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Heat Loss Determination of District Heating Pipelines. A Comparison of Numerical and Analytical Methods

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Abstract **– Assessing the energy efficiency of district heating systems considers the network heat losses. For example, life cycle assessments of engineering structures like these necessitate an understanding of heat losses incurred during their operational phase. Therefore, it is essential to know the heat losses of district heating pipelines with the utmost accuracy. In this study, three different methods for determining specific heat losses for buried pre-insulated steel pipes are compared. The first method involves an analytical calculation in accordance with EN 13941, while the second utilizes an equivalent mesh current approach. The third method employs finite element analysis. The objective was to evaluate the accuracy of the methods, the achievable range of results, and the possible input parameters. Therefore, typical 2-dimensional cross sections including different pipe diameters were selected. In situ measurements were not part of this study. Consequently, the analysis centres on the deviation between the methods. All three methods determine the heat loss in both the supply and return pipes. While the analytical calculation method does not consider multiple soil layers, the equivalent mesh current method can handle more complex tasks and gives detailed results at predefined points in the system. With the finite element method, a high degree of detail can be achieved, but the number of input parameters for solving the algorithms increases. An emerging trend in district heating involves reducing operational temperatures in both new and existing networks. This will change the relation between heat losses and heat delivered to the customers. Subsequently, an increasing interest in the actual heat losses and the precision of calculation is expected within this development. Therefore, it remains essential to evaluate the performance of different models.**

Keywords **– District Heating; equivalent mesh current method; finite element analysis; heat losses.**

Nomenclature		
D_i, d_o	Inner and outer diameter	m
h	Heat loss factor	–
q	Specific heat loss (linear density)	W/m
H	Burial depth	m
R	Thermal resistance	(m·K)/W
C	Distance between the pipe axis	m
T	Temperature	K
Z	Distance from the surface to the pipe center	m

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Z_c	Corrected value of depth	m
λ	Thermal conductivity coefficient	W/(m·K)

1. INTRODUCTION

District heating (DH) is an important part of the European strategy for the decarbonization of the building sector [1]. Consequently, heating networks will have to be newly built and expanded whilst an additional increase in construction demand is to be expected due to the maintenance of existing DH networks. Therefore, the pre-insulated bonded pipe with a steel service pipe bedded in the sand will be the most used design, but also a diversification of technical solutions for heat network construction, like polymer service pipes, flexible pipe systems [2] or recycled backfilling materials [3] is to be expected. The expansion of DH-networks gives occasion to examine existing design criteria for their application and relevance.

Network heat losses not only define the efficiency of a DH system but also influence decision-making processes related to design and maintenance. For instance, Dalla Rosa *et al.* [4] focus on heat losses and propose a method for the optimal design of pipes for low-energy applications. While Wang *et al.* [5] introduce a model which takes into account a heat loss profile to improve the accuracy of the location of damaged insulation and to evaluate the thermal deterioration and ultimately the maintenance of the network. Furthermore, the trend toward lower operating temperatures could result in higher relative heat losses, which are the heat losses relative to the distributed heat [6].

Heat losses of DH pipes, due to fluctuating operating temperatures and varying soil temperatures, are inherently time-dependent and thus constitute a case for transient heat transfer analysis [7]. To achieve the most accurate results, numerical finite element method (FEM) analyses of transient heat transfer should be employed [7], [8]. The implementation of temperature-dependent thermal conductivity coefficients [4] or the combination of simulation and in-situ measurements [9] can obtain an even more precise heat loss determination. Nevertheless, steady-state heat transfer methods are also performed, and this approach is usually state-of-the-art in terms of designing a DH network [4]. Although steady-state heat transfer is not achieved in reality, satisfactory results can be achieved with steady-state models and certain parameters [10]. Previous projects and reports have dealt with the topic of steady-state heat loss determination of buried pipes in the ground, but have not compared the relative strength and limitations of these methods. Additionally, in practice, however, it is often the case that no detailed information is available on e.g. the thermal properties and current temperatures of the soil, furthermore, steady-state methods offer the advantage of requiring less computational effort. Therefore, this study aims to compare three commonly employed methodologies in the district heating sector based on the steady-state heat transfer analysis for determining specific heat losses of buried pre-insulated bonded pipes to provide insights into their applicability and their deviation.

