-destructive methods of district heating pipes. In Proceedings of the 12th ECNDT, Sweden, Gothenburg (2018)

Paper 3 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).

ADDITIONAL PUBLICATIONS

The following publication is related to the topic but is not part of this thesis:

Paper 4 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, submitted to IEEE Transactions on Power Delivery.

Abbreviations

DH	District heating
NDT	Non-destructive testing
PUR	Polyurethane
PE	Polyethylene
HDPE	High density polyethylene
TDR	Time domain reflectometry
TC	Thermocouple
DN	Nominal diameter
LSA	Lumped system analysis
LT	Laplace transformation

Contents

1 Introduction

District heating (DH) networks have been used for decades and the usage increased substantially in the 1960s in the US and Europe, and especially during the oil crisis in the 1970s. The main idea with DH is to deliver heat that has been produced from local heat resources, which often are rest products from other activities, and thereby cheap in comparison to other heat sources. In Sweden, DH is commonly produced from excess heat from burned household waste or excess heat from industries, with small environmental impact. Internationally, fossil fuels are still the dominating heat source for DH. The DH has its greatest potential in areas with high heat density, which means areas with high heat demand within short distance from power plants, where the DH is produced (Werner, 2017). Larger distances obviously demand several kilometers of pipes and the total heat losses from the pipes thereby increase.

The pipe types that have been used through the history vary. Old networks used steel pipes within concrete or asbestos boxes insulated with e.g. mineral wool or cellular concrete foam. Today polyurethane (PUR) pre-insulated single pipes are very common and these pipes were taken into use in the late 1960s (Fredriksen and Werner, 2013). There are supply and return pipes 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. During the cold season the media temperature varies between 80 to 115 °C, and normal casing pipe temperatures then range from approximately 5 to 20 °C. In a single pipe the inner service pipe (water pipe) is normally made of steel and surrounded by PUR foam insulation, an outer casing pipe of high density polyethylene (HDPE), and two measuring wires for moisture surveillance embedded in the insulation, see Fig. 1.

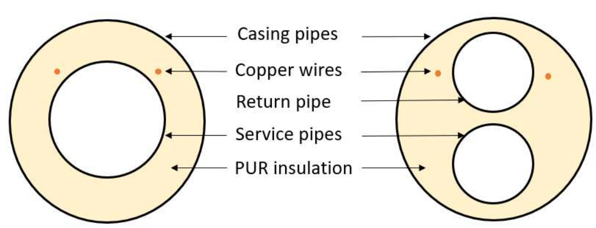

Fig. 1. Illustration of rigid pre-insulated DH pipes. A single pipe to the left and a twin pipe to the right.

There are two types of measuring surveillance systems: the Nordic system with bare copper wires (typical for Sweden) and the NiCr system with insulated nickel-chromium wires

(Brandes, 2019). The dimension of a pipe is given by the nominal diameter (DN) of the service pipe and the casing pipe e.g. DN50/140 (mm).

Owners of the pipe network, normally energy companies, can measure what they produce in heat energy and what they deliver to customers, thus the heat losses for the whole network can be determined. The largest dimensions of pipes in the network, the main pipes, are the ones with the highest heat losses, under the assumption that the whole network is equally aged. In Sweden, around 10% of the energy supplied to the DH networks is lost through heat losses from the distribution pipes (Berge et al., 2015), where aging with degradation of the PUR insulation is one of major reasons (Kręcielewska and Menard, 2014). Heat losses may be costly, and the cost impact is governed by the price of the used heat source.

It is an advantage for many energy companies to estimate the remaining service life of pre-insulated DH pipes. The distance of 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 beneficial. For DH networks that rely on an expensive heat source, pipe replacements may be beneficial for shorter distances than DH networks relying on less expensive heat resources.

To estimate the remaining service life of a network is difficult, and today's thermal assessment techniques only give rough estimations. Infrared thermography is commonly used as an NDT method by energy companies for detection of heat losses, which may indicate water leakages from DH pipes (Friman et al., 2014, Zinko et al., 1996). Thermography is conducted with a thermal camera and supplies the user with ground surface temperatures and thereby may unnatural high temperatures indicate heat losses. However, the thermal status of the pipe insulation cannot be assessed with high resolution by this technique, since e.g. surrounding soil environment and its thermal properties also affect the resulting surface temperature of the ground.

One existing method with high accuracy for assessment of thermal performance of the pipes is the SP plug method (Sällström et al., 2013). This method provides a good status assessment of the excavated part but demands excavation and interference in the pipe network, where smaller samples of the PUR insulation are taken out and the thermal and mechanical properties of the sample are determined in a laboratory. The method is destructive, and it should be conducted in a point-by-point manner, which only provides basis for a local assessment, whereon there still is a large uncertainty in the status of the total investigated pipe length. Thus, a non-destructive testing (NDT) method which can provide thermal performance over a long distance with reasonable or high accuracy is needed.

1.1 Aim and objectives

The aim of this thesis is to present results related to development of a new NDT method for assessment of thermal performance of DH networks in operation, with high accuracy in comparison with other existing NDT methods. The developed NDT method should be suitable for thermal performance assessments of pipes with a length of a few meters up to a kilometer or more.

1.2 Delimitations

The method is delimited to be non-destructive without adding any other component to the existing DH network. The focus is on rigid pre-insulated single DH pipes, consisting of an inner service pipe of steel surrounded by PUR-insulation, an outer casing pipe of polyethylene (PE), and in most cases, two copper wires for moisture surveillance embedded in the insulation. Dimensions that have been studied range from DN250/450 to DN350/560.

1.3 Methodology - research design

The methodology for the development of the NDT method is based on a literature review of existing methods, a choice of method to test, and laboratory and field measurements with analysis and evaluations.

A literature study was performed for identification of potential NDT methods from other fields than DH, and existing measurement methods within the field of DH that could be modified. This opened up for the choice between developing a new method or modifying a previous method. A modified method was chosen and tested, analyzed, and evaluated in laboratory environment. Laboratory results were satisfactory, and field measurements were conducted with following analyses and evaluations. The results of the first field measurements were promising for the development of the method. Thus, additional field measurements were carried out in different locations. A mathematical model for evaluation of the field measurement results is under development. Furthermore, a future sensitivity analysis of the method through repeated field tests, together with the mathematical model for determination of thermal performance of DH pipes based on measured data. The methodology of the PhD work is presented in Fig. 2.

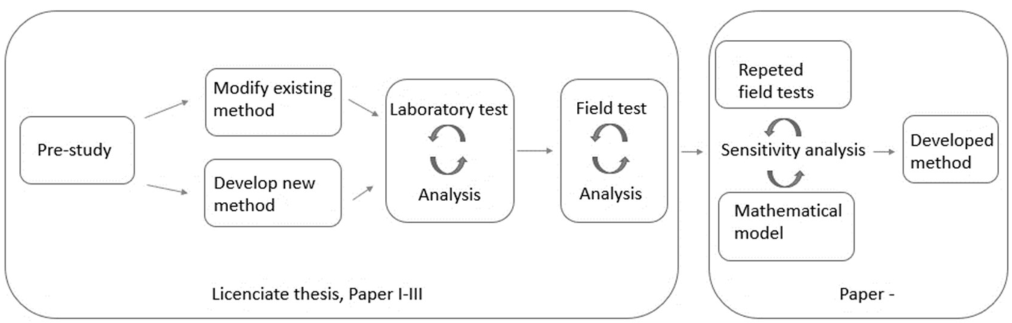

Fig. 2. PhD work process for development of an NDT method for thermal status assessment of operational DH pipes.

2 Review of potential non-destructive testing methods

Paper 1 highlights the pre-study conducted by Kakavand and Adl-Zarrabi (2015), and completed the pre-study by methods within the field of DH. Furthermore, a new concept for a method was suggested.

The pre-study covers a literature review of several reports and scientific articles from other fields, outside the field of DH, with methods that may be implemented with modifications to suit the objectives of this work. The pre-study aimed to find a method for remote detection of chemical, electrical and thermal properties of PUR after natural thermal degradation. The studied methods were limited to be only non-destructive. The suitability for applying these methods on the DH pipes was evaluated by ranking them concerning a number of criteria, e.g. portability, level of consistency, inspection time, and level of non-destructiveness.

The study highlighted Raman spectrometry, Frequency domain reflectometry (FDR), and Time domain reflectometry (TDR), to have the highest potential for an assessment of a DH network. However, it was not possible to correlate the measured entities/units by these methods with thermal performance of the pipe. If it is possible to make use of these methods for thermal assessment of DH pipes is highly uncertain and the procedure for development is unclear.

