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Potential influence of sewer heat recovery on in-sewer processes

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Potential influence of sewer heat recovery on in-sewer processes

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Abstract

Heat recovery from combined sewers has a significant potential for practical renewable energy provision as sources of heat demand and sewer pipes are spread across urban areas. Sewers are continuously recharged with relatively hot wastewater, as well as interacting with heat sources from surrounding air and soil. However, the potential effects of modifying sewage temperature on in-sewer processes have received little attention. The deposition of Fats, Oils and Greases (FOGs) and hydrogen sulphide formation are biochemical processes and are thus influenced by temperature. This paper utilises a case study approach to simulate anticipated temperature reductions in a sewer network due to heat recovery. A laboratory investigation into the formation of FOG deposits at temperatures varying between 5°C and 20°C provided mixed results, with only a weak temperature influence, highlighting the need for more research to fully understand the influence of the wastewater composition as well as temperature on FOG deposit formation. A separate modelling investigation into the formation of hydrogen sulphide when inflow temperature is varied between 5°C and 20°C showed considerable reductions in hydrogen sulphide formation. Hence, heat extraction from sewers could be a promising method for managing some in-sewer processes, combined with traditional methods such as chemical dosing.

1 Introduction

The EU aims to achieve a clean energy transition by 2050, resulting in an energy system where primary energy supply would largely come from renewable energy sources (EC, 2018). Some of the UK's utilities have set targets of being carbon neutral by 2050. Given that 23% of UK energy consumption is consumed for heating (BEIS 2017), heat extraction from sewers could play a significant role in utilities achieving these targets.

Heat recovery from sewers presents a great potential since sewers are spread across the country often near sources of heat demand. They are continuously recharged with relatively hot wastewater (Cipolla, 2014) and also gain heat from surrounding air and soil. Although heat exchange technology is mature, implementation in the sewer network is slow for various reasons, such as the possible negative impact on the biological treatment process at the wastewater treatment plant (WwTP) and a lack of incentive because the beneficiaries of recovered heat may not be the ones managing the sewer system. Abdel-Aal et al. (2018) developed a city-scale sewer heat recovery model to assess the potential viability of heat recovery from sewer networks and its effects on sewer temperatures. Viability in this context was defined as maintaining temperatures above 5°C in sewer pipes and above 9°C at the WWTP influent. Applying the model to a 79500 PE (Population Equivalent) combined sewer network predicted that between 116 and 207 MWh/day of viable heat may be recovered, equivalent to meeting 7 % to 18 % of the domestic heat demand in the catchment.

In addition to meeting some of a city's heat demand, heat recovery may also benefit the operation of the sewerage system. FOG (Fats Oils Grease) deposition is commonly simplified to the cooling of fats, but actually involves a number of physical-chemical and biological processes which are affected in different ways by temperature changes (Iasmin et al., 2016): solidification, saponification, precipitation and biofilms. Solidification of FOG is linked to the nature of the lipid; their chemical structure and physical properties and generally low temperatures facilitate the congealing of FOG containing high percentages of saturated fatty acids. Saponification is the chemical process of soap formation from the reaction of short or long organic fatty acids with cations such as Calcium (Ca^{2+}); a process that is slowed down by any reduction of temperature. This process can also be biologically mediated and therefore a reduction in temperature will slow it down. One of the sources of organic fatty acids to the saponification process is the hydrolysis of triglycerides (lipids). Hydrolysis is carried out by biological enzymes produced by the microbial community in the sewer and low temperatures both slow down the reactivity of hydrolytic enzymes and their production rate. Biological degradation can consume lipids and fatty acids by conversion into new biomass, smaller organic molecules or carbon dioxide. This effect can therefore remove one of the contributing factors to FOG deposition and its rate can be increased by higher temperatures in the sewer.

Other processes like chemical precipitation or adhesion of organic materials to biofilms can be both chemically or biologically induced with an opposing effect to temperature variations. In general terms, chemical and biological reactions, such as saponification and hydrolysis, will tend to slow down when a drop-in temperature occurs and hence deposit creation will be slower (He et al., 2017). In contrast, unsaturated fats will solidify more rapidly when the temperature drops. The relative contribution of these reactions will define the overall FOG deposition rate. A better understanding of the temperature impact on these contributions could help in optimising the variation in temperature in a sewer network, through engineered solutions aimed at the recovery or dispersion of heat into the system and potentially help in controlling FOG deposit formation.

Hydrogen sulphide, like FOG deposits, is formed due to temperature dependent microbial processes in sewer networks. The formation of hydrogen sulphide takes place under anaerobic conditions, which often prevails in rising mains where the pipes are flowing full. It can be envisaged that the temperature might be lowered by extracting heat from the pump sump before the rising main. Hydrogen sulphide formation is also closely linked to the organic matter cycle and particularly the availability of readily biodegradable organic matter which are both associated with the consumption of oxygen through heterotrophic microbial activity and can lead to the anaerobic conditions needed for the hydrogen sulphide production (Gudjonsson et al., 2002; Pomeroy, 1959). Lowering the temperature will also increase the solubility of oxygen in the wastewater, which has the potential to limit the formation of anaerobic conditions and hence limit the formation of hydrogen sulphide (Hvitved-Jacobsen et al., 2013). In addition to this, the hydrogen sulphide formation is in itself a biological process that is temperature dependent, with the rate of formation reducing at lower temperatures (Nielsen, 1987).

As described in He et al. (2013), sewer corrosion releases Ca^{2+} from concrete pipes or structures in the sewers which is an ingredient for the saponification process. This Ca^{2+} leakage is mainly due to corrosion processes caused by the formation of sulphuric acid from the reaction of H_2S with water. Hence a reduction of H_2S formation by temperature control through heat recovery could lead to an additional benefit of FOG deposits formation control (and consequent blockage reductions) showing interesting interlinks between these processes.

The aim of this paper is to provide an overview of the impacts of temperature on in-sewer processes and define the directions of work to facilitate the implementation and management of heat recovery schemes in the UK. The outputs will inform the feasibility of using sewer heat recovery to assist in managing in-sewer processes.

