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Modelling heat transfer in the sewer system – towards a city-wide model for heat recovery from wastewater

R. Saagi[1], M. Arnell[1,2], D. Reyes[1], R. Sehlén[3], U. Jeppsson[1]

[1] Division of Industrial Electrical Engineering and Automation (IEA), Department of Biomedical Engineering, Lund University, PO Box 118, SE-22100 Lund, Sweden (ramesh.saagi@iea.lth.se, ulf.jeppsson@iea.lth.se)
[2] RISE Research Institutes of Sweden, Gjuterigatan 1D, SE-58273, Linköping, Sweden (magnus.arnell@ri.se)
[3] Tekniska Verken in Linköping, PO Box 1500, SE-58115 Linköping, Sweden (robert.sehlen@tekniskaverken.se)

Abstract: Majority of the energy consumed for urban water services is used to heat tap water. In order to allow for a system-wide evaluation of heat recovery possibilities from wastewater, this paper presents a one-dimensional model that can describe temperature and flow rate variations in a sewer pipe. The model is applied to successfully predict downstream wastewater temperature for sewer stretches in two Swedish cities (Linköping, Malmö). The model can be used to study various heat recovery possibilities from wastewater. It can be easily integrated with models developed to generate flow rate and temperature profiles from households as well as standard activated sludge models for modelling wastewater treatment plants so that a system-wide heat recovery study can be made possible.

Keywords: heat transfer; sewer system; heat recovery; modelling, simulation

Introduction

A staggering 90% of the total energy used for urban water services (drinking water treatment, water supply, wastewater transport through sewer system and treatment) is spent on heating tap water for domestic needs (Olsson, 2012). A large percentage of this heat is discharged into the sewer system eventually reaching the wastewater treatment plant (WWTP). While recovering heat from various locations (households, building level, sewer system) is an attractive option, it can adversely affect the performance of the wastewater treatment plant as lower temperatures reduce microbial activity. Especially in colder climates, this effect may have a severe negative impact on nitrogen removal. Hence, heat recovery possibilities should be evaluated at an integrated level.

Such a model-based evaluation requires tools to describe: i. generation of wastewater from households; ii. temperature variation in the sewer system; iii. effect of temperature drop on WWTP performance; and finally iv. heat recovery equipment. In this paper, a heat transfer model for sewer systems is presented that can be easily integrated with upstream wastewater generation models from households, WWTP and heat recovery equipment models. Detailed two-dimensional heat transfer models for sewer networks already exist in literature (Dürrenmatt and Wanner, 2014; Elias-Maxil et al., 2017). A more simplified approach is described by Abdel-Aal et al. (2014) where temperature dynamics in the sewer network are described using a one-dimensional model.

This paper uses the heat transfer phenomena described in Adbel-Aal et al. (2014) as the starting point and includes additional components to develop an improved one-dimensional heat transfer model for sewer pipes. The model performance is evaluated using data for a section of the sewer network from two different cities in Sweden.

Material and Methods

Model description

Variations in wastewater temperature and flow rate are described using a sewer network model developed in Matlab®/Simulink®. The model can describe both gravity and pressurized sewer networks. The model is divided into two sub-models for describing: i. temperature and ii. hydraulics.

Temperature sub-model

Temperature dynamics are modelled for the wastewater (T_w) and the sewer concrete pipe (T_p). Figure 1 provides an overview of the state variables and major heat fluxes considered in the model.

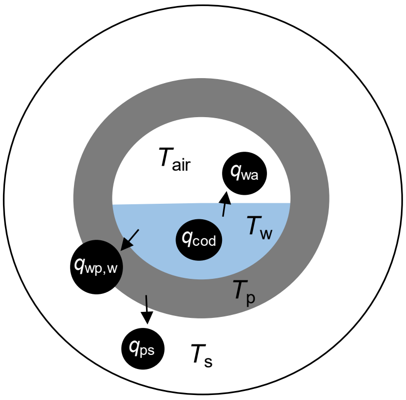

Figure 1. Overview of the temperature sub-model for the sewer system. Key state variables (T_w, T_p) and measurements (T_{air}) are marked. Major heat fluxes considered in the temperature model are highlighted.