The first method employs analytical calculations following the guidelines outlined in EN 13941 [11]. In contrast, the second method utilizes the equivalent mesh current method (EMCM) as introduced by Zeitler [12]. Finally, the third method involves finite element analysis (FEM). The objective of this research is twofold: firstly, to evaluate the input parameters and the application itself of each method; secondly, to assess the achievable range of results obtained through these methodologies. To facilitate this comparison, typical 2-dimensional cross-sections comprising different pipe diameters are developed by creating representative scenarios for the DH network construction in Germany.

Notably, this study focuses solely on comparative analysis and does not incorporate in-situ measurements. Consequently, the examination primarily centres on discerning deviations between the methods and understanding their relative strengths and limitations.

2. METHODS AND METHODOLOGY

To analyse and compare the three steady-state heat loss models, it is necessary first to develop a scenario to elucidate the application of parameters and the computational framework. Therefore, the following section describes the parameters of heat loss analysis in general and defines the parameters for this study. To compare the three models the FEM model is understood to represent the original system the best and therefore was set as the base for comparison. Next, we briefly present Wallentén's [13] 'approach, as outlined in EN 13941, introduce the EMCM by Zeitler [12], describe the FEM, and refer to model-specific assumptions at the relevant points.

To conduct a comprehensive heat loss analysis, several variables need to be considered. According to Dalla Rosa *et al*. [4] these variables can be divided into 4 categories. Firstly, operational data such as flow, return, and outdoor air temperatures, along with climatic data. The second category encompasses factors like the heat conductivity of insulating materials and soil properties. The third and fourth categories pertain to the geometric characteristics of pipes and their arrangement. This includes specifications like pipe diameter, insulating layer thickness, laying depth, and pipe distance.

2.1. Operational/Climatic Data and Thermal Conductivity Coefficients

For the analysis two climatic scenarios, a winter and a summer case are investigated. The relevant temperatures include the flow (T_f) and return (T_r) temperatures, as well as the outdoor air (T_a) and the soil temperature (T_s). In both climatic scenarios, typical average operational temperatures as indicated by Lund [14] for a 3rd generation DH network are assumed. Subsequently, in winter the flow and return temperature is set at 110 °C / 80 °C. The summer scenario, due to lower heat demands is assumed with 80/60 °C respectively. The outdoor air temperature for the winter and summer cases is set to 0 °C and 20 °C. Another parameter for analysing specific heat loss is the soil temperature which is significantly impacted by the outdoor air temperature.

Initially, Wallentén [13] suggests using the temperature at the ground surface. However, this contrasts with Bøhm's [10] investigation, which advocates for the undisturbed soil temperature position, corresponding to the temperature at the top of the casing. The EN 13941 adopts Bøhm's [10] approach and uses an undisturbed soil temperature in a depth Z which is equivalent to the pipe axis. As outlined by Dahlem [15], soil temperature variations can be depicted seasonally. The undisturbed soil temperature in about 1 m depth in Germany can be assumed at 4 °C in winter, and 16 °C in summer [15].

Lastly, the material properties, particularly the coefficients of thermal conductivities of pipe components and the surrounding soil play a pivotal role in the analysis. In this study, the selected pipes correspond to the insulation standard series 1 with a thermal conductivity (λ_i) of 0.029 W/(m·K) according to EN 253 [16]. The thermal conductivity coefficients of the steel (λ_{st}) and casing (λ_c) were taken as 50 W/(m·K) and 0.40 W/(m·K), respectively. The thermal conductivity of the soil (λ_s) is primarily dependent on the moisture content and bulk density [17]. Therefore, EN 13941 categorizes the thermal conductivity according to the moisture content into dry, medium-moisture, and wet soil. In winter we assume that the soil has a higher level of humidity, therefore medium wet soil with 1.6 W/(m·K) is assumed.

