Fibre optic and embedded sensing concept for long term monitoring of district heating pipes at the District-LAB Kassel

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Abstract

District heating systems are expected to operate with lower temperatures and a higher share of renewable and volatile heat sources, which increases the need for experimental data on pipe soil interaction and insulation behaviour. This paper presents the concept and realisation of a full-scale district heating test section within the flexible heating grid of the District-LAB at Fraunhofer IEE in Kassel. The measurement setup combines distributed fibre optic temperature sensing on the pipe surface, in the bedding and in the surrounding soil with embedded temperature and humidity sensors in the PUR foam and soil moisture sensors close to the pipes. The paper focuses on the design, installation and initial functional checks of this integrated measurement concept, which provides a platform for future investigations of heat losses, insulation ageing and moisture processes under realistic and dynamic operating conditions.

Introduction

District heating systems consist of heat generation units, distribution grids, and heat consumers. In particular, buried district heating pipe systems in densely populated areas are characterized by high investment costs (AGFW, 2021). This makes them a key leverage point for the politically intended expansion and transformation in the course of decarbonization in Germany and the EU in order to achieve the legally anchored climate protection targets (Deutschland. (2021); European Union. (2021)). Factory pre-insulated pipe systems are the most widely used pipe systems in Germany (AGFW, 2021). Their design and lifetime assessment require detailed knowledge of the thermo-mechanical properties of the pipe assemblies as well as the resulting heat losses. Improved condition monitoring enables an extension of service life and thus an increase in economic and resource efficiency.

In the course of the transformation, district heating systems are expected to be increasingly operated with renewable, often volatile heat sources in the future. It is anticipated that grid temperatures will be progressively reduced and the number of decentralized heat generation units will gradually increase (Lund et al., 2014). In parallel, the use of new pipe materials (e.g. plastics instead of steel), alternative bedding materials and innovative jointing technologies is foreseeable. These changes will have far-reaching impacts on district heating systems.

This work focuses on the thermal interaction between the pipe systems and the surrounding bedding material and their long-term behaviour. The resulting effects on heat losses, insulation ageing and structural integrity can only be predicted to a limited degree and with restricted reliability using conventional, predominantly steady-state models, particularly under dynamic operating conditions (Hay et al., 2025). Against this background, district heating systems are being investigated experimentally in the flexible heating grid of the “District-LAB” experimental facility at Fraunhofer IEE in Kassel (Kallert et al., 2021)but is also put in question. To face these challenges, research on innovative district heating concepts is required like the feed-in of decentralized renewable energy or the design of new modes of operation. Against this background, the new experimental facility District LAB is set up serving as a test and development platform for innovative district heating systems in close cooperation with collaborates from industry and research. By using the facility, it is targeted to investigate the system behaviour of flexible heating networks, to conduct component tests and to develop innovative control concepts for new management strategies. To

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reach these goals the District LAB consists of a flexible heating grid, a pipe test bench for mechanical tests and management respectively control units. This way the possibilities of the already existing facilities are expanded. Compared to tests in real operating district heating grid (demonstration. One focus is on long-term monitoring in the bedding material as well as in the foam region of pipe and joint using fibre-optic distributed temperature sensing in combination with point-wise humidity and temperature sensors. The aim is to capture, by measurement, the influence of reduced operating temperatures and dynamic load profiles on heat losses, ageing processes and service life of the pipe systems, thereby improving the data basis for further investigations.

This paper describes the implemented measurement concept and its installation and presents the results of initial functional tests of the embedded sensors. In terms of its integrated design and density of fibre-optic instrumentation within a district heating test facility, the measurement concept is, to the best of current knowledge, novel. Against this background, the practical experience gained during installation of the measurement system is discussed.

Motivation

To begin with, the influence of ageing-dependent changes in the thermal conductivity of PUR foam on heat losses for an existing heating network with a total length of approx. 13.8 km and a known diameter-length distribution of the pipes is calculated in a motivating manner.

The thermal conductivity of PUR foam is determined by the proportions of solid material, radiation and cell gases, with the cell gases having a significant influence on the overall thermal conductivity. Due to permeation processes, the gases diffuse from the foam cells through the PE coating into the environment over the course of the product's service life. The cell gases originally contained in the foam, such as cyclopentane and carbon dioxide, which have low thermal conductivity, are replaced by ambient atmospheric gases such as oxygen and nitrogen, which have significantly higher thermal conductivity. This leads to a gradual increase in overall thermal conductivity and thus to higher heat losses.

In (Frederiksen & Werner, 2013), the change in thermal conductivity of PUR foam over 30 years is given for some nominal diameters (DN) of the insulation series one. To perform the calculation for the heating network, values for additional DNs are also required. These are determined using linear interpolation. The result is shown in Figure 1. Solid lines are values taken from (Frederiksen & Werner, 2013), while dotted lines are interpolated. It can be seen that the thermal conductivity is identical for all diameters immediately after manufacture and then increases over time. The magnitude of this increase depends on the diameter. A significantly greater increase can be seen for small diameters.