Major phenomena describing temperature dynamics for wastewater in the sewer system are:

1. Convective heat transfer between sewer wastewater and in-sewer air in gravity sewers (q_{wa}) [W]

$$q_{wa} = \alpha_{wa} w_{ww} l_p (T_w - T_{air}) \quad (1)$$

where, α_{wa} [W/m^2.K] is the heat transfer coefficient between wastewater and in-sewer air, w_{ww} [m] is the width of the wastewater surface in the pipe, l_p [m] is the length of the pipe, T_w [K] and T_{air} [K] are the wastewater and in-sewer air temperature, respectively.

2. Heat transfer between wastewater and sewer pipe ($q_{wp,w}$) [W] through: i. forced convection between wastewater and inner sewer pipe wall; and ii. conduction from wastewater near the inner sewer pipe wall to centre of the sewer pipe.

$$q_{wp,w} = \alpha_{wp} W_p l_p (T_w - T_p) \quad (2)$$

$$\frac{1}{\alpha_{wp}} = \frac{1}{\alpha_{ww}} + \frac{1}{\frac{k_p}{w_t 0.5}} \quad (3)$$

$$\alpha_{\mathrm{w}} = \frac{0.023 Re_{\mathrm{w}}^{\frac{4}{5}} Pr_{\mathrm{w}}^{\frac{1}{3}} \lambda_{\mathrm{w}}}{R_{\mathrm{h,w}}} \quad (4)$$

where, α_{wp} [W/m^2.K] is the overall heat transfer coefficient between wastewater and centre of the sewer pipe wall, α_{ww} [W/m^2.K] is the heat transfer coefficient for forced convection due to turbulent flow of wastewater, W_p [m] is the wetted perimeter of the pipe, T_p [K] is the sewer pipe temperature, k_p [W/m.K] is the heat conductivity of sewer pipe, w_t [m] is the sewer pipe thickness, Re_w (-) is the Reynolds number and Pr_w (-) is the Prandtl number for wastewater flow, λ_w [W/m.K] is the thermal conductivity of wastewater and $R_{h,w}$ [m] is the hydraulic radius of the sewer pipe.

3. Heat gain due to biological activity (modelled using COD degradation) (q_{cod}) [W].

$$q_{cod} = r_{cod} e_{cod} \quad (5)$$

where, r_{cod} [kgCOD/m^3.s] is the reaction rate and e_{cod} [J/kgCOD] is the reaction enthalpy.

The overall energy balance equation for wastewater at each sewer section is:

$$\rho_{\mathrm{w}} V_{\mathrm{w}} c_{\mathrm{p,w}} \frac{dT_{\mathrm{w}}}{dt} = \rho_{\mathrm{w}} Q_{\mathrm{w}} c_{\mathrm{p,w}} \left(T_{\mathrm{w,in}} - T_{\mathrm{w}}\right) - q_{\mathrm{wa}}(t) - q_{\mathrm{wp}}(t) + q_{\mathrm{cod}}(t) \quad (6)$$

where, ρ_w [kg/m^3)] is the density of wastewater, V_w [m^3)] is the volume of wastewater, c_p [J/kg.K] is the heat capacity of wastewater, Q_w [m^3/d] is the wastewater flow rate, $T_{w,in}$ [K] and T_w [K] are the input and output wastewater temperatures, respectively. Time (t) is in days.

For the sewer pipe temperature model (Tp), the main processes considered are:

1. Heat transfer between wastewater and sewer pipe ($q_{wp,p}$) [W] through: i. forced convection between wastewater and inner sewer pipe wall; and ii. conduction from wastewater near the inner sewer pipe wall to centre of the sewer pipe pipe:

$$q_{\mathrm{wp,p}} = \alpha_{\mathrm{wp}} W_{\mathrm{p}} l_{\mathrm{p}} (T_{\mathrm{p}} - T_{\mathrm{w}}) \quad (7)$$

$$\frac{1}{\alpha_{\mathrm{wp}}} = \frac{1}{\alpha_{\mathrm{ww}}} + \frac{1}{\frac{k_{\mathrm{p}}}{w_{\mathrm{t}} 0.5}} \quad (8)$$

