Methane formation in sewer systems

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by

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Picture on front page: Manhole beside Turning Torso, Malmö, photograph taken by Malin Isgren.

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Preface

This Master Thesis represents our last step in becoming Chemical Engineers at the Faculty of Engineering in Lund. It was executed at Water and Environmental Engineering at the Department of Chemical Engineering in collaboration with VA SYD. As always there is a lot of work and persons behind the results and hence we will thank those who have made this interesting work possible.

First of all we would like to thank our three irreplaceable supervisors Jes la Cour Jansen, Oriol Gutierrez and David Gustavsson. Jes for the countless hours that he has spent on us, both in person and through emails during day and night. We would also like to thank you for the knowledge and solutions that you have provided us with during rough times and of course also for the guidelines throughout the Master Thesis. Oriol, who is working at the Catalan Institute for Water research (ICRA), for all the mail conversations that we have had when giving us feedback or answering our questions. David for the whole idea and thus the opportunity to perform this thesis. The valuable knowledge that he has provided us with and of course all the practical help.

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Our samplers, Tomas Wolf and Ricky Merikanto who have done a tremendous field work and for that, we are very grateful. Also other staff members that have helped us, thank you.

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Malin Isgren & Patrick Mårtensson
Summary

Hydrogen sulphide in sewer systems is a well-known problem. However, formation of the potent greenhouse gas methane has not received as much attention. A few studies have been executed on rising mains since these are theoretically the ones with the highest potential for methane formation. Gravity mains are the most common kind of pipes but they are still poorly investigated. Investigations of these are necessary if methane formation in sewer systems shall be fairly evaluated. Factors that affect methane formation are among other things the presence of organic carbon in anaerobic conditions. The amount of methane formed per volume wastewater depends on the ratio between the inner surface wall area covered with biofilm and the volume of the pipe. This theory has been proved, not only in studies on rising mains but also correlate well with formation of hydrogen sulphide. The main aim of this work was to develop a sampling method for determination of dissolved methane in wastewater samples and to detect any methane content in gravity mains with the highest potential for methane production in Malmö, Sweden.

Field samples were collected at the inlet, downstream a pressurized system at Sjölunda Wastewater Treatment Plant (WWTP) and in scattered selected manholes in the sewer system of Malmö, Sweden. In two pipe lengths, one pressurized and one non-pressurized, the methane formation rates were calculated as well. The sampling technique enables sampling and at the same time avoids getting air into the sampling bottles. This was accomplished by keeping the collection vials under water, while putting the cap on. Wastewater sampling at the WWTP was executed by lowering a sampling bottle close to the incoming pipe. The rubber stopper was released when the bottle reached the selected level. Sampling in manholes was executed by climbing down and filling sampling bottles. From the sampling occasions all laboratory analysis were performed within 24 hours. The sampling analyses were done by filling about half of a vacuum tube with wastewater, then the vacuum was released, the tube was shaken and then equilibrium was allowed. The methane content was determined with a gas chromatograph and the amount of methane was calculated with Henry’s law and mass balances.

The methane analysis of the samples taken from non-pressurised manholes located in Malmö showed that methane is present. The concentration varied in every manhole and the highest and lowest encountered was 0.6 and 0.06 mg CH₄/L respectively. The formation rate in the non-pressurized pipe examined became 0.12 mg/m/min in the wastewater.

The methane from the incoming pipe at Sjölunda WWTP was examined twice. The methane amount varies during the day and the amount released is about 2 kg/h. The samples were taken in the middle of the winter (water temperature around 14°C) and as methane formation is favoured by increased temperature this value can be taken as a minimum that enters the WWTP. Marginal differences in flow and temperatures will not affect the formation of methane and hence not the concentration. The formation rate was calculated in a pressurized pipe in the field to 1.2 mg/m/min in the wastewater.

