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Development of a Non-destructive Testing Method for Assessing Thermal Status of District Heating Pipes

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Abstract

Pre-insulated district heating (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 and mechanical aging, which leads to higher heat energy losses. A non-destructive method based on a cooling method is under development for assessing the thermal performance of a DH network. 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 temperature at the position of the copper wire. The method involves a shutdown of a selected part of a network for less than 2 h and evaluating the cooling process by measuring the supply pipe temperature and the temperature of the copper wire. The method was applied in a DH network during heating season. The thermal conductivity calculated by the method [0.027 W/(m K)] was in good agreement with the reference value [0.026 W/(m K)]. The cooling of the network can be measured at a valve or at other more easily accessible steel parts. It was also shown that the method is applicable for DH networks without a copper wire. However, a temperature measurement is needed on the casing pipe.

Keywords District heating network · Non-destructive testing · Cooling method · Copper wire · Thermal status · Polyurethane

1 Introduction

DH networks have been used for decades and the usage increased substantially in the 1960s in the US and Europe. The pipe types that have been used varies, but polyurethane (PUR) insulated single pipes are very common [1]. The energy companies can measure what they produce in heat energy and what they deliver to costumers, thus the heat losses for the whole network can be determined. In Sweden, around 10% of the energy supplied to the DH networks are lost through heat losses from the distribution pipes [2], where aging and degradation of the PUR increases the heat losses [3].

A typical rigid DH pipe in the Swedish DH network consists of an inner service pipe of steel and an outer casing pipe of polyethylene (PE). Between the steel service pipe and outer casing there is a gas-filled closed cell PUR insulation and two thin (1.5 mm²) soft copper wires are embedded

in the insulation for detection of water leakage. In production of DH pipes, mounting distances are used for centering a service pipe into a casing pipe. The copper wires run through the mounting distances either 15–18 mm or 36–39 mm from the service pipe [4].

Cyclopentane and carbon dioxide are used as the low conductive gases in the cells. Thermal aging and degradation of the PUR insulation take place due to high temperatures in the service pipe and diffusion of gases through the PE-casing pipe [3]. In this process, oxygen and nitrogen molecules in ambient air penetrate into the PUR and replace the blowing agent gases [5].

Many energy companies need to renew their DH-networks. Thermography is used by energy companies for detection of heat and water losses, mainly during the winter periods. However, the thermal status of pipe insulation cannot be assessed with high resolution. Thus, there is a lack of a suitable non-destructive method for assessing the thermal performance of a network. A literature study was conducted to identify a non-destructive method [6]. The study highlighted Raman spectrometry and time domain reflectometry (TDR) to have high potential for assessment of a DH-network. However, the accuracy of these methods for assessment of a DH-network is inadequate since no thermal

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assessment is possible. The TDR is currently applied on the DH pipes for detection of water leakage and it is based on resistance measurements between the service pipe and the copper wires. The measured electrical resistance indicates whether moisture is present in the insulation.

A cooling method was proposed by the authors of this paper as a potential non-destructive method for assessing the thermal behavior of a DH-network [7]. The cooling method, previously developed for flexible pipes in a laboratory environment by Reidhav [8], is based on a temporary shutdown of a part of the pipe network while the cooling process is registered by temperature sensors on the casing pipe and the supply pipe. The cooling method was evaluated by the authors of this paper on a mineral wool insulated rigid service pipe in a controlled environment. Furthermore, the possibility of using the existing copper wire as a temperature sensor instead of using the temperature of casing pipe, suggested by Reidhav [8], were investigated [9]. The temperature decreases at the service pipe and the casing pipe were measured during the cooling process and the thermal conductivity was thereafter calculated. Steady state thermal condition in the water and the insulation material was required before starting the cooling phase. By measuring time and temperature decrease, the heat losses and the overall thermal conductivity of the pipe can be calculated by Eqs. (1–4) [10]. Total heat capacity of the water (C_{water}) 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.