Usually in summer, the soil is drier. Therefore, we assume a thermal conductivity of 1.0 W/(m·K) [18]. The underlying thermal conductivities for this analysis are summarized in Table 1.

TABLE 1. THERMAL CONDUCTIVITY

	Symbol	Value	Unit
Steel service pipe	λ_{st}	50	W/(m·K)
Insulation	λ_{i}	0.029	W/(m·K)
Casing	λ_{c}	0.40	W/(m·K)
Dry soil (summer)	$\lambda_{s\ dry}$	1.0	W/(m·K)
Medium wet soil (winter)	$\lambda_{s\ medium}$	1.6	W/(m·K)

2.2. Geometry and Arrangement of Pipes

In the construction of DH pipelines, pre-insulated pipe systems, consisting of a steel carrier pipe, polyurethane foam insulation, and a polyethylene (PE) casing, are typically employed. To account for a variation in the geometric framework, three pipe settings DN 50, DN 150, and DN 400 are investigated. The pipe dimensions and diameters used comply with EN 253 [16]. Usually, DH pipes are installed as rigid single-pipe systems with flow and return lines in an open trench construction. The pipes are typically bedded with fine-graded sand in the pipe zone and the trenches are backfilled with coarse mixed-graded materials in the filling zone. The dimensions of the trenches for this study are derived from the European DH standard EN 13941 in accordance with the German national construction standard for excavation pits and trenches, DIN 4124 [19]. The trench dimensions usually rely on the pipe diameter and the overburden height. As overburden height, a typical value of 1.2 m is assumed. The design representation is based on simplified assumptions and provides the minimum dimensions for the trenching. Requirements like temporary supporting walls are not considered. Fig. 1 illustrates the three pipe arrangements investigated in this study.

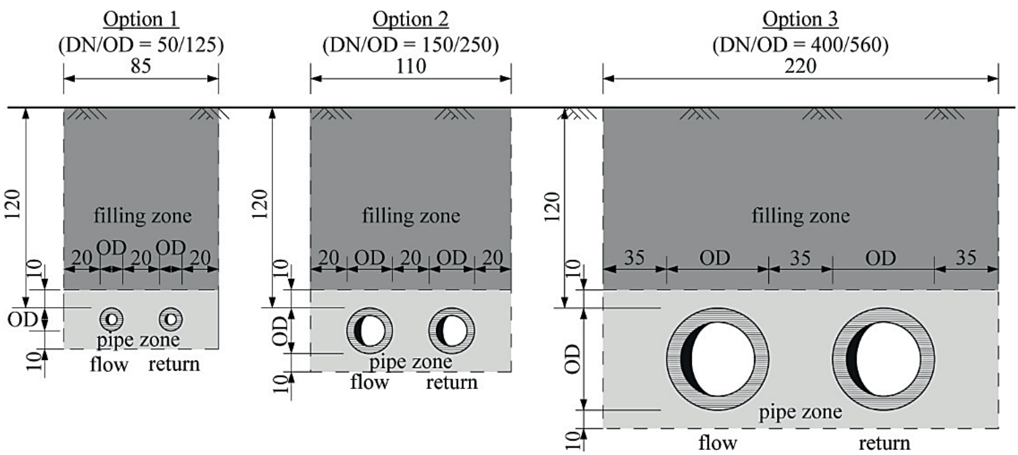


Fig. 1. Pipe arrangements.

