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MODELING OF THERMAL ENERGY BALANCE IN SEWER SYSTEMS

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Recent studies have indicated that wastewater contains relatively large amounts of thermal energy. Recovering this thermal energy can be used to decrease the CO_2 footprint of the water cycle. This paper describes the development of a model to simulate the heat balance and predict the temperature in a sewer system. The model can be used to estimate the recoverable thermal energy and its dynamics. The model was verified with field data. It was concluded that the model is a powerful and accurate tool to simulate the heat balance of a sewer system at the urban district level. It was found that the recoverable heat show highly dynamic patterns, directly related to water consumption patterns. The recoverable heat depends on technical aspects as well as regulations for maximum acceptable temperature differences due to heat abstraction.

INTRODUCTION

Many water utilities in the world have high sustainability ambitions. This means that their production and distribution of drinking water, and the collection and treatment of wastewater has to be done in an energy efficient way and with limited use of chemicals. Many utilities have optimized their treatment systems and have installed automatic process control to minimize their energy consumption. A second important factor to achieve sustainability for utilities is to minimize their emissions of greenhouse gases. Because their own energy consumption is already at a minimum, other ways have to be found to reduce or compensate their CO_2 emissions[1].

Recent studies showed that the energy required for providing warm water for showering and bathing, for laundry washing and for dish washing at homes is 10 to 20 times higher than the operational energy required for the water and wastewater treatment and transport [2, 3]. The warm water at homes is discharged to the sewer after use. This means that the sewer is an important heat sink in the modern house: up to 50 % of the energy used in a home will be lost in the sewer. Heat recovery in the sewer can therefore be an interesting option to reduce use of primary energy sources. Many water utilities are therefore investigating heat recovery from sewers as an additional service to their customers and as a measure to compensate for their CO_2 emissions.

An important question for heat recovery from sewers is where the most optimum location in the sewer system is to install a recovery system. Close to the homes, the temperature of the waste water is still relatively high, but the volume flow is low and highly dynamic. On the other hand, going further downstream the sewer system, the flow will be higher and more continuous, but the temperature or heat content will be lower, because of the heat loss to the soil during transport. In this paper a model is developed to dynamically predict the heat content of sewage, based on the heat input at the homes and the heat balance of the sewage system. Furthermore, measured field data will be presented to validate the model results and estimate heat transfer parameters in the model.

MODEL DEVELOPMENT

Model overview

To determine the heat balance of a sewer system two aspects are important: the (external) heat input, coming from warm water discharged into the sewer. The main source is domestic wastewater. Of course other discharges of warm water may occur, mainly from smaller industrial users (industrial laundry, food industry etc.). For the model application, the latter is discarded. The heat content of the domestic wastewater is predicted by stochastic demand patterns of drinking water. The second aspect is the heat balance of the sewer system itself. This describes the heat transport by the water and the heat loss to the environment. Both aspects are described in more detail below.

External heat sources

The most important heat load for the sewer system is the discharge of warm water from homes (in The Netherlands). Also warm water uses in sports accommodations, hotels and office buildings may contribute to the heat load of the sewer system. The discharge of wastewater from homes is closely connected to the water use in the home. Sometimes a short time delay between the water use moment and the discharge may occur – e.g. a bath tub is first filled and emptied after some time – but the total discharged volume will be closely connected to the water use. Furthermore the temperature of the discharged water is related to the water use in the home. E.g. a shower or bath has a temperature of around 35°C.

A detailed model (SIMDEUM®) has been developed to predict water uses in homes [4] and later in hotels, office buildings, nursing homes and other non-residential buildings [5]. These stochastic models accurately predict the water use in these buildings on high frequency level (minutes). The models also include information of the specific application of the water and therefore can predict also the temperature of the water. The SIMDEUM model can therefore be used to dynamically predict the water flow [6] and temperature input to the sewer from homes and other buildings.

Heat balance of a sewer

A detailed sewer heat model was developed by Dürrematt *et al.* [7-9]. This model was used as a starting point for model described in this paper. Dürrematt *et al.* describe all possible heat generation or heat loss factors relevant in a sewer section. For calculations on a full scale sewer system of a whole city district or neighborhood with many sewer pipes and nodes, this would be too complicated so simplifications are required. To simplify the model, it was necessary to know which heat flows in the model are determining the heat balance and which can be neglected.

