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Thermal Behaviour of Piggyback-Laid District Heating and District Cooling Pipes

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***Abstract* – District heating (DH) and district cooling (DC) networks are key to sustainable urban energy systems. This study investigates thermal interactions between DH and DC pipelines installed in a piggyback configuration within a shared trench using a combination of in-situ temperature measurements and transient heat transfer simulations. A 175-meter section of Munich's DH and DC network was analysed through experimental temperature measurements and a finite element method (FEM)-based thermal model in MATLAB. Results show that DH operation increases trench soil temperatures, leading to continuous heat gains in the DC flow pipe. Although the impact within the investigated area is limited due to the short piggyback-laid section, large-scale implementations will experience greater thermal interference. A simulated scenario without DH in operation confirmed that the pipe placement aligns ground temperatures with DC flow temperatures, avoiding heat gains. The validated model serves as a reliable tool for assessing heat losses and gains, contributing to future DH and DC network designs in urban infrastructure planning.**

***Keywords* – Energy infrastructure; field measurements; finite element analysis; heat transfer analysis; pipeline construction technology.**

Nomenclature		
T(*x*, *y*, *t*)	Temperature function of space *x*, *y* and time *t*	
t	time	s
x, *y*	Spatial coordinates	m
ρ	Density of the material	kg/m³
c_p	Specific heat capacity	J/(kgK)
λ	Thermal conductivity coefficient	W/(mK)
f	Heat source term	W/m²

1. Introduction

District heating (DH) and district cooling (DC) play a crucial role in achieving climate goals, particularly with the parallel decarbonization of heat and cooling generation and the expansion of energy-efficient thermal networks. In Germany, for example, an expansion of approximately over 40 000 km of district heating networks until 2050 [1] is planned to support the transition toward sustainable energy systems. Additionally, ongoing urbanization and infrastructure developments, such as the transition in wastewater networks and the

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expansion of fiber-optic networks, are increasing competition for underground space [2], [3]. Metropolitan areas, with their high heat demand density, offer a suitable environment for the implementation of both DH and DC networks. One of the main cost drivers in laying such networks is trench construction. Typically, infrastructures are installed separately in designated corridors, however, in a short section of Munich, an innovative construction approach was executed where district heating and district cooling pipelines were installed as a piggyback system within the same trench see Fig. 1(b). Piggyback-laid pipes can reduce construction costs because of narrow trenching, and they offer more flexible routing [4]. This method is unusual in Germany due to regulatory constraints, the involvement of different operators, and territorial boundaries [5]. In this case, both systems are managed by the same operator, allowing for the implementation of a shared trench solution.

The water used for district cooling originates from a subway siphon and therefore exhibits fluctuating temperatures. To be suitable for cooling purposes, the water may only warm up slightly during transport. [6] also shows that the ground temperature is a very crucial parameter for the cold losses of a DC network. A key question in this context is how the district heating pipelines influence the district cooling system. Due to heat losses from the buried pipes, the soil temperature around DH lines increases. Studies on the further influence on other infrastructures, such as drinking water networks or the overall subsurface heat, have shown that there can be significant impacts [7]–[10]. To minimize heat transfer, regulations in Germany recommend 1.0 meter between district heating (DH) pipes and drinking water lines [11]. However, in this case such a distance cannot be maintained.

To evaluate these thermal interactions, the operator installed several temperature sensors within the trench. However, due to the delayed operation of the DC system, measurement errors, and defective sensors, a comprehensive analysis of real-world performance has not yet been possible. This study, therefore, investigates the thermal behaviour of this network section using a combined approach that integrates the evaluation of available measurement data with a transient heat transfer model. First, an introduction to the investigated route section, the measurement concept, and the operational parameters of the DH and DC systems are provided. This is followed by a qualitative evaluation of the measurements to gain insight into the real-life thermal behaviour of the system. To further analyse heat transfer dynamics, a transient thermal model based on the finite element method (FEM) was developed using MATLAB. The application of transient thermal models is well-established in district heating research, particularly for assessing and optimising specific heat losses, and has been used in numerous studies [12]–[15]. However, re-modelling ground temperatures remains a challenge due to fluctuations in soil thermal properties [12], [14]. Despite these complexities, the methodology employed in this study provides valuable insights into the heat flux within the cross-section of the installed system. The modelling process consists of three key steps. First, the model is calibrated to align as closely as possible with the measured values. Second, heat losses and gains for the pipelines are determined. Finally, to assess the influence of DH on DC, the DH pipelines are deactivated within the model, allowing for a comparative analysis of their impact. By comparing real-world measurements with simulation results, this study aims to assess whether piggyback-laid pipelines influence the thermal performance of the district cooling system and whether this method offers a viable approach for future urban energy networks.