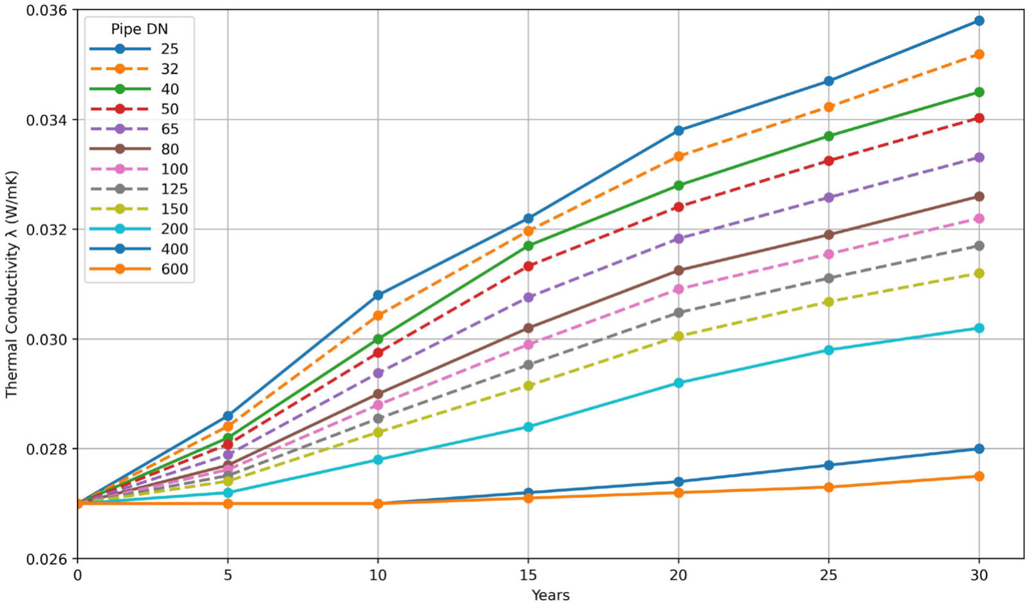

Figure 1: Change in the thermal conductivity of PUR foam over 30 years for insulation series one. Solid lines are taken from (Frederiksen & Werner, 2013); dotted lines are interpolated.

The heat losses $\dot{Q}_{loss}$ of pre-insulated pipe systems are calculated with Equations (1) and Equation (2) (Frederiksen & Werner, 2013, pp. 78–79). The definitions of the used geometric dimensions are shown in Figure 2. In order to perform the calculation, numerical values according to Table 1 are used in addition to the information on the length-diameter distribution in the heating network.

$$\dot{Q}_{loss} = L\pi d \frac{(T_{sup} - T_g) + (T_{ret} - T_g)}{R_i + R_g + R_c} \tag{1}$$

With the length of the pipe L , supply, return and ground temperature T_{sup}, T_{ret} and T_g and the thermal resistances R_i , R_g and R_c which are defined as:

$$R_i = \frac{d}{2\lambda} ln\left(\frac{D}{d}\right), \qquad R_g = \frac{d}{2\lambda_g} ln\left(\frac{4H}{D}\right), \qquad R_c = \frac{d}{2\lambda_g} ln\left(\sqrt{\left(\frac{2H}{s}\right)^2 + 1}\right) \tag{2}$$

with the cover height h, the pipe spacing a and the thermal conductivity of the soil λ_g (see Figure 2).

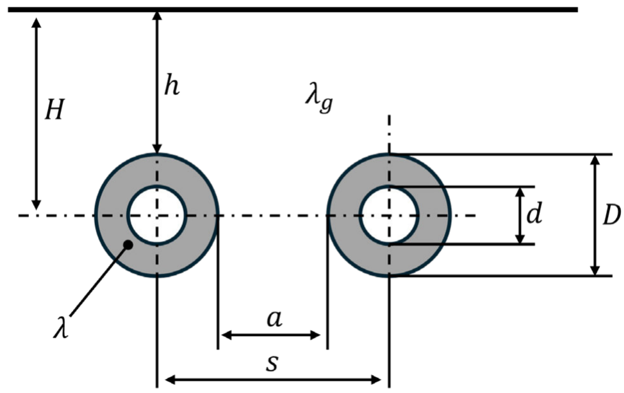

Figure 2: Definition of parameter names for geometry

Parameter	Value
T_{sup} $[°C]$	100
T_{ret} $[°C]$	60
T_g $[°C]$	10
h $[m]$	0.8
a $[m]$	0.2
$\lambda_g [W/mK]$	1.2

Table 1: Numerical values used for the calculation

Figure 3: Network-weighted relative heat loss Increase over time shows the calculated relative heat losses of the district heating system, along with the relative shares of pipe diameters used in the calculation. PUR ageing is represented λ solely R_i by an increase of the thermal conductivity in and all other parameters are kept constant according to Table 1: Numerical values $t = 0$ used for the calculation. Also, it is assumed that all pipes were manufactured at time . This point in time also serves as the reference for the percentage increase in the calculated relative heat losses. The black curve illustrates that, after 30 years, the heat losses increase by approximately 20 %. This increase is well approximated by a linear trend, represented by the red linear fit. The corresponding fit equation indicates that the relative heat losses rise by about 0.7 % per year.