2.3. Models for Steady-State Heat Loss, EN 13941 Method

In calculating steady-state heat losses, the predominant assumption is pure heat conduction, while factors such as convection, moisture transport, and phase changes are disregarded. Additional assumptions include homogeneous material properties and the absence of thermal resistances in the service pipe and casing [4], [6]. The process described by most steady-state heat loss models for DH applications involves radial heat conduction through the insulation to the soil as well as between the pipes [6]. The EN 13941 method, based on the findings of Wallentén [13], characterizes the heat loss of each DH pipe by combining symmetrical (q_s) and anti-symmetrical (q_a) heat losses, employing the multi-pole method. Following the EN 13941 the heat losses for both the flow (q_f) and return (q_r) pipe can be computed using Eq. (1) and (2).

$$q_f = q_s + q_a \tag{1}$$

$$q_r = q_s - q_a \tag{2}$$

The calculation of symmetrical and anti-symmetrical heat losses, Eq. (3) and (4), involves utilizing the flow and return as well as the undisturbed soil temperature. Furthermore, it includes a symmetrical (h_{sym}) and an anti-symmetrical (h_a) heat loss factor.

$$q_s = \left(T_{sym} - t_s\right) \cdot 2\pi\lambda_s \cdot h_{sym} \tag{3}$$

$$q_a = T_a \cdot 2\pi\lambda_s \cdot h_a \tag{4}$$

$$T_{sym} = \frac{T_f + T_r}{2} \tag{5}$$

$$T_a = \frac{T_f - T_r}{2} \tag{6}$$

The symmetrical and anti-symmetrical heat loss factors according to zero-order multipole formulae are described in Eq. (7) and Eq. (8). Z_c is a corrected value and is the sum of depth Z and the surface transition insulation R_o at the soil surface. R_o can usually be valued at 0.0685 (m^2·K)/W. Eq. (9) defines the dimensionless thermal resistance parameter β.

$$h_{sym}^{-1} = \ln\left(\frac{4Z_c}{D_i}\right) + \beta + \ln\left(\sqrt{1+\left(\frac{2Z_c}{C}\right)^2}\right) \tag{7}$$

$$h_a^{-1} = \ln\left(\frac{4Z_c}{D_i}\right) + \beta - \ln\left(\sqrt{1+\left(\frac{2Z_c}{C}\right)^2}\right) \tag{8}$$

$$\beta = \frac{\lambda_s}{\lambda_i} \ln\left(\frac{D_i}{d_o}\right) \tag{9}$$

2.4. Models for Steady-State Heat Loss, Equivalent Mesh Current Method (EMCM)

The Equivalent Mesh Current Method (EMCM) is a technique derived from the commonly known mesh current method used to analyse electrical circuits. As in [12], this method is now transferred to the problem of calculating heat losses of buried thermal insulated pipes. Mathematically EMCM does not differ from the traditional mesh current method. Both methods are based on Kirchhoff's voltage law (KVL) and can be solved using Gaussian elimination. Fig. 2 illustrates the EMCM for two buried DH pipes.

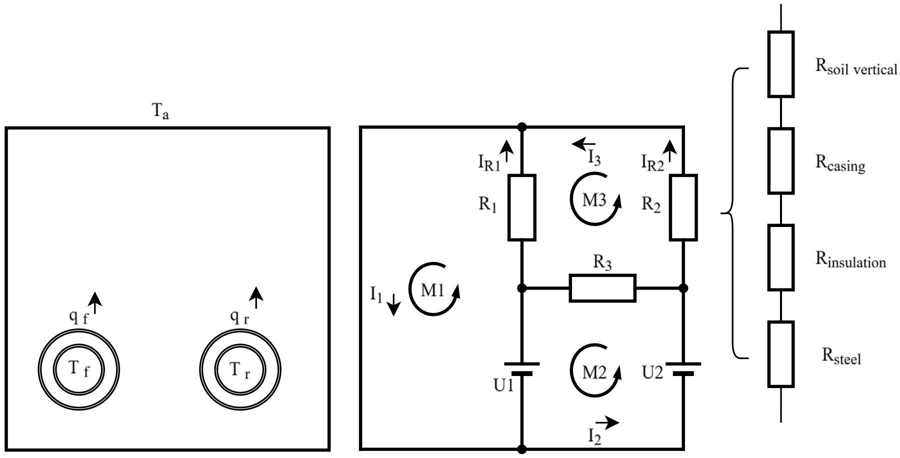


Fig. 2. Equivalent Mesh Current Method.