The highest methane concentration measured was at the inlet at Sjölunda WWTP together with the end of the pressurized pipe. Pressurized pipes are the most potential methane formation place since those are completely filled with wastewater and thus anaerobic. To overcome the issue with methane formation in the future more research is required.
Knowledge in this area will help the minimization of the methane formation and thus contribute to a reduction of the global warming since methane is a greenhouse gas.
Reading instructions

To better follow this work and for an easier understanding, these reading instructions may help the reader to be guided through the report. Chapter 1 is the introduction chapter and all background is presented here. It starts with greenhouse gases in general and is narrowed against methane and the formation of methane the further it goes in the chapter. In the end the aim of the thesis is described together with some facts about VA SYD which this Master Thesis is done in collaboration with.

Chapter 2 and 3 consists of the literature study that was executed to get a deeper understanding of the problem. In Chapter 2 are sewer systems in general described, how it is built and what it contains. Some other necessary facts are also presented here for better understanding of the report. In Chapter 3 the theory about methane formation in sewer systems is described, how and why it appears.

In Chapter 4 the method for methane concentration estimations in sewer systems is described. This includes sampling method, analyses and calculations for the methane formation in the sewers. The most optimal method is described since it has been developed throughout the thesis. The method presented in this Master Thesis is the one that came out from trials and errors throughout the work. The whole process of the development of the method is also described in Chapter 6.

The sampling sites and the reason why those were chosen are described in Chapter 5. Mostly “hot spots” but also random scattered sites are chosen for investigation. The choices of these sites are also more thoroughly explained here.

Chapter 6 is built up in three sections: laboratory analysis, wastewater treatment sampling at wastewater plant and in manholes. Each section describes first the theory and how the sampling is done, afterwards an evaluation of how it worked in reality and what improvements that could be done to the next sampling round follow. Each part is built up with the following sections, ideas and performance, result, problems and improvements.

Chapter 7, 8 and 9 describes the results. In Chapter 7, all data is presented together with a small description of the results in words. In Chapter 8, the results are evaluated and thus the discussion chapter. In Chapter 9, the conclusions of the work are presented.

Since this subject is rather unexplored there is a lot of work left to do. Suggestions to this are described in Chapter 10. Chapter 10 also describes the parameters that are needed in order to make a proper estimation of the total methane emission from a certain sewer system.
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1 Introduction

1.1 Background

Methane formation in sewer systems has not received as much attention as the production and emissions of hydrogen sulphide. Hydrogen sulphide is a well-known problem due to odorous problems and corrosion on the walls of the sewer pipes but at the moment methane is an unexplored subject (Guisasola et al., 2008). The methane formation in Swedish sewer systems has not yet been investigated even though it might exist. If methane formation is present and is somewhere in the sewer released to the atmosphere without being noticed, the carbon footprint of the sewer system is higher than previously thought. Besides the consideration of carbon footprint, methane emissions is also a risk since it is explosive in air at a certain concentration, thus dangerous environments could possibly occur. A carbon footprint describes all the greenhouse gases that are released acquire a certain object (e.g. the chair that one sits in when working, the carbon footprint is calculated through adding up all the emissions of greenhouse gases for manufacturing, transportation etc.). An exact carbon footprint is impossible to estimate due to the huge amount of data that is needed but a good approximation can be close enough (Martin, 2008). The carbon footprint is always recalculated to carbon dioxide equivalents for easier comparison. If the carbon footprint shall be estimated for a sewer system, possible methane in sewers needs to be quantified to get a proper result. At Sjölunda Wastewater Treatment Plant in Malmö, southern Sweden, some work has been done (Gustavsson et al., 2011) but to complete the estimation of the carbon footprint of the total wastewater system all the direct emissions must first be identified and estimated.

1.2 Aim

The aim with this Master Thesis was to develop a method for methane concentration estimations in sewer systems. It is important that the method developed is easy to use and have a good reproducibility. The methane formation rate for two different types of pipes shall be estimated, pressurised and non-pressurised. The occurrence of methane in manholes shall be evaluated. The variation of methane during a day in the sewer shall be evaluated by measurements of the wastewater at the inlet at a wastewater treatment plant. Solutions for decreasing the emission should be discussed. This study will help minimizing the methane emissions in the future. By identifying the “hot spots” in the sewer system, this will give a first draft of where methane is formed.