These results suggest that ageing of the PUR insulation leads to a noticeable increase in distribution heat losses over the lifetime of a district heating system and should therefore be taken into account in long-term energetic, environmental, and economic assessments. However, the present calculation is based on a simplified steady-state approach with idealised, temporally constant operating temperatures. In real district heating systems, especially with the increasing integration of volatile renewable heat sources, frequent and sometimes rapid changes in operating conditions are to be expected. Such dynamic temperature variations may affect the ageing behaviour of the PUR foam and thus its effective thermal conductivity, potentially leading to deviations from the quasi-linear trend assumed here. Against this background, more detailed investigations under dynamic boundary conditions, for example using transient simulations or long-term field measurements, appear necessary in order to robustly quantify the impact of volatile operating strategies on the evolution of heat losses. In order to address these limitations and to better understand the coupled thermal and hygric behaviour of pre-insulated district heating pipes under realistic and dynamic operating conditions, the following research questions are formulated, which guide the design of the implemented measurement concept in the District-LAB:

1. To what extent can distributed fibre optic temperature sensing capture asymmetric heat flows, thermal interaction between neighbouring pipes and locally altered heat transfer conditions, for example in expansion sections?
2. How do reduced operating temperatures and more volatile renewable heat inputs affect the ageing behaviour of PUR insulation and its effective thermal conductivity under realistic moisture conditions?
3. How do moisture dynamics in the PUR foam and in the sand bedding evolve over time, and how reliably can embedded humidity sensors and soil moisture sensors detect and quantify these processes?

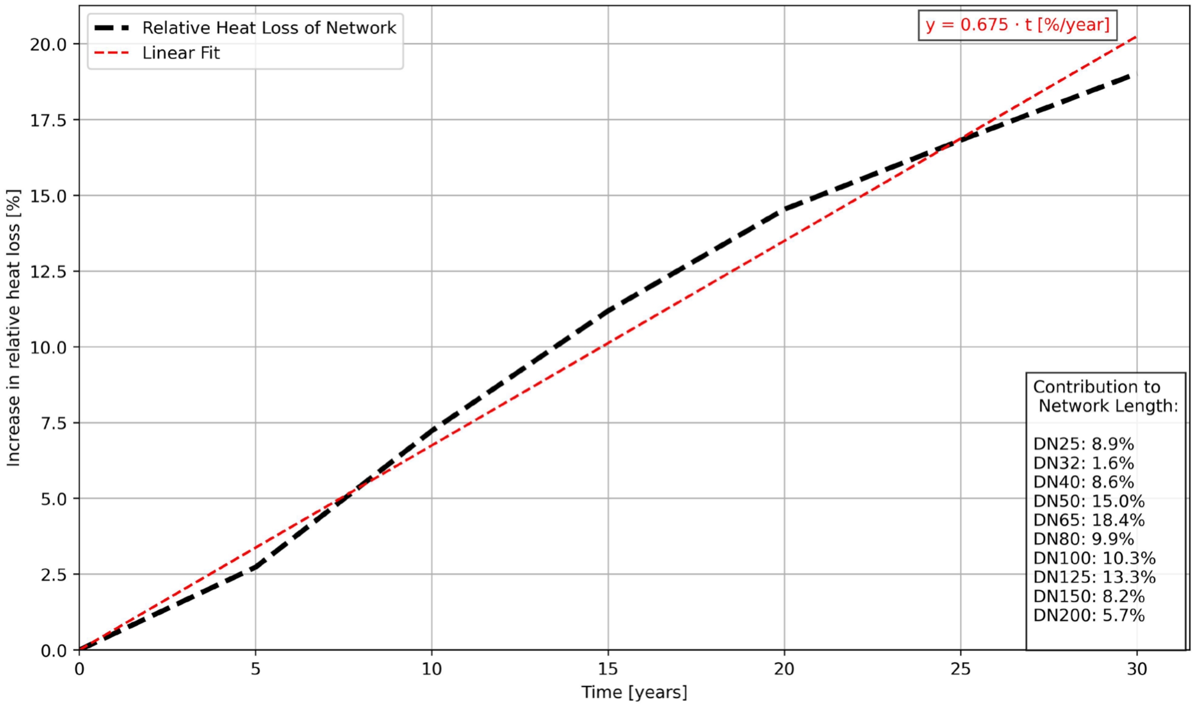

Figure 3: Network-weighted relative heat loss Increase over time

Methodology

Experimental setup/District-LAB

In Figure 4: Aerial view of the District LAB during construction work, with the experimental fields “pipe test bench” (blue) and “flexible heating grid” (green) marked., an aerial view of the District-LAB during the pipe construction work is shown. The test facility comprises two experimental areas: the area highlighted in blue shows the experimental field “pipe test bench”. Here, tests focusing on the interaction between pipelines and bedding material are carried out in close cooperation with the Technical Infrastructure Management group of Prof. Weidlich. Details on the setup and the measurement concept of the pipe test bench can be found in the contribution by Stefan Dollhopf within this “Insights”. The area highlighted in green contains the experimental field “flexible heating grid”, which also includes the long-term experiments discussed in this paper. This is necessary because only for these pipelines operating periods of several years are to be expected.