Electrical current describes the flow of charged particles. In EMCM the electrical current is translated into the heat current and ultimately the heat losses of the DH pipes as in Eq. (10) and Eq. (11). Through the principle of superposition, the element currents of I_{R1}, I_{R2} which describe the heat losses of flow and return pipe can be identified.

$$q_f = I_1 - I_2 \tag{10}$$

$$q_r = I_2 \tag{11}$$

Voltage is the difference in electrical potential between two points. EMCM translates the voltage to the temperature difference between two points. In our case between the outdoor air temperature and the flow and return temperature of the DH pipes as described in Eq. (12) and Eq. (13).

$$U_1 = T_f - T_a \tag{12}$$

$$U_1 = T_f - T_a \tag{13}$$

The extent to which an object resists the flow of electric current is indicated by its electrical resistance. The EMCM translates electrical resistance to thermal resistance (R) which describes the opposition a material offers to the heat current. Identical to a series circuit the thermal resistances of the materials are added up and described in Eq. (14) and Eq. (15). Since flow and return pipe have identical geometries and thermal properties they can be described as in Eq. (14).

$$R_1 = R_2 = R_{st} + R_i + R_c + R_{s\text{-ver}} \tag{14}$$

$$R_3 = R_{st} + R_i + R_c + R_{s\text{-hor}} + R_{st} + R_i + R_c \tag{15}$$

2.5. Models for Steady-State Heat Loss, Finite Element Method (FEM)

The determination of heat losses using the FEM is performed using the MATLAB program and its Partial Differential Equation (PDE) Toolbox. In general, FEM is a numerical technique for solving a variety of physical problems. It divides the geometric domain into small discrete elements. These elements are assembled into a system of algebraic equations and this system of equations is then solved using approximation techniques, such as iterative solvers or direct solution methods. The solution of a steady-state thermal model in MATLAB is based on the differential equation for steady-state heat transfer for the two-dimensional space as described in Eq. (16).

$$\frac{d^2T}{dx^2} + \frac{d^2T}{dy^2} = 0 \tag{16}$$

FEM typically adopts the following approach. Firstly, the model geometry of the system must be developed, where all relevant geometric parameters of pipes and trenches can be modelled based on shapes and coordinates within the two-dimensional space. The geometry thus sets the boundaries for mesh generation. Subsequently, a mesh is developed, further discretizing the model. Mesh generation is done automatically with pre-defined and case-specific boundary conditions for minimum and maximum triangle meshing. After mesh generation, in the case of steady-state heat transfer, boundary conditions are entered. These include the outdoor air temperature and convection coefficient of the ground, the soil temperature at the boundaries of the outer surrounding soil layer, the operating temperatures of the pipes at the inner pipe wall, and all thermal conductivities coefficients of steel service pipe, insulation, and casing, as well as different soil layers. After setting the boundary conditions, the system can be solved. The model determines both temperatures and heat fluxes at all nodes.

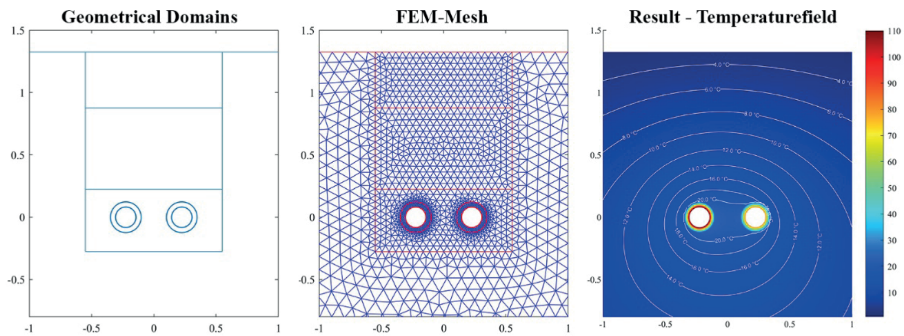


Fig. 3. Steady State Heat Transfer Analysis using MATLAB and PDE Toolbox.