$$T_t = T_1 + (T_0 - T_1) * e^{-\frac{t}{t_c}} \quad t > 0 \quad (1)$$

$$t_c = \frac{C}{G} \quad (2)$$

$$C_{\text{water}} = \rho * c * V \quad (3)$$

$$G = \frac{2 * \pi * \lambda * L}{\ln\left(\frac{r_2}{r_1}\right)} \quad (4)$$

where T_t (K) is service pipe temperature at $t > 0$, T_1 (K) is casing pipe temperature at t_0 , T_0 (K) is service pipe temperature at t_0 , t (s) is time, t_c (s) is the intrinsic time-scale of the lumped system, G (W/K) is the thermal conductance of the whole pipe, $\rho * c * V$ (J/K) is total heat capacity of water, λ (W/(m K)) is the overall thermal conductivity of the pipe, L (m) is pipe length, r_2 (m) is the casing pipe radius and r_1 (m) is the service pipe radius.

The result of evaluation indicated that it is possible to determine the thermal conductivity of the insulation material [9]. However, the cooling method cannot be directly implemented for a DH-network due to lack of the temperature sensors on the casing pipe.

Generally, implementation of the cooling method needs knowledge about two temperatures i.e. supply temperature and temperature of an arbitrary position over the cross section of a pipe. In a DH-network the supply temperature is measured by energy companies and the temperature of an arbitrary position can be the position of the copper wire embedded in PUR insulation as described in [7]. The temperature at the position of the copper wire can be determined by measuring the electrical resistance of the copper wire. The electrical resistance is a linear function of the temperature, T , as expressed in Eq. (5) [11].

$$R_T = R_{T_0}(1 + \alpha(T - T_0)) \quad (5)$$

where R_T (Ohm) is resistance at the temperature of interest, R_{T_0} (Ohm) is resistance at reference temperature, T_0 (K) is a reference temperature, $(1/K)$ is the temperature coefficient of resistivity and T (K) is temperature of interest. Electrical resistivity of the soft copper wire is 0.01130 (ohm m) at 20 °C (T_0) [4, 12] and the temperature coefficient of resistance, α_{copper} is 3.93×10^{-3} (1/K) [12].

The purpose of this paper is to present the results and analyses obtained by utilizing a cooling method, based on temperature measurements with the copper wire, for assessment of the thermal performance of a DH-network in operation.

2 Field Measurement of a DH-Network

The modified cooling method was implemented in selected parts of Falun and Mölndal DH-network. Three experiments were performed, and the setup was refined after each experiment, i.e. by adding insulation on a valve and minor repositioning of thermocouples (TC). The measurements were performed during heating season, Dec 2018–Feb 2019. The final setup was applied on the DH-network of Falun.

2.1 Pipe Network and Measurement Setup

The measurement was carried out on a 496 m newly installed pipe network, which mainly consisted of dimension DN350/560 (350 mm in diameter of steel pipe/560 mm in diameter of casing pipe). The studied part of the DH-network (A–D) is presented in Fig. 1. Point A and B represent the position of the valves. The length of pipe section C is 55 m. The dimension of the pipe in the middle of section C was changed from DN125/450 to DN100/355. The copper wire length was 992 m (496×2) measured by an eco-pulse instrument. The network (A–D) was connected to the main network (E).

The energy company planned to add a new connection in point A and the area around point A was already excavated. The excavation created the opportunity to perform additional