2. Conductive heat transfer (q_{ps}) [W] from: i. centre of the sewer pipe to the outer sewer pipe wall; and ii. outer sewer pipe wall to the soil:

$$q_{\mathrm{ps}} = \alpha_{\mathrm{ps}} W_{\mathrm{p}} l_{\mathrm{p}} (T_{\mathrm{p}} - T_{\mathrm{s}}) \quad (9)$$

$$\frac{1}{\alpha_{\mathrm{ps}}} = \frac{1}{\frac{k_{\mathrm{s}}}{d_{\mathrm{s}}}} + \frac{1}{\frac{k_{\mathrm{p}}}{w_{\mathrm{t}} 0.5}} \quad (10)$$

where, α_{ps} [W/m^2.K] is the overall heat transfer coefficient between the centre of the sewer pipe and soil, T_s [K] is the soil temperature, k_s [W/m.K] is the thermal conductivity of soil and d_s [m] is the soil depth considered for heat transfer.

The overall heat balance for the pipe material at each sewer section is:

$$M_{\mathrm{p}} c_{\mathrm{p,p}} \frac{dT_{\mathrm{p}}}{dt} = -q_{\mathrm{wp,p}}(t) - q_{\mathrm{ps}}(t) \tag{11}$$

where, M_p [Kg] is the mass of the concrete pipe and $c_{p,p}$ [J/kg.K] is the heat capacity of concrete.

Hydraulics sub-model

Wastewater flow rate is modelled using a kinematic wave approximation of the standard St. Venant's Equation (Saint-Venant, 1870). The model uses detailed sewer characteristics (pipe diameter, length, slope, etc.) and input data (upstream flow rate, infiltration flow rate). In addition to the flow rate at the outlet of each sewer pipe, the model can also predict other sewer variables (e.g. water height, wetted perimeter, surface area, etc.). These variables are essential to simulate heat transfer phenomena in the sewer system.

The volume balance for each pipe is described as:

$$\frac{dQ(t)}{dt} = Q_{\mathrm{in}} - Q(t) \tag{12}$$

where, Q_{in} [m^3/d] and Q [m^3/d] are the input and output flow rates, respectively.

Manning's formula is used to compute outflow based on sewer system characteristics as:

$$Q = \frac{A R_{h,w}^{\frac{2}{3}} \sqrt{S_0}}{\eta} \tag{13}$$

where, A [m^2] is the flow area , $R_{h,w}$ [m] is the hydraulic radius, S_o [m/m] is the horizontal slope and η [s.m$^{-1/3}$] is the Manning's coefficient. The output Q [m^3/d] is calculated based on lookup tables defined in Rossmann (2017). For pumped sewer pipes, input and output flow rates are assumed to be the same and the pipe is assumed to be always full.

The model combines both the flow rate and temperature dynamics in the same simulation platform allowing for easy integration with wastewater generation and treatment models that will allow for a city-wide evaluation of heat recovery possibilities.

Case study details

Table 1 Overview of the sewer system characteristics for measurement locations in the cities of Linköping and Malmö in Sweden.

Location	Linköping	Malmö
Length	2.1 km	1.5 km
Pipe diameter	225 mm; 400 mm	500 mm
Average upstream flow rate	1 600 m^3/d	3 300 m^3/d

Temperature measurements are taken from a sewer network in Linköping municipality, Sweden. Temperature sensors are installed at the upstream and downstream pumping stations. Flow measurements already exist for these locations. The total distance of the sewer network is 2.1 km of which 200 m is a pumped system with a pipe diameter of 225 mm and the rest is a gravity system with pipe diameter of 400 mm (Table 1).

For the city of Malmö, a 1.5 km stretch is chosen. Temperature and flow measurement equipment already exists at the downstream sewer point. Sensors for wastewater and in-sewer air temperature are installed at the upstream point. No infiltration flow is assumed. Also, no additional connections are assumed between the upstream and downstream points as a model simplification. The upstream flow rate is much higher than the combined flow rate arising from connections in between the two pipes and hence the assumption is considered to reduce model complexity and additional data requirements.