Thus, the FEM model encompasses all pipeline geometries and trench details, along with the thermal conductivity coefficient assigned to each material. The soil is modelled as one layer with a thermal conductivity corresponding to the seasonal parameter. Furthermore, the thermal conductivity coefficient at the ground surface is assumed to be 14.6 W/(m·K) [20], and an estimated soil temperature of 8 °C for the winter scenario and 12 °C for the summer scenario according to Dahlem [15] is set on the bottom of the model at a depth of 3 m. Through the discrete mesh, results can be precisely interpolated at all locations within the model, and temperature profiles as well as heat flow profiles can be depicted in figures. This enables the dedicated evaluation of the temperature field and heat transfer. The steps of the steady state heat transfer analysis in MATLAB with PDE Toolbox are illustrated in Fig. 3.

3. RESULTS

3.1. Comparison of Input Parameters

A total of 17 possible input parameters were identified for the presented analysis and mapped in the FEM model. In contrast, the calculation model according to the EN 13941 standard is limited to seven parameters. The EMCM model forms the median, here eleven parameters are mapped. The parameter comparison reveals that EN 13941 and EMCM share relatively similar input parameters. For instance, the operating temperatures are equally captured by the three models. However, climatic data is implemented differently in varying levels of detail. In the FEM model, the outdoor air temperature, the thermal conductivity coefficient at the Earth's surface, and the soil temperature at a chosen depth are included to represent the climatic data, whereas the EMCM model only computes the external temperature.

TABLE 2. INPUT PARAMETERS

	Symbol	EN 13941	EMCM	FEM
Operational and climate data				
Flow and return temperatures	T_f, T_r	x	x	x
Undisturbed soil temperature	T_s	x^1		x^2
Outdoor air temperature	T_a		x	x
Coefficient of thermal conductivity				
Steel service pipe	λ_{st}		x	x
PU-Insulation	λ_i	x	x	x
PEHD casing	λ_c		x	x
Soil pipe zone	λ_{pz}		(x)	(x)
Soil backfill zone	λ_{bz}		(x)	(x)
Undisturbed soil	λ_s	x	x	x
Convection coefficient of ground surface	α_g			x
Geometry of pipes				
Steel service pipe	–		x	x
PU-insulation	–	x	x	x
PEHD casing	–		x	x
Pipe arrangement				
Geometry of trench (pipe, backfill zone)	–			x
Distance between pipes	z	x	x	x
Distance between casing and trench wall	b			x
Overburden height	H	x	x	x

Note: x = included, (x) = possible, but not included in this analysis, 1: at pipe, 2: gradient

The EN 13941 model, on the other hand, considers the undisturbed soil temperature at the level of the pipe axis and excludes the outdoor air temperature. Regarding the geometry and thermal conductivity parameters, it is observed that the FEM model reproduces the real system in the greatest detail. In terms of materials and geometries, the system can be represented in the last detail, e.g., the exact layer structure of the pipeline trench or other domains like additional pipes within the cross-section. EMCM simplifies geometry representation but offers a relatively detailed representation of the system, e.g., EMCM can model different soil layers and materials in the trench or different components of the carrier pipe. The EN 13941 method represents a clear simplification of the real system in terms of the geometries and materials depicted, the surrounding soil is represented as one layer and the pipe system is only represented by the thermal insulation. Table 2 provides an overview of the input parameters used in each heat loss model.

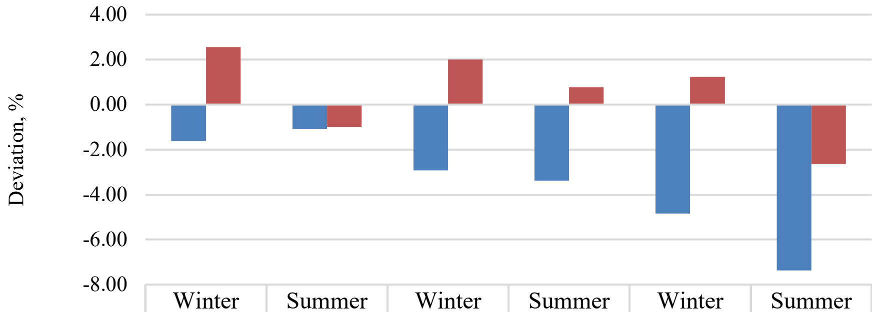
3.2. Evaluation of Results and Deviation of Models