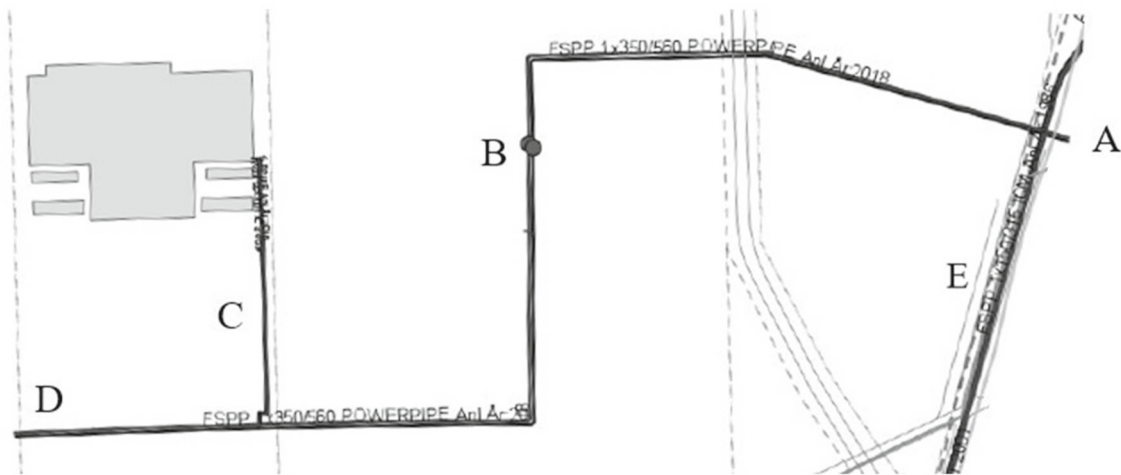


Fig. 1 DH-network (A–D) for field experiment. Point A and B represent the position of valves, section C represents a smaller dimension of the pipe included in the experiment, point D is currently the end of the small network and E is a part of the larger main network

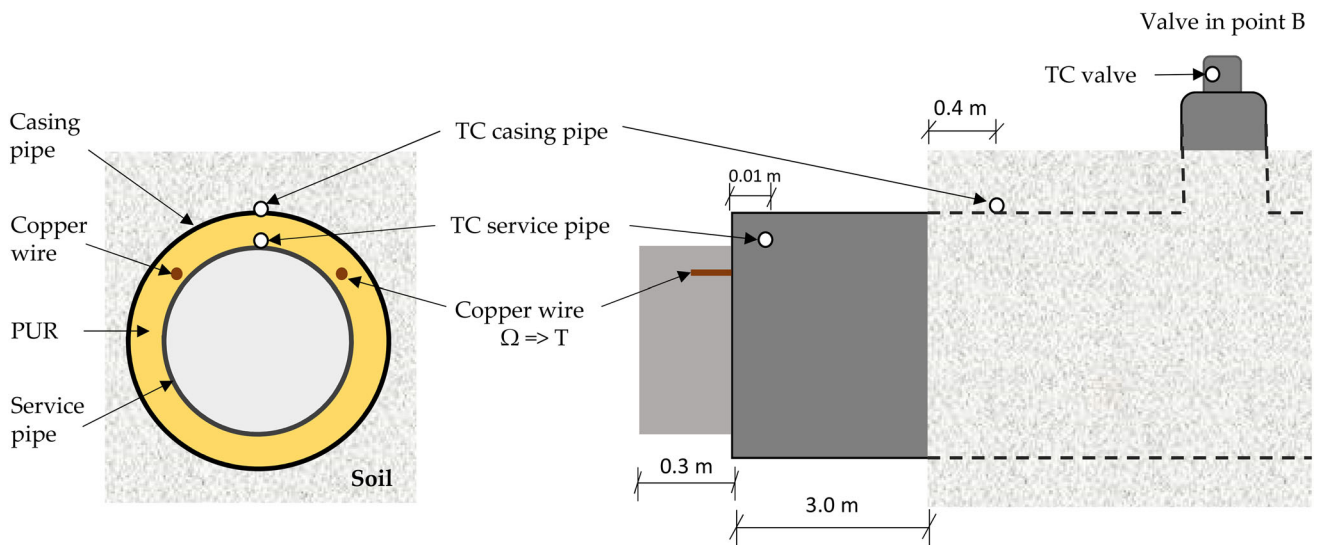


Fig. 2 Illustration of measurement set-up at the excavation (point A in the network). The temperature measurements were conducted with thermocouples (type K), for service pipe (placed 0.01 m inside the PUR, on top of the service pipe), on the casing pipe under soil for sensitivity

