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Integrative consideration of sustainable heat management of urban quarters by thermal activation of infrastructure systems of residential water management

Prise en compte intégrée de la gestion durable de la chaleur dans les quartiers urbains par l'activation thermique des systèmes d'infrastructure de gestion de l'eau dans les habitations

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ABSTRACT: The inter-/transdisciplinary joint research project “IWAES” pursues the goal of adapting infrastructure systems of residential water management for the storage of thermal energy within an urban quarter under integrative consideration of urban development processes to create the basis for optimized heating and cooling balance. To this end, it must be investigated whether a balanced heating/cooling budget within an urban district can be achieved through technical, urban planning optimization and how an efficient, technically feasible infrastructure for the distribution and storage of heat energy using a sewer system looks like.

RÉSUMÉ : Le projet conjoint inter-/transdisciplinaire "IWAES" a pour objectif d'adapter les systèmes d'infrastructure de gestion des eaux urbaines au stockage de l'énergie thermique dans un quartier urbain en tenant compte des processus de développement urbain afin de créer les bases d'un équilibre optimisé entre chauffage et refroidissement. À cette fin, il s'agit d'étudier si un budget équilibré de chauffage/refroidissement peut être atteint dans un quartier urbain grâce à des optimisations techniques du développement urbain et de voir à quoi ressemble une infrastructure efficace et techniquement réalisable pour la distribution et le stockage de l'énergie thermale en utilisant les structures de la gestion des eaux urbaines.

KEYWORDS: Near-surface geothermal energy, sewer construction, composite heat network

1 INTRODUCTION

The production of thermal energy takes 70% of the total energy consumption in a German household. Currently, only 14% of this thermal energy is generated from renewable energies. The status quo regarding carbon emissions means a temperature rise to 4.8°C in the upcoming 100 years. Since thermal energy is produced mainly by fossil fuels, developing sustainable energy sources is necessary to stop global warming. The research project IWAES considers the development of sustainable systems for thermoregulation, which will be mandatory in mostparts of the world due to globally rising temperatures. The idea of IWAES is to use the infrastructure of the urban wastewater to both transport heat from household to household in an urban district as well as extracting heat energy from the ground and the wastewater flow. The thermal activation of the duct system enables energy savings through transportation and regenerative energy extraction through withdrawal. The final goal is to achieve a thermal energy balance in a defined urban district.

2 IWAES RESEARCH PROJECT

2.1 *Hybrid sewer*

2.1.1 *Hydrothermal basics*

The hybrid sewer consists of a sewer that carries wastewater and is additionally thermally activated. The absorber pipes are either integrated into the shell of the sewer mostly in the case of concrete ducts or placed on the outer circumference in a typically helical arrangement (Fig. 1).

Figure 1. Hybrid sewer with helical absorber

The cross-sectional area of the sewer is defined by standards [DIN EN 732]. The flow characteristics of the wastewater are the result of the hydraulic gradient and volume of wastewater. The flow characteristics within the absorber pipes are the result of the geometry of the absorber pipes. A reduction in the cross-section of the absorber pipes leads to an increase in the flow velocity at a constant flow rate and vice versa (see Eq. 1)

$$v = \frac{Q}{A} \quad (1)$$

v: Flow velocity [m/s]
Q: Water flow [m³/s]
A: Area [m²]

The non-radial heat flow is calculated from the temperature gradient and the heat transfer coefficient h (see Eq. 2).

$$\dot{Q} = \int_0^A h \cdot (\vartheta_2 - \vartheta_1) dA \quad (2)$$

$\dot{Q}$: Heat flux [W]
h: Heat transfer coefficient [W/(m²K)]

The main heat flow in the absorber pipes is achieved by forced convection. The dimensionless heat transfer coefficient of forced convection is known as the *Nusselt* number. The *Nusselt* number is not constant but depends on several factors, including the flow velocity. An increase in the flow velocity leads to an increase in heat transfer. In addition, a large surface-volume ratio ensures a high heat transfer between the absorber pipes and the surrounding soil. That means the larger pipe diameters have a lower surface area to volume than smaller pipe diameters and therefore conduct less heat.

Absorber pipes should provide high heat transfer property. Therefore, as you can see in Fig. 1, they have small diameters. On the other hand, transport tubes should allow a small heat transfer. On the other hand, pipes that should allow a small heat transfer have a large diameter as this is chosen for the three transport tubes above the sewer canal (Fig. 3 & 4).