In fact, TDR is already used on DH pipes. The TDR method is originally used as an accurate NDT method for identifying and measuring dielectric properties of transmission and distribution lines (Ariffin et al., 2012). Within the field of DH, the method has been implemented to detect and locate water leakage in the PUR insulation, between service pipe and casing pipe. With TDR, a pulse generator produces an electromagnetic signal over a conductor, such as the copper wire and the service pipe. The measurement probe registers the reflected voltage if impedance mismatches are detected on the conductor. Impedance mismatches will cause all or some of the transmitted signal to be sent back towards the oscilloscope. The oscilloscope monitors the pulses that are generated from TDR. The distance of discontinuity can also be determined by measuring the reflection time of the pulse. Small leakages can be hard to distinguish and exact locations hard to determine, especially if moisture is present between the copper wire and the casing pipe (Nilsson et al., 2006).

The most interesting previous research, conducted in the field of DH with a connection to the scope of this thesis, is a method introduced by Reidhav and Claesson (2010), which can assess the thermal conductivity (λ) of flexible twin pipes. In this method, the flexible pipe was placed in a pool with cold tap water. Thereafter, warm water with a temperature of 80 ˚C (service pipe temperature) was circulated in the flexible pipe. The circulation of water was then stopped and the cooling time and the temperatures of the pool and the supply water were measured and analyzed. The temperature decline of hot stagnant water in the pipe, immersed in cool water, depends on the thermal conductivity of the pipe. Thus, the thermal conductivity can be calculated by transient inverse calculation of the partial differential equations of heat transfer.

The idea behind the cooling method, to measuring the temperature decline of a DH pipe, was assessed to have potential for development as an NDT method in field. However, the lack of temperature sensors on a service pipe in operation was a drawback of using the cooling method without modification. Generally, implementation of the cooling method needs knowledge about two temperatures, i.e. the service pipe temperature and the temperature at an arbitrary position over the cross section of the pipe, instead of the temperature of the pool. Thus, the results of the literature review showed that there is no NDT method for assessment of thermal performance of DH pipes, which can be directly applied without modification.

3 Development of a new method

A new approach was needed. With the objectives in mind a main hypothesis was created, which is presented in **paper 1 and paper 2**.

The main hypothesis is that a modified cooling method can fulfill the criteria for development of an NDT method. The hypothesis is based on that an operating DH network can be shut down for a couple of hours, then the temperature decline of a pipe will be measured. By analyzing the cooling time and temperatures it is possible to assess the thermal performance of the pipe. The temperature decline can be measured on the service pipe, the position of the existing copper wires, and finally on existing accessible valves, welded to the service pipe. The largest pipe dimensions, main pipes, are the ones with the highest heat losses, and consequently the main target of the new method. From the main pipes, the network spreads as branches with pipes of smaller and smaller dimensions. However, main pipes are difficult to shut down without affecting a high number of customers. Therefore, pipes with lower or zero impact on the customers are used for the development of the method.

3.1 Utilization of copper wires for temperature measurements

The temperature at the position of the copper wires can be determined by coupling the two wires in one point. A circuit is created while measuring the electrical resistance (Ohm) of the copper wire loop with a multimeter (**paper 1**). The electrical resistance is a linear function of the temperature, T (K), as expressed in Eq. 1 (Cutnell and Johnson, 2003). The outcome of a measurement, after converting resistance to temperature, will be a mean value of the temperature for the total length of the pipe, at the position of the copper wire.

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

In which $R_T(\mathrm{Ohm})$ is resistance at the temperature of interest, R_{T_0} (Ohm) is resistance at reference temperature, T_0 (K) is a reference temperature, $\alpha\,(1/\mathrm{K})$ is the temperature coefficient of resistivity and T (K) is temperature of interest. Electrical resistivity of the soft copper wire is 0.0113 $(\mathrm{Ohm} \cdot \mathrm{m})$ at 20 °C (T_0) (Powerpipe, 2018, ASTM, 2018) and the temperature coefficient of resistance, α_{copper} is 3.93 10^{-3} $(1/\mathrm{K})$ (ASTM, 2018).

Determining the temperature at the position of the copper wire was proven to be possible by laboratory measurements, performed using a guarded hot pipe device according to EN 253 (**paper 2**). The results of the measurements are presented in Fig. 3.

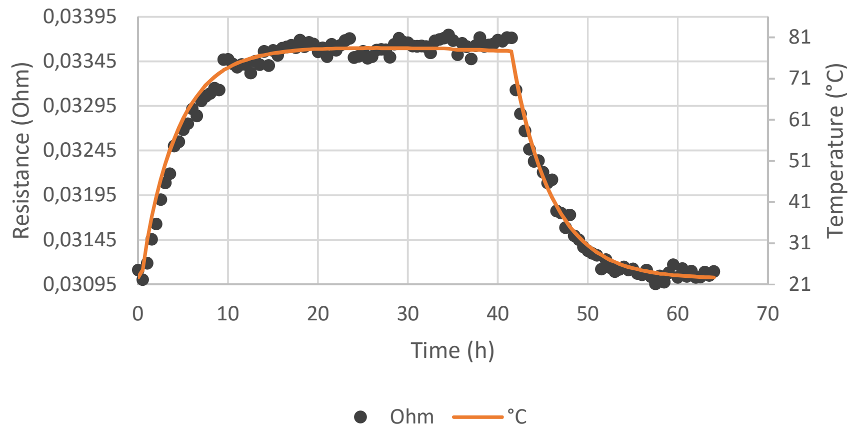

Fig. 3. Measurements of service pipe temperature and electrical resistance of the copper wire in a guarded hot pipe apparatus. The axes of the figure were selected in order to show the shape of the curves for the temperature and the resistance increase and decrease. In reality, a time lag exists between the curves due to the thermal inertia of the insulation.

A clear relation between the electrical resistance and the temperature can be seen in Fig. 3. The results also indicated that it is fully possible to measure the temperature of a position inside the polyurethane insulation, i.e. at the position of the copper wire.

3.1.1 Copper wire position

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

Pipe production technique will have an impact on the final copper wire position within the PUR. The pipes that are assessed in this thesis are produced in individual sections one by one. The standard SS-EN14419 requires a mechanical tightening of the copper wires, e.g. by weights, as shown in Fig. 4. Other production techniques exist, in which the pipes are produced as endless lengths and where the insulation form 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 allows the service pipe to be centralized within the casing pipe. Thereafter, PUR foam is 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 for insertion of the copper wires. The copper wires final distance from service pipe is uncertain and depend on the selected hole, which can vary from 15 to 40 mm (Frick, 2020). This may differ between manufacturers and different production techniques used in the past. In this thesis, 21 mm are used in calculations, based on measurements from the service pipe to the midpoint of one of the small holes in a spacer.

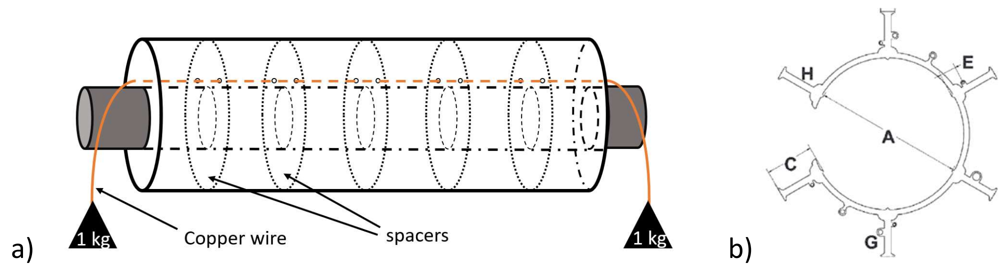

Fig. 4. a) Mechanical tightening of the copper wires during pipe production, in which pipes are produced in sections one by one. The wires are threaded through holes in the spacers and tightened with weights during insertion of PUR foam. b) Illustration of a spacer with several smaller copper wire holes.

3.2 Service pipe temperature

The energy companies can measure the supply temperature at several points in a DH network, mainly at the customers' DH centrals and at the heating plant on outgoing supply water, i.e. the supply temperature is known before shutting down a part of the network. The distance from these measuring points to an assessed part of the network will be case specific and the accuracy of these temperature measurements is governed by the heat losses from point to point. Furthermore, the temperature decline of the service pipe must be measured during the assessment. Thus, it is necessary to measure the media temperature before and after shutting down a part of the network. When temperature sensors are placed at a pipe under assessment, they should favorably be placed in such a way that they can capture the actual media temperature. The service pipe is the best place, if accessible.

3.3 Valve temperature

Valves that are directly welded on the service pipe enables another possible measurement of service pipe temperature. These valves are commonly reachable through manholes or culverts. Temperature sensors can be attached directly on e.g. a ventilation/drainage valve, which is in direct contact with the media water. The valves are shown in Fig. 5.