Already known trends from heat losses of DH pipes can be derived from the results. For instance, lower heat losses are observed in summer than in winter, or a non-linear relationship between the heat loss and pipe size. As an example, the pipe cross-section of the DN 400 pipe is around 16 times larger than the cross-section of the DN 50 but the heat losses only correspond to a factor of 2 to 3, even though the insulation thickness does not increase proportionally with the nominal diameter. Each investigated scenario shows deviations due to the use of the different models. In terms of combined heat losses of the flow and return pipe, the EN 13941 model shows the lowest values, while the EMCM illustrates the highest. The results of the FEM model are in the middle range. The achieved results are presented in the following Table 3.

TABLE 3. RESULTS OF COMBINED HEAT LOSSES

	Scenario	**EN 13941**	**EMCM**	**FEM**	**Unit**
DN 50	Winter	42.081	43.868	42.775	W/m
	Summer	23.069	23.089	23.322	W/m
DN 150	Winter	72.535	76.214	74.721	W/m
	Summer	38.464	40.113	39.810	W/m
DN 400	Winter	89.540	95.257	94.090	W/m
	Summer	47.699	50.135	51.497	W/m

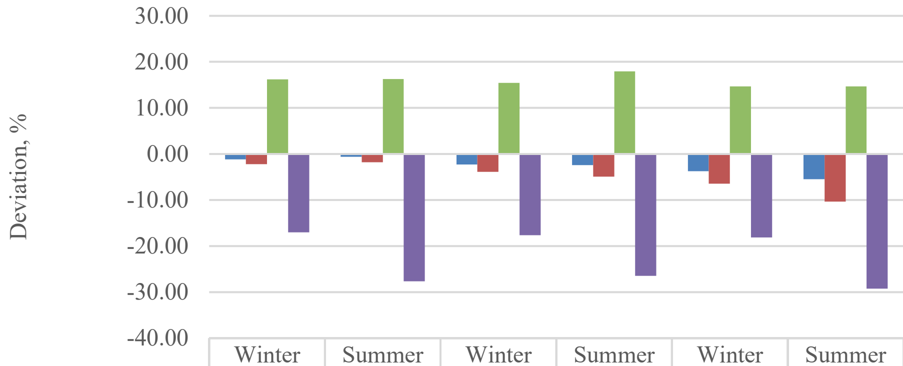
With the FEM model set as a base for comparison, the maximum negative deviation occurs with the EN 13941 method for a summer case with a DN 400 pipe, at −7.38 %. Conversely, the maximum positive deviation is seen with the EMCM for a winter case with a DN 50 pipe, at 2.56 %. The values from Table 3 indicate that for the EN 13941 method larger pipe dimensions correspond to higher deviations. Conversely, the EMCM results indicate that increasing pipe dimensions could lead to a reduction in deviation from the FEM Model for the winter case. In summer, the EMCM fluctuates between lower values and higher values when compared to FEM results. The deviations of EN 13941 and EMCM methods from the FEM method for combined heat losses of flow and return pipes are summarized in Fig. 4.



	Winter DN 50	Summer DN 50	Winter DN 150	Summer DN 150	Winter DN 400	Summer DN 400
EN 13941	-1.62	-1.08	-2.93	-3.38	-4.84	-7.38
EMCM	2.56	-1.00	2.00	0.76	1.24	-2.64

Fig. 4. Deviation of combined heat losses.