2.2 Operating modes and their layouts

For the integration of the hybrid sewer into a sustainable heat management of urban quarters different operating modes were defined to enable the distribution of thermal energy within the urban district. Three operation modes: feeding-in, transport, and energy withdrawal consider decisive factors for designing a hybrid sewer system. Depending on the operation mode, an optimal configuration for the absorber pipes can be chosen.

2.2.1 *Feed-in mode*

All designed sewer cross-sections are suitable for feed-in operation, as absorbers mounted on the outer circumference of the sewer do not reduce the internal cross-sectional area of the sewer and do not interact with the objectives of the other operating modes. For an effective feed-in operation (see Fig. 2), a large area in contact with the ground is generated by externally installed, helix-shaped absorbers. In feed-in mode, the surrounding soil serves as a heat reservoir.

2.2.2 *Transport mode*

By adding external transport tubes, it is possible to transport thermal energy (Fig. 3). The transport pipes are not directly connected to the sewer´s cross-section and located separately in the ground. The aim is to reduce transport losses due to the interaction between the transport pipes and the sewer. The only task of the transport lines is to connect different users or hubs (Fig. 5) with heat supply and demand.

2.2.3 *Extraction mode*

It is shown in Fig. 4 that the internal absorbers and a steel chute were added to the hybrid duct. Every steel chute element has a length of 1 m. The right internal absorber pipe is the inflow. The steel chute consists of two sheets lying on top of each other with a gap of 2 mm. The heat transfer fluid flows through the inflow pipe to the outflow pipe (the bigger pipe on the left). Every sewer element is 6 meters long and thus has six steel chute elements. For a hydraulically balanced system, the pipelines must be of equal length to and from the steel chute according to the "Tichelmann" method [Laasch]. Therefore, a third pipe is necessary. The internal absorbers achieve the highest heat output through direct contact with the flowing wastewater. But for reasons of occupational health and safety the installation of internal absorbers is only possible for diameter ≥ 800 mm on.

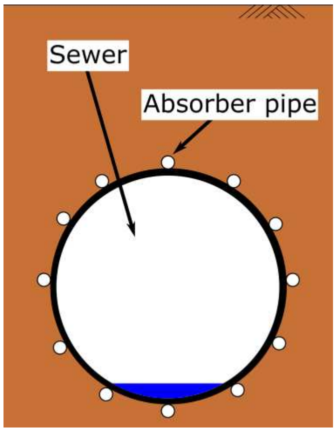

Figure 2. Hybrid sewer with feed-in function (outer absorber)

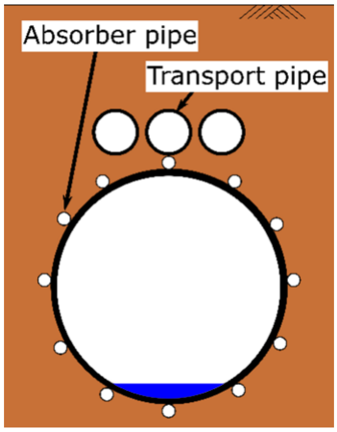

Figure 3. Hybrid sewer with feed-in and transport function

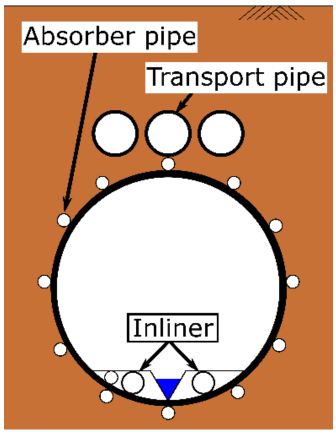

Figure 4. Hybrid sewer with feed-in, transport and extraction function

2.2 *Thermal supply concept*

The thermal supply of a single user shouldn´t be considered individually but as part of a network. This network comprises all users in different buildings of a quarter. In an ideal concept, all the buildings are connected to a system, where every user can insert and extract thermal energy. For this purpose, IWAES uses the available infrastructure of urban water management.