1.3 Greenhouse gases

A gas that contributes to an increase in the earth temperature is called a greenhouse gas (GHG) (Lengeler, 1999). A further increase in emission of these greenhouse gases can have devastating consequences for the earth, i.e. global warming. Some GHGs are more common than other and the most occurring are carbon dioxide, water vapour and methane. E.g., carbon dioxide is formed when fossil fuels are completely combusted. The amount of carbon dioxide also increases as the area of the rainforests decreases since less is consumed in the photosynthesis. The atmospheric amount has increased with 30% since the industrialization and it stands for 70% of the total GHGs today. Other not so common GHGs are nitrous oxides and fluor compounds etc. (Eriksson, 2008).
The greenhouse effect occurs when the sunrays effectively penetrate through the atmospheric layer containing GHGs, bounce against the surface of the earth while it at the same time converts the sunrays to heat radiation and then send them back towards space. If the atmosphere contains too much GHGs, the radiation will not be able to penetrate the atmosphere (e.g. enter the space again) but instead bounce back to hit the earth surface again and therefore increase its temperature (Rummukainen, 2005). The greenhouse gas effect is from the beginning an evolutorial invention that creates the possibility of life on earth, because without the natural global warming the average temperature on earth would be around -18 °C. Due to all the emissions of GHGs the natural global warming is deranged and the overall global warming is intensified. The UN climate panel has calculated that a 6 °C average earth temperature increase will appear during this century if the emission of GHGs continues to increase in the same rate as it has until today (Lengeler, 1999).

There are some predictable problems that will occur if the temperature will continue to increase. The polar ice together with many glaciers will melt, even faster than they are today. This will not only create limited space for many animal species (e.g. the polar bear whose survival depends on if there is enough area with a cold climate to live and hunt in) but also increase the sea level and therefore cause possible flooding of cities and countries that are associated to the sea. The countries around the equator will probably suffer by huge famine due to the absent of food from their croplands. Water will also become scarce, even more than today. Natural disasters, like hurricanes, will become much more common. Many animals and plants that are common today will face extinction (Eriksson, 2008).

1.3.1 Methane as Greenhouse gas
Following water vapour and carbon dioxide, methane is the most abundant greenhouse gas in the troposphere. Both on a molecular and mass basis, methane are also more effective as a greenhouse gas than carbon dioxide (Wuebbles et al., 2001). One molecule of CH₄ traps about 25 times more heat than CO₂ on a GWP₁₀₀ scale and thereby methane contributes to about 20% of the total global warming. It is estimated that about 50% of global methane emissions are related to human activities, this includes landfills, natural gas and petroleum systems, wastewater treatment, agriculture and certain industrial processes (El-Fadel et al., 2001).

The majority of the natural emissions comes from wetlands where the conditions for methanogenesis (methane producing archaea) are favourable, i.e. anaerobic environment and a large supply of organic materials. Another of the world’s natural methane sources might seem a bit surprising for someone, the methane production from termites. Termites produce methane when processing their food. The exact emission is hard to estimate due to the fact that the population of termites varies depending on location in the world. Other natural contributors can be wild fires where organic matter is incompletely combusted, oceans, rivers and wild animals such as buffalos (Solomon et al., 2007). The largest anthropological contribution to methane emissions are rice cultivations. This is due to the large flooded land that contains the right moisture content and abundant accent to organic matter (and of course the absence of oxygen).

One of the world’s largest human-related sources is livestock. This is because methane production lies in the cattle’s natural digestive processes. In connection to cattle, their manure is transported or kept in tanks and silos respectively. This condition creates a beneficial environment for methanogens to live, and produce methane in. Other human-related emission sources are landfills, coal-mining, production of natural gas, petroleum systems and wastewater treatment plants (Solomon et al., 2007).
1.4 Gaseous emission from wastewater facilities

There are different types of gaseous emissions from wastewater facilities. In a study by Dimitriou et al. (2009), it was divided in the following groups, odourant emissions, greenhouse gas, emission from collection systems, physicochemical emission control methods, biological odour control methods, odour monitoring and odour impacts.