For the temperature measurements, encapsulated thermistor probes (Figure 2a) with a 10-meter cable (PB-5015-10M), which can record temperatures from -40 °C to +105 °C ±0.2 °C, are used. These probes are connected to waterproof (IP68) data loggers (Tinytag Plus 2 TGP-4020) (Figure 2b) that store the measurements at a 5 minute frequency. The sensors and loggers used in Linköping were checked against a calibrated reference thermometer for quality control. Field visits are made to procure data using a custom software (EasyView) from the manufacturer. The sensors have provided reliable data. Occasionally, data quality issues are noticed due to debris attaching to the sensors mainly during wet weather events. Overall, the maintenance and data quality issues are not considered to be very high.

a b

Figure 2 (a). Thermistor probes for temperature with a weight attached to it for submerging in water and (b). Data logger connected to the thermistor probe recording temperature measurements at a pre-defined frequency of 5 minutes.

Results and Discussion

Linköping

Two different datasets from Linköping are presented here. The first dataset is from November 2018 and the second from February 2019. The model uses upstream flow rate and temperature as inputs. A constant in-sewer air temperature of 10.5 °C is used for the first data set. Measured in-sewer air temperature is used for the second dataset.

Soil temperature is assumed to be 5 °C and 4 °C for the first and second datasets, respectively. Other model parameters remain the same for both datasets (Table 2). Calibration is performed manually using a trial-and-error approach. A systematic calibration approach will be devised in the future.

Table 2 Major parameters for the sewer temperature model.

Parameter	Linköping	Malmö
Heat transfer coefficient from wastewater to in-sewer air (h_{wa})	5 W/m^2.K	5 W/m^2.K
Thermal conductivity of concrete pipe (k_p)	0.5 W/m.K	2.3 W/m.K
Thermal conductivity of soil (k_s)	2.5 W/m.K	5.5 W/m.K
Pipe thickness (w_t)	10 mm	4 mm
Soil depth for heat transfer (d_s)	0.5 m	0.1 m
Reaction enthalpy for COD degradation (e_{cod})	14 x 10^6 J/kg COD	14 x 10^6 J/kg COD
COD degradation rate in sewers (r_{cod})	1 x 10^{-6} kg/m^3.s	1 x 10^{-6} kg/m^3.s

For both datasets, the model was able to predict the variations in temperature at the downstream sewer section (Figure 3). For the first dataset, downstream temperature data from day 1 is very noisy. In addition, there is noisy data during certain periods between day 1 and day 7. Hence, maximum prediction error (difference between measured and modelled temperature at the downstream sewer section) is calculated for a smoothed (5-point moving average) downstream temperature from day 2 to day 7 for dataset1. The maximum prediction error is 0.9 °C and 0.7 °C for dataset1 and dataset2, respectively.

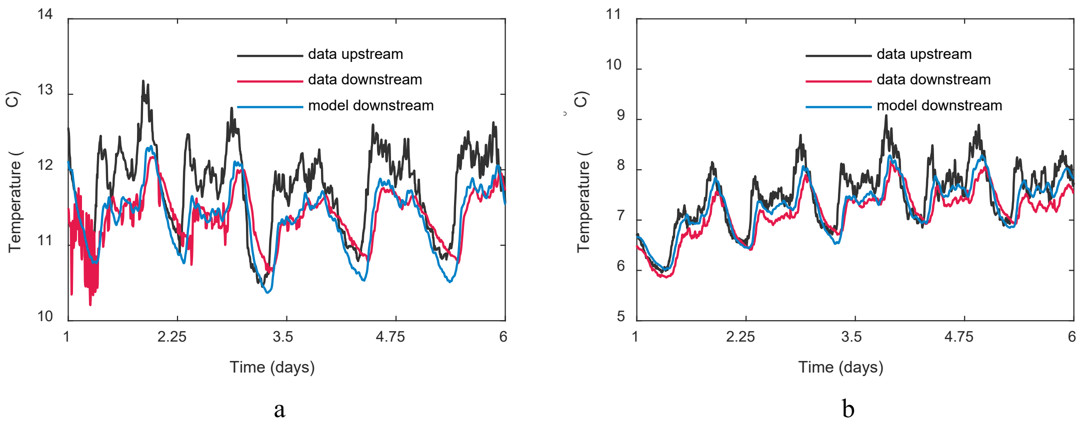

Figure 3 Comparison between measured data and simulation results for downstream temperature from a sewer pipe for two different datasets (a. Dataset1 (Nov 2018) and b. Dataset2 (Feb 2019)) from Linköping, Sweden.