analysis (inserted 0.4 m from the side), on the copper wire (indirectly by measurement of electrical resistance with a multimeter) and at a valve (point B in the network)

temperature measurements with TCs i.e. the temperature of the supply pipe (instead of supply pipe temperature collected by the energy company) and the temperature of the casing pipe. Furthermore, the temperature of a valve in point B could be measured.

The temperature measurements were carried out at the excavation in the end of the network, point A, by type K thermocouples. The network (A–D) was located 0.51 m below ground surface, covered with soil. The soil material which covered the network was removed in position A for 3.0 m towards point B, see Fig. 2. The service pipe temperature was measured 0.01 m inside the PUR on top of the service

pipe. The temperature of the casing pipe was measured by a TC inserted in the soil 0.4 m along the casing. The temperature of a steel valve in point B was also measured (200 m from point A), by adding a TC directly on the lower parts of the steel and covering it with insulation. The electrical resistance of the copper wire was measured at the two wire ends in point A. The positions of all TCs are shown in Fig. 2.

The measured temperature of the service pipe at the excavation during the cooling phase should be lower than the rest of the network (A–D) since the end part of the service pipe (about 0.3 m) was insulated by mineral wool and three meters of the covering soil material was removed.

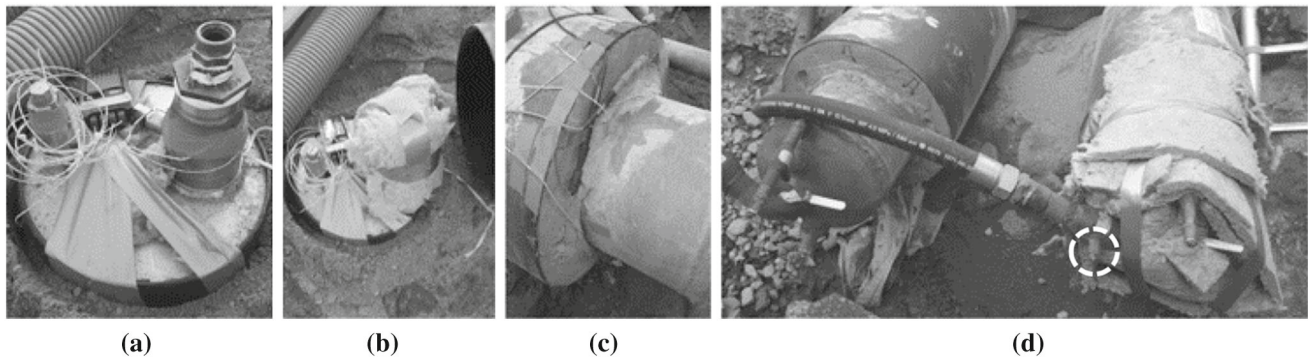


Fig. 3 **a** Valve at point B with thermocouples; **b** the same valve after insulation with mineral wool; **c** the service pipe at the excavation with thermocouples and crocodile clamps on the ends of the copper wire,

connected to a multimeter; **d** the same pipe, to the right in photo, after insulation with mineral wool. White dotted circle shows the valve on the flexible pipe for shutdown

Figure 3 below presents photos (a, b) on the valve at point B and photos (c, d) shows the excavation at point A. Photo (d) also shows the flexible pipe that connected the pipe network (A–D) with the main network (E), a flexible pipe of approximately 20 m.

The temperature distribution over the cross section of a pipe section should be in steady state condition prior to evaluation of a network. The main supply pipe (E) that served network (A–D) had a water temperature of approximately 94 °C, according to data collected by the energy company. Two hours of stable water temperature was enough to achieve a steady state condition prior to performing the cooling experiment. Temperature data for the main supply pipe (E) from the power plant is presented in Fig. 4.