Sewer gas is a complex mixture of toxic and non-toxic gases that can be present at varying levels depending on the source. It is formed from household and industrial wastewater. Highly toxic components of sewer gas include hydrogen sulfide and ammonia. Sewer gas also contains methane, carbon dioxide, sulphur dioxide, and nitrous oxides. In addition, chlorine bleachs, industrial solvents, and gasoline are frequently present in municipal and privately owned wastewater treatment systems (Dimitriou et al. 2009).

1.4.1 Methane emissions from wastewater facilities

Global methane emission is estimated to approximately 500 Tg in total per year (Orlich 1990, USEPA 1994). Earlier estimated methane emissions from wastewater management are reported at an average of 2.3 and 33 Tg/year respectively (Orlich 1990, USEPA 1994). Recently the emission is estimated at an average of 1.3 and 2.4 Tg/year, this corresponds to about 5% of the total global methane emissions (El-Fadel et al., 2001). The methane emission from wastewater facilities differs a lot in developing countries and developed countries. In developing countries a very small fraction of industrial wastewater is treated while almost all wastewater is treated in developed countries. The main contributor to the organic load and later on the following methane production is the pulp and paper, meat and poultry and organic chemical industries (El-Fadel et al., 2001).

The management and treatment of domestic and industrial wastewater have been identified as an important source of methane. During the anaerobic decomposition activated by methanogens, methane is subsequently released to the atmosphere by diffusion or mechanical aeration. The methane could be collected for use as fuel after purification (El-Fadel et al., 2001).

1.5 Methane

Methane has an odourless colourless gas at room temperature. The molecule formula is CH$_4$ and it is the simplest alkane with only one carbon atom and four hydrogen atoms (Nyns, 2000). Methane is an explosion risk when it is mixed at rather low concentrations with air, 5-15% (Guisasola et al., 2008).

Methane is an important trace gas in the atmosphere that controls numerous chemical processes and species in the troposphere and stratosphere. Early in the earth’s history about 3.5 billion years ago there were thousands of times more methane in the atmosphere as there is today. The earliest methane was released into the atmosphere by volcanic activities. The methane level depends on increasing sources, decreasing sinks or a combination of both. The concentration of CH$_4$ in the earth’s atmosphere has been increased recently at a global rate of about 1% annually during the twentieth century, and reached 1.72 ppmv (by volume) in 1990 (Badr et al., 1992). The concentration of methane has more than doubled since the pre-industrial time (Wuebbles et al., 2001).
1.5.1 Methane formation
Methane is produced under anaerobic conditions by archaea. The substrate could for e.g. be acetic acid which is cleaved by the archaea and fermented to methane and carbon dioxide with a certain yield due to the following formula.

\[ \text{H}_3\text{C-COOH} \rightarrow \text{CH}_4 + \text{CO}_2 \]

Other archaea use different substrate and another possible reaction is to oxidize hydrogen with carbon dioxide as the following formula describes.

\[ 4\text{H}_2 + \text{CO}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} \]

Methane is not only produced, there are actually even sinks for the atmospheric methane. Most of the tropospheric methane is destroyed, according to the following reaction formula.

\[ \text{CH}_4 + \text{OH} \rightarrow \text{H}_2\text{O} + \text{CH}_3 \quad (\text{Badr et al., 1992}) \]

There are two different temperatures for optimum methane formation by metanogenesis, the mesophilic is 35°C and the thermophilic is approximately 55°C. Thermophilic metanogenesis result in faster production and higher yields, but the drawback is that the process is often unstable. Between 20 and 30°C both methane production and microbial growth are possible, but microbial growth becomes gradually slower the closer the temperature is to 20°C. A reaction scheme for all the possible products are shown in Figure 1 (Nyns, 2000). Since the wanted conditions for methane formation is reached in the sewer this is of interest.

\[ \text{Anaerobic} \hspace{1cm} \text{Aerobic} \]

**Figure 1. Flow sheet that describes all the possible products and reaction ways for methanogens (Prescott et al., 2008). Reproduced with permission.**

1.5.2 Methanogens
Methanogens is a group of archaea that produces methane as a metabolic by-product. There are about fifty methanogens known today and they can have different forms and shapes but the most common is spherical or rod shaped (Prescott et al., 2008).