The flexible heating grid is approximately 35 m long and about 6 m wide and consists of two levels, each with five pipelines arranged in a U-shape. At the end, there is an expansion section with expansion pads. The gaps between the pipes as well as between the two pipe levels are backfilled with sand followed by excavated material. The cover height above the upper pipelines is approximately 0.7 m to ensure the required mechanical and thermal properties. The cross-section of the flexible heating grid is shown in Figure 8: Cross-section of the flexible test grid and route of the fibre-optic measuring cable on the outer pipes. It illustrates further geometrical dimensions of the structure, including the spacing between individual pipes and the vertical distance between the levels. Further details and information can be found in (Kallert et al., 2021)but is also put in question. To face these challenges, research on innovative district heating concepts is required like the feed-in of decentralized renewable energy or the design of new modes of operation. Against this background, the new experimental facility District LAB is set up serving as a test and development platform for innovative district heating systems in close cooperation with collaborates from industry and research. By using the facility, it is targeted to investigate the system behaviour of flexible heating networks, to conduct component tests and to develop innovative control concepts for new management strategies. To reach these goals the District LAB consists of a flexible heating grid, a pipe test bench for mechanical tests and management respectively control units. This way the possibilities of the already existing facilities are expanded. Compared to tests in real operating district heating grid (demonstration.

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Figure 4: Aerial view of the District LAB during construction work, with the experimental fields “pipe test bench” (blue) and “flexible heating grid” (green) marked.

Fibre optic measurement technology

Compared to conventional temperature measurement methods, in which temperatures are measured at specific points on the pipe or in the ground using individual sensors, fibre optic measurement technology enables continuous temperature measurement along the entire length of the laid fibre optic cable. This replaces a large number of individual sensors and allows temperature profiles to be recorded with high spatial resolution both on the outside of the pipes and in the surrounding bedding material. The District-LAB uses the OSSCAD CMS-1022 system with a cable length of 2000 m.

The fibre optic measurement system essentially consists of a fibre optic cable that functions as a linear temperature sensor and an evaluation device equipped with a laser source and optoelectronic detectors. The measuring device injects short laser pulses into the fibre optic cable and detects the light scattered back along the fibre. The temperature as a function of position along the fibre can be determined from the time delay and spectral composition of this backscattered signal. In this way, a continuous temperature profile can be calculated over the entire length of the cable, allowing local temperature changes, leaks or anomalies in the network to be measured.

Figure 5: Course of the fibre optic measuring cable for longitudinal measurement

Figure 5: Course of the fibre optic measuring cable for longitudinal measurement shows the routing of the fibre-optic cable for the longitudinal measurement on the outer pipe in the lower level. The cables follow the U-shape and are installed once at the 12 o'clock position and once at the 6 o'clock position of the outer pipe. No longitudinal measurements are carried out on the four inner pipelines. The same configuration is used for the upper level.

The fibre-optic cable has continuous metre markings printed on it at regular intervals. These can also be seen in the yellow fields. During commissioning of the measurement system, they will be used to subdivide the individual measurement sections.

Figure 6: Installation of the fibre optic cable on the outer pipes

Figure 6: Installation of the fibre optic cable on the outer pipes shows details of the installation of the fibre-optic cable for the longitudinal measurement. The cable is taped to the upper side of the pipe (top left) as well as to the lower side of the pipe (top right). To keep the distance between cable and pipe as small as possible, the cable is also fixed firmly to the pipe at regular intervals using cable ties. This arrangement along the entire length enables continuous acquisition of the pipe surface temperature at the upper and lower edge of the pipe and thus possibly the detection of asymmetric temperature distributions.

Figure 6: Installation of the fibre optic cable on the outer pipes also shows the expansion pads and the routing of the fibre-optic cable in this area. Here, too, the fibre-optic measurement cables are fixed to the upper and lower sides of the pipe casing. Above the measurement cables, expansion pads and mats are installed. The primary function of the expansion pads is to accommodate thermal longitudinal expansion of the pipeline in a controlled manner and to dissipate mechanical stresses. This area is of scientific interest: in contrast to the rest of the pipeline section, the direct contact between the pipe wall and the surrounding sand is missing here, as the expansion pads act as a separating layer. This leads to locally altered heat transfer conditions and the associated temperature gradients along the pipe axis. The aim of using fibre optics in this area is to capture these temperature differences and to use them for a quantitative assessment of heat losses caused by heat accumulation in the expansion section.

In addition to the longitudinal measurements, transverse measurements were also implemented using fibre-optic sensing. The routing of the measurement cable for the transverse measurements is illustrated in Figure 7: Course of the fibre-optic measuring cable during transverse measurement. In the area of the crossings marked in blue, each pipeline is wrapped three times with the measurement cable. This is intended to enable the analysis of both local temperature gradients on the pipe surface and thermal interactions between adjacent pipes. In particular, the differences in temperature distribution between the sections facing neighbouring pipes and the outward-facing pipe sections are to be captured, allowing a more differentiated assessment of the thermal interaction within the pipe bundle.