The goal - a harmonious heat balance - is achieved when the sum of the thermal requirements within the network is zero. To achieve this goal, the balance between the heat source and heat sink between all users would be the optimum. However, the implementation of this requirement is complex due to a large number of users and their different demand profiles. The heat balance is therefore balanced on several levels, starting at the lowest level - the building level (first level) - and ending at the top level - the quarter level (third level). The levels are oriented towards the urban structure and the sewerage network

At the first level, the thermal demand is to be covered by the thermal balance of the individual users or by locally available renewable energies. If there is still a thermal demand, heat is extracted from or added to the second level. If no thermal compensation is possible in the second level, thermal energy is first extracted from the ice storage. When the potential of the ice storage is completely reduced, heat is extracted from the third level. If thermal compensation is also not possible in the third level, heat is extracted from the sewer system and other local renewable thermal energy sources. Through the thermal equalization over several levels, it is possible to determine which heat demand exists in which part of the quarter.

Based on empirical data, typical residual load curves can be developed for the quarter, which can be used to evaluate the need for additional thermal buffer storage. Storage of thermal energy is necessary for a balanced thermal budget to achieve a temporal decoupling of the heating and cooling demand load profiles. In a final step, the possibility of covering the remaining thermal requirements by renewable energy sources available in the quarter will be checked..

2.3 *Project area*

The research site 'Rosenstein-Quarter' is located in Stuttgart, Germany, close to the city center. Due to the relocation of the railway infrastructure to the underground an area of 850 000 square meters can be converted into a residential quarter. The target of the municipality is to create a "plus energy quarter", where more energy is produced than consumed. One component to reach this goal is an effective and regenerative thermal energy system. A high population density and accordingly high volume of wastewater will characterize the new residential area. Furthermore, there is no existing sewer system and thus no restriction in sewer geometry. The project area is located in a mineral spring protection area, which leads to obligations in terms of additives. It is prohibited to use glycol as a heat transfer fluid to prevent frost damages. Therefore pure water should be used as the refrigerant fluid in the absorber loops. Consequently, the minimum flow temperature is 0°C, so the maximum amount of heat energy extraction is limited.

2.4 *Practical implementation of the thermal concept*

By applying the concept to the study project area 'Rosenstein-Quarter', the different levels can be considered (see Fig. 1):

- First scope: building block, Equilibrium through heat and cold transportation.
- Second scope: Hub area, Equilibrium through heat and cold transport and optional heat insert and extraction and optional ice storage
- Third scope: Entire quarter. Equilibrium through heat and cold transportation and optional heat insert and extraction.

2.5 *Transport and distribution concept*

The transport and distribution of thermal energy to the consumers takes place at the building block level (first level). The difference to a classical building distribution system is that the different consumers consider as either heat sinks or heat sources which should be balanced with each other. For this purpose, the distribution network is designed as a ring (first level). Within the ring, the heat can be injected (feed-in) in and out. Also, other