The Dürrematt *et al.* model includes 12 processes that have an influence on the heat balance: (1) water transport, (2) advective heat transport, (3) heat transfer from water to the pipe wall, (4) heat exchange from the pipe wall to the surrounding soil, (5) heat conduction through the pipe material and the soil, (6) heat exchange between water and air in the pipe, (7) heat exchange between air and the pipe material, (8) air flow in the pipe, (9) evaporation or condensation, (10) transport of water vapor, (11) heat exchange by condensation at the pipe wall and (12) heat exchange by condensation of supersaturated vapor (mist formation).

<u>Heat transport in water</u>

The first process, i.e. water transport, can be solved by one dimensional flow equations for open surface flow [10], the equations for the other processes can be found in [8].

The heat transport equation can be expressed as follows:

$$\frac{\partial A_w T_w}{\partial t} + \frac{\partial Q_w T_w}{\partial X} - \frac{1}{c_{p,w}\rho_w} \dot{q_{Rw}} L_w = 0 \qquad (1)$$

with T_w the water temperature (K), A_w the water surface area (m2), L_w the wetted perimeter (m), Q_w the water flow ($m^3 s^{-1}$), $c_{p,w}$ the specific heat of water (J $kg^{-1}K^{-1}$) and ρ_w the water density (kg m^{-3}).

The heat flux from the pipe wall to the water is calculated as follows:

$$\dot{q_{Rw}} = \alpha_{Rw}\left(T_{pw}^{(1)} - T_w\right) \qquad (2)$$

with $T_{pw}^{(1)}$ the pipe wall temperature at the beginning. The parameter α_{Rw} is the heat transfer coefficient (W $m^{-2}K^{-1}$). It depends among others on the flow rate and turbulence of the water. Its value can be calculated from the Nusselt number:

$$\alpha_{Rw} = \frac{Nu_w \lambda_w}{R_w} \qquad (3)$$

with λ_w the thermal conductivity (W $m^{-1}K^{-1}$) and R_w the hydraulic radius (m). The Nusselt number can be derived from the empirical Dittus-Boelter equation [11], using the Reynolds (Re) and Prandtl (Pr) numbers:

$$Nu_w = 0.023\, Re^{4/5} Pr^{1/3} \qquad (4)$$

<u>Heat transport in pipe wall</u>

The (radial) heat transport in the pipe wall is described by

$$\frac{\partial T_p}{\partial t} + \frac{\lambda_p}{r c_{p,p}\rho_p}\frac{\partial}{\partial r}\left(r\frac{\partial T_p}{\partial r}\right) = 0 \qquad (1)$$

At the pipe-water interface this equation is constrained by the heat flux being equal at both sides but with opposite sign. The heat flow in the surrounding soil is described by a similar equation.

Sensitivity analysis

The contribution of all individual heat exchange processes in the sewer section was determined by a sensitivity analysis using different scenario's. The contribution of each process in the three heat balance equations (equations 5, 9 and the heat balance of the soil) were calculated for the winter and summer situation, dry and humid air in the sewer, with or without air ventilation, and 10% or 90% filling of the sewer pipe. Additionally a dynamic and a stationary (> 24hr) situation were distinguished, while focus was on the smaller sewers in urban neighborhoods that directly receive waste water from the dwellings.

The sensitivity analysis indicated that for smaller sewers where the dynamic situation predominates, the heat exchange between the water, the pipe material and the surrounding soil needs to be included in the model. All air related heat processes can be neglected. For the larger transport sewers, with a more stationary flow character, the air related processes can play a relevant role.

Implementation

For the model implementation, the SOBEK®-suite was used [12]. SOBEK® is a powerful modeling suite to simulate and predict complex water flows [10] in open surface networks (1D, rivers, canals, sewer systems) and horizontal grids (2D, e.g. stormwater run-off). The suite can be seen as an industry standard for sewer modeling. Many sewer networks of Dutch municipalities are designed and optimized using this system. The heat balance equations were programmed in the Delwaq water quality module of SOBEK® which is an opten source multi-dimensional solver for the advection-diffusion equation, with the assumptions from the sensitivity analysis for small sewer mains. The heat input for SOBEK® was generated by demand and temperature patterns from SIMDEUM®.

RESULTS

Model simulations

Figure 1 shows a cross section of sewer mains that is filled for 50 % with water of 30°C. From this figure it is clearly seen that the warm water is heating up the pipe material and the surrounding soil, especially, as expected, at the bottom side of the pipe.

After some validation measurements (not shown here) the model was used to simulate the sewer system of an entire urban district, the Danswijk in the city Almere. The Danswijk is a residential area mainly consisting of one family homes. In total approximately 6,000 PE are connected to this separated sewer system. The entire system consists of PVC mains of 250 mm diameter, except for the three most downflow pipes, which are 315 mm in diameter. Figure 2 show a schematization of the area.