2 Methodology

Figure 1 illustrates areas in a sewer network that could be targeted to study the implications of heat recovery on wastewater temperatures. Based on potential heat temperature reductions that may be feasible, the effects of reduced temperatures on FOG and H_2S formation are investigated.

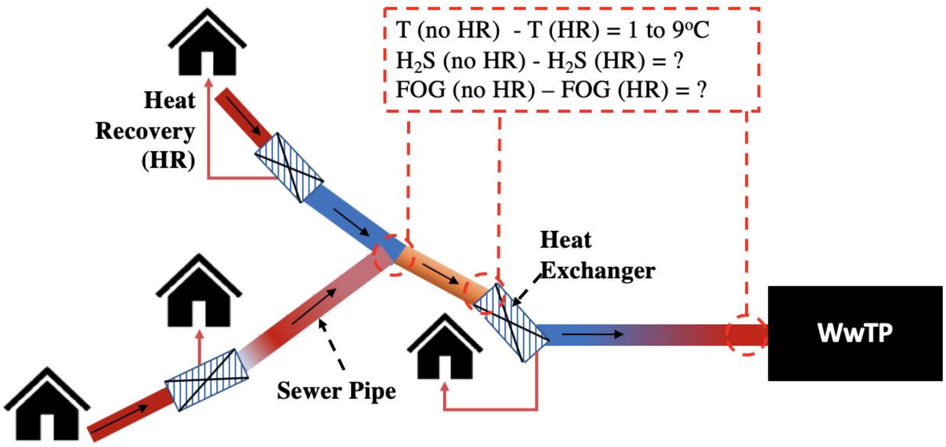

Figure 1: Schematic illustration of the potential impact of heat recovery (HR) on temperatures.

2.1 Modelling investigation of sewer heat recovery scenarios on a sewer network scale

The heat transfer model implemented on a 79500 PE sewer network described in Abdel-Aal et al. (2018) was utilised to simulate a number of heat recovery scenarios and estimate wastewater temperatures throughout the sewer network with and without heat recovery. The heat transfer model simulates heat exchange between wastewater, in-sewer air and surrounding soil, and has been validated under dry weather flow conditions using field measurements of wastewater temperatures in the case study network. Hydraulic data, derived from a validated Infoworks CS hydrodynamic model, was utilised in the heat transfer model along with other key inputs such as soil and ambient air temperatures measured in the case study catchment. Soil temperatures in the heat transfer model were varied between 9°C and 10°C, depending on the average depth of the modelled sewer pipe. These soil temperatures were based on field measurements at 2 locations in the catchment, at 3.75 m and 1.5 m depths. In-sewer air temperatures were varied between 8.6°C and 15.5°C, based on measurements at two locations within the sewer network. Refer to Abdel-Aal et al. (2018) for the full list of model assumptions, inputs and boundary conditions, and Abdel-Aal (2015) for detailed descriptions of the dataset used. Heat recovery has been simulated by including heat extraction points throughout the network in pipes with a flow rate over 25 L/s and a minimum temperature of

9°C. Six heat extraction scenarios were simulated: extracting 200, 300 and 400 kW respectively from multiple points. Results are presented for the 7:00 – 8:00 AM period for a representative dry weather flow day in the months of March and May.

2.2 Laboratory investigations of temperature influence on FOG deposit formation

Laboratory scale batch tests were performed to determine the dependency on temperature of FOG formation processes in wastewater. The temperatures selected for the assessment were 5, 10, 15 and 20°C, a range derived from the study of in-sewer wastewater temperatures simulated before and after heat recovery (Abdel-Aal et al., 2018). A synthetic wastewater was used during the experiments prepared according to the standard OECD (2001) with the addition of 500 mg/L of cooking oil and 50 mg/L of oleic acid (99%, Alfa AesarTM), (Oleic solution) or 50 mg/L of stearic acid (97%, ACROS OrganicsTM), (Stearic solution). To introduce micro-organisms, a 100µL volume of real wastewater was added to each 50 mL volume of synthetic sewage. The synthetic sewage was prepared using tap water.

Batch tests were performed in 250 mL flasks filled with 50 mL of synthetic wastewater. Each test was maintained in agitation during the experiment by using an orbital shaker at a rotation speed of 80 rpm. The assessment of FOG deposits formation was conducted over a nine-day period and sacrificial tests were carried out to measure the weight of the FOG deposits every two days. This time range was selected to assess deposits formation over relatively short (two days) and long (nine days) retention times and also to achieve measurable deposits sizes for the laboratory scale system. The first FOG precipitates occurred at around two days. FOG deposits formation was assessed by measuring the dry weight of deposits. FOG deposits were harvested by vacuum filtration (Whatman GF/F glass 0.7 µm retention filter).

Dry weight was measured gravimetrically by drying the material retained by the filter at 40°C for 72 h (EPA 160.3). The one-way analysis of variance (1-way ANOVA) was used to compare the deposits formation among the temperature testes while two-way analysis of variance (2-way ANOVA) was used to evaluate the effects of the two acids used.

2.3 Model investigation on the effects of temperature reduction on hydrogen sulphide formation

Exploratory modelling of the dependency of hydrogen sulphide formation on temperature has been carried out using the WATS model (Hvitved-Jacobsen et al., 2013), looking at the effects of wastewater entering an anaerobic rising main with temperatures of 5, 10, 15, and 20 °C. The temperature effects were modelled in a rising main where it is assumed that the heat extraction takes place in the pump sump located before the rising main. Rising mains would be specific assets of concern regarding hydrogen sulphide formation in most sewer networks, hence they are the focus of this modelling scenario. The modelled rising main has a diameter of 250 mm and results are based on an overnight residence time of 12 hours and standard model parameters from the WATS model (Hvitved- Jacobsen et al., 2013; Wang, 2017). The initial COD of the wastewater was set to 600 $gCOD/m^3$ and the starting concentration of oxygen was 4 g/m^3.