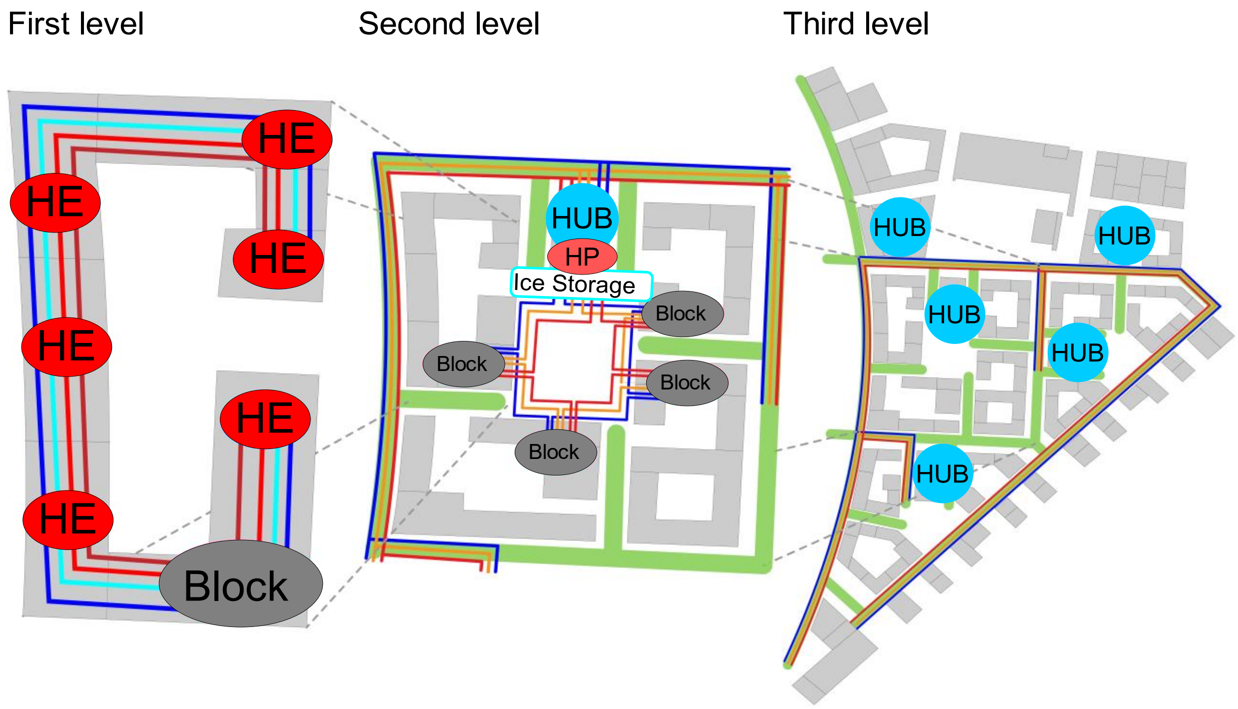

Figure 5. Three-stage system on the level of a quarter with the integration of the thermally activated sewer network. (HE = heat exchangers, HP = heat pump) The blue line represents cold transport lines, the yellow line a medium-warm transport line and the red line a warm transport line [IWAES].

regenerative thermal sources can be integrated as energy producers (solar thermal energy, outside air, (direct) geothermal energy, etc.).

A supply ring (second level) is also provided for the hub areas level, which connects the individual supply rings of the building block level with one connection each. This enables heat equalization between the blocks. The heat energy of the wastewater absorber and other regenerative thermal energy sources are coupled into the supply ring via the hub. The residual heat and cold requirements for the hub area are to be covered centrally from the hub with the processed thermal energy of the wastewater absorbers or the buffer storage. The processing is carried out by a heat pump integrated into the hub.

Depending on the operating mode, the hubs are connected at three levels to a primary ring which serves as a heat sink/source for the heating/cooling machines. The primary ring (3. level) is consisted of various channel cross-sections (see 5.3) and can transport thermal energy and supply or extract thermal energy from the wastewater. The quarter hubs are the interface between the primary ring and the second ring of the hub areas. This function predestines the hub as the location of the thermal buffer storage.

Each connection between two rings is equipped with heat exchangers, thus ensuring hydraulic decoupling between the rings. The quarter hubs and partly the connections of the building block level are equipped with heating/cooling machines to raise the transport fluid to the desired temperature. If the desired useful temperature is already available in the ring simply by exchanging waste heat, the heating/cooling machine can be bypassed.

3 NUMERICAL SIMULATION

The numerical simulation considers the heat flows from all the thermally boundary conditions such as solar radiation, wastewater temperature, and the airflow temperature in the duct. Also, all hydraulic influences from the flow of the wastewater and the absorber fluid are considered.

3.1 2D Simulation

The entire model has a width of 20 m and a height of 10 m. The soil cover of the sewer varied from 0.5 m up to 4.5 m. The surrounding soil is cohesive, the sewage pipes and the absorber pipes are made of plastic (Fig. 6).

The lower and lateral edges of the model are considered to be thermally adiabatic. The upper boundary is defined as a *Dirichlet* boundary condition. The temperature curve was plotted with the location-accurate test reference years of the German meteorological service. The aforementioned Rosenstein-Quarter in Stuttgart was considered as reference location (Fig. 7). The heat transfer coefficient was determined according to [Beisel 1999] solely from the average wind speed at the earth's surface. The usual method of inferring the *Nusselt* coefficient using the *Reynolds* number does not work in urban areas, as the necessary length of the already overflowed slab cannot be determined.

$$\alpha = \begin{cases} 1{,}8 + 4{,}1 \cdot v & v \leq 5\frac{m}{s} \\ 7{,}3 \cdot v^{0{,}73} & v > 5\frac{m}{s} \end{cases} \tag{3}$$

The boundary conditions on the surface, the inner wall of the absorbers, the surfaces in contact with the wastewater, and the duct air are modeled with Dirichlet boundary conditions. The velocity of the wastewater was determined from the wastewater volume and the gradient. Measured data from the main sewage treatment plant in Stuttgart were taken as the wastewater temperature. The wastewater air was assumed to have the same temperature as the wastewater and to have no flow velocity. The pipe-specific *Nusselt* number was assumed for the heat transfer between the sewer air and the inner sewer wall. For the heat transfer between the wastewater and the sewer wall, the *Nusselt* number for flat plates was assumed. The wastewater usually only flows in the bottom of the sewer, which is why this can be assumed to be a flat plate.