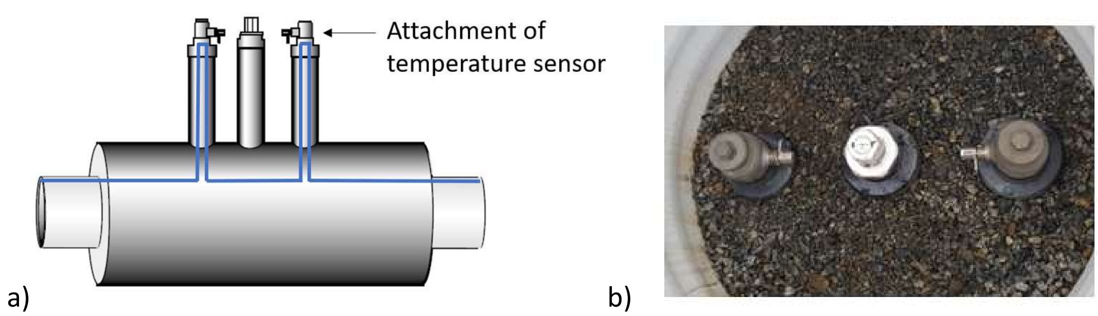

Fig. 5. a) Illustration of valves. An open/close ball valve in the middle and ventilation/drainage valves to the left and to the right . The blue line represents the upper part of the media water in a pressurized system. The illustration is modified after Uponor (2018). b) Similar valve arrangement as the illustration, where the photo shows a manhole with the accessible parts of the valves.

3.4 Casing pipe temperature

During a thermal assessment of a DH network with the suggested cooling method, casing pipe temperature can be of interest as a third measuring point on the pipe if it is accessible, e.g. if the pipe is excavated. In absence of copper wires this measurement is needed for an accurate analysis, since in addition to temperature measurements from the service pipe, an extra measuring point is required.

3.5 Condition based temperature measurements

Thermal assessment of a DH network by the suggested modified cooling method requires a shutdown of a part of the network for a couple of hours. Shutting down the hot water supply is not preferred either by energy companies or by customers. Therefore, it should be planned carefully. An assessment can e.g. be performed during low season or during shutdown opportunities in relation to pipe renovation or replacement activities. Thus, there are two major conditions, namely 1) assessing the pipes during a maintenance activity, when parts of the pipe is excavated or 2) assessing the pipes under operation. However, a third condition exists, namely 3) assessing the pipe ending at a customer.

It is generally possible to measure temperatures at several points, see Fig. 6. Depending on above mentioned conditions, these points can be:

1. Service pipe temperature (water temperature) T_s
2. Copper wire temperature T_{co}
3. Casing pipe temperature T_{cp}
4. Valve temperature T_v

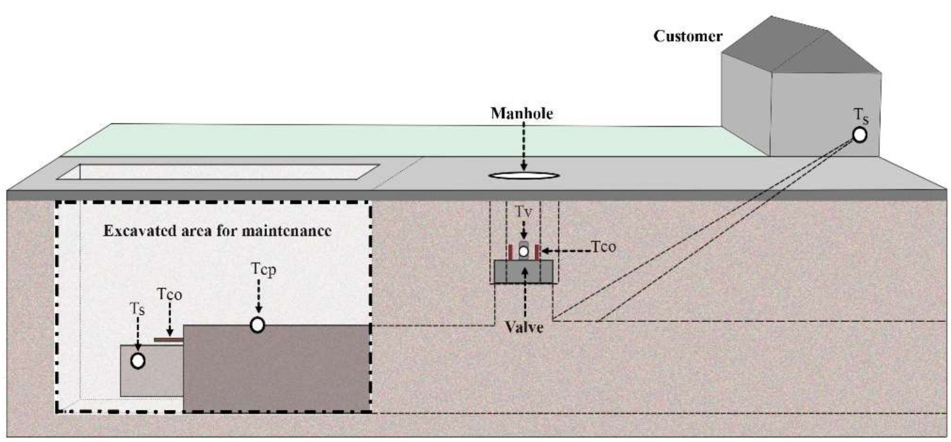

Fig. 6. Illustration of the four measuring points.

The three conditions with their different possibilities to measure temperatures at the four above mentioned points create six different alternatives:

Condition 1, Measuring thermal properties of the pipe during maintenance:

> **Alternative 1:** Copper wires exist. In this alternative all four temperatures can be measured: **T_s, T_{co}, T_{cp} and T_v.**

> **Alternative 2.** Copper wires do not exist. In this alternative three temperatures can be measured: **T_s, T_{cp} and T_v**.

Condition 2, Measuring thermal properties of the pipe under operation:

> **Alternative 3:** Copper wires exist. In this alternative two temperatures can be measured: **T_v and T_{co}.**

> **Alternative 4**: Copper wires do not exist. In this alternative only one temperature can be measured: **T_v**.

Condition 3, Measuring thermal properties of the pipe ending at a customer:

> **Alternative 5:** Copper wires exist, and T_s can be measured directly at a customer connected to the pipe. In this alternative three temperatures can be measured: **T_s, T_v and T_{co}**.

> **Alternative 6:** Copper wires do not exist, and Ts can be measured directly at a customer connected to the pipe. In this alternative two temperatures can be measured: **T_s and T_v**.

All three conditions contain alternatives with or without copper wires. In alternative 3 and 4, T_s is measured at another location by an energy company. Thus, uncertainties are mainly governed by the distance from the measuring point.

In alternative 5 and 6, in which the pipe ends at the customer, measurements of T_s and T_v during the cooling phase can introduce higher uncertainties. After the closing, cooling of measuring point T_s, at the customer, will likely be faster than the rest of the pipe and cannot be used. Measurements of T_v will take place on the valve which, if closed, separates the investigated pipe from the main pipe with an ongoing flow. Thus, the measurement accuracy is affected by the higher temperature on the operating side. T_s and T_v can therefore only be measured with high accuracy before shutdown of the network. For alternative 1-4, measurements will take place on an open or closed valve. If closed, it is exposed to stagnant water on both sides i.e. equal temperatures. All alternatives are summarized in Table 1.

Table 1. Measurement opportunities at different conditions and alternatives, before and during shutdown.

Measurement		T_s		T_{co}		T_v		T_{cp}	
Cooling period		before	during	before	during	before	during	before	during
Cond. 1	Alt. 1	X	(X)	X	X	X	X	X	X
Cond. 1	Alt. 2	X	(X)	-	-	X	X	X	X
Cond. 2	Alt. 3	O	-	X	X	X	X	-	-
Cond. 2	Alt. 4	O	-	-	-	X	X	-	-
Cond. 3	Alt. 5	X	(X)	X	X	X	(X)	-	-
Cond. 3	Alt. 6	X	(X)	-	-	X	(X)	-	-

X Measurable

(X) High uncertainty

O Measured by energy company

- Unmeasurable

Thermal performance of DH pipes can be assessed by measuring the temperature at different points depending on available conditions in the field. In the field measurements presented in this thesis, alternative 1 and 2 are used due to available conditions.

4 Thermal properties and requirements of DH pipe components

There is a large difference between the thermal properties of the different pipe components, which has an impact on the heat flow and measured temperatures.

4.1 Service pipe and valves

According to SS-EN253, the steel service pipe should be of type P235GH or P235TR1/P235TR2, which are carbon steels. Steel is a highly conductive material and the thickness of the service pipe is from 2 to 10 mm, depending on the size of the pipe. For the examined pipes in this thesis, the thickness varies from 5.0 to 5.6 mm. Thermal resistance of the steel service pipe is neglectable in heat transfer calculations. Thus, the temperature of a steel service pipe can be assumed to represent the temperature of the water inside the pipe. However, in transient condition, the key parameter is thermal inertia, a measure of the responsiveness of a material to its surrounding temperatures. Therefore, thermal properties of the steel need to be taken into consideration, since they have an impact on the temperature measurements during the cooling phase.

As with a steel service pipe, the steel type of the valve also has an impact on the measurement of the temperature. According to SS-EN488, "The quality of the steel at the welding ends of the valve or valve assembly shall match with steel of the service pipes". Steel parts that penetrate the casing material and thereby are exposed to ground conditions, should consist of stainless steel (SS-EN488, 2015). While analyzing the temperature measurements, one needs to consider the properties of carbon steel for service pipe measurements and the properties of stainless steel for valve measurements. Thermal properties of the required steel types used for calculations in this thesis are presented in Table *2*.

Table 2. Material properties of carbon steels and stainless steel used in district heating networks (Matmatch, 2020).

Steel type	Density (kg/m^3) at 20 °C	Thermal conductivity (W/m·K) at 20 °C	Specific Heat capacity (J/kg·K) at 20 °C	Thermal diffusivity (m^2/s) at 20 °C
P235GH	7850	57.5	460	$1.59 \cdot 10^{-5}$
P235TR1/P235TR2	7850	56.9	460	$1.57 \cdot 10^{-5}$
AISI 304 (stainless)	7800	16.0	500	$4.10 \cdot 10^{-6}$

4.2 PUR, HDPE and water

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 new pipes should have a thermal conductivity coefficient at 50 ˚C (λ50) ≤ 0.029 W/m·K (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, 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 with around 10% over 30 years (Adl-Zarrabi et al., 2017).