2. Methods and Methodology

2.1. Experimental Setup and Measurement Location

The study refers to a pipeline section where the DH and DC systems in Munich run in a piggyback configuration over 175 m. Figure 1 presents the schematic of the measurement locations and the experimental setup.

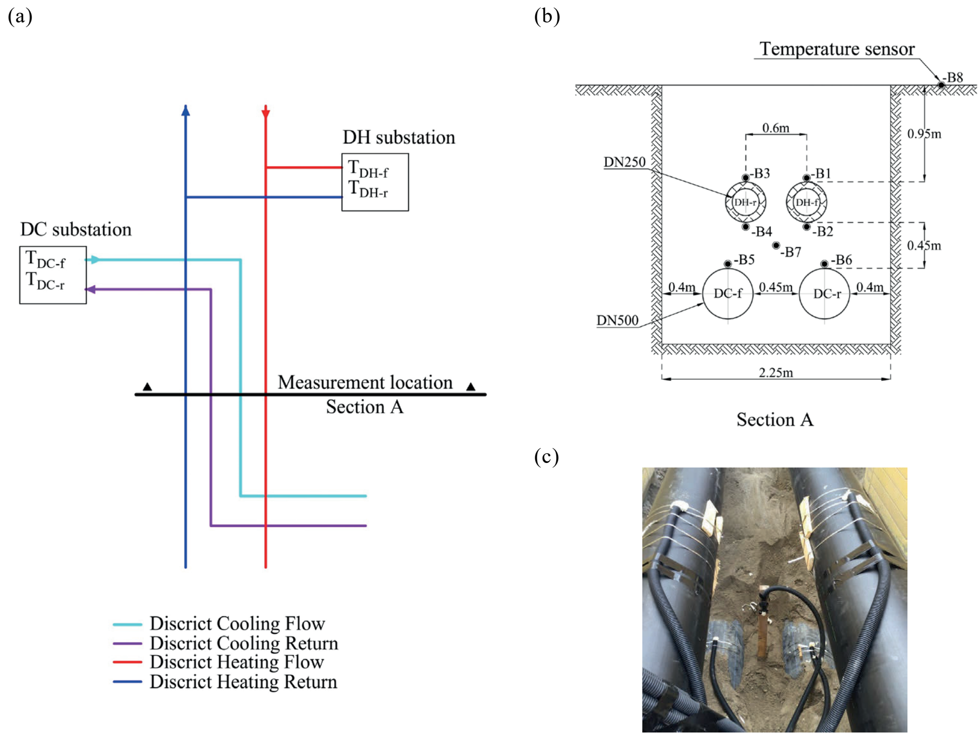


Fig. 1. Schematic: (a) Measurement Location; (b) Sensor Locations on the Pipelines; and (c) Placing of Sensors.

The pipelines were constructed in 2016, and temperature sensors were installed to monitor thermal conditions in the surrounding soil. The DH pipeline was commissioned in the same year, while the DC pipeline became operational later, in 2022. However, two sensors to monitor the temperature at the DC pipes (B5 and B6) were defective from December 2022 to February 2024, resulting in a lack of recorded data during this period. Consequently, for this study, the year 2022 was selected as the reference period, as it represents the only complete dataset available for both the DH and DC systems. The pair of pre-insulated DH pipes (DN 250) have the same dimensions: outside diameter is 403.6 mm, wall thickness is 5 mm, polyurethane (PUR) insulation thickness is 63.5 mm, and casing thickness is 3.6 mm. The pair of non-insulated polyethene (PE) DC pipes (DN 500) also share the same dimensions: outer diameter is 500 mm and a wall thickness of 15 mm. The overburden of the DH pipeline is 0.95 m, and the distance between the DH flow and return pipe is 0.2 m. Measurements of temperature were carried out at chosen locations on DH and DC pipelines. The schematic of in-situ measurements is shown in Fig. 1(b). Temperature measurement spots are located on each pipe (Sensors B1–B6). While the DH pipes have two measurement spots each (located at 12 and 6 o'clock), the DC pipes have one each (12 o'clock). Additionally, the soil temperature between the pipes (B7) as well as the surface temperature (B8) on site is measured. The surface temperature on site is measured on the bottom of the electrical cabinet where the data loggers are placed. In total, eight temperature sensors have been placed. The setup uses four data loggers (Type TinyTag TGP-4520) for two temperature measurements each. In total, 32 000 measured values can be recorded. They can be used in temperatures between −40 °C and +125 °C. The accuracy from 0 °C to 70 °C is ± 0.4 °C. The recording period with an hourly interval is approximately 666 days. The soil surface temperature was measured with an encapsulated thermistor probe (Type TinyTag PB-5015-10M), which measures temperatures from −40 °C to +105 °C. The accuracy from −40 °C to +100 °C is ± 0.5 °C.