The simulations consist of two simulations. In the first simulation, the initial temperature regime is generated, which is influenced only by the surface heat input. The second simulation builds on the results of the first simulation. Now the temperature influences from the duct air, wastewater, and the activated absorbers are added. The mesh of the 2D simulation is coarse on the outside and becomes finer towards the absorbers and the sewer canal (Fig. 6).

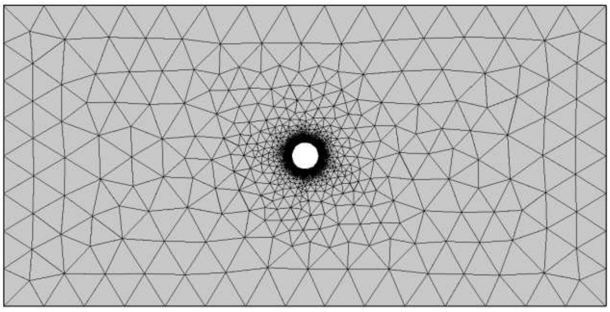

Figure 6. Mesh of the 2D model

3.1.1 *Load profile*

Load curves specify the consumer´s demand and consumption of heat energy. The load curves used so far are based on the Technical Rules for workplaces, which stipulate that workplaces must be cooled for outside temperatures above 26°C and heated below 12°C. In accordance with the load curve, the quarter is heated for 4770 hours a year and cooled for 178 hours a year, see Fig. 7. A detailed, spatially resolved residual demand curve for the entire quarter is currently being determined. During the hours in which cooling is required, the absorbers at the sewer are supplied with an inflow temperature of 30°C, and during the hours in which heating is required, they are supplied with a temperature of 2°C. In summer, the aim is to transfer as much heat as possible to the waste water. In winter, the goal is to gain as much heat as possible from the wastewater. To create as high a temperature gradient as possible (see Eq. 2), a warm heat transfer fluid is used in summer, which is cooled by the wastewater and then cools the building. In winter, a cold heat transfer fluid is used, which absorbs heat from the wastewater and then heats the building.

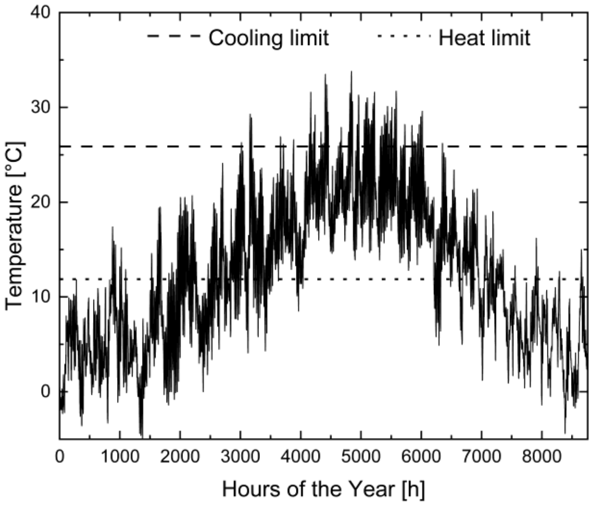

Figure 7. Load profile for the “Rosensteinquartier” in the year 2045

The results show that heat extraction with and without inner absorbers (Fig. 2.) has an average power of up to 35 W/m² and 85 W/m² respectively with heat input (cooling) into the sewer, a power of up to 85 W/m² without inner absorbers with inner absorbers a power of up to 105 W/m² is possible.

3.2 3D Simulation

The geometry of the 3D simulation is 20m wide, 10m high and 6m deep. The external absorbers are mounted helically on the sewer. If the absorbers were mounted in parallel as in the 2D simulation, the lowest absorbers would be crushed during the installation of the sewer.

Like in the 2D calculation, the three-dimensional calculation covers two years with 8760 hours each. A parameter study at this computation time would take too long, which is why the system was reduced in geometry as a first step. A deviation of 1% in the extraction performance in the first month was accepted. The reduced model has the dimension of 4m* 4m*6m for width, height, and depth respectively.