The areas marked in orange indicate sections where the cable was placed directly on the slope at the interface between the natural soil and the sand bedding. The intention is to obtain comparative temperature measurements in practically unaffected ground. This configuration is identical on the upper and lower pipe levels.

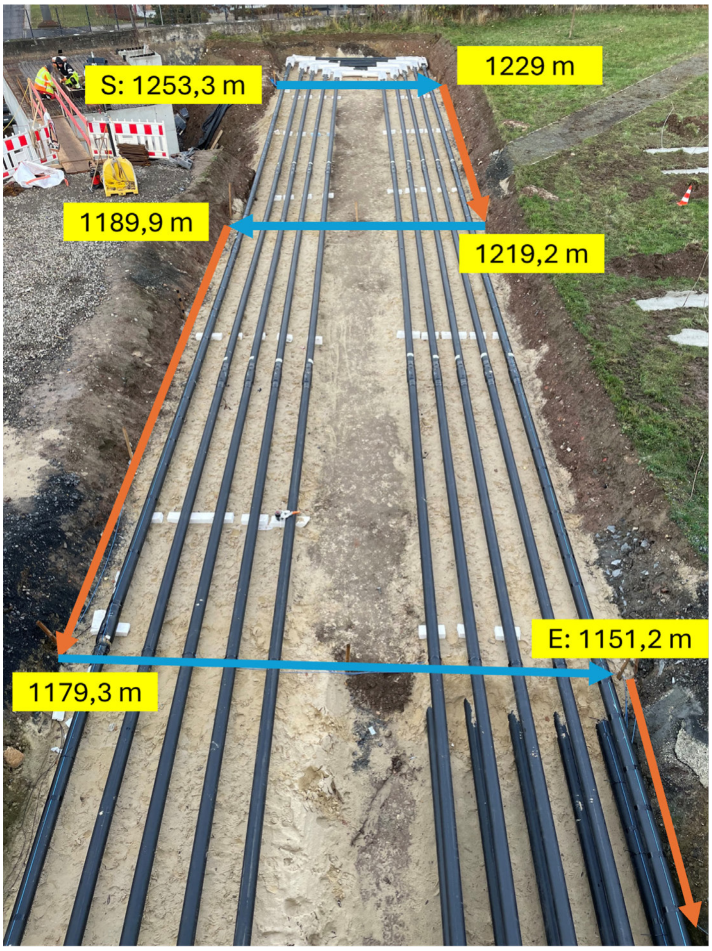

Figure 7: Course of the fibre-optic measuring cable during transverse measurement

The experimental implementation of the described measurement concept for the transverse measurements is shown in Figure 9: Installation of the fibre-optic measuring cable on the pipes by winding it around them and on the slope using wooden pegs.. The figure illustrates the actual routing of the measurement cable, the wrapping around the pipes, and the routing directly along the slope using wooden stakes, as well as its fixation to the pipe by means of adhesive tape and cable ties.

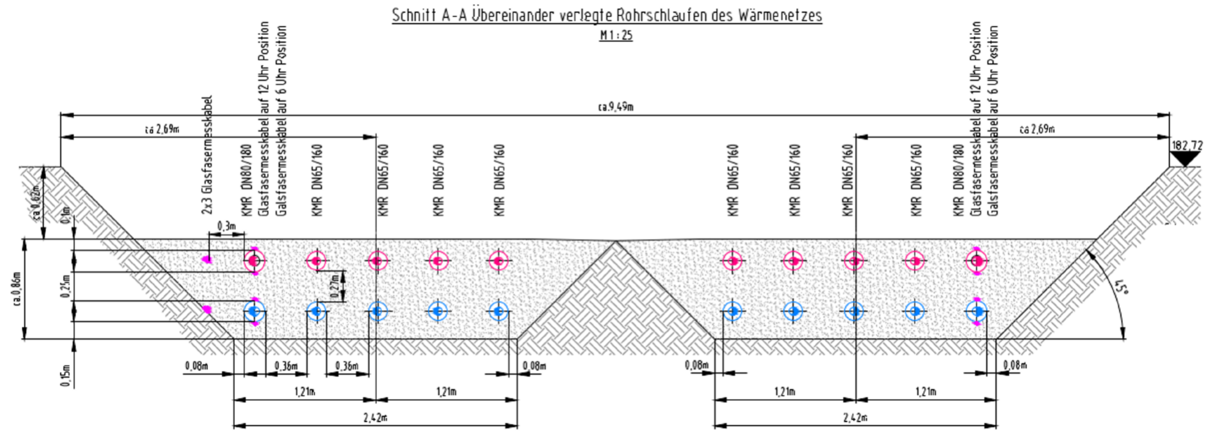

Figure 8: Cross-section of the flexible test grid and route of the fibre-optic measuring cable on the outer pipes

Figure 8: Cross-section of the flexible test grid and route of the fibre-optic measuring cable on the outer pipes shows the cross-section of the structure with the most important geometrical dimensions. The fibre-optic cable installation on the upper and lower sides of the outer pipes, as described above, as well as in the slope area is also illustrated.