The soil temperature between the pipes and the casing was measured with surface thermistor probes (Type TinyTag PB-5003-5M), which measure temperatures from −40 °C to +125 °C. The accuracy from −40 °C to +125 °C is ± 0.6 °C. Against mechanical stress from the soil, the sensor cables are protected with a cable conduit Kabuflex R 40 for underground installation between the data logger and the measuring point. It is assumed that the flow and return temperatures at the measurement location correspond to the temperature in the primary circuit of the customer's substation. Therefore, the flow and return temperature measurements are taken from the primary side of the nearby substations. The frequency of the measurements was hourly at the same time in all measurement spots. It is important to point out that a calibration of the temperature sensors was not performed by the authors. This setup enables a satisfying representation of thermal conditions within the network, forming a basis for this analysis.

2.2. Transient Heat Transfer Model

The analysis uses MATLAB's PDE Toolbox, which enables numerical simulation of heat transfer processes. The governing equation for transient heat transfer in a two-dimensional domain is given by Eq. (1).

$$\frac{\partial T}{\partial t} = \frac{1}{\rho c_\mathrm{p}}\left(\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)\right) + \frac{f}{\rho c_\mathrm{p}} \tag{1}$$

The model geometry consists of a trench in which DH and DC pipelines are installed. The DH pipelines include a steel service pipe, PUR insulation, and an outer PE casing, whereas the DC pipelines consist solely of a polymer service pipe. The trench geometry encompasses various elements, including the pipe zone, trench walls, and overburden, ensuring a realistic representation of heat transfer processes in the ground. To capture the thermal interactions between the pipelines and their surroundings, the surrounding soil is modelled as a 20 m × 10 m area. Each component within the model, including the individual pipeline layers and the soil, is assigned distinct thermal properties. A FEM is developed to discretize the model domain, enabling efficient numerical computation. The mesh is designed to balance computational performance and accuracy. A refined mesh is applied in critical areas such as the pipe zone and trench, where thermal gradients are expected to be steep. Conversely, a coarser mesh is used for the surrounding soil to reduce computational complexity. The final mesh consists of approximately 3200 nodes, ensuring sufficient resolution for accurate results within the investigated area. A quality check is performed to verify the mesh integrity, as distorted elements can lead to numerical instability. The mean mesh quality is determined to be 90 %, indicating a well-structured and reliable computational grid. The heat flux at the model boundaries is set to zero, assuming no external heat exchange beyond the defined domain. The top boundary of the model represents the ground surface and is assigned to a constant temperature based on measurements from sensor B8. The operational temperatures of the DH pipelines are applied as ambient temperatures, with a convection coefficient of 2500 W/(m²K) to account for heat exchange between the pipes and their surroundings. For the low flow velocity within the DC pipelines a convection coefficient of 100 W/(m²K) is set. The initial temperature of the entire model domain is set to 10 °C, providing a uniform starting condition for the simulation. The simulation covers the period from February 1 to December 31, 2022. Within this time span, no sensor failures occurred, and the complete measurement dataset is available for comparison and validation. A time step of 3600 seconds (one hour) is selected, resulting in approximately 8760 calculations per year. This allows a dynamic assessment of temperature variations and heat transfer processes over time. Additionally, the model permits the application of new parameter sets with each time step, enabling a flexible and adaptive simulation approach. To enhance computational efficiency, several simplifications are introduced. Moisture and water transport within the soil are neglected. Additionally, diffusion effects are not considered, and phase-change phenomena, such as ground freezing and thawing, are omitted. Thermal properties are assigned per domain and are assumed to remain constant within the designated domain. Also, it is important to keep in mind that the operational data is not measured at the same location as the sensors are placed, but from nearby substations.