Even if they adopt different forms they all belong to the group Archaea. The methanogens are anaerobic, they can survive for a certain amount of time in the presence of oxygen but their
production is inhibited. (Prescott et al., 2008). The optimal pH for methane production has been shown to be 6 but some archaea that have been found can have a methane production at a pH as low as 3 and at as high as 9 (Williams et al., 1984).

1.5.3 Methane concentration as COD
The impurity of water is often measured as the amount of present organic matter in the form of chemical oxygen demand (COD). COD is determined by measuring the amount of oxygen needed to reduce the organic matter until totally degraded. The method that was used in the past to check if there was any carbon matter present in a liquid was a qualitative method where one added a strong reducing agent that coloured the liquid. As the amount of the reducing agent decreased (was reduced) the more of the colour disappeared. The most common method used today for wastewater is by estimating the COD oxidability by adding potassium dichromate, which is an oxidant, at a specified concentration, catalytic, acidic and temperature (Vianna da Silva et al., 2011). When converting a methane concentration to a COD concentration the value is multiplied with four. This value is found from the balanced reaction formula when methane is totally oxidized to carbon dioxide and water, as one can find is four moles of oxygen needed for oxidation of one mole of methane.

\[ \text{CH}_4 + 2 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O} \]

1.6 Biofilms
A biofilm is an aggregate of microorganisms in which cells adhere to each other on a surface (Harrison, 2005). The formation of a biofilm is analogous to the development of a multicellular organism. A typical biofilm forms when free moving microorganism absorbs to a biotic surface. Adhesion is the first change on the path to a biofilm lifestyle. As the microorganisms grow, division signals are passed between them. Mature colony produces extracellular polymeric substances, a polysaccharides matrix (Harrison, 2005). Figure 2 shows how the biofilm is formed.

Figure 2. Biofilm formation (Harrison, 2009). Reproduced with permission.
That formation of biofilm inside the wall of a sewer system exists has been known for a long time. Most of the microorganisms live in large groups and forms visible colonies, the individual microorganism itself is hard to see but the whole group are visible (for instance as biofilms). The most recognized biofilm is probably the slippery slime covering the rocks in lakes and oceans. This slime consists of microorganism, fungi and algae. Everything begins with a bacterium that colonizes a rock and starts producing an electrostatically substance that traps clay, food and other compounds that makes it possible for microorganism to live and reproduce. As time goes, more and more will stick to this gel and finally a centimeter thick biofilm in steady state might be formed. This biofilm is often called a hydrogel which refers to a gel that contains many times its own weight of water. This hydrogel is spread due to the fact that some parts is detached and then follows the water until it lands on a new rock and builds up a new colony there. Biofilm can be formed practically everywhere, on boats, rocks wastewater pipes, but the method of how it is formed is basically the same and it can consist of one or many different spices.

1.7 VA SYD

Field analyses from Malmö sewer system is used as a ground for the estimation of methane formation in the sewer system. This study is done in collaboration with VA SYD. VA SYD is a municipal joint authority that was formed in 2008 and operates in the municipalities of Malmö, Burlöv, Lund and Eslöv. The main task for VA SYD is to supply the mentioned municipalities with drinking water and handle the wastewater.

The sewer systems in the operating municipalities are 2900 kilometers long and connected to each other like a giant cobweb. VA SYD is a nonprofit authority which means that no unnecessary costs will appear for the consumers.
2 Sewer systems

Sewer systems are an essential component of urban wastewater management. They collect and transport wastewater from a source to a wastewater treatment plant. In Sweden the total length of the sewer system is about 92,000 km which is slightly above two times the perimeter of the earth (Fakta om vatten och avlopp, 2005). This value is only the municipality owned sewer pipe. The sewer handles both wastewater and stormwater but mostly in separate pipes nowadays. The conduits in the ground contains mostly concrete, in fact 80%, the other 20% is PVC and polyethylene. The pipes that are built today contain mostly plastic materials.