3 Preliminary Results

3.1 Potential temperature reductions due to heat recovery scenarios

Table 1 indicates the number of pipes where the wastewater temperature was reduced by more than 1°C, and the ranges of potential temperature reductions. The simulated wastewater temperatures in these pipes varied between 12°C and 13°C without heat recovery, and between 5°C and 12 °C with heat recovery in March. Simulated results in May showed a wastewater temperature variation between 14.5°C and 15°C without heat recovery and between 5°C and

14°C with heat recovery. The scenarios with heat recovery of 200 and 300 kW per heat recovery location in May showed less than 1°C temperature reductions.

Table 1. Summary of temperature changes (dT) throughout the network, for heat recovery scenarios and no heat recovery, for pipes where temperature was reduced by more than 1°C Heat recovery in kW at each heat recovery location.

		Heat recovery in kW at each heat recovery location		
		200	300	400
March	Max dT (°C)	-7.6	-7.5	-8.6
	Min dT (°C)	-1.1	-1.1	-1.1
	Average dT (°C)	-4.3	-4.6	-4.9
	Nr of pipes with more than 1°C reduction	49	35	27
May	Max dT (°C)	n/a	n/a	-4.8
	Min dT (°C)	n/a	n/a	-1.1
	Average dT (°C)	n/a	n/a	-3.0
	Nr of pipes with more than 1°C reduction	0	0	30

3.2 Temperature impact on FOG deposits formation.

Formation of FOG deposits was observed during all experimental conditions for both solutions (Figure 2). This confirms the possibility to replicate FOG formation at laboratory scale under controlled conditions from a synthetic wastewater. The weight of FOG deposits increased for all conditions between the start and the 4th day of the experiment. A reduction was observed from some tests after the 7th day (e.g. oleic solution at 15°C and 20°C) whilst for the other tests the trend was of a further increase or a plateau to a certain value of the weight of deposits. The reduction of weight indicates a possible disaggregation of the deposits due to either a biological degradation or a breakage due to the shear from the agitation of the jar tests. It is noted that a growing trend can be observed for both solutions for experiments at 5°C while a peak followed by a decrease for those at 20°C.

Despite these differences in the trends with time, the formation of the FOG deposits for the Oleic solution was not influenced ($p>0.05$ – 1-way ANOVA) by the temperature at each step of the experiments (Figure 2a). This suggests that the formation of FOG deposits for this solution follows a dynamic that is independent of the temperature (for the range of temperatures tested in this study). Similar results were obtained with the Stearic solution with the exception that an effect of temperature was recorded ($p<0.05$ – 1-way ANOVA) for the formation at 7 days. This suggests a possible interaction between the composition of the wastewater (FFA type) and temperature in the temporal evolution of the deposit formation. Comparing the data between oleic and stearic solutions, deposits from the latter resulted in smaller FOG deposits ($p<0.05$ – 2-way ANOVA) after 2 days of experiment but without demonstrating an effect of temperature. Impacts from both temperature and FFA type were recorded for the 7th day ($p<0.05$ – 2-way ANOVA) suggesting that the difference in wastewater composition and the temperature may both affect the FOG deposit formation. On the contrary, no difference ($p>0.05$ – 2-way ANOVA) was recorded for the data at the end of the experiment indicating that all FOG deposition was comparable between all conditions.

These results suggest that variations of the temperature in the sewer system can have a limited effect on the formation of FOG deposits and the characteristics of the wastewater need to be taken into account. The results also suggest that there was an interaction between temperature and wastewater composition in the solution containing stearic acid, with a lower level of deposit formation at lower temperatures (Figure 2b, 7 days). However, for longer residence times the kinetics seem to lead to comparable amounts of FOG deposits ($p>0.05$). This indicates that the interaction between wastewater composition and temperature might have an effect only during the initial phase of the phenomenon but not on its later stages.

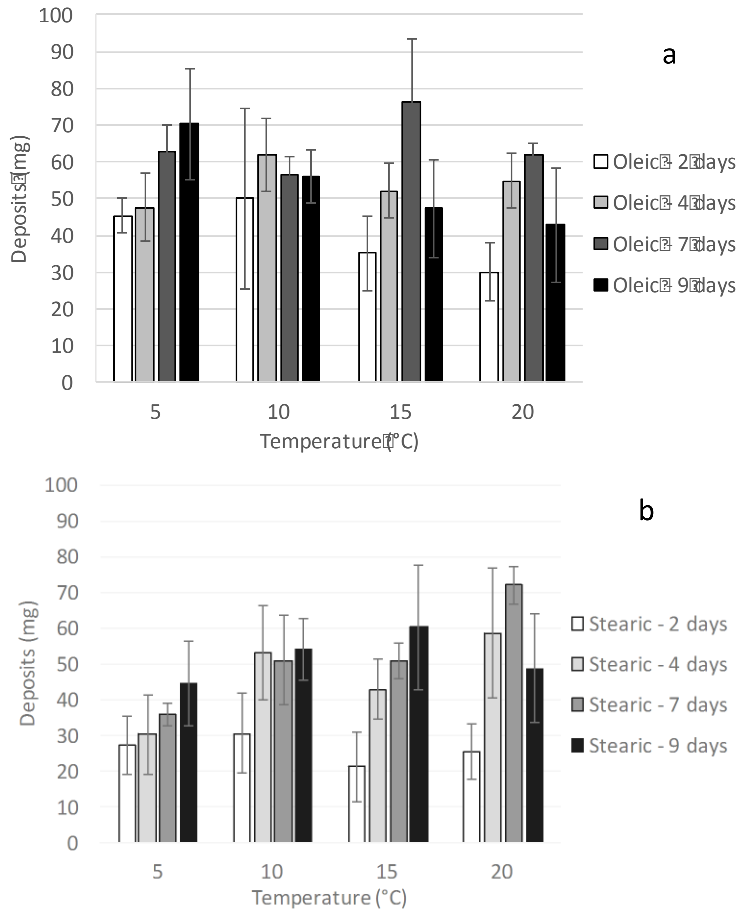

Figure 2. Average weight of FOG deposits during batch tests at the different temperatures for oleic solution (a) and stearic solution (b). Error bars indicate the standard deviation of the experimental results.