2.3. Model Calibration

The initial calculations are conducted using a static parameter set for thermal properties, providing a baseline for comparison. The results from these simulations are then compared with temperature data obtained from in-situ sensors to assess the accuracy of the model.

TABLE 1. PARAMETER SET 1 (STATIC PARAMETERS)

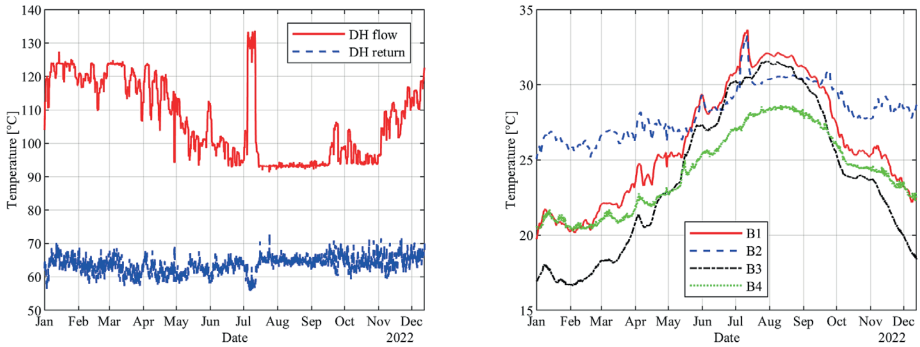
	Thermal Conductivity, W/(mK)	**Specific Heat Capacity, kJ/(kg°C)**	**Density, kg/m³**
Steel Service Pipe (DH)	50	450	7860
PUR Insulation	0.029	80	80
Casing	0.4	1900	965
Polymer Service Pipe (DC)	0.4	1900	965
Soil	1.6	1600	1700
Bedding Material (sand)	1.6	1600	1700

These values are in accordance with the provided thermal conductivity values for bonded pipes in EN 13941 [16], additional material thermal properties in DIN EN ISO 10456 [5] which were also used in a former study [15], as a typical parameter set for the calculation of heat losses. The soil thermal properties fluctuate with respect to their volumetric water content according to [17]–[19]. For the first calculation, no change in these properties is accounted for as in [13]. To improve the agreement between measured and modelled data, a parameter sweep is performed, incorporating dynamic thermal properties for the soil and bedding materials. These properties are adjusted seasonally to better represent real environmental conditions. The calibration process continues until the mean deviation between measured and modelled sensor data is within an acceptable range of ±1.5 K. This designated tolerance of ±1.5 K for the model calibration is considered acceptable due to inherent simplifications in the heat transfer analysis, as well as uncertainties arising from measurement accuracies of the sensors and limitations in the measurement setup. Additionally, while the sensor locations were modelled according to the conceptual design, their exact positions in the field were not directly measured, introducing further potential discrepancies. Once the thermal properties are calibrated, the model is used to evaluate the heat flow within the system. A comparative analysis is conducted to determine heat losses and gains in the DC system. This assessment provides insights into the overall thermal performance of the piggyback-laid pipeline configuration. Furthermore, the specific impact of the piggyback section by analysing localized heat interactions is determined.