The density requirement according to SS-EN 253 is ≥ 55 kg/m^3. A large German study evaluated thermal and mechanical properties of 110 pipes aged in field for 2-25 years. The study also included foam densities and the mean value was approximately 75 kg/m^3 (GmbH, 2004). In another study of foams for DH pipes aged in field, the foam densities were found to be 55-72 kg/m^3 (Jarfeldt and Ramnäs, 2006). Thermal properties used in this thesis are shown in Table 3.

Table 3. Material properties of PUR and HDPE. PUR data (Powerpipe, 2018, GmbH, 2004, Bing, 2006), HDPE data (Matmatch, 2020). Thermal diffusivity is calculated from the table values.

DH component	Density (kg/m^3) at 20 °C	Thermal conductivity (W/mK) at 20 °C	Specific Heat capacity (J/kgK) at 20 °C	Thermal diffusivity (m^2/s) at 20 °C
HDPE casing	950	0.38-0.51	2,100-2,700	$1.97 \cdot 10^{-7}$
PUR insulation	61*	0.026*	1,400-1,500	$2.31 \cdot 10^{-7}$
DH water	998	0.60	1,484	$1.40 \cdot 10^{-7}$

* New pipes (Powerpipe, 2018)

5 Heat transfer equations for the cooling method

Three main heat transfer mechanisms are conduction, convection and radiation. Depending on observation level all mechanisms are involved, e.g. heat transfer in PUR insulation, which is a gas field 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. Heat is transferred from the inner hot region of a pipe towards the colder outside. The general equation for heat transfer by conduction is presented in Eq. 2, in which the left side in Eq. 2 is given by the product of the volumetric heat capacity ρ·c (J/m^3K) and the temperature change over time. On the right side in Eq. 2 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. 3.

$$\rho c \frac{\partial T}{\partial t} = -\nabla q \qquad (2)$$

$$q = -\lambda \nabla T \qquad (W/m^2) \qquad (3)$$

While calculating heat losses from a pipe, one needs to consider the circular geometry. Normal cartesian coordinates need to be transferred to cylindrical polar coordinates. In a circular geometry there is a radial coordinate, in which the radial distance r is used, see Fig. 7.

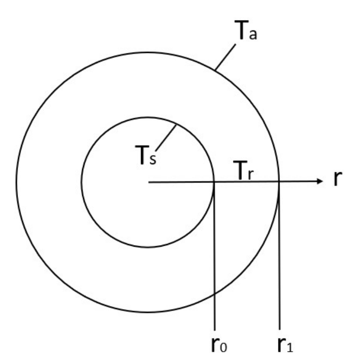

Fig. 7. DH pipe where Ts is the service pipe temperature, T_a is the ambient temperature, r_0 is the service pipe radius, r_1 is the casing pipe radius, and T_r is the temperature at an arbitrary position between r_0 and r_1.

In a steady-state condition, the transient term on the left-hand side of Eq.2 is zero, since temperatures do not change over time. If assuming a constant thermal conductivity λ (W/mK) of the insulation, the pipe can be described by an annular cylinder, i.e. the PUR insulation, with the temperature at the inner boundary T_s (K), corresponding to the temperature of the service pipe, and a temperature at the outer boundary T_a (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. 4-6.

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{\mathrm{dT}}{\mathrm{dr}} = 0 \qquad (4)$$

$$T(r_0) = T_\mathrm{s} \qquad \text{(K)} \qquad (5)$$

$$T(r_1) = T_\mathrm{a} \qquad \text{(K)} \qquad (6)$$

The temperature at any position in the PUR insulation can be calculated with Eq. 7 by assuming boundary conditions according to Eqs. 5-6.

$$T(r) = T_s + (T_a - T_s)\,\frac{ln\,(\frac{r}{r_0})}{ln\,(\frac{r_1}{r_0})} \qquad \text{(K)} \qquad r0 \le r \le r1 \qquad (7)$$

The heat flow Q (J) from a pipe can be calculated by Eq. 8 if a length L (m) of the pipe is considered.

$$Q = \frac{2\pi\lambda L}{ln(\frac{r_1}{r_0})}(T_s - T_a) \qquad \text{(J)} \qquad (8)$$

5.1 Transient conditions

Two different transient calculations have been used in this thesis to assess the thermal conductivity of the pipe insulation from a cooling process, namely: assuming the pipe as a lumped system, and solving the transient differential equation by Laplace transformation.

5.1.1 Lumped system

A lumped system analysis (LSA) is based on a body with 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. Equation 9 can be described as a mass 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).

$$Q = -\frac{dE}{dt} = -\rho c V\frac{dT}{dt} \qquad (9)$$

The heat losses are governed by the difference between the internal service pipe temperature T_s and the ambient temperature T_a, and the conductance K (W/K) between the material in the volume and the ambient temperature. The heat loss Q can be written as Eq. 10.

$$Q = K(T_s(t) - T_a) \qquad (10)$$

From now, both the water and the service pipe temperature is denoted T. By inserting Eq. 10 into Eq. 9:

$$-\rho cV\frac{dT}{dt} = K(T(t) - T_a) \tag{11}$$

which can be further rewritten as:

$$T + \frac{C_W}{K}\frac{dT}{dt} = T_a \tag{12}$$

Consider that the temperature of the interior of the pipe is T_0 at time zero while the ambient 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* is the conductance written with cylindrical coordinates as in Eq. 15. Equation 13 can then be rewritten and if T_0, T_1, and *T(t)* for any given time are known, the thermal conductivity λ (W/mK) can be calculated by Eq. 16. In Eq. 16, T_1 can represent the temperature at an arbitrary position between the service pipe and the casing pipe, e.g. the copper wires within the insulation.

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

in which L (m) is the pipe length, r_1(m) is an arbitrary position in the insulation, and r_0 (m) is the service pipe radius. For this equation a quasi-steady-state approximation is used for T_1 (Dzierwa, 2014). Furthermore, the total heat capacity of the water C_W is about 30 times higher than the total heat capacity of the insulation material. Thus, in these equations the influence of the total heat capacity of the insulation is neglected.

5.1.2 Laplace transformation

Another approach for solving the differential equation of heat conduction (Eq. 2) is by considering an infinitely long circular cylinder with infinite outer radius, containing a perfect conductor (or well mixed water) with the actual heat capacity of the water and the steel inside the annular insulation. This is a valid approach for the analysis of the initial phase of the cooling of the pipe water. A analytical solution, using the Laplace transform Eq. 17 is found in (Carslaw and Jaeger, 1986).

Using superposition technique, the cooling process can be isolated as the process where a constant heat flow *Q*, corresponding to the heat loss at time zero, is extracted from the water starting at time zero. The initial condition inside the insulation outside the pipe is zero.

The temperature decline of the service pipe temperature Δ*T(t)* is given by Eq. 18. Here *a* (m^2/s), is the thermal diffusivity of the insulation, and $\Delta(u)$ (Eq. 19) is a function determined by Bessel functions. The parameter α is given by (Eq. 20). In the second part of Eq. 18 it is combined with Eq. 8.

By fitting the measured temperature drop of the water, *ΔT(t)* to *Eq. 18* the thermal diffusivity of the insulation and the parameter α can be found, which together determines the thermal conductivity λ.

$$F(s) = \int_0^\infty f(t)e^{-s}\,dt \tag{17}$$

$$\Delta T(t) = \frac{2\cdot Q\cdot\alpha^2}{\pi^3\cdot\lambda}\int_0^\infty \frac{(1-e^{-\frac{a\cdot t\cdot u^2}{r_0^2}})du}{u^3\cdot\Delta(u)} = \frac{4\cdot(T_s-T_a)\cdot\alpha^2}{\pi^2\ln\left(\frac{r_1}{r_0}\right)}\int_0^\infty \frac{(1-e^{-\frac{a\cdot t\cdot u^2}{r_0^2}})du}{u^3\cdot\Delta(u)} \quad \text{(K)} \tag{18}$$

$$\Delta(u) = [uJ_0(u) - \alpha J_1(u)]^2 + [uY_0(u) - \alpha Y_1(u)]^2 \tag{19}$$

$$\alpha = \frac{2\cdot\pi\cdot r_0^2\cdot\rho c_i}{\pi\cdot r_0^2\cdot\rho c_w} = \frac{2\cdot\rho c_i}{\rho c_w} \tag{20}$$

in which ρc_i is the volumetric heat capacity of the insulation (J/m^3K) and ρc_w is the volumetric heat capacity of water (J/m^3K).