3.3 Temperature impacts on hydrogen sulphide formation

Temperature influences the heterotrophic transformation of the organic matter, which leads to the formation of anaerobic conditions on the rising main. Figure 3 shows the time taken for wastewater in a rising main to become anaerobic at different temperatures. It takes 21 minutes for the wastewater, at 20°Cm to become anaerobic, whereas at 5°C this period is extended to 60 minutes. Preliminary modelling results suggest that if the wastewater enters the rising main at a temperature of 5°C, it would lead to a reduction of 40% in the hydrogen sulphide concentration after 12 hours in the rising main. Figure 4 shows the changes in hydrogen sulphide concentration after 12 hours residence time in the rising main.

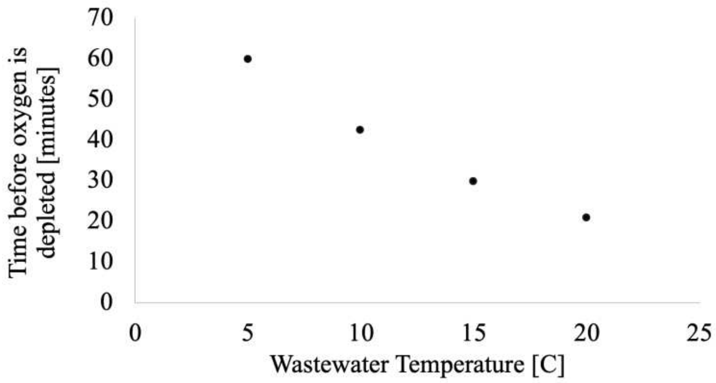

Figure 3. Time before wastewater in rising main becomes anaerobic at different temperatures.

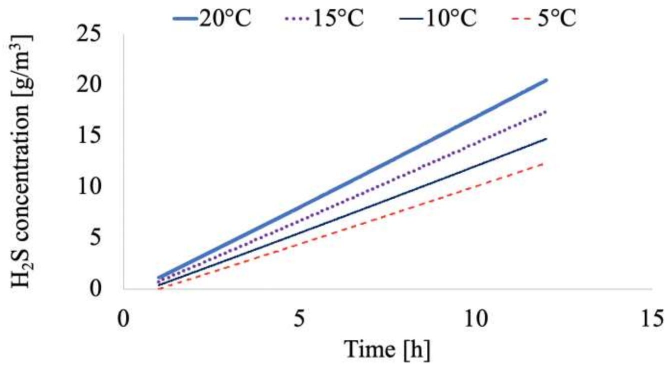

Figure 4. Hydrogen sulphide production in the rising main over 12 hours at varying temperature.

4 Discussion

The simulations with the heat transfer model indicated a range of potential temperature reductions throughout the network, with between 27 and 49 out of 3048 simulated pipes having temperature reductions between 1°C and 9°C when comparing the simulations with and without viable sewer heat recovery scenarios. The larger reductions were found in March, when the measured ambient air and soil temperatures were lower. Initial sensitivity analysis suggested heat exchange between air and wastewater should not be ignored when modelling heat transfer in sewer systems (Abdel-Aal, 2015); however, data on in-sewer air velocity and variation of in-sewer air temperature throughout a network is limited. Heat transfer coefficients between sewage, in-sewer air and sewer pipes and surrounding soil were calibrated, and the calibrated parameters showed different values for different months and site characteristics (Abdel-Aal et al., 2018). Hence, questions remain on the uncertainty of such coefficients. Ideally, the boundary conditions and heat transfer coefficients would vary throughout the network in better accordance with the conditions at the sewer pipe that are likely to change.

Boundary conditions are altered by seasonal temperature fluctuations which may change the near-surface ground temperature by ±6°C in a western European climate, potentially more depending on the surface covering, affecting the top 2 m of ground where the majority of sewer pipes are buried. This affects both the temperature of the wastewater and the temperature of the air phase within the sewer pipe, and so the potential temperature gradients driving the exchange of thermal energy between the wastewater and its surrounding environment. Heat transfer coefficients are then set by the specific ground conditions around the pipe, i.e. the soil type and the water content of the in-situ ground (Mohamed et al., 2015). Heat transfer is primarily associated with volumetric water content (Haigh 2012), with greater water contents responsible for increased thermal conductivity in soils. To be effectively deployed in a network model, information about local weather conditions, local hydrogeology and potentially a link between thermal conductivity and soil moisture deficit values would be required. Given the availability of these information sources, it remains useful to build empirical relationships based on measured data, albeit ones that cannot be simply transferred to different networks without considering the burial conditions of the sewer pipes. The challenges of estimating boundary conditions and thermal conductivity coefficients, with their spatial and temporal variations somewhat explain the difference in performance of the modelled heat recovery between March and May.

If sewer heat recovery was to be utilised also for the benefit of managing in-sewer processes, a complex spatial optimisation analysis would need to be conducted as to where best to extract the heat while satisfying constraints in the sewer system (minimum temperature of wastewater entering wastewater treatment plant, and not freezing any pipes). For example, Yousefelahiyeh et al. (2017) have made initial attempts at predicting FOG hotspots in a network and this would need to be extended to improve confidence in the findings.

Further research would also be needed on the practical feasibility of recovering and potentially utilising heat from the pump-sump directly upstream of rising mains. The available case study sewer system did not have any rising mains, hence in the current study the simulated temperature reductions in the network were only used to inform the different temperatures at the inlet to the rising main hydrogen sulphide model. Heat transfer between the rising main and the surrounding soil has not been modelled, but is likely to be minor as most rising mains are relatively short in length.