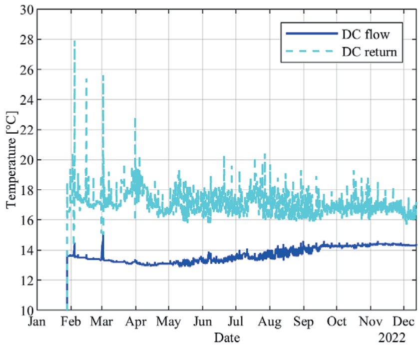
3. Results

3.1. Evaluation of Measurements

The DH and DC systems exhibit distinct operational temperature profiles due to differing demand patterns. The DH flow temperature is dynamically regulated based on the outside air temperature, with elevated operational temperatures during winter to meet increased heating demand and reduced temperatures during summer. An exception occurs in July when the DH flow temperature can reach up to 130 °C for internal testing purposes. In contrast, the DH return temperature remains relatively constant throughout the year, as customers are required to return the fluid at a set temperature to the network. Compared to DH, the DC operational temperatures are more stable, as cooling demand remains relatively constant year-round due to a limited number of customers. The mean DC flow temperature is 13 °C, while the return temperature averages 16 °C. A slight fluctuation of approximately 0.5 K in the DC flow temperature is observed between mid-May to mid-September, which could be attributed to minor seasonal variations or measurement noise. Temperature measurements in the soil surrounding the DH and DC pipes presented in Fig. 2(b) and (d) provide valuable insights into temperature distribution and profile around the pipes. In 2022, the average soil temperature between the pipes remained stable at 20 °C (B7) and did not drop below 17.5 °C. The surface temperature (B8) fluctuated throughout the year, reaching its peak during summer. Among all measurement points, the area surrounding the DH flow pipe exhibited the highest temperatures, with an average of 26 °C (B1, 12h) and 28 °C (B2, 6h), and a recorded maximum of 34 °C. The DH return pipe also caused elevated ground temperatures, averaging 23.5 °C (B3, 12 h) and 24 °C (B4, 6 h). In contrast, the temperatures measured on top of the DC pipes were significantly lower, with the DC flow and return pipes averaging 16.5 °C (B5, 12 h) and 19 °C (B6, 12 h).



(a) (b)



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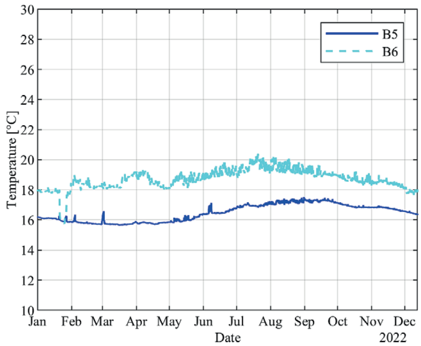

(d)

Fig. 2. Temperature Measurements: (a) DH Flow and Return; (b) Sensors at DH Pipelines (B1-B4); (c) DC Flow and Return; (d) Sensors at DC Pipelines (B5 and B6).

The cooling fluid exhibited a temperature difference of 3.5 K relative to its surrounding pipe, with an average of 16.5 °C and a maximum of 17.5 °C. In general, the measured temperatures correlate with the measured fluid temperatures. For instance, the warmest temperatures are measured around the DH flow pipe and the coolest around the DC flow pipe. Thus, the seasonal influence of elevated soil temperatures in summer can be observed in the sensors B1 to B6. However, due to the lack of direct measurements of undisturbed soil temperature, further investigations are necessary.

3.2. Simulation Results – Model Calibration

The results of the initial calculations using the static Parameter Set 1 provide insight into parameter tendencies for subsequent adjustments. However, the comparison between modelled and measured temperatures reveals significant deviations. Fig. 3 illustrates the discrepancies observed for sensors B1 to B6, while the mean deviations are summarized in Table 2. The calculations based on Parameter Set 1 indicate that for the sensors positioned at the DH pipes (B1 to B4), the model significantly underestimates the temperatures. Furthermore, the deviations between measured and simulated values are more pronounced in summer than in winter. This seasonal discrepancy suggests that variations in ground temperature strongly influence the thermal behaviour within the trench.

TABLE 2. MEAN DEVIATION OF MODEL TO MEASUREMENT

Parameter Set	B1	B2	B3	B4	B5	B6	B7
1 (static, initial)	−2.762	−4.645	−3.066	−3.914	−1.3150	−0.827	−1.746
2 (dynamic, improved)	+1.348	+0.079	−0.240	−0.656	−1.1310	−0.392	+0.006

Overall, the model underestimates temperatures significantly, which may be attributed to multiple factors. Potential causes include a higher-than-assumed thermal conductivity of the pipeline materials and seasonal lower thermal conductivity of the surrounding soil. The impact of these parameters on thermal performance has been proven in several studies like [13], [15], [20].