6 Field tests with the cooling method

The cooling method has been tested in selected parts of Mölndal and Falun DH network, the results of these field tests are presented in **paper 3**. Three experimental field tests were performed, and the setup was refined after each field test, i.e. by adding insulation, measuring temperature of a valve, and minor repositioning of thermocouples (TCs). The measurements were performed during heating season, Nov 2018 - Feb 2019. The three field tests were all of field condition 1 and alternative 1 according to chapter 3.5, i.e. measuring thermal properties of the pipe during maintenance where a part of the pipe was excavated. Thus, all four temperatures (T_s, T_{co}, T_{cp} and T_v) were measured. However, since all the four temperatures were measured it was also possible to analyze the results assuming alternative 2, i.e. as if only T_s, T_{cp} and T_v were known. For temperature measurements in the field tests the temperature has been measured with Testo 176 T4 loggers, with TCs of type K . Resistance has been measured with multimeter Fluke 289 and crocodile clamps.

6.1 Field test 1

The first field test with the cooling method was performed in November 2018 on a network part of Mölndal Energi (municipal energy company of Mölndal) at an excavation (alternative 1), before the network owner connected additional pipes to the existing part. Thus, there was an excavation, in which the ends of return and supply pipes were exposed to the ambient air, see Fig. 8.

Fig. 8. The excavation with two single pipes, of which the field test was carried out on the supply pipe (to the right). The small uninsulated vertical interconnected pipe can be seen between supply and return pipe in the photo.

The existing pipes were also newly installed, with a pipe dimension of DN250/450 (mm), and a length of 528 m, which was measured with a TDR instrument. A temporary minor interconnecting pipe between supply and return pipes allowed a small water flow through the pipes.

A multimeter was connected to the copper wires at the excavated supply pipe end, for electrical resistance measurements, which enabled calculation of T_{co}. A logger with two TCs were used for measuring T_s and T_{cp}. One TC (T_s) was inserted 2 cm into a small existing space of 2 mm between the service pipe and the PUR insulation. The second TC (T_{cp}) was attached to the casing after some shovels with fillings were removed. Fillings were repositioned after attachment. Figure 9 shows the excavation, as well as the manhole with a valve where the copper wires were coupled to a circuit.

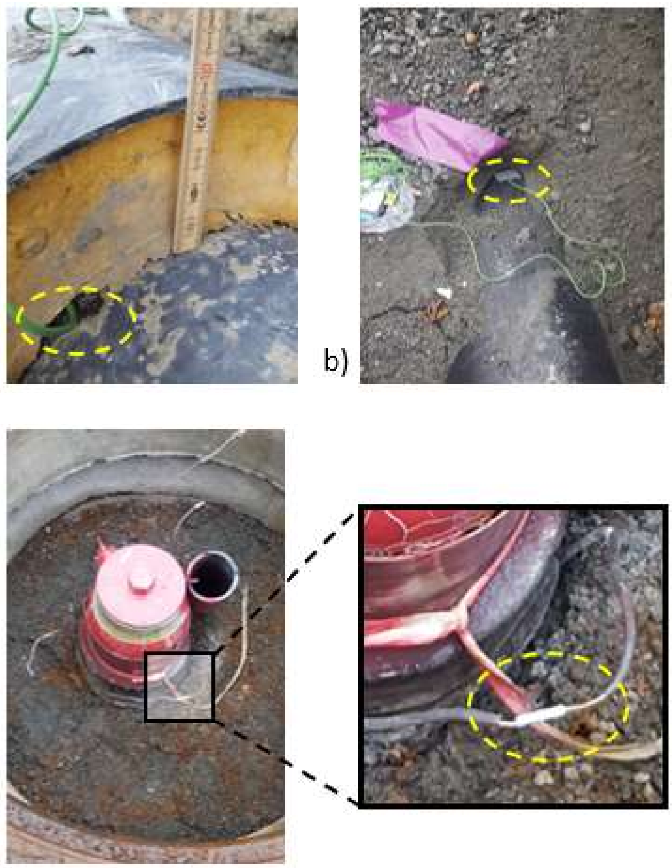
a) b) c)

Fig. 9. a) TC for measuring T_s inserted under the PUR. b) TC for measuring T_{cp} attached to the casing before fillings were laid back. c) Coupled copper wires next to a valve in a manhole.

Logging frequency of the multimeter was set to one measurement per minute, likewise for the temperature logger. The temperature and resistance measurements started 10 minutes prior the shutdown. The temperatures were constant during this period. Thereafter, the flow was switched off at the valve on the interconnected pipe for 147 minutes.

6.1.1 Measurement data - field test 1

Measured temperatures for the three points T_s, T_{cp} and T_{co} for the 147 minutes of cooling are presented in Table 4.

Table 4. Temperature data from field test 1. There is a time lag between measured T_s and T_{co}, due to heat capacity of insulation material, thus ΔT for each temperature measurement is calculated after 137 min. The supply temperature data from DH plant prior cooling is received from the energy company (Barenfeldt, 2018).

Time (min)	Supply temp max-min (°C)	Ambient air (°C)	T_s (°C)	T_{cp} (°C)	T_{co} (°C)
-120 Prior	70.60-70.25	11.50	-	-	-
0 (start)	-	12.40	63.90	12.40	52.30
10	-	12.40	63.80	12.40	52.30
60	-	11.80	63.00	12.40	52.15
137	-	10.40	61.80	12.40	52.05
147 (end)	-	10.40	61.70	12.40	52.00
ΔT (°C) 137min	-	-	2.10	0.00	0.30

During a shutdown of a DH pipe the temperature decline of the different pipe components do not start simultaneously, which can be seen in Table 4. There is a time lag for the temperature decline, which is governed by the thermal diffusivity. The heat penetration depth into a material can be calculated by Eq. 21 (Claesson and Hagentoft, 1994).

$$D = \sqrt{a}t \qquad \text{(m)} \qquad (21)$$

in which *D* is the penetration depth (m), *a* is the thermal diffusivity (m^2/s), and *t* is the time (s). An illustration of how the thermal penetration depth affects the temperature response time for the different pipe components is shown with an example in Fig. 10.

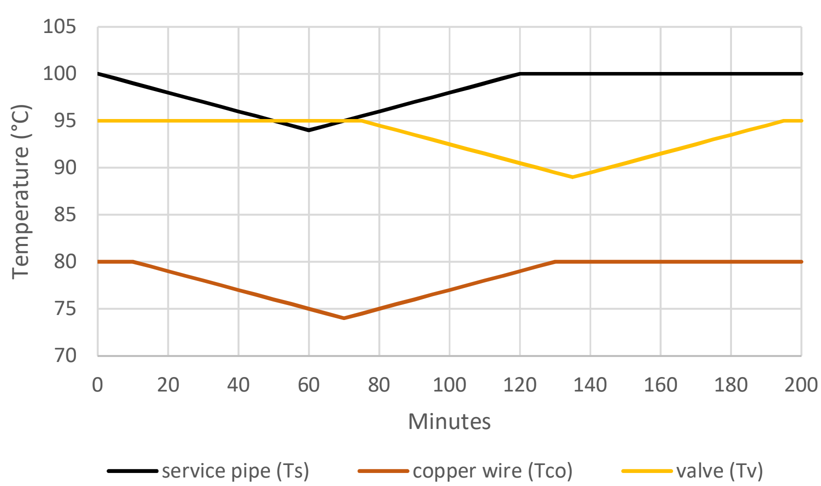

Fig. 10. Illustration of the effect from thermal diffusivity on the time lags at different measuring points.

In this example a shutdown starts at time 0 and ends after 60 minutes. Due to the different thermal diffusivities and dimensions, the temperature decline occurs with a time lag, which is 0 min for T_s, 10min for T_{co}, 75min for T_v and 180 min for T_{cp}. The copper wires are placed 20 mm from the service pipe and the top of the valve is 500 mm from the service pipe. The casing pipe is located 100 mm from the service pipe (low temperatures and slow response time, not included in figure). The used material properties are according to tables 1 and 2.

6.2 Field tests 2 and 3

The second and third measurements were carried out on a 496 m newly installed pipe network, owned by the municipal energy company of Falun. The network mainly consisted of pipe dimension DN350/560. The cooling method was conducted on a part of the DH network (A-D), presented in Fig. 11. Point A was excavated, i.e. alternative 1, and point B represent the position of a valve. The length of pipe section C is 55 m. The dimension of the pipe switched from DN125/450 to DN100/355 at the middle of section C. The copper wire length (coupled in point D) was measured to 992 m (496x2) using a TDR instrument. The network (A-D) was connected to the main network (E).

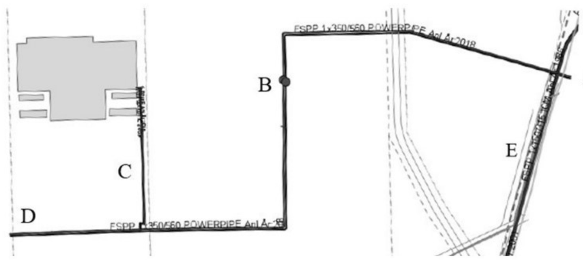

Fig. 11. Overview of the DH network (A-D) for field tests 2 and 3. Measurements of T_s, T_{co} and T_{cp} were conducted in the excavated area at point A, measurements of Tv were conducted in point B on an open valve, approximately at half the stretch of the total network. Heat plant is located only 100 m right of point A (not visible in figure).