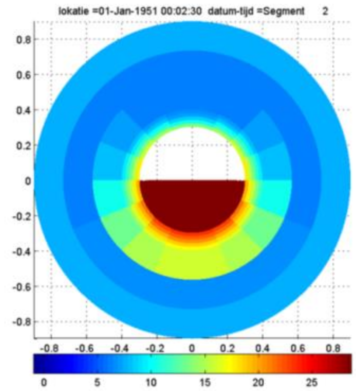

Figure 1. Cross section through a half filled sewer pipe. Colors represent predicted temperature levels.

The model was fed with discharge and temperature patterns generated by SIMDEUM® and temperature and flow data were calculated at several nodes in the system. From the flow and temperature data, the heat content of the water can be calculated. Also different seasons were assumed: winter, summer and spring/autumn with soil temperatures of respectively 8, 18 and 13°C for the local situation in the Danswijk, derived from meteorological data and a correction for the urban heat island effect.

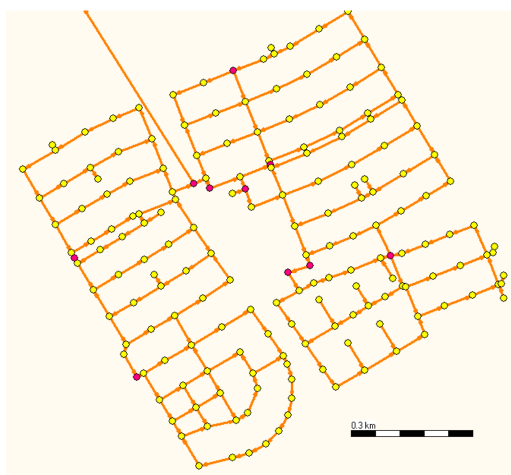

Figure 2. SOBEK® schematization of the sewer system layout of the Danswijk (nodes represent manholes interconnected by sewer pipes).

In the next step the recoverable heat was calculated. The recoverable heat can be calculated in several ways. each method requires some assumptions. Option 1 (PTmin) assumes that the temperature at the sewage treatment plant may not drop below a certain level. In our case we assumed 20°C as a minimum. Option 2 (PWin) assumes a recoverable energy based on a maximum temperature difference of the sewage water of 1°C. In Option 3 (Ptsa) a is counter current heat exchanger is simulated in SOBEK® with assumed temperature levels in the cooling liquid suitable for storing the heat in an aquifer thermal energy storage (ATES) system.

Figure 3 shows the results for the three situations in the spring/autumn season during 5 week days. The recoverable heat of the three options is shown for the total discharge of the Danswijk (6,000 PE). The figure shows that the recoverable heat is highly dynamic, depending largely on the water consumption patterns. The highest levels of recoverable heat are found around 8 am and between 4 and 11 pm. During the night the recoverable energy drops almost to zero.

Furthermore the recoverable energy depends on the option used and for practice of course which of the three options is used. If option 3 is assumed (Ptsa) on average 100 kW, or 3.2 GJ/y, can be recovered from this wastewater stream.

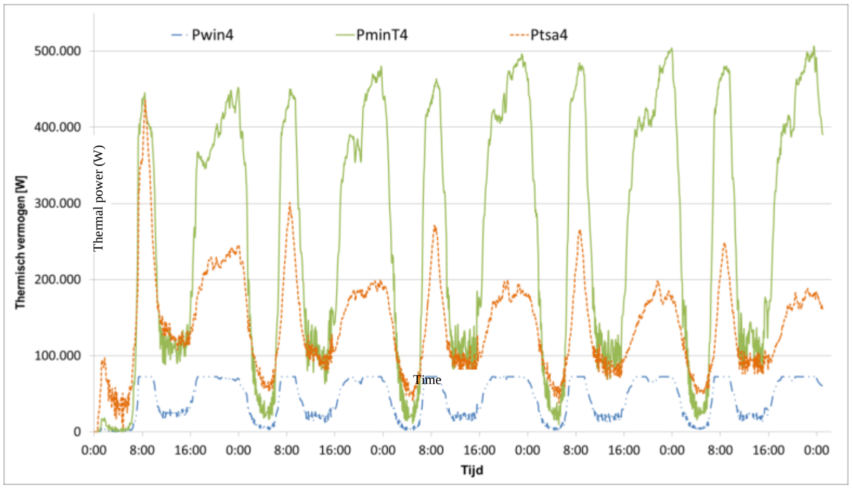

Figure 3. Simulated recoverable heat for 6000 PE in the Danswijk, Almere during spring or autumn at week days

Field data

In 2012 actual temperatures and flows in a sewer pumping station in Amsterdam were monitored for two months. The pumping system was connected to two dead end sewer branches with in total 143 apartments connected. Figure 4 shows the measured flow at the pumping station and the sewage water temperatures of both sewer branches just before the pumping station. The data show again the highly dynamic behavior, related to the water consumption patterns of the homes. The patterns are different from the patterns used to simulate the Danswijk, because the water use is more constant during the day (the morning and evening peaks are missing). From the data the recoverable heat was calculated using Option 1 (PTmin) with a reference temperature of 12 °C.