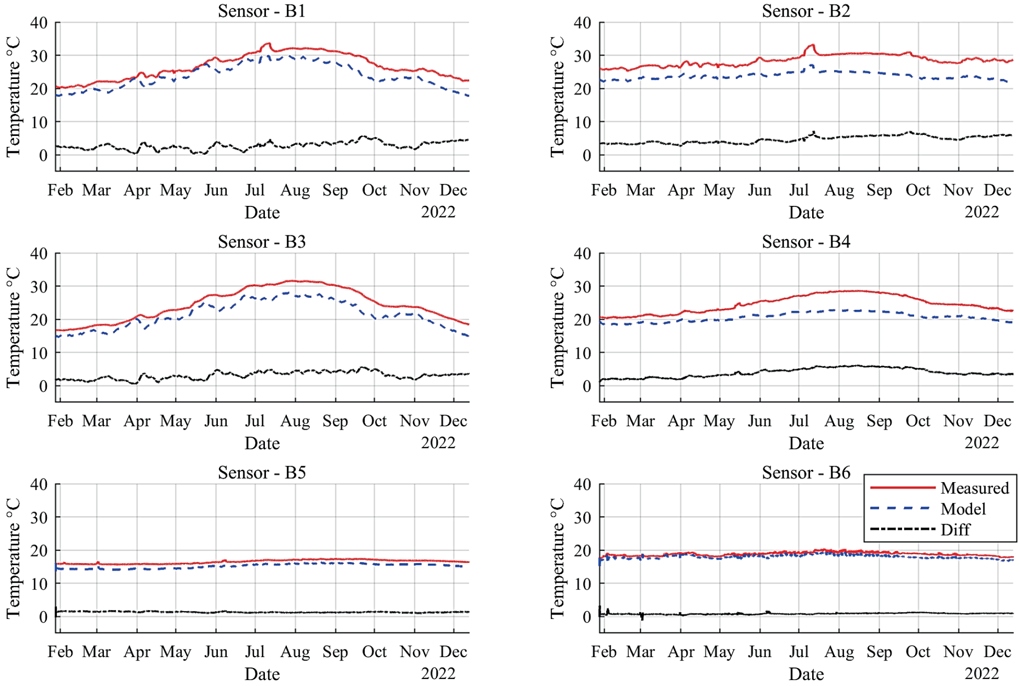

Fig. 3. Comparison of Measured and Modelled Temperatures for Parameter Set 1.

To improve the model's accuracy, several parameter adjustments were tested, leading to the following key tendencies. Seasonal variation in soil properties was introduced to reduce the summer-winter discrepancy. Additionally, it is assumed that the pipe zone is dryer than the surrounding soil and the upper layer backfill zone. This reflects the findings of [21] for high voltage cables that due to the heat flux within these infrastructures, usually the soil close to pipelines has lower water content and lower thermal conductivity. Also, an increased thermal conductivity of the pipe insulation was considered, which can be explained by two factors: (1) the known increase in PUR thermal conductivity at temperatures above 50 °C [18], and (2) ageing effects [22], as the pipelines have been in the ground for six years, potentially altering their insulation properties. These adjustments aim to refine the model calibration and improve the agreement between simulated and measured temperatures. The improved Parameter Set 2 can be found in Table 3.

The results of the simulation using Parameter Set 2 demonstrate a strong correlation between modelled and measured temperatures, which can be seen in Fig. 4. The implementation of seasonal parameters significantly improves accuracy in both summer and winter, reducing the seasonal discrepancies observed in the initial simulation. Among all sensors, the highest mean deviation is observed at sensor B1, which is placed on top of the DH flow pipe. However, the other sensors placed at the district heating pipes show excellent agreement with the measured data. For sensors B2, B3 and B7, which are placed between the DH and DC pipelines, the mean deviation is less than 0.5 K, indicating a high level of accuracy in this region of the model. The model also shows improved temperature predictions for the DC pipes as Sensors B5 and B6 indicate a slight deviation, though the simulated values remain slightly underestimated. Nonetheless, all modelled temperatures fall within the designated tolerance range, confirming the validity of the applied adjustments. With this improved calibration, the model provides a reliable approximation of heat losses, making it a valuable tool for further investigations into the impact of the DH pipes on the DC pipes and the overall thermal performance of the system.