The temperature measurements were carried out at point A and B. The network (A-D) was located approximately 0.5 m below ground surface, covered with soil. The end part of the service pipe at the excavation pit was insulated with mineral wool, to be compared with field test 1 where the end part was directly exposed to ambient air. In field test 2 the valve in point B was uninsulated and in field test 3 it was insulated with mineral wool. The positions of T_s, T_v, T_{cp} and T_{co} are shown in Fig. 12.

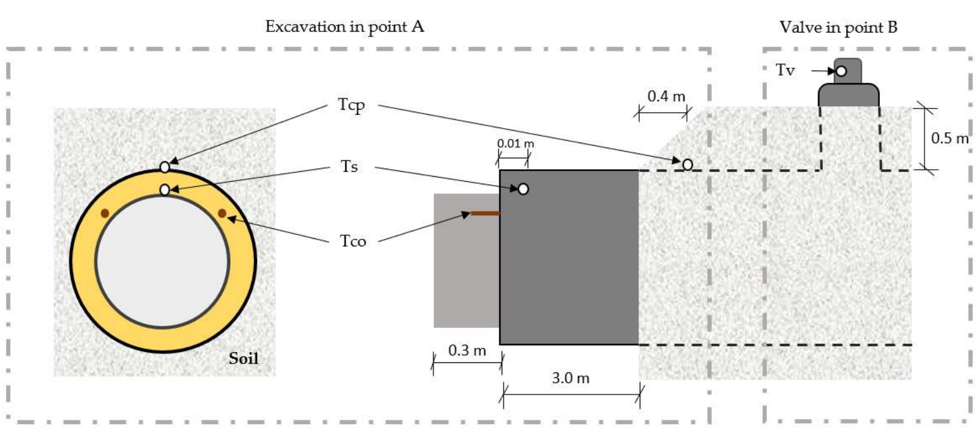

Fig. 12. Illustration of measurement set-up at point A and B in the network. At point A, the TC measuring T_s was inserted 0.01 m into a small space between service pipe and the PUR, TC measuring T_{cp} was attached to the casing pipe by removal and replacement of 0.4 m soil a multimeter was connected to the two copper wires and at a valve. At point B, TC measuring T_v was attached to the valve.

Figure 13 presents photos (a-b) of the valve at point B and photos (c-d) show the excavation at point A. Photo (d) also shows a flexible pipe of 20 m that connected the pipe network (A-D) with the main network (E).

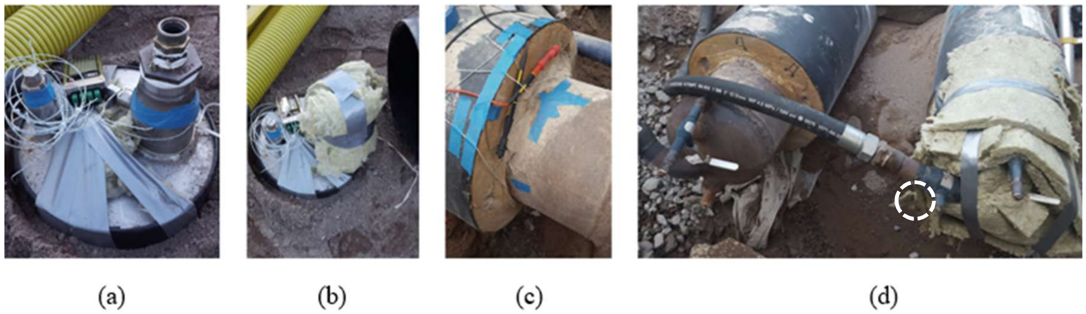

Fig. 13. (a) Valve at point B with TC attached on the valve to the right. (b) The same valve after insulation with mineral wool. (c) The service pipe at the excavation with TCs measuring T_s and crocodile clamps on the ends of the copper wires, connected to a multimeter.(d) The same pipe (supply), to the right in photo, after insulation with mineral wool. White dotted circle shows the valve on the flexible pipe which was switched off for the shutdown.

The cooling test took place on the 27th 11:20-14:36 and 28th 11:30-15:01 of February, with a shutdown of 176 minutes for field test 2, and 211 minutes for field test 3.

6.2.1 Measurement data - field test 2

Measured temperatures for the four points T_s, T_{cp}, T_{co} and T_v for the 176 minutes of cooling are presented in Table 5. The start time for the temperature decline in the measuring points are with a time lag due to different thermal diffusivity of the involved materials and follows the same principle as for field test 1.

Table 5. Temperature data from field test 2. There are time lags between measured T_s, T_{co}, and T_v due to the heat capacity of the insulation material, thus ΔT for each temperature measurement is calculated after 110 min. Supply temperature data from DH plant prior cooling is received from the energy company (Bjurman, 2019).

Time (min)	Supply temp max-min (°C)	Ambient air (°C)	T_s (°C)	T_{cp} (°C)	T_{co} (°C)	T_v (°C)
-120 Prior	92.30-93.40	-1.00	-	-	-	-
0 (start)	-	-0.50	89.70	6.90	70.70	73.50
10	-	-0.50	89.60	7.00	70.70	73.50
75	-	-0.50	88.50	7.10	70.55	73.50
100	-	0.00	88.40	7.20	70.40	73.40
176 (end)	-	0.00	88.00	7.20	70.20	73.15
186	-	-	-	-	-	73.10
ΔT (°C) 110 min	-	-	1.30	0.30	0.35	0.40

6.2.2 Measurement data - field test 3

Measured temperatures for the four points T_s, T_{cp}, T_{co} and T_v for the 211 minutes of cooling are presented in Table 6, with time lags as for tests 1 and 2.

Table 6. Temperature data from field test 3. There are time lags between measured T_s, T_{co}, and T_v due to the heat capacity of the insulation material, thus ΔT for each temperature measurement is calculated after 175 min. Supply temperature data from DH plant prior cooling is received from the energy company (Bjurman, 2019).

Time (min)	Supply temp max-min (°C)	Ambient air (°C)	T_s (°C)	T_{cp} (°C)	T_{co} (°C)	T_v (°C)
-120 Prior	93.7-94.4*	-2.3	90.20	6.50	70.70	85.00
0 (start)	-	-2.5	90.85	6.60	71.26	85.00
10	-	-2.5	90.70	6.60	71.26	85.10
75	-	-2.6	89.70	6.50	71.05	85.60
175	-	-2.6	89.30	6.60	70.80	85.10
211 (end)	-	-2.6	89.10	6.60	70.65	85.00
250	-	-	-	-	-	84.90
ΔT (°C) 175min	-	-	1.55	0.10	0.50	0.70

* -120 min – 0 min

7 Calculation of thermal conductivity

Heat losses are higher during the cooling phase at the measuring point in the pipe at an excavation, compared to the parts which are covered by soil. Hence, the measured service pipe temperature was lower than the temperature of the network under ground during the cooling phase. However, the service pipe temperature T_{S1} (K) in the excavation prior shutdown, was expected to be equal to the rest of the network under assessment. It can be assumed that the temperature decrease of a valve represents the cooling of the whole service pipe length more accurately. Therefore, a measured temperature of the valve during cooling was adjusted according to Eqs. 22-23, in which the unknown service pipe temperature T_{s2} after cooling was calculated.

$$\frac{T_{v1}-T_a}{T_{s1}-T_a} = \frac{T_{v2}-T_a}{T_{s2}-T_a} = P \qquad (22)$$

$$=> \quad T_{v2} - T_a = P(T_{s2} - T_a) \quad => \quad \frac{P \cdot T_a + (T_{v2} - T_a)}{P} = T_{s2}$$

$$\Delta T_S = T_{S1} - T_{S2} \qquad (23)$$

in which T_{V1} (K) is the valve temperature before cooling, T_{V2} (K) is the valve temperature after cooling, T_a (K) is the ambient temperature, P (%) is the percentual difference, and ΔT_S (K) is the adjusted temperature decline of the service pipe.

The requirements in standard SS-EN253 refer to a thermal conductivity of the PUR at 50 °C. Thus, the calculated thermal conductivities at other temperatures than 50 °C were adjusted according to Eq. 24 for better comparison (Olsen et al., 2008, Adl-Zarrabi, 2005).

$$\lambda_T = \lambda_{50} + 0.00016(T - 50) \qquad (24)$$

in which λ_T (W/mK) is the thermal conductivity, λ_{50} is the thermal conductivity at 50 °C, and T (K) is the temperature.