Figure 9: Installation of the fibre-optic measuring cable on the pipes by winding it around them and on the slope using wooden pegs.

In addition to the longitudinal and transverse measurements directly on the pipelines, the fibre-optic cable was also installed in the sand bedding midway between the two levels and directly at the interface between sand and natural soil (see Figure 8: Cross-section of the flexible test grid and route of the fibre-optic measuring cable on the outer pipes). The aim of this installation is the continuous recording of thermal effects in the sand that arise as a result of the different temperature conditions in the pipelines. The cable routing geometries used for this purpose are shown in Figure 10 and Figure 11. Figure 10 illustrates the installation between the two pipe levels, and Figure 11 shows the installation at the interface between sand and natural soil.

Figure 10: Cable routing on the level between the pipes

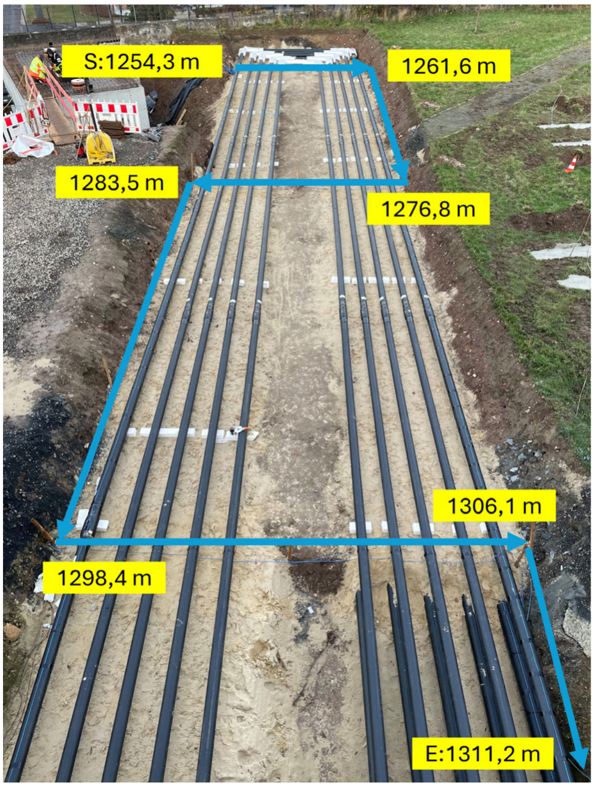

Figure 11: Cable routing at interface between sand and natural soil

Embedded sensors in PUR and joints

Even small amounts of water or moisture in the PUR foam can critically affect the material properties and, in extreme cases, lead to damage of the pipe. For this reason, leakage detection systems are used in district heating pipes in order to localize water ingress in the pipeline network at specific points and thus prevent more extensive damage. The most commonly used system consists of two wires that are foamed into the insulation. If water penetrates into the foam, for example due to a leak, damage to the outer casing, leakage at joints, or diffusion processes, the electrical resistance of the wires changes, enabling the fault to be detected and localized.

However, this system is not suitable for continuous monitoring of changes in the water content within the foam. To capture these changes under operating conditions, more advanced measurement technology is required. For this reason, the flexible test network was additionally equipped with embedded moisture sensors and temperature probes in the foam. In a pre-insulated pipe DN80/160, two sensors were installed before foaming: a PT1000 temperature sensor EU-325-G10000-0 from Driesen + Kern GmbH, positioned approximately 3 m from the pipe end directly on the outside of the carrier pipe, and a DKRF517 sensor from Driesen + Kern GmbH, which can measure both temperature and relative humidity and which was likewise placed at a distance of about 3 m from the pipe end, approximately midway between the outer surface of the steel pipe and the inner surface of the plastic jacket. The installation condition of the sensors is shown in Figure 12: Installation of the humidity and temperature sensor and the surface temperature sensor in the pipe. Figure 13: Sensors foamed into the pipe shows the sensors embedded in the pipe foam.

Figure 12: Installation of the humidity and temperature sensor and the surface temperature sensor in the pipe

Figure 13: Sensors foamed into the pipe

The embedded sensors were tested a few days later in order to verify their functionality. For this purpose, the fully foamed pre-insulated pipe was brought into a heated laboratory hall after spending a cool night outdoors. There, both sensors were connected to a control unit to display and record their output signals. First, a short-term recording was carried out, followed by a second short-term recording after a brief interval. Subsequently, a long-term recording was started. After the long-term recording had been running for some time, an additional sensor for measuring the room temperature was connected. The recorded temporal profiles of temperature and relative humidity are shown in Figure 15: Measurement results of the temperature sensors: PT1000 surface temperature sensor on the carrier pipe (blue), combined temperature and humidity sensor in the middle of the foam (red) and air temperature sensor in the laboratory (yellow) and Figure 16: Measurement results of the relative humidity recorded by the sensor located in the middle of the foam..