The pipes in a sewer system are built up in two different ways. The wastewater in the pipe is either driven by the gravity or by pumping stations and is therefore called gravity mains and rising mains respectively (Guisasola et al., 2008), see Figure 3.

![Figure 3. Inside of a gravity main and a rising main respectively.](image)

The layout and design of a sewer system depends largely on the topography of the area. The pipelines are located most of the time in a way so that the wastewater flows naturally downhill in partially filled pipes that are not under pressure. Pipe sizes and slopes must be designed in a range that provides scouring velocities at minimum flows but also limits excessive velocities in order to prevent abrasion of the pipe walls at maximum flows. In flat surroundings, wastewater must sometimes be pumped under pressure through force mains directly to a treatment plant or to a point where it can again flow downhill by gravity.

Manholes are located over the pipeline at frequent intervals for pipe cleaning and repair services as well as for sampling and flow measurements. The manholes are typically cylindrical in shape and are made of brick, concrete, or concrete block with a circular cast iron frame cover, to stand traffic loads and keep out surface water. The entire network of sewer pipes, manholes, pumping stations, force mains, and other appurtenances is called a sewerage system (Nathanson, 2012).
2.1 Modeling of biofilm in sewer pipes

Modeling of methane formation is such a novelty and not many models for methane formation in sewer system exist. None of the existing models concerns the variation in biofilm along the sewer pipe. The intersection of a half filled sewer pipe is shown in Figure 4 and this illustrates where the biofilm is formed.

The biofilm is dynamic and heterogeneous along the sewer. There are several models currently available for hydrogen sulphide (H\textsubscript{2}S) prediction, but most of the models assume constant biofilm activities along the rising mains which is a simplification of the reality.

![Figure 4. A sewage pipe and biofilm formation in an intersection.](image)

A study performed by an Australian research group, (Mohanakrishnan et al., 2009) examined their hypothesis whether the biofilm along the sewer is homogenous or not. The experiment was performed on a rising main at the Australian Gold Cost. The rising main in the study was 1084 meters long and wastewater samples for analyse was taken at five different sites along the main. Unfortunately the researchers were not able to collect biomass direct from the real sewer pipe. To be able to analyse the biomass a side stream was coupled and connected to three Robbins devices, RD, which is an instrument used for biomass analysis. The stream was pumped in the RDs for 9 months before the tests were performed, this to let the biofilm formation reach steady state in the devices. The equipment and couplings is shown in Figure 5.

![Figure 5. The coupling of the equipment (Mohanakrishnan et al., 2009).](image)

Analysis of wastewater from the two streams showed that both in the rising main and in the RD set up sulphate decreased through the pipes while the sulphide concentration increased. This showed that the two streams were rather similar and that the biomass might be similar as well. This was unfortunately not established because it was different inlet concentration of
sulphate at the different pumping events when the biofilm was formed in the two streams (e.g. the biofilm formed in the RDs was formed due to the water that was pumped through the devices during 9 months. The biomass in the rising main was formed from the water that has been pumped in the main also before the RDs were set up).

When the biofilm formed in the RD devices was studied it could be seen that the substrate was consumed in a higher rate at the beginning of the main than in the end. They also found that more biomass was formed in the beginning than in the end of the pipe. When a deeper study of the biomass in the different RDs was executed the researchers found that the biofilm formed were heterogeneous and contained different amounts of different microorganism. Their final conclusion then became that as long as the wastewater contains different amounts of different compounds the biofilm formed will not be uniformed through the sewer pipes (Mohanakrishnan et al., 2009). Their main results are presented in Table 1.

Table 1. Results of the biomass study that were performed showed that variation in the biofilm formed exists (Mohanakrishnan et al., 2009).