The power plant was located about 100 m from the excavation. The temperature decrease in DH-networks is normally 0.1–0.2 °C per kilometer. Thus, it was expected that the temperature of the service pipe in network (A–D) should be about 94 °C. However, the influence of a 20 m poorly insulated flexible pipe which connected the main supply pipe (E) to the network (A–D) should dominate the temperature difference between the main supply pipe (E) and the network (A–D). The cooling experiment took place on the 28th of February, the valve in point A (Fig. 3d, white dotted circle) was closed at 11:31 and reopened 14:26, thereby a shutdown of 175 min.

3 Results and Analyses

Ambient temperature was recorded during experiment and varied between 0.60 and 2.40 °C. The measured temperature on the casing pipe was unchanged, 6.60 °C, before and after the cooling phase. This means the temperature decrease of the service pipe during the cooling procedure has not reached the casing pipe. Furthermore, the thermal inertia of the soil material can be neglected in Eqs. (1–4).

The temperature of the service pipe in the network (A–D) during the cooling phase (175 min) is shown in Fig. 5. The measured temperature decrease was 1.55 °C (from 90.85 to 89.30 °C).

The electrical resistance of the copper wire was measured to 13.466 (Ohm) before start of the cooling phase, which decreased to 13.446 (Ohm) at the end of the cooling phase, see Fig. 6. The temperature at the position of copper wire was calculated by Eq. (5) to a decrease from 71.26 to 70.85 °C. Unlike the service pipe which is in direct contact with the water, the cooling of the copper wire did not start immediately when the valve was switched off.

3.1 Calculating Thermal Conductivity by Using Temperature Decrease at the End Part of the Service Pipe

Thermal conductivity in insulation between service pipe and copper wire was calculated to 0.069 W/(m K) at 81 °C by using Eqs. (1–4) and approximating quasi steady state condition for T_1 as copper wire temperature. The temperature 81 °C represents the mean temperature between service pipe and copper wire. The calculated thermal conductivity was far from the expected value at this temperature range. The reason was that the measured service pipe temperature at the excavation was not representative for the network (A–D), as mentioned before.

3.2 Comparing Calculated and Measured Temperature of the Copper Wire

The position of the copper wire was expected to be at 16.5 mm, the mean value of 15–18 mm, from service pipe. The temperature of the copper wire was calculated at steady state condition, before starting the cooling experiment, by using the measured temperatures of the casing pipe (6.6 °C)

Fig. 4 Temperature in main supply pipe (E) from power plant, two hours prior to shut down. Data received from power plant