The results from the FOG experiments highlighted how the variability of the wastewater matrix adds a layer of complexity on assessing the impact of temperature on FOG deposit formation. In the range of temperatures assessed, differences between the maximum and minimum deposit formation rate can be as high as 50% (e.g. stearic at 7 days) but this difference seems to be only transitional and the phenomenon tends ultimately to comparable values. The results from the initial phase of the stearic solution indicate anyway that lower temperatures tend to slow down the formation process therefore smaller deposits are formed at lower temperatures. When combining this observation with the non-dependency from temperature of deposits from the oleic solution, it is not possible to state that the reduction in temperature following heat recovery scenarios tested in the case study sewer network would have a significant impact on FOG deposit formation. Further studies are needed to provide more insights on the specific effects of wastewater composition on deposit formation and its interaction with temperature variations.

The assessment of the effects of wastewater composition on deposits formation is also an essential aspect in defining the efficacy of mitigation strategies based on the use of dosing solutions (e.g. enzymes/bacteria). If a reduction in temperature could lead to a reduction in FOG deposit formation, a potential saving on the costs of dosing solutions could be balanced in the financial costs and gains of the installation of heat recovery systems in the sewer network.

The management of blockages and of FOG deposits in the sewer network is a challenging and costly task for the water utilities. FOG accumulation in sewers is linked to about 50% of the over 20,000 flooding events in the UK with the water utilities spending annually between £15 and £50 million to remove FOG deposits and ensure the sewer network remains operational (Wallace et al., 2017). It is clear that solutions delivering a reduction on FOG formation could lead to important financial savings for the sector.

Figure 3 has shown that under long residence time, the sulphide production rate is affected mainly by temperature, which is important for the final concentration of sulphide in the wastewater. One particularly important effect for the shorter residence times is the delayed onset of the anaerobic conditions. Hydrogen sulphide is mainly controlled by dosing of chemicals to the wastewater streams to either oxidise the sulphide and inhibit the sulphate reducing bacteria or precipitate the sulphide to a solid form, generally iron sulphide (e.g. Zhang et al., 2008). The efficiency of the remediation methods is also likely to be temperature dependent, which needs to be included in these considerations as well. Concrete corrosion is costly for sewer operators, either in pipe repair and replacement or in chemical dosing (e.g. Jiang et al., 2015), hence if the extraction of energy can provide both corrosion limitation and value of the recovered energy the benefit could be two-fold. Overall the observed effects are interesting and could have potential for reducing costs of chemical dosing during the day where residence times are short and energy demands are usually higher.

5 Conclusions

A clear, unique temperature dependency on the rate of FOG deposit formation was not found in the current laboratory test set-up and in the range of temperatures tested. Some evidence was produced that, in certain circumstances, the rate of FOG formation could be reduced by lowering temperatures. However, the rate of FOG deposition seemed to be controlled by a number of other processes. Clear and considerable potential for H_2S reduction was found when the temperature of sewage entering rising mains is reduced. Hence, heat extraction from rising main pump sumps would be an interesting area for further research, as well as research into the effect of heat reduction on any remediation methods needed down-stream of the rising mains. Feasible heat recovery scenarios in the case study sewer system provided 1°C to 9°C drop in several tens of pipes (< 2 %) in a 79500 PE system for the scenarios investigated. However, there would be scope to further optimise this potential if the aim of heat recovery would not just be to provide heat to end users, but also, for controlling in-sewer processes. A cost-benefit analysis would be required to compare more traditional methods of controlling in-sewer processes, such as chemical dosing, and physical control of processes through reducing sewage temperature.