In the first investigations, the influence of parameters on the extraction performance of the absorbers was examined. The diagrams in Figs. 9 - 12 each show the influence of a parameter on the extraction capacity in the month of January.

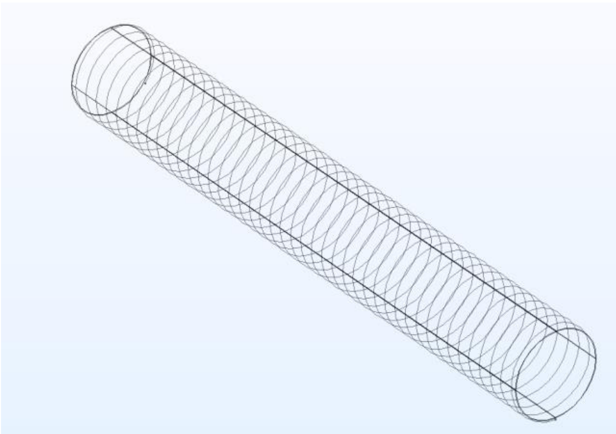

Figure 8. Geometry of the helical absorber

The heat flow at the surface is the same as in 2D as the *Dirichlet* boundary condition. The volume flow of the heat transfer fluid inside the absorber pipe is 0.8 m³/h, which induces a flow condition in the transition range (Re ≈ 3000). According to [VDI 4640], this flow condition is optimal for ground-coupled heat pump systems. A higher Reynolds number would increase the friction and thus the necessary pump energy. A smaller Reynolds number would reduce the dimensionless heat transfer coefficient. The channel and the helix are made of plastic (mainly Polypropylene). The surrounding soil is cohesive. The heat transfer fluid is normal water; as already mentioned, the use of glycol is prohibited in the Rosensteinquartier. Consequently, no inlet temperature below 0°C can be used. On the one hand, this restriction reduces the maximum possible temperature gradient and thus the heat flux density; on the other hand, the use of glycol reduces the specific heat capacity and also reduces the maximum heat flux density, see Eq.4.

$$\dot{Q} = \dot{V} \cdot c_p \cdot \rho \cdot (\vartheta_{outlet} - \vartheta_{inlet}) \quad (4)$$

The thermal boundary conditions were applied and determined in the same way as in the two-dimensional model. As already mentioned, investigations are being carried out concerning the flow velocity and temperature of the duct air. Initial three-dimensional investigations showed that the wastewater flow increases the possible heat extraction capacity. Fig. 10 shows that the influence of the velocity of airflow in the sewer on the extraction rate is marginal. The temperature boundary for the air inside the sewer was not define separately.

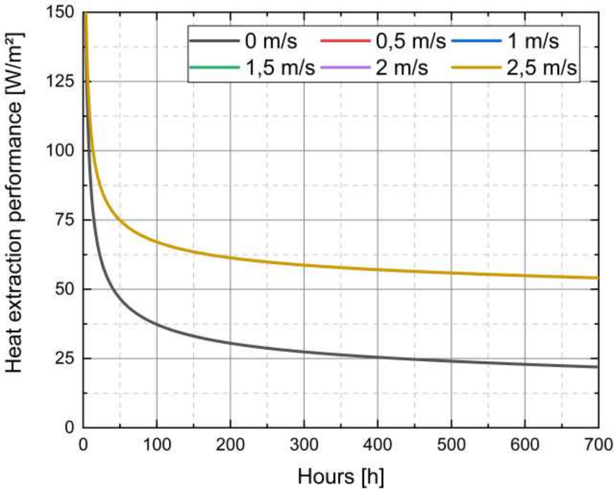

Figure 9. Heat extraction as a function of the flow velocity of the wastewater. The values above 0 m/s are approximately identical and are therefore overlaid in the diagram