<u>Malmö</u>

Temperature and flow measurements from March 08 to March 26 2019 are used for model calibration. Soil temperature is assumed as 13.1 °C. As there is limited data on soil temperature, it is treated as a model calibration parameter. The results show that variations between upstream and downstream temperature measurements are reasonably predicted by the model (Figure 4). The maximum prediction error is 0.7 °C. However, the temperature loss is lower in the Malmo dataset compared to that from Linkoping. Further investigation is required to determine the contribution from additional connections or infiltration flow in the stretch, leading to higher temperature variation than predicted by the model.

Several factors affect the extent of temperature loss (ambient temperature, flow rate, pipe characteristics, infiltration flow etc.). In neither case infiltration flow is included. It is assumed that the contribution from infiltration will be marginal (for the short distances considered here) in comparison to the wastewater flow rate from the upstream sewer network. The model includes components to describe such extraneous flows, if required.

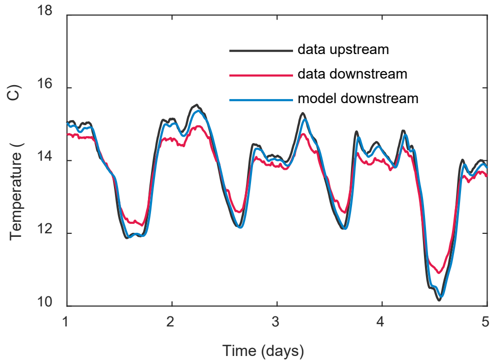

Figure 4 Comparison between measurements and model results for the 1.5 km sewer stretch in Malmö.

<u>Model application for heat recovery studies</u>

The model has been demonstrated to successfully describe temperature variations in the sewer network. During the model development, ease-of-integration with other modelling tools used for urban city-wide heat recovery studies is taken into consideration. The model can be directly integrated with: models generating household flow rate and temperature profiles with varying levels of complexity (Sitzenfrei et al., 2017) and heat recovery models. The model outputs from the sewer network can be easily integrated with standard wastewater treatment process models (which is essential to study the effect of heat recovery at household or sewer network level on the wastewater treatment plant performance). The model has the possibility to include several pollutant state variables that are transported through the sewer network. Currently, only transport of pollutant state variables is considered and no biological degradation is considered. However, the model framework provides the possibility to expand the sewer network model to include biological transformations as well.

Conclusions

A one-dimensional model describing temperature and flow rate dynamics in sewer systems is developed. The model is applied to describe temperature variation for two sewer stretches from different cities in Sweden (Linköping & Malmö). The maximum prediction error for the sewer section from Linköping is 0.9 °C and 0.7 °C for the first and second datasets, respectively. For the sewer section in Malmö, the maximum prediction error is 0.7 °C. Next steps will be towards performing a global sensitivity analysis of the model parameters to identify key calibration parameters followed by a systematic model calibration process.

References

Abdel-Aal, M., Smits, R., Mohamed, M., De Gussem, K., Schellart, A. & Tait, S. (2014). Modelling the viability of heat energy recovery from combined sewers. *Water Science & Technology*, *70*(2), 297-306.

Dürrenmatt, D.J., & Wanner, O. (2014). A mathematical model to predict the effect of heat recovery on the wastewater temperature in sewers. *Water Research*, *48*(1), 548-558.

Elías-Maxil, J.A., Hofman, J., Wols, B., Clemens, F., van der Hoek, J.P. & Rietveld, L. (2017). Development and performance of a parsimonious model to estimate temperature in sewer networks. *Urban Water Journal*, *14* (8), 829-838.

Olsson, G. (2012). *Water and Energy – Threats and Opportunities*. IWA Publishing, London, UK.

Rossman, L.A. (2017). *Stormwater Management Model reference manual volume II – Hydraulics*. US Environmental Protection Agency, Cincinnati, OH, USA.

Saint-Venant, A.J.C.B. (1870). Démonstration élémentaire de la formule de propagation dune onde ou dune intumescence dans un canal prismatique;et remarques sur les propagations du son et de la lumière, sur les ressauts, ainsi que sur la distinction des rivières et des torrents. *Comptes rendus des séances de l'Académie des Sciences*, *71*, 186-195 (in French).

Sitzenfrei, R., Hillebrand, S. & Rauch, W. (2017). Investigating the interactions of decentralized and centralized wastewater heat recovery systems. *Water Science & Technology*, *75*(5), 1243-1250.