7.1 Thermal conductivity results

The results from the LSA are presented as thermal conductivities for alternatives 1 and 2, see Table 7. The results from field tests 2 and 3 with alternative 2 are marked in bold since they indicate reasonable thermal conductivities. In alternative 1, the copper wire distance was set to 21 mm from service pipe, which has a great impact on the resulting thermal conductivity. Results for alternative 1 represent the thermal conductivity of the insulation between copper wires and service pipe. The thermal conductivity for alternative 2 represents the whole part, from casing pipe to service pipe. The reason for the high thermal conductivities in field test 1 is due to the unadjusted service pipe temperature.

Table 7. Thermal conductivity results calculated according to the LSA. Copper wire distance 21 mm from service pipe has been used for alternative 1.

	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**

The calculations according to LT is currently limited to alternative 2, with no copper wire temperature, since the equation only includes one temperature point (Eq. 18). Thus, only the service pipe temperature with the known heat flow from the measured temperature decline in water was used for calculation of the thermal conductivity. The result presented in Fig. 14 is from field test 3.

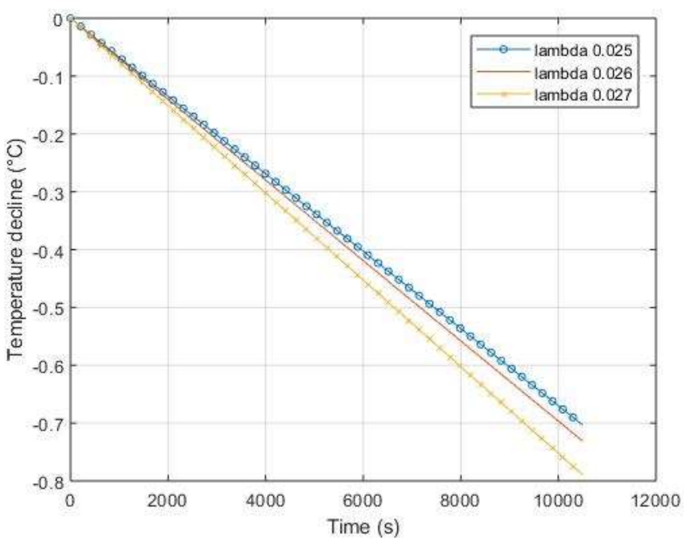

Fig. 14. Calculated service pipe temperature decline during cooling in field test 3. Thermal conductivity result was obtained by solving the transit differential equation by LT. The presented result is for thermal conductivity at 58 °C.

The calculated thermal conductivity of 0.025 W/mK results in a temperature decline in service pipe of 0.7 °C, comparable to the decline in the valve. A slightly higher temperature decline, 0.74 °C, is calculated when the adjustment according to Eq. 22-23 is used. Thus, the thermal conductivity of 0.026 is assessed to be a better match with the true temperature decline in the service pipe, see Fig. 14.

8 Discussion

The cooling method under development shows good potential to meet the aim of the project, and it can be a future tool for the network owners. As with all methods there are uncertainties that need to be addressed and handled. This chapter highlights the main uncertainties that have been identified. Some are only present for a specific condition or alternative, but there are also uncertainties that exist for all six alternatives.

The accuracy of the calculated thermal conductivities in alternative 1 and 2, depend on the uncertainties of the temperature measurements, but also the assumptions and simplifications made in the equations.

The possibility to measure temperatures at several points is a key to performing a thermal assessment with high accuracy. However, as in condition 1 (excavated pipe), other uncertainties, such as increased heat losses, will arise even though the accessibility to measurements on the pipe increase.

8.1 Heat losses in condition 1, excavated pipes

When pipes are excavated, as in condition 1, there is normally a low flow in the pipe, circulating through a small bypass pipe. The majority or all customers are temporarily disconnected, so there is no need for a high flow. This affects the temperature levels on the assessed pipe compared to outgoing supply temperature from the DH plant. For field tests 2 and 3, in which the assessed network was only 100 m from the DH plant, the low flow resulted in a media water temperature 4 °C below outgoing supply temperature. In addition, the excavated part of the pipe is a thermal bridge, by its connection to ambient air.

While there is a 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 for the whole pipe under assessment. However, at shutdown, heat losses increase at the exposed end, in comparison to the buried pipe under ground, which makes temperature measurements uncertain. The excavated and exposed pipe end will cause a buoyancy effect, i.e. natural convection in water due to the temperature caused density differences, which will have an impact on the total temperature decline of the pipe. Its effect, which will be analyzed in the future work of this method, can be calculated if the exposed end is seen as a thermal bridge. How large this effect will be, depends on the temperature difference between the exposed pipe and ambient air, and the proportion of excavated pipe out of total length of buried pipe.

8.2 Accuracy of insulated and uninsulated measuring points

Insulating the valve affects the absolute temperature and the accuracy. The valve measurements from field test 2 (uninsulated) and field test 3 (insulated) show large differences in R-squared values, which implies that high fluctuations, due to heat convection in the air, take place at valve surface and make uninsulated valve measurements uncertain, see Fig. 15.

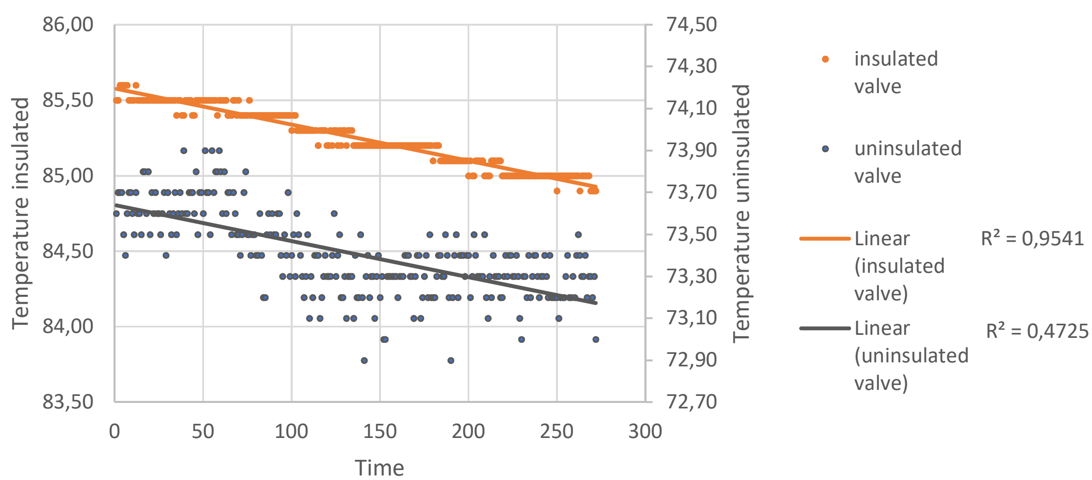

Fig. 15. Comparison of insulated and uninsulated valve measurements.

Insulating the thermocouples, and also crocodile clamps at copper wire connections, reduces the spread in measurement data, i.e. provides higher accuracy. Thus, in future measurements the measuring points will be insulated with mineral wool.

8.3 Time lag due to thermal diffusivity

The start time for temperature decline at the measuring point at the top part of the valve (see Fig. 5 in chapter 3.3) is governed by the thermal diffusivity and length of the valve, and heat convection in the water within the valve. The measured temperature on the valve clearly shows that a temperature decline does not occur at shutdown 11:31, see Fig. 16.

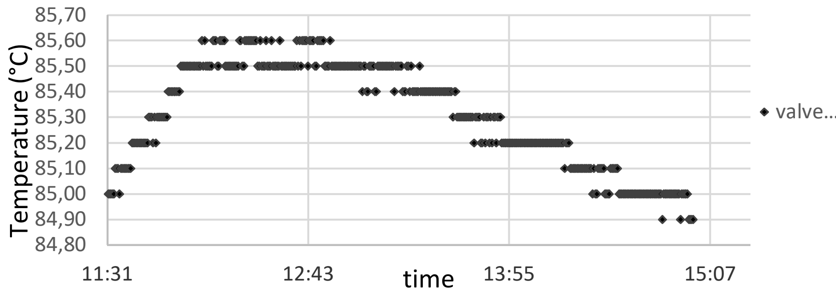

Fig. 16. Valve temperature during cooling of test 3. Shutdown started at 11:31. A temperature rise in the media water of 0.65 °C took place prior shutdown. Thus, the decline started first at approximately 12:45, indicating a time lag of 75 minutes.

120 minutes prior shutdown there was a temperature increase of 0.65 °C in media water from the DH plant, which can also be seen in the valve and copper wire measurements, see Table 6. The temperature decline starts first at approximately 12:45 at the valve measuring point, even though the start time is hard to read from the graph. This implies that the response time is 75 minutes. The response time can also be calculated by Eq. 21. Assuming a valve height of 720 mm and thermal diffusivity of $4.1 \cdot 10^{-5}$ m^2/s, and calculating the duration for the total heat front to reach the measuring point, gives a response time of 120 minutes. This would result in a start time for temperature decline at 13:31. However, this calculation does not consider the convective heat transfer within the water in the valve, which is due to the colder top part of the valve. The convective heat transfer would lead to a faster heat flow from the warmer underlying media water up to the measuring point, hence reducing the response time.