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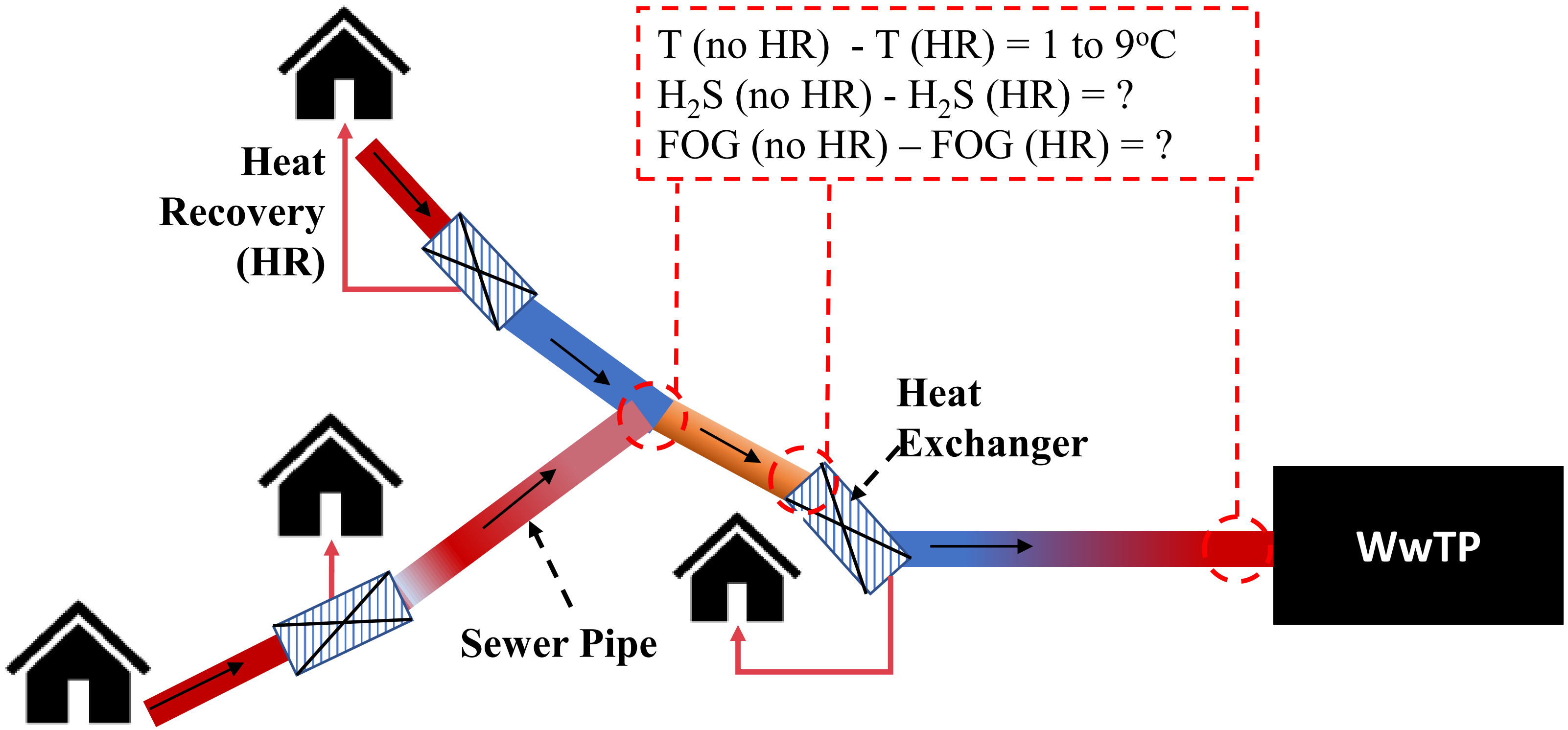
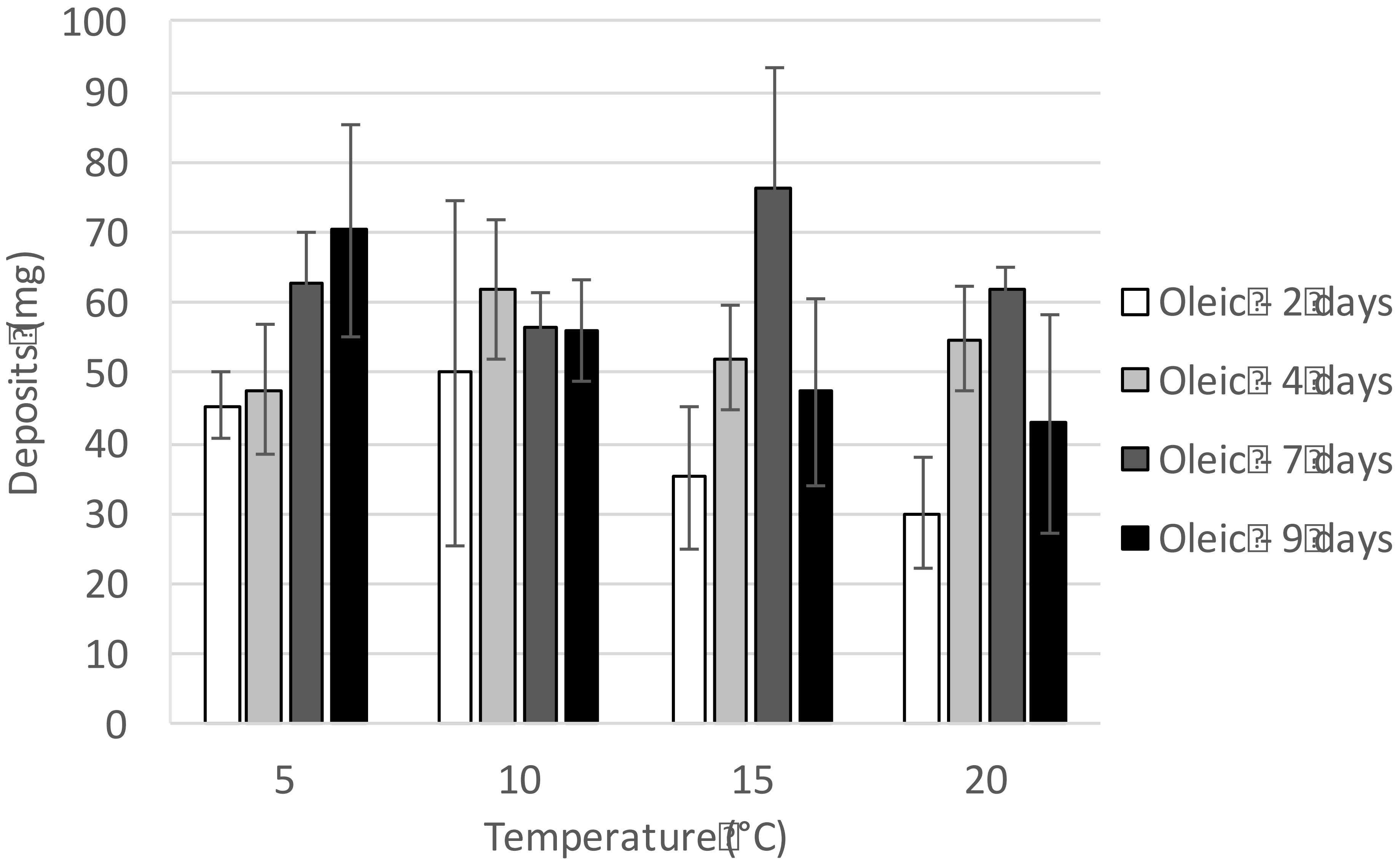
Figure 1



T (no HR) - T (HR) = 1 to 9°C
H2S (no HR) - H2S (HR) = ?
FOG (no HR) – FOG (HR) = ?
Heat Recovery (HR)
Heat Exchanger
Sewer Pipe
WwTP

Figure 2

a)



100
90
80
70
60
50
40
30
20
10
0
Deposits (mg)
5
10
15
20
Temperature (°C)
Oleic - 2 days
Oleic - 4 days
Oleic - 7 days
Oleic - 9 days