A detailed examination is conducted to gain a deeper insight into individual pipe heat losses. The findings highlight significant deviations in heat loss calculations, particularly for the return pipe when compared to the FEM model. The EMCM model exhibits a maximum deviation of −29.25 %, whereas the EN 13941 method calculates lower heat losses by approximately 10.32 % for the return pipe. Conversely, calculations for heat losses in the flow pipe reveal a negative deviation of 5.46 % by the EN 13941 method and up to 17.95 % by the EMCM method. Additionally, the EMCM model tends to determine higher heat losses in the flow pipeline and lower heat losses in the return pipeline for all cases investigated. Fig. 5 summarizes deviations in heat loss calculations between the EN 13941 and EMCM models, specifically focusing on flow and return pipe.



	Winter DN 50	Summer DN 50	Winter DN 150	Summer DN 150	Winter DN 400	Summer DN 400
EN 13941 flow	-1.19	-0.64	-2.27	-2.43	-3.74	-5.46
EN 13941 return	-2.23	-1.78	-3.88	-4.89	-6.42	-10.32
EMCM flow	16.20	16.28	15.43	17.95	14.66	14.65
EMCM return	-17.02	-27.65	-17.61	-26.45	-18.11	-29.25

Fig. 5. Deviation of combined heat losses.

4. CONCLUSION

The heat losses vary depending on the scenario and model employed. Furthermore, the integration of possible input parameters plays an important role in determining heat losses from buried thermal insulated pipes. In our analysis, we compared the results of three steady-state heat loss models (EN 13941, EMCM, and FEM), with a focus on their input parameters and the achieved results. Therefore, we characterized the input parameters into four categories. First the operational and climate data. Second, thermal conductivity. Third, pipe geometry, and fourth, the pipe arrangement. With regard to input parameters, the FEM model shows the highest number of included parameters, followed by the EMCM, and lastly EN 13941. In short, more input parameters enable the representation of the original system in a dedicated manner and thus offer a potentially high level of detail. However, the more complex the model is the more knowledge is acquired to establish and interpret it and usually a higher computational effort is included. It could also lead to more assumptions and mean values being used in the calculation, which results in a subjective improvement in the results.

The evaluation of the input parameters shows that differences in all four parameter categories exist. However, not each category influences the heat losses the same. While EN 13941 simplifies the system by reducing thermal conductivities and pipe geometries to insulation levels, the impact on heat losses is marginal due to the diminished influence on the thermal conductivity of the service steel pipe and the casing. However, for future developments in pipe components, it may be necessary to adjust the EN 13941 standard for the calculation of heat losses in DH pipelines. Since polymer service pipes have a significantly lower thermal conductivity compared to steel service pipes. Additionally, homogeneous trench structures and multiple material layers as found in latest DH network developments with alternative bedding materials cannot be considered with the EN 13941 method. Yet the influence of recycled building materials, such as recycled concrete aggregates may have an impact on heat losses which is currently under investigation in the research project UrbanTurn.

Another essential point that should be highlighted is the possible outputs the three models can generate. While the calculation formulas of the EN 13941 method are limited to the calculation of heat losses, combined or separately for flow and return, the EMCM and the FEM model enable a more detailed evaluation of the system. For example, the EMCM model also holds the potential to calculate the temperatures and heat flows at predefined points within the cross-section. Similarly, the FEM model offers both textual and visual output of the system investigated including temperatures as well as heat flows at arbitrary points which allows a comprehensive understanding of the system.

Because the FEM model considers the most input parameters of the three models it is understood to represent the original system the best and therefore was set as the base for comparison in this analysis. Derived from this assumption the EN 13941 and EMCM methods deviate from the FEM model. Considering the combined heat losses, it can be concluded that the deviation of the EN 13941 method is lower than 8 %, and the one of the EMCM method is lower than 3 %. A more detailed investigation of the individual heat losses of the flow and return pipes showed significant deviations in results for the EMCM method. Therefore, the EMCM method might be applicable to calculate combined heat losses, however, to analyse individual heat losses of the flow and return pipe it is unsuitable.

Since no validation of the results with measured data has been done, the deviation between the three steady-state heat loss models should be understood as indicative. Therefore, the next step is to evaluate the results of the study with measured data. This is planned to be done in the research project En-Eff_Netzregelung.

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