8.4 Copper wire distance from service pipe

The copper wire distance from the service pipe has a great impact on its 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 (alternative 1), 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 chapter 3.1.1, 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 manufacturers declared value for new pipes (0.026 W/mK). However, knowledge of the temperatures T_s, T_{co} and T_{cp} during steady-state conditions, gives the mean position of the copper wires within the insulation. For the field tests presented in this thesis, all three temperatures were known, hence the copper wire can be positioned. If the measured steady-state temperatures T_s, T_{co} and T_{cp} are used, the copper wire distance in field test 2 is positioned to 23 mm, as shown in Fig. 17. The thermal conductivity will then be calculated to 0.0250 W/mK, i.e. 4% below 0.026 W/mK.

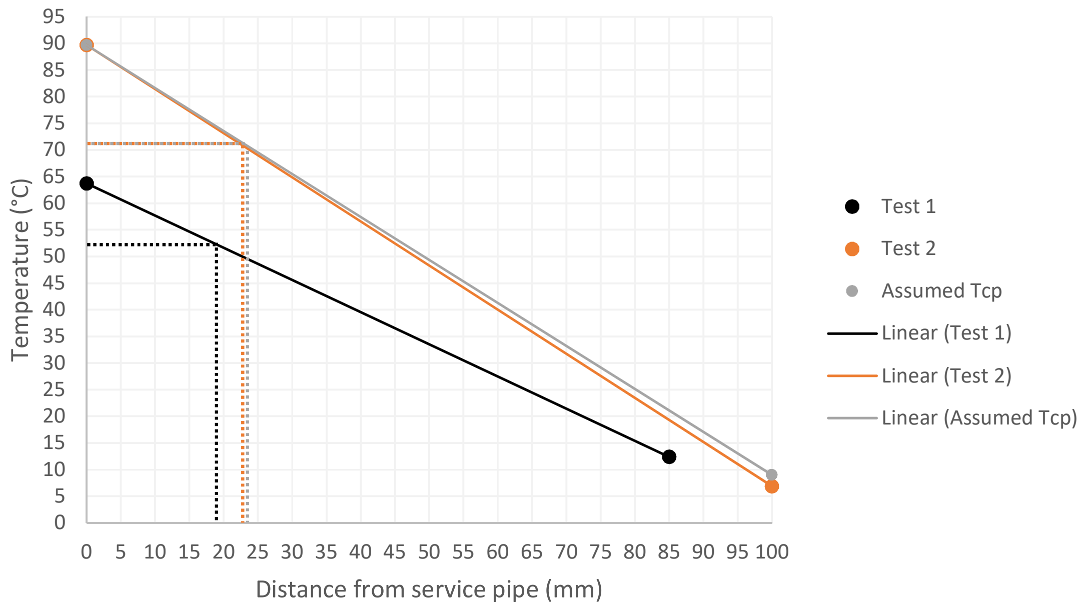

Fig. 17. Temperature gradients across the insulation at time 0 with steady-state conditions for field tests 1 and 2. Measured temperatures for T_s, T_{cp} and T_{co}. Mean copper wire distances from the service pipes are illustrated with dotted lines, 19 mm for field test 1 and 23 mm for field test 2. Furthermore, a grey line is presented to show an unknown and assumed gradient, if T_{cp} in field test 2 is assumed to 9 °C, rather than the measured 6.6 °C.

This shows that the three temperatures are very valuable for positioning the copper wire. However, T_{cp} might not be accessible, and if this is the case, knowledge of soil temperature might give sufficient accuracy. The temperature of the upper soil layer above the pipe will not differ much from the actual T_{cp}. Now assume that the actual T_{cp} (6.6 °C) was unknown in field test 2, and instead the soil temperature 20 cm below surface was measured to e.g. 9 °C. Assuming T_{cp} is also 9 °C results in a copper wire position of 23.5 mm from service pipe. The thermal conductivity is then calculated to 0.0256 W/mK, which is close to 0.0250 W/mK, that was calculated with the knowledge of the real T_{cp}. This shows that even if the soil temperature differs several degrees from the true T_{cp}, copper wire positioning with steady-state condition will give higher accuracy than the position assumed in the field tests.

8.5 Shutdown duration

A shutdown of less than two hours has been proven to be sufficient for assessing the thermal status of a network. The shutdown may be shorter for pipe dimensions less than the ones analyzed in this thesis. However, a short shutdown time demand equipment with high accuracy and resolution. The optimal duration of a shutdown can be decided by balancing the consequences for the customers of the shutdown and the desired accuracy.

8.6 Determining thermal conductivity: uncertainties and possibilities

Calculations for determination of thermal conductivities conducted according to the LSA are assessed to be more accurate compared to calculations conducted according to LT. In calculations according to LT, the inner boundary T_s is known but the outer boundary is not. However, in calculations according to LSA, the inner and outer boundaries are known. In calculations with LSA, both the service pipe temperature and copper wire temperature are included in the calculations. However, the heat capacity of insulation material is not taken into consideration.

The mathematical analysis, according to LT, needs to be further calibrated by field measurements. It can be done if thermal conductivity of a sample of a pipe which is assessed in the field also is measured at laboratory by guarded hot pipe method.

In the measurement result presented in chapter 7.1, the thermal conductivity, according to LT, was set to be 0.026 (based on λ for new pipes) in order to match the decline of 0.74 °C. With knowledge of the heat flow (J/s) for a specific thermal conductivity, the service pipe volume, and the shutdown time, new calculations can be made for an assessment of another pipe in the field. In future field tests the temperature decline can be measured, and the thermal conductivity matching that decline can be calculated.

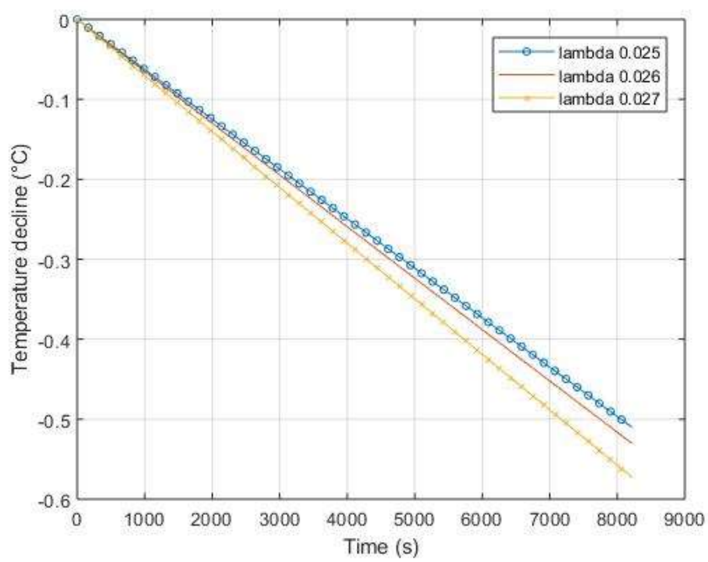

Fig. 18. Temperature decline in service pipe in field test 1. Calculated with the basis of results from field test 2.

The temperature decline in service pipe in field test 1 was not representative (2.1 °C), since it was from the measurement in the excavation. However, Fig. 18 shows what the temperature decline would be at a certain conductivity.

9 Further research

The future work for further development of the method includes a sensitivity analysis, by repeated field tests, in which also the mathematical analysis will be modified. The field tests will be conducted in a structured manner with repeated tests at each location. All six alternative set-ups from the three conditions are planned to be conducted. It will cover and reduce the uncertainties related to:

- Time lag – The temperature declines in the copper wire and the valve will be evaluated, focusing on the influence of the heat capacity in insulation material (PUR), and convective heat transfer.

- Determination of copper wire position – Different dimensions of pipes will be assessed, and temperature measurements of soil will be included in all coming field tests.

- Accuracy of valve temperature – Results have shown the possibilities and uncertainties for using the valve as an indirect measurement of the service pipe temperature. The uncertainties will be quantified and implemented in the mathematical analysis.

- Validation – If pipes shall be replaced, they can be brought to laboratory after a field assessment. The measured thermal conductivity by the modified cooling method can be validated by comparing measured thermal conductivity in laboratory by guarded hot pipe analysis.

- Network assessment – Study the impact of secondary pipes, which can be connected to the main pipe under assessment.

- Shutdown duration – The method aims at being an easy tool for network owners to implement as a status assessment. Thus, the required duration of a shutdown will be further evaluated, since it will have an impact on the future implementation of the method by the users.

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