TABLE 3. PARAMETER SET 2 (DYNAMIC PARAMETERS)

	Thermal Conductivity, W/(mK)			Specific Heat Capacity, kJ/(kg°C)			Density, kg/m³
Steel Service Pipe (DH)	50			450			7860
PUR Insulation	0.035			80			80
Casing	0.4			965			1900
Polymer Service Pipe (DC)	0.4			965			1900
	Winter	Summer	Spring/ Autumn	Winter	Summer	Spring/ Autumn	
Soil	2.0	1.6	1.8	1600	400	1500	1700
Bedding Material (Sand)	1.6	0.8	1.2	1400	1000	1200	1700

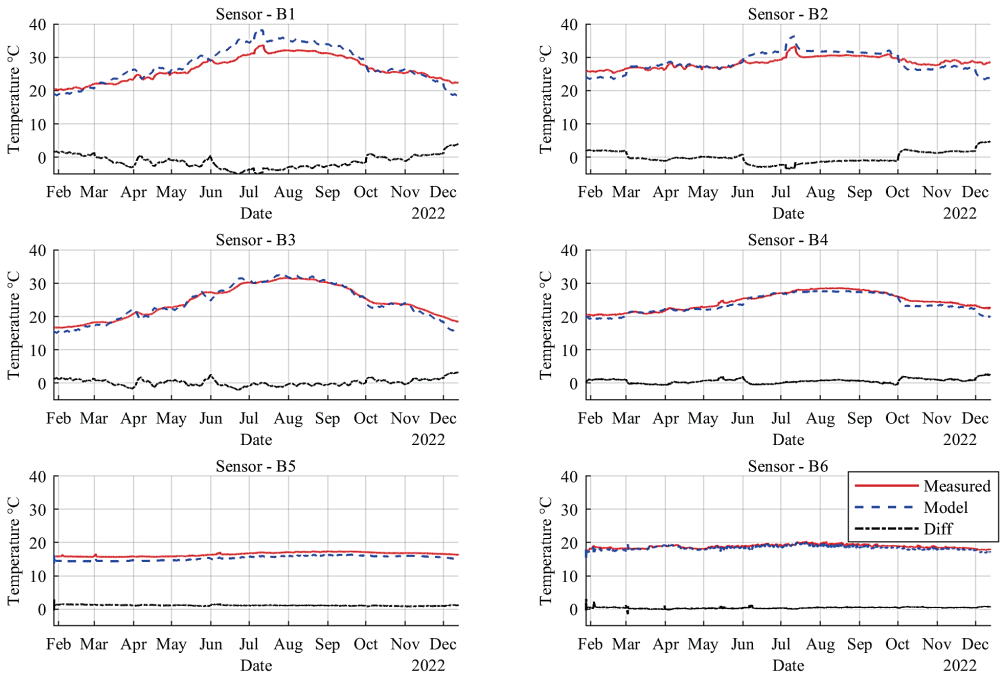

Fig. 4. Comparison of Measured and Modelled Temperatures for Parameter Set 2.

3.3. Simulation Results – Determination of Heat Losses and – Gains for District Cooling

The determination of heat losses and gains for the DC pipes is illustrated in Fig. 5 and Fig. 6. The first step in this evaluation involves analysing the modelled heat flux within the DC pipes while the DH line is in operation. For the DC flow line, heat gains occur throughout the entire year, indicating that the surrounding soil temperature is consistently higher than the DC flow temperature. These heat gains reach their peak in July and August, with a maximum of approximately 20 W/m. The mean value of the heat flux into the DC flow line within the scope is a heat gain of 15.0 W/m. In contrast, the DC return line experiences heat gains only between May and December, with a clear seasonal pattern. As expected, heat gains are more pronounced in the summer months than in winter, which can be attributed to the seasonal variation in ground temperature. The influence of soil temperature fluctuations plays a crucial role in the thermal behaviour of the system, significantly impacting heat exchange between the buried pipelines and their surroundings. Fig. 6 illustrates the heat flux of the DC pipes when the DH line is not in operation. For this calculation, the temperature of the DH pipes is set to the undisturbed ground temperature at the height of the pipe axis. The results clearly show significantly lower heat gains into the DC flow pipe compared to the scenario with the DH system in operation. Heat gains occur only between May and November, reaching a peak of approximately 10 W/m in August. For the DC return line, no heat gains are observed; instead, the pipeline experiences continuous heat losses throughout the year. This suggests that the surrounding ground temperature remains lower than the DC return medium temperature for the entire year. The mean heat flux for the DC flow line is determined to be a heat gain of 0.7 W/m, further highlighting the influence of the DH system on the thermal behaviour of the DC pipes.