An identical setup was implemented during the installation of the joint connection in the area of the first joint, i.e. after the first 6 m of the pipe section that had been prepared with sensors. For routing the sensor cables, a welded nozzle was used. Fibre-optic cable was subsequently also installed in this area. Finally, the nozzle was protected with expansion pads to prevent it from tearing off due to the temperature-induced expansion of the pipe. In the last step, SMT100-10-10000-0 soil moisture sensors from Driesen + Kern GmbH were placed in the sand bedding in the immediate vicinity of the measurements inside the pipe and the joint. This setup is shown in Figure 14: Joint with welded nozzle for routing the sensor cables.

Figure 14: Joint with welded nozzle for routing the sensor cables

Results

Testing of the embedded sensors

The following Figure 15: Measurement results of the temperature sensors: PT1000 surface temperature sensor on the carrier pipe (blue), combined temperature and humidity sensor in the middle of the foam (red) and air temperature sensor in the laboratory (yellow) shows the measured temperature profiles of the embedded sensors and of the test room over a period of approximately 23 hours. Here, blue indicates the PT1000 surface temperature sensor directly on the carrier pipe, red indicates the combined temperature and humidity sensor located in the middle of the foam, and yellow indicates a temperature sensor used to measure the air temperature in the laboratory hall.

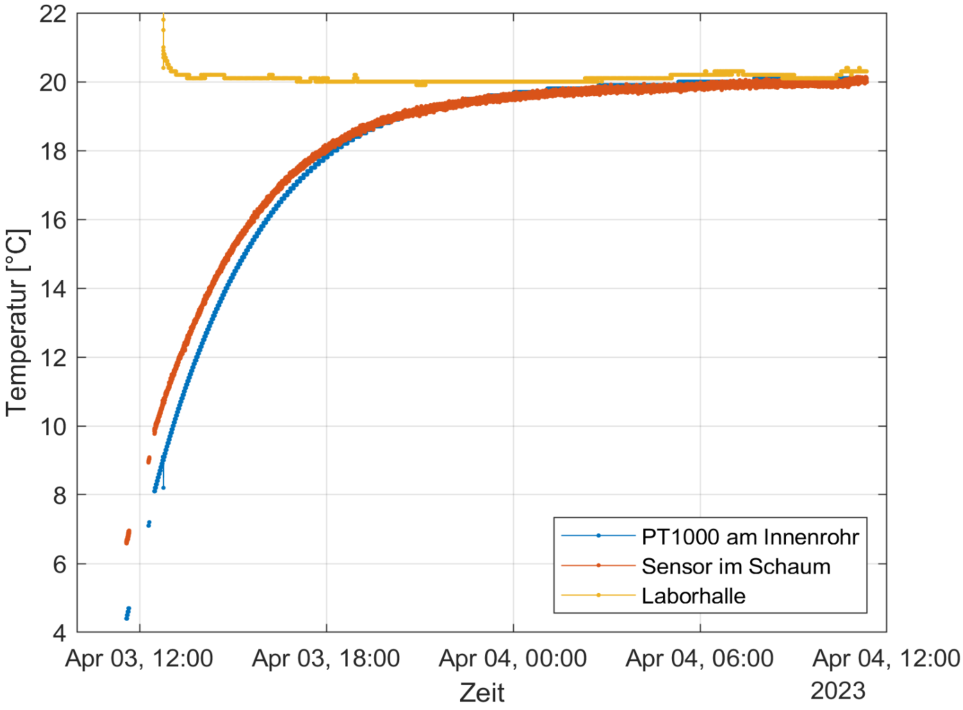

Figure 15: Measurement results of the temperature sensors: PT1000 surface temperature sensor on the carrier pipe (blue), combined temperature and humidity sensor in the middle of the foam (red) and air temperature sensor in the laboratory (yellow)

At the beginning of the measurements, the temperatures in the pipe were low due to outdoor storage combined with frost during the night. The differing initial temperature values can be explained by the morning sunlight to which the pipe was exposed outside. The sensor located in the middle of the foam was more strongly affected by this than the PT1000 sensor mounted on the inner pipe. Over the course of several hours, the temperatures inside the pipe adjusted to the room temperature. This demonstrated that both sensors are capable of capturing the heating process through the PUR foam and representing the thermal inertia of the pipe structure.

Figure 16: Measurement results of the relative humidity recorded by the sensor located in the middle of the foam. shows the development of the measured relative humidity. A slight decrease in relative humidity can be observed during the measurement period. This decrease can be attributed to the warming to room temperature: if the absolute moisture content in the foam remains constant, the relative humidity decreases as the temperature rises. Due to the installed position, it was not possible to deliberately expose the sensor to humid air during this test. Nevertheless, the measurement results confirm the fundamental functionality of the humidity sensor in the embedded condition.

From these results it can be concluded that the sensors withstood the foaming process well and remain fully functional.