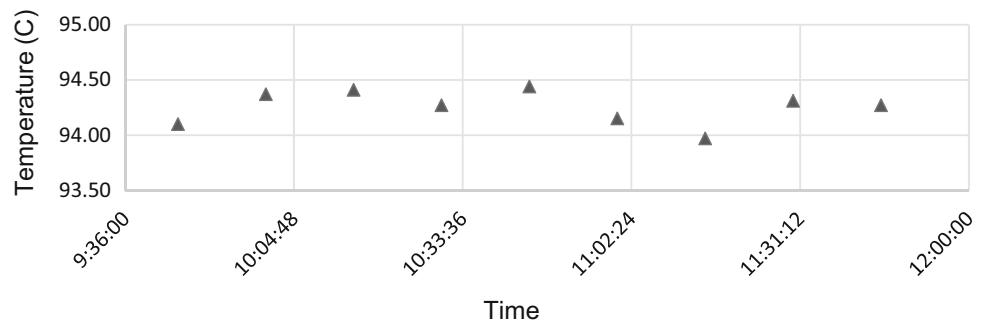


Fig. 5 Measured temperature on the service pipe during cooling phase

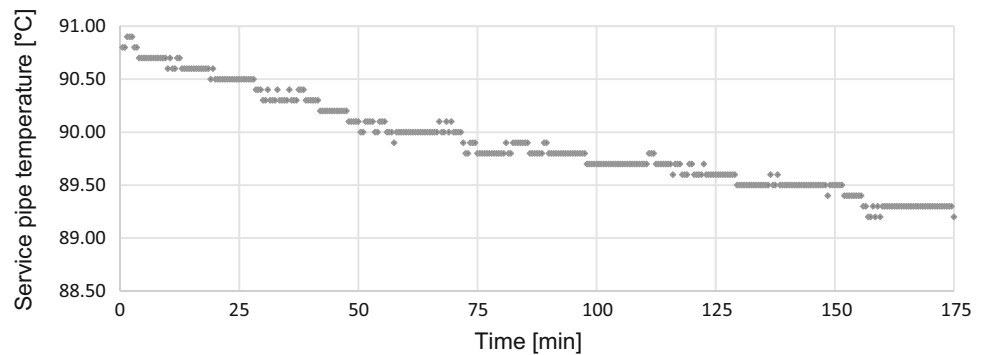


Fig. 6 Decrease of electrical resistance in copper wire during cooling process

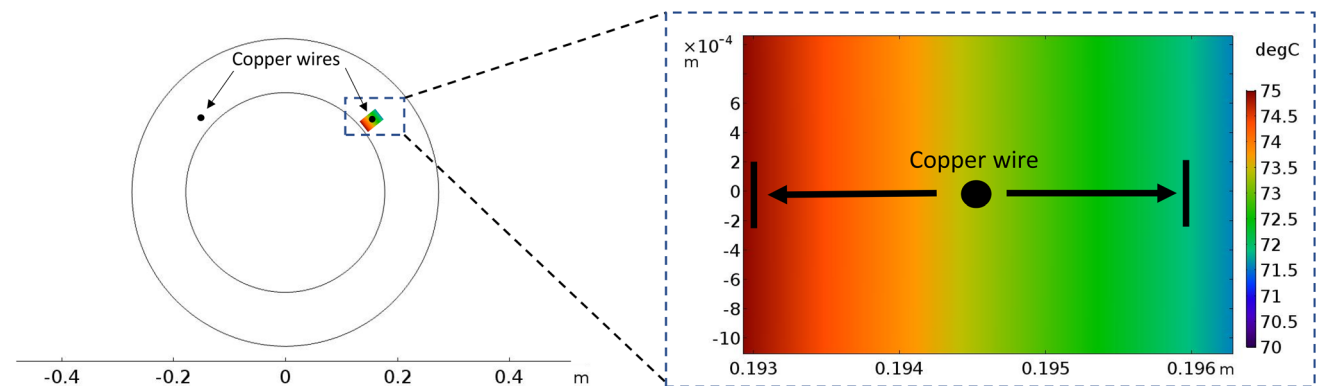
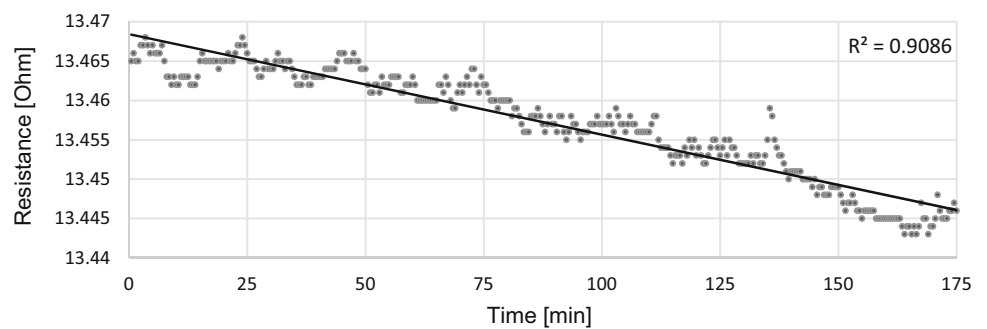