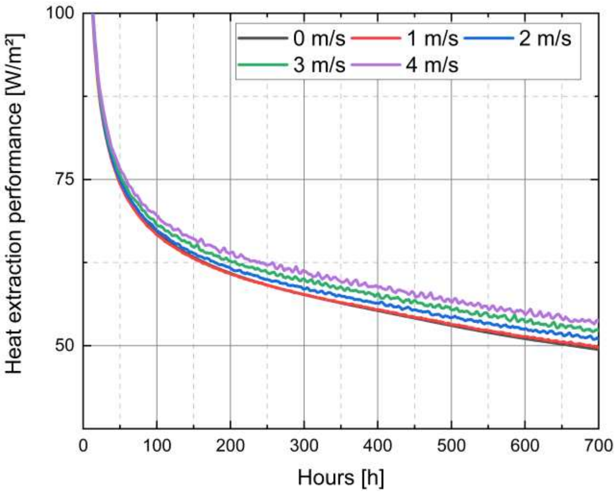

Figure 10. Heat extraction as a function of the flow velocity of the air in the sewer

Fig. 11 shows the influence of the wastewater temperature. The flow velocity of the wastewater was 0 m/s during the simulation. Fig. 12 shows the influence of the air temperature in the sewer. The wastewater had a velocity of 0 m/s and a temperature of 10°C during the simulation. It can be seen that the influence of the temperature of the wastewater is more significant than the influence of the air temperature inside the sewer.

3.2 Validation

Usually, the validation of a numerical calculation is done by comparison with measurement results. Unfortunately, complete field measurement data that allows a comparison between numerical results and measured data are currently not available.

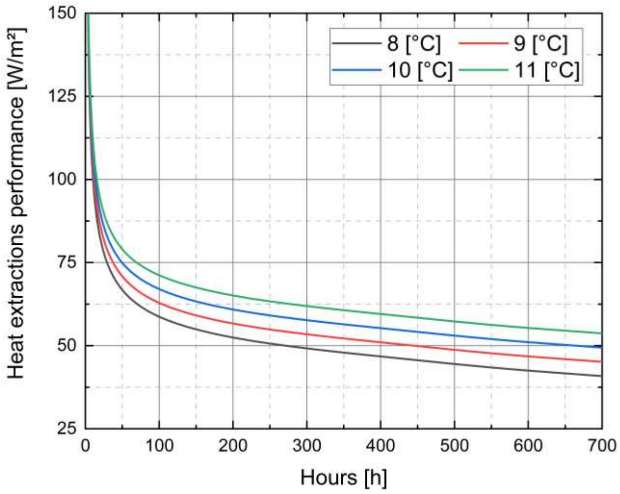

Figure 11. Heat extraction as a function of the wastewater temperature

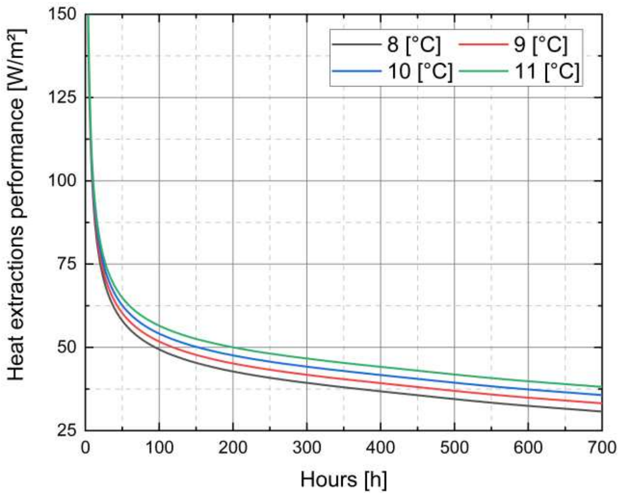

Figure 12. Heat extraction as a function of the duct air temperature

Therefore, the validation has been done step by step. Each step is checked for reasonableness and the models are built up from simple to increasingly complex.

Moreover the results of 2D calculations were compared with 3D calculations. However, this is only possible if the absorbers generate a constant heat flux density over the model depth. And the 3D models can be mapped two-dimensionally without reducing the geometry, i.e. a helix cannot be mapped completely two-dimensionally. For the parallel absorbers with applied *Dirichlet* boundary conditions, the same values were calculated in 2D as well as in 3D.

Exact validation is only possible if measured data are available. As long as these are not available, the approaches mentioned must be specified and improved. Further three-dimensional calculations are carried out, but waiting for further validation means that the results have to be checked carefully.

4 CONCLUSIONS

The thermal supply concept developed is based on absorber systems. The thermal activation of the sewers is particularly suitable, as an already existing infrastructure can be used. The constant flow of wastewater continuously transfers heat into the ground and the wastewater system, and the absorbers can both extract and supply heat to the hybrid sewer at the baseload.

5 ACKNOWLEDGEMENTS

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