DISCUSSION

The modeling results and field data show that wastewater contain considerable amounts of thermal energy, which can be harvested. The heat content varies in highly dynamic patterns, directly related to the drinking water demand patterns of the homes in the urban district. This means that recoverable heat is available mainly during daytime with peaks in the morning and evening.

The recoverable heat depends largely on the assumptions for heat recovery. The three options used for the calculations depend on technical aspects (the heat exchange equipment) but also to a great extend to regulations for maximum temperature decrease of the waste water or the minimum temperature required at the influent of the sewage treatment plant. The three options result in a large differences for the recoverable thermal energy: a factor 2 to 3 difference was observed.

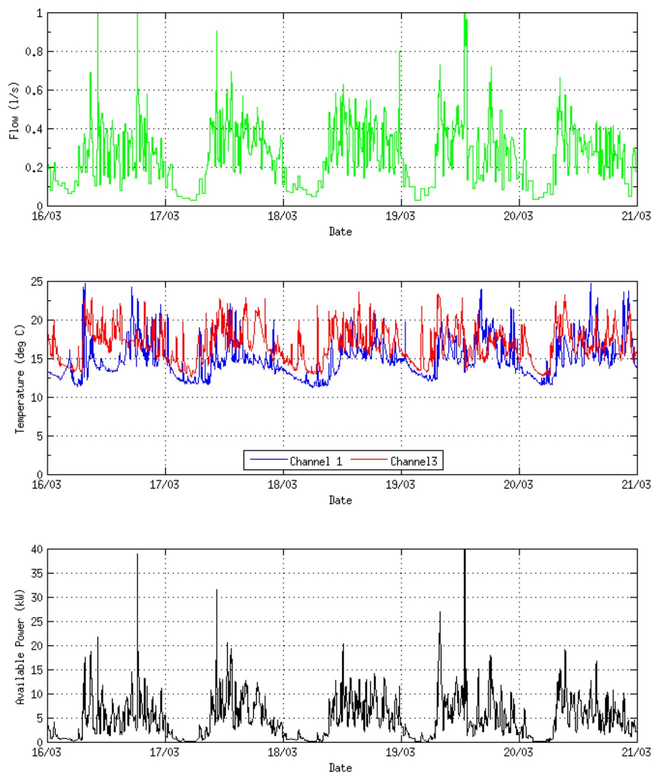

Figure 4. Measured flow and temperature data in a sewer pumping station (143 dwellings) and the calculated heat content, relative to a reference temperature of 12 °C.

When considering the Ptsa option, where a practical heat exchanger was simulated, on average 100 kW or 3100 GJ/y could be recovered from the waste water of 6,000 PE. An average home in The Netherlands uses 1,600 m^3 (72 GJ/y) of natural gas to for spatial heating and preparation of warm tap water [13]. The recovered heat is therefore sufficient to supply 43 homes or one office building, sports accommodation or nursing home with thermal energy. For practical reasons, delivery of the heat to al single larger user as an office building or sports accommodation is preferred. For the future, improved thermal insulation of homes is enforced by regulations, which means that the energy required for spatial heating will decrease. The reuse of the thermal heat from the sewer will become even more attractive in that situation.

The model can be scaled up to an entire sewer network of a city. In that case it can be used to predict the heat content in a wider area and match it with potential heat users. Furthermore it can be used to calculate the effect of heat recovery on the temperature of the waste water arriving at the sewage treatment plant. In that way the heat recovery can be optimized for locations and total recoverable thermal energy.

CONCLUSIONS

The sewer heat balance model is a powerful and accurate tool to estimate the heat content and recoverable heat from the sewer system. The data have revealed a highly dynamic availability of thermal energy that can be directly related to water demand patterns at homes. The recoverable heat depends on technical aspects as well as regulations for maximum acceptable temperature differences due to heat abstraction. Although the available heat seems to be only a small fraction of the total energy used in the homes for spatial heating and preparation of warm tap water, it is believed that recovery is beneficial, especially if a larger user, such as an office building, is available.

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