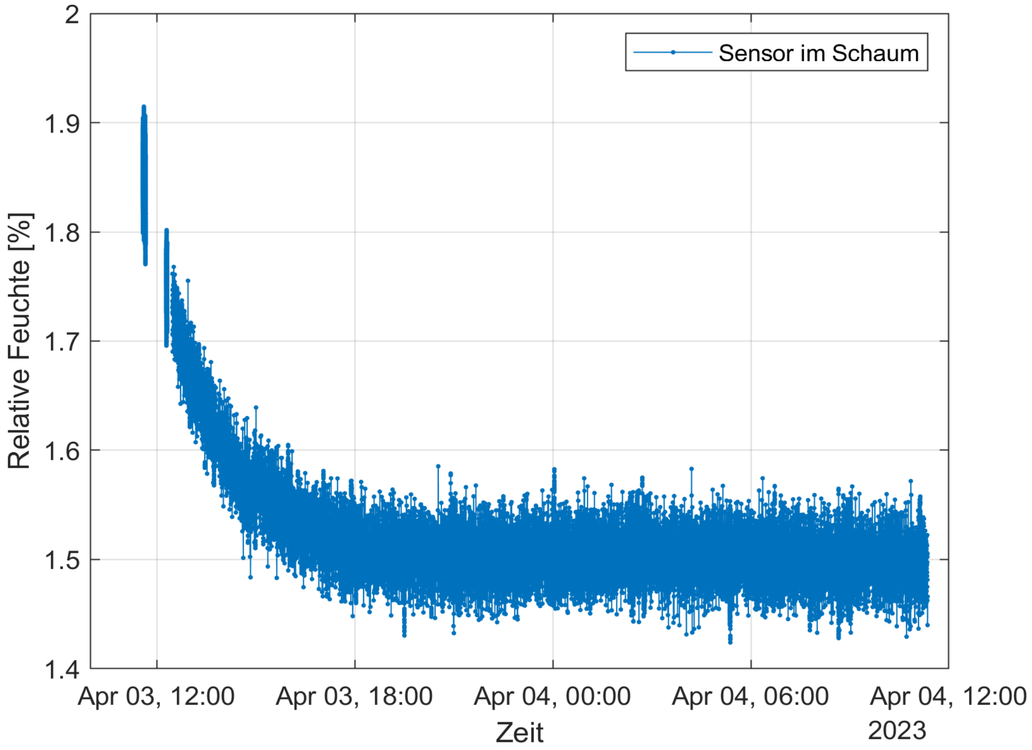

Figure 16: Measurement results of the relative humidity recorded by the sensor located in the middle of the foam.

Practical experience with fibre optic measurement technology

In practical use, the fibre optic measuring cable proved to be robust and durable overall. However, due to its stiffness, the cable tends to roll up on its own, so regular and sufficiently tight fastening is necessary to ensure accurate positioning. On the positive side, the cable can be cut if necessary and later reconnected by splicing. Fastening it to the pipes with adhesive tape and cable ties worked well as long as the pipes were completely accessible and dry. If the pipes were already partially filled or moist, mounting adhesive had to be used instead, which proved to be much more difficult and time-consuming. Overall, it became clear that careful planning of the cable routing is essential. In particular, accessible loops should be provided to enable subsequent sectioning, for example using cold spray. When laying the cable, it is very helpful to have several people working together to avoid tangling (‘cable salad’). In addition, careful documentation of the laying process is necessary in order to be able to clearly assign the subsequent measurement data to specific locations. The measurement system has not yet been commissioned, so no results can be presented at this stage.

Discussion and Conclusion

The measurement concept implemented in the District-LAB combines fibre-optic measurement cables at the pipe surface and in the bedding with embedded temperature and humidity sensors in the PUR foam and soil moisture sensors in the surrounding sand. This provides a comprehensive basis for experimental investigation of district heating systems. Distributed fibre optic sensing enables spatially highly resolved and almost continuous temperature measurements along the pipe route, around the pipe circumference and in the bedding. This makes it possible to analyse stationary temperature fields and dynamic effects caused by volatile renewable heat inputs, reduced operating temperatures and innovative operating strategies. The transverse winding of the cable helps to detect asymmetric heat flows and thermal interaction between neighbouring pipes, while the cable in the bedding captures the propagation of heat in the sand layers and the adjacent ground. The specific instrumentation in the expansion section allows a more detailed assessment of modified heat-transfer conditions and possible heat accumulation.

The embedded sensors in the PUR foam provide additional information on the condition of the insulation. The tests of the foamed in PT1000 sensor and the combined temperature and humidity sensor show that both the thermal inertia of the pipe structure and changes in relative humidity inside the foam can be captured. This enables more continuous and condition-based monitoring than with conventional leak detection alone. Together with the understanding of PUR ageing and the associated increase in thermal conductivity, the measurement setup offers the potential to estimate thermal conductivity, heat losses and service life of the pipe system more accurately under realistic operating conditions. In particular, the influence of lower operating temperatures and volatile renewable heat sources on PUR ageing and moisture ingress can be investigated, which is crucial for the long-term efficiency and stability of district heating systems.

In summary, the measurement concept realised in the District-LAB provides the basis for evaluating transformation strategies in the district heating sector in an experimentally supported way. These strategies include reduced temperature levels, the use of new pipe materials, alternative bedding materials and new operating concepts. The data obtained from the facility will make it possible to quantify more reliably how these measures affect heat losses, insulation condition and service life. This supports the targeted optimisation of future district heating networks with respect to efficiency, operational reliability and decarbonisation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used FhGenie by Fraunhofer in order to improve the linguistic clarity and grammar. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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