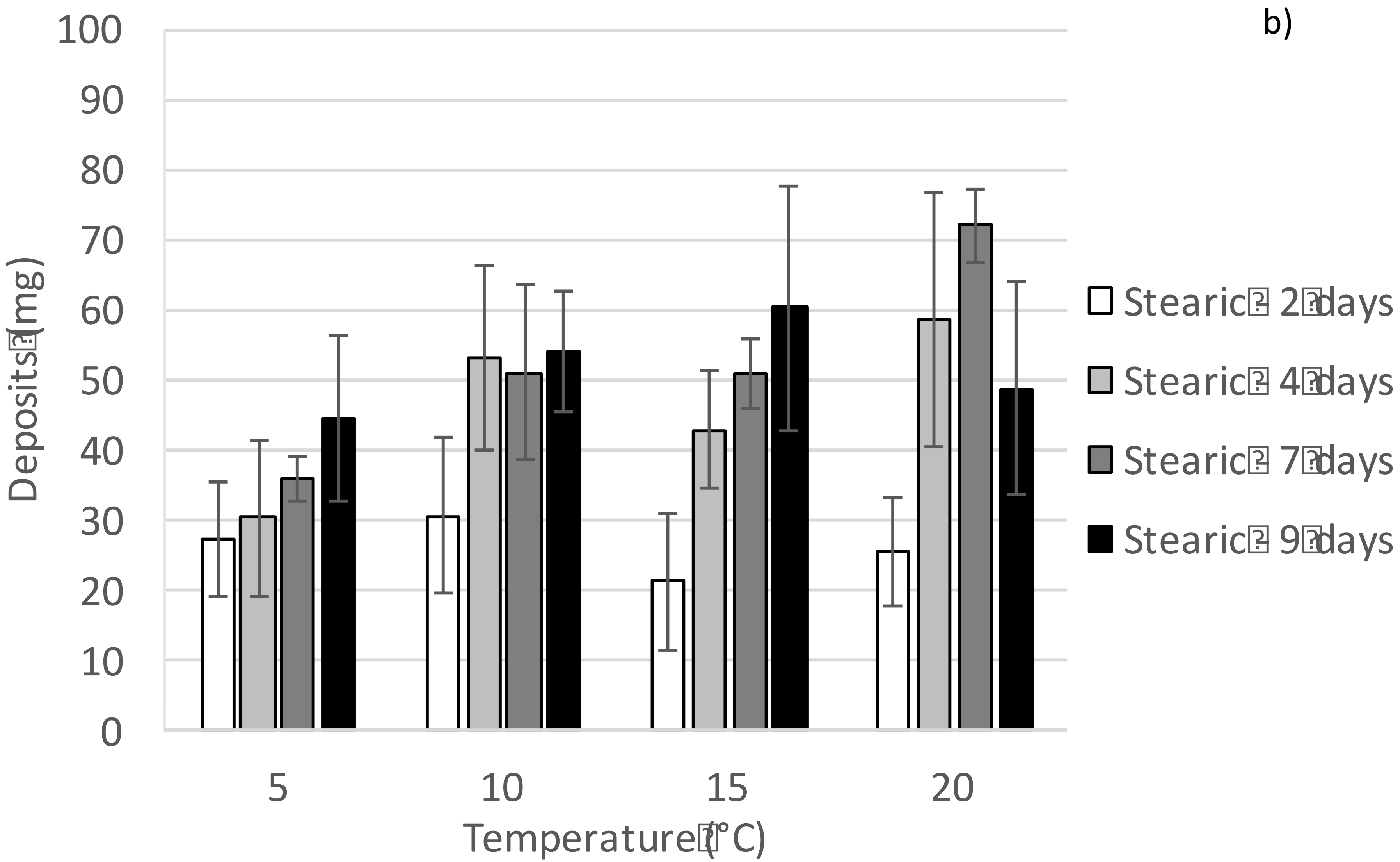

b)
Deposits (mg)
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
Temperature (°C)
Stearic - 2 days
Stearic - 4 days
Stearic - 7 days
Stearic - 9 days