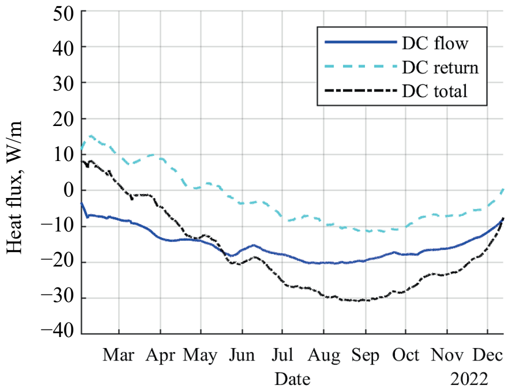

Fig. 5. Heat Flux DC Pipes – DH in operation.

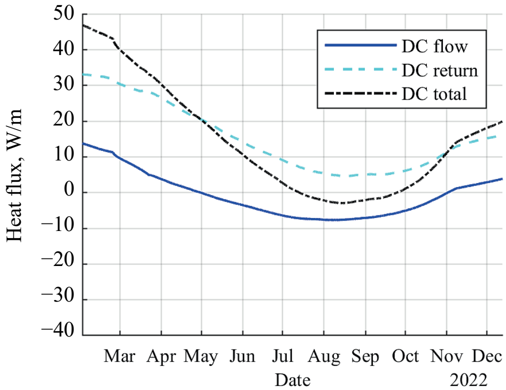

Fig. 6. Heat Flux DC Pipes – DH not in operation.

4. CONCLUSION

The study demonstrates that the presence of DH pipelines significantly influences the thermal behaviour of the DC system when laid in a piggyback configuration. The increased ground temperature within the trench due to DH operation leads to continuous heat gains in the DC flow pipe, reaching a peak of 20 W/m in summer. However, considering the large diameter of the DC pipes (DN 500), the overall thermal impact remains relatively low within the investigated section. On a larger scale, this effect could become more significant, potentially affecting the efficiency of DC systems. The transient heat transfer model developed in MATLAB, calibrated using seasonal soil parameters and adjusted thermal conductivities, closely aligns with measured temperatures. The results show that the model accurately predicts soil temperatures with DH and DC in operation, with mean deviations of less than 0.5 K for sensors B2, B3, B6 and B7. However, slight underestimations remain for sensor B5 at the DC flow pipe and a slight overestimation for sensor B1 at the top of the DH flow pipe, which may be attributed to the uncertainty in soil thermal properties, sensor placement inaccuracies, and operational data deviations. The seasonal fluctuation in ground temperature plays a crucial role in thermal interactions, with higher heat gains for the DC pipes observed in summer due to elevated soil temperatures. The measurement setup provided valuable insights into temperature distributions but also introduced uncertainties. Sensor placement was based on design positions rather than exact field measurements, which could have contributed to deviations in measured and modelled temperatures. Additionally, the surface temperature sensor (B8) was positioned at the bottom of an electrical cabinet rather than directly exposed to ambient conditions, which may have influenced the measured values. The absence of moisture content sensors limited the ability to account for soil water content variations, which are known to significantly affect thermal conductivity. Possible mitigation strategies to reduce heat gains in the DC pipes include modifying the trench design by increasing the distance between DH and DC pipelines. While such adjustments could reduce thermal interference, they would also lead to higher construction costs, which seems out of relation concerning the short section. Therefore, it is not recommended. The results suggest that, without DH operation, the current placement of the DC pipes in the investigated section already meets a burial depth where no heat gains occur. However, introducing an insulation layer between the DH and DC pipelines in operation could reduce thermal interference. To improve future investigations, in-situ measurements of the exact sensor positions, additional moisture content sensors, and fluid temperature monitoring before and after the 175 m long study section are recommended. Additionally, placing sensors beneath the DC pipes would provide a more comprehensive understanding of the heat transfer mechanisms. With the improved calibration achieved in this study, the transient heat transfer model is a valuable tool for estimating heat losses and gains, facilitating further optimisation of DH and DC system designs in urban infrastructure planning.

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