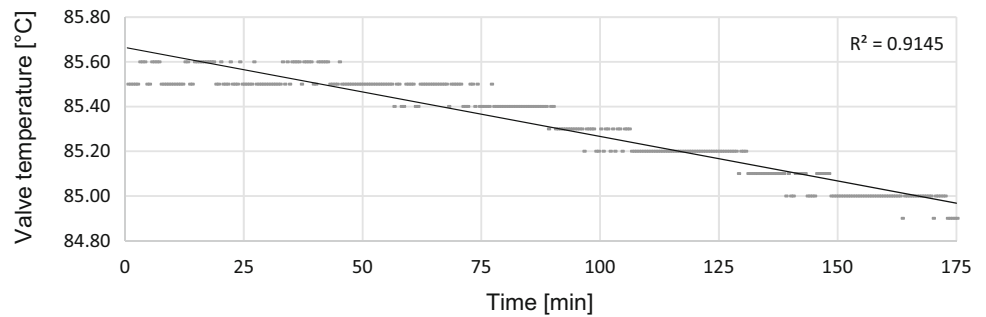
Fig. 7 Calculated temperature profile for position of the copper wire (15–18 mm from the service pipe) when temperature of the service pipe was 90.85 °C and temperature of casing pipe was 6.6 °C. Black dot represents the location of the copper wire at 16.5 mm (distance from the pipe center was 0.1945 m) from service pipe, with a temperature of 73.50 °C at steady state condition

dot represents the location of the copper wire at 16.5 mm (distance from the pipe center was 0.1945 m) from service pipe, with a temperature of 73.50 °C at steady state condition

and the service pipe (90.85 °C) as the boundary condition. The calculated temperature was 73.50 °C at the copper wire position, approximately 2.2 °C higher than measured

(71.26 °C). Assuming the maximum possible distance of the copper wire from the steel service pipe (18 mm), the copper wire temperature was calculated to 71, 80 °C, see Fig. 7.

Fig. 8 Temperature measurement on valve (representing service pipe) during cooling process



3.3 Determination of Thermal Conductivity by Using Temperature Decrease in the Valve

The absolute temperature for the valve in point B decreased from 85.60 to 84.90 °C, a temperature difference of 0.70 °C, see Fig. 8. The thermal diffusivity of steel offsets the cooling phase for the valve by approximately 60 min.

Removal of the soil in the point A leads to higher heat losses at the measuring point than at the parts which were covered by soil. Hence, the measured service pipe temperature was lower than the actual temperature of the service pipe at the network (A–D). Thus, it was assumed that the temperature decrease of the valve in point B represents the cooling of the service pipe more accurately. Therefore, the measured temperature of the service pipe of the network (A–D) after cooling was adjusted according to Eqs. (6–8).

$$\frac{T_{S1} - T_{V1}}{T_{V1}} = P \tag{6}$$

$$(P + 1) * T_{V2} = T_{S2} \tag{7}$$

$$\Delta T = T_{S1} - T_{S2} \tag{8}$$

where T_{S1} (K) is service pipe temperature before cooling, T_{V1} (K) is valve temperature before cooling, P (%) is percentual difference between T_{S1} and T_{V1} , T_{V2} (K) is valve temperature after cooling, T_{S2} (K) is service pipe temperature after cooling and ΔT (K) is adjusted temperature decrease of service pipe.

The adjusted temperature decrease of the service pipe in the network (A–D) was 0.74 °C. The thermal conductivity of the PUR between the service pipe and the copper wire was calculated to 0.031 W/(m K) at 81 °C by using the adjusted temperature decrease. Furthermore, thermal conductivity of the PUR at 50 °C was calculated to 0.027 W/(m K) by using Eq. (9) [13].

$$\lambda_T = \lambda_{50} + 0.00016(T - 50) \tag{9}$$

where λ_T [(W/(m K))] is thermal conductivity, λ_{50} is the thermal conductivity at 50 °C and T (K) is temperature.