Figure 3

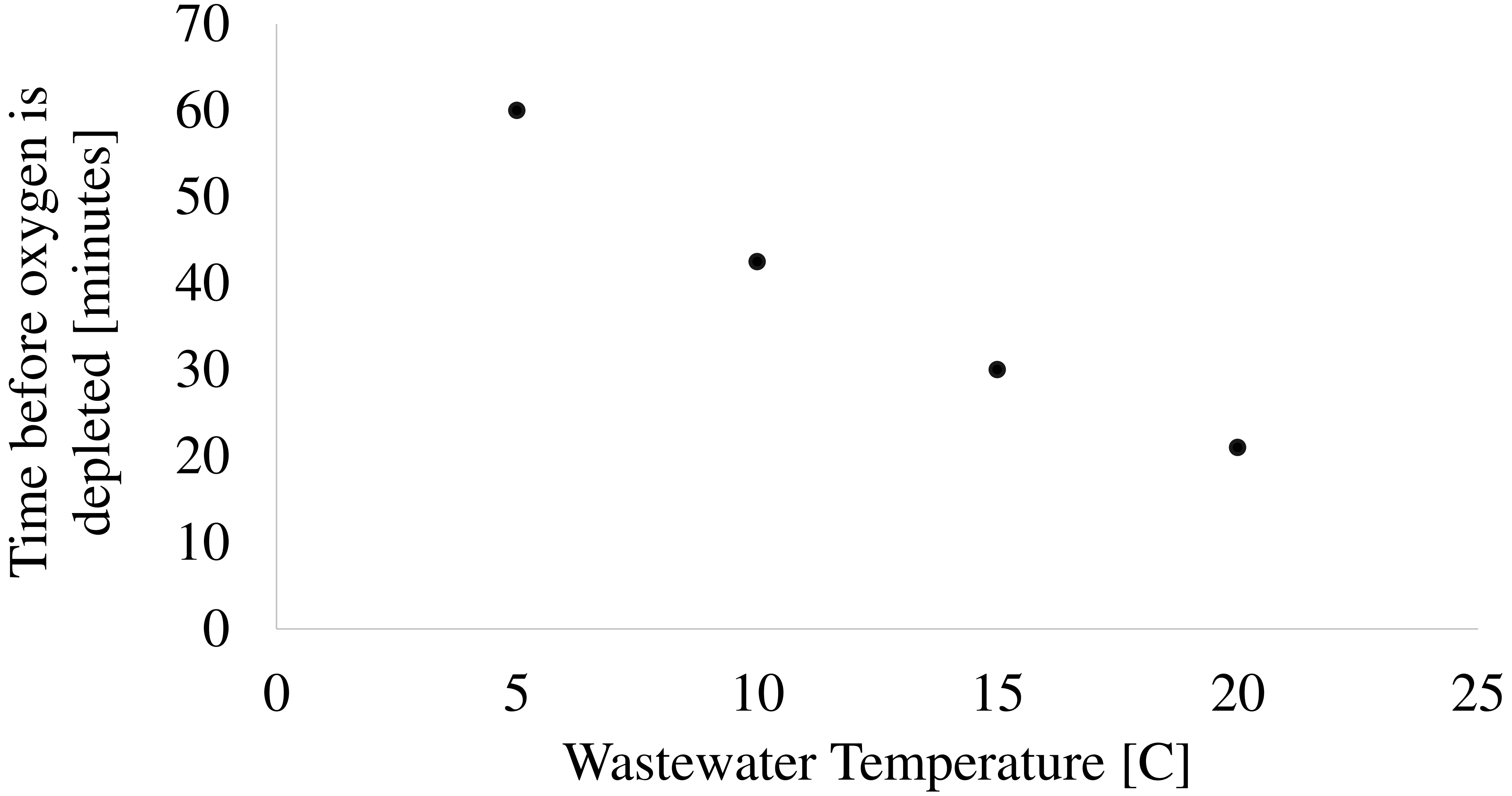
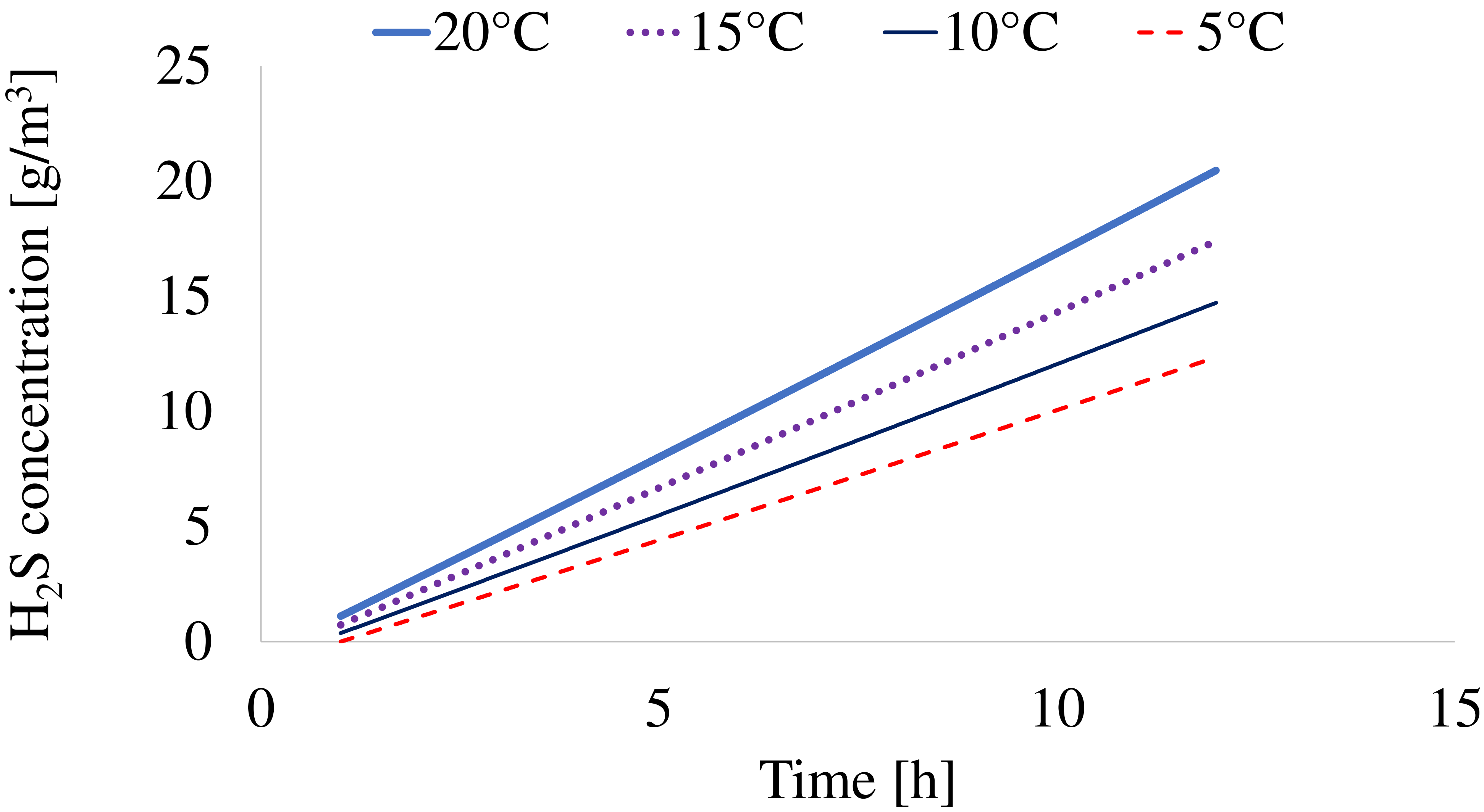

Time before oxygen is depleted [minutes]
70
60
50
40
30
20
10
0
0
5
10
15
20
25
Wastewater Temperature [C]

Figure 4



20°C
15°C
10°C
5°C
25
20
15
10
5
0
0
5
10
15
Time [h]
H_2S concentration [g/m^3]

Table 1

		Heat recovery in kW at each heat recovery location		
		200	300	400
March	Max dT (°C)	-7.6	-7.5	-8.6
	Min dT (°C)	-1.1	-1.1	-1.1
	Average dT (°C)	-4.3	-4.6	-4.9
	Nr of pipes with more than 1°C reduction	49	35	27
May	Max dT (°C)	n/a	n/a	-4.8
	Min dT (°C)	n/a	n/a	-1.1
	Average dT (°C)	n/a	n/a	-3.0
	Nr of pipes with more than 1°C reduction	0	0	30