3.4 Simplified Sensitivity Analysis

According to the producer of the pipes (PowerPipe systems AB), thermal conductivity at 50 °C of a newly produced pipe should not exceed 0.026 W/(m K) [4]. The cooling method was performed on newly installed pipes. The thermal conductivity calculated at 50 °C by the cooling method, 0.027 W/(m K), is in very good agreement with the declare value of the producer. However, accuracy of the calculated thermal conductivity depends strongly on the position of the copper wire. A sensitivity analysis was conducted where the service pipe temperature prior to cooling (90.85 °C), the measured casing pipe temperature (6.60 °C) and the adjusted temperature decrease in the service pipe (0.74 °C) were used to calculate the overall thermal conductivity of the network (A–D), which was calculated to λ_{50} 0.024 W/(m K). The calculated overall thermal conductivity is 9.4% lower compared to the result obtained by using the measurement temperature of the copper wire at 16.5 mm from service pipe.

The thermal conductivity of PUR at 50 °C was calculated to 0.028 W/(m K) by using the measured temperature of the copper wire (71.26 °C) and assuming the 18 mm distance between the copper wire and the service pipe. This results in a difference of 7% compared to the calculated thermal conductivity with the assumption that the copper wire distance was 16.5 mm from service pipe.

A compilation of all calculated thermal conductivities is presented in Table 1.

The energy loss during the cooling process corresponded to the temperature decrease (ΔT) in the service pipe, which governs the result. The calculated thermal conductivity at 50 °C 0.027 W/(m K) was related to a temperature decrease of 0.7 °C at the valve in point B and adjusted to 0.74 °C by Eqs. (6–8). A temperature decrease of 0.6–0.8 °C would have resulted in a thermal conductivity of 0.020–0.029 W/(m K).

4 Conclusion

A non-destructive method for thermal status assessment of a pipe network is under development. The results obtained by

Table 1 Compilation of calculated thermal conductivities for PUR, at mean temperature for evaluated part of insulation. Together with its corresponding thermal conductivity calculated at 50 °C by Eq. (9)

Evaluated part of the insulation	λ [W/(m K)]	λ_{50} [W/(m K)]
Between service pipe and copper wire ^a	λ_{81} 0.031	0.027
Between service pipe and copper wire ^b	λ_{81} 0.033	0.028
Between service pipe and copper wire ^c	λ_{81} 0.069	0.064
Between service pipe and casing pipe ^d	λ_{49} 0.024	0.024

^a ΔT for copper wire (16.5 mm) and ΔT for service pipe, adjusted by Eqs. (6–8)

^b ΔT for copper wire (18 mm) and ΔT for service pipe, adjusted by Eqs. (6–8)

^c ΔT for copper wire (16.5 mm) and ΔT for service pipe

^d ΔT for casing pipe and ΔT for service pipe, adjusted by Eqs. (6–8)

the non-destructive method indicate that thermal conductivity of degraded PUR insulation can be determined for aged buried pipes, which is an indicator for increased heat losses from the distribution pipes. Furthermore, the measured thermal conductivity can be used for making decisions related to the replacement of the pipe.

Measurement uncertainties indicate that it is possible to improve the accuracy of the method. High precision measurements of the temperature decrease of the service pipe are crucial during cooling phase. However, the absolute temperature is of minor significance. Thus, valves or other more easily accessible steel parts can be used to capture the cooling process.

A shutdown of less than two hours has been proven to be sufficient for evaluating thermal status of the network. The cooling process may be shorter for dimensions less than DN350/560. The present thermal status assessment can be included in regular drift stops during maintenance activities by energy companies in a network.

The accuracy of the method should be further investigated with a comprehensive sensitivity analysis, which include i.e. positioning of copper wires and measurement uncertainty of the devices in use. Further on, when the method is ready, repeated measurements should be performed.

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