<table>
<thead>
<tr>
<th>Devices</th>
<th>n&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Sulphate reduction rate (g S/m&lt;sup&gt;2&lt;/sup&gt;d)</th>
<th>VFA production rate (g COD/m&lt;sup&gt;2&lt;/sup&gt;d)</th>
<th>Colour</th>
<th>Average (g biomass/m&lt;sup&gt;2&lt;/sup&gt;) of coupon</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD 1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>7</td>
<td>1.12 ± 0.13</td>
<td>4.19 ± 0.66</td>
<td>Creamy brown</td>
<td>48.13 ± 3.85</td>
</tr>
<tr>
<td>RD 2&lt;sup&gt;b&lt;/sup&gt;</td>
<td>4</td>
<td>0.89 ± 0.16</td>
<td>1.53 ± 0.44</td>
<td>Grey brown</td>
<td>32.56 ± 3.10</td>
</tr>
<tr>
<td>RD 3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>4</td>
<td>0.37 ± 0.12</td>
<td>0.28 ± 0.11</td>
<td>Brown</td>
<td>35.29 ± 2.45</td>
</tr>
</tbody>
</table>

<sup>a</sup>n = total number of studied.
<sup>b</sup>Mean ± standard error.

2.2 Ventilation of sewer system

Ventilation of sewer system is of interest because it may be in this way that the methane leaves the sewer. When measuring the methane concentration in the sewer no consideration to the airflow out is done, but obviously the production rate is affected by the ventilation in general and the flow through the pipe in specific.

Ventilation of sewer system is dependent on the pressure difference between the ambient air and the pressure in the conduits. Obviously when the pressure is the same inside the pipe as the ambient air there will be no flow of air via the manhole. Some municipal sewer systems are sometimes mechanically ventilated using auxiliary ventilators such as a blower or a fan. This is done to get rid of corrosive, odours and other hazardous gases. The ventilation performance curve depends on a number of factors including speed, motor power, efficiency etc. To provide a model for ventilation of a sewer would require both theoretical analysis and field data.

Many factors are contributors to the ventilation such as the wind speed outside the conduits. These factors are not included in the model that describes the ventilation in sewer system but still affect the volumetric air flow (Edwini-Bonsu, 2006). Also a pressure difference between the air and the gas headspace in the sewer can induce ventilation. If the pressure inside a pipe,
where a manhole is located, is lower than the surrounding air above the manhole, the pressure difference will be equalized by air entering the sewer through the pick holes at the manhole. If the pressure is higher in the sewer, the sewer gas will be discharged into the air until the pressure difference is equalized.

Assumption of constant conditions in the conduits is needed to model velocities of the airflow. The truth is that the only thing that is constant in the sewer is the change. This means that all models are more or less consistent with the reality. To be able to make a model over the system it has to be broken down to elements and nodes. For a large sewer system a lot of data is then needed. This is not an option in this project since it is not the main focus and it takes a lot of effort (Edwini-Bonsu, 2006). For deeper studies of the production rate, a certain pipe could be investigated in detail. This will however require a lot of information, including e.g. flow rate, filling of the pipe and mechanical and natural ventilation opportunities.

2.2.1 Air velocity in sewer pipes
The airflow above the wastewater surface is of interest in order to be able to calculate the production rate of methane. The production rate of methane is dependent on the exchange of air in the conduct. If no ventilation exist on a specific distance all produced methane remains in the pipe.

The air in the sewer pipe is dragged by the wastewater flow but not with the same velocity. Assumption regarding the ratio of the wastewater and the air velocity is hence needed. In one article it is assumed that the air velocity is half the wastewater velocity irrespective of the sewer hydraulics (Edwini-Bonsu, 2004). This is of course a rough estimation since the real value is dependent of filling degree, geometry and if the flow is laminar or turbulent etc. The driving force for the airflow is the friction at the air water interface. There are more factors that affect the air speed than the wastewater speed but this one affects the most and acts continuously. With no other ventilation mechanisms (no manhole or ventilator), air and wastewater flow is co-current, see Figure 6. Recirculation flow may however exist when openings between sewer and ambient atmosphere occurs.
Figure 6. Sketch over the airflow in the conduits.

The pressure force for the air in the pipe acts in the opposite direction of the wastewater. The wastewater is falling downhill in the gravity direction while the air travels towards lower pressure which is upwards. But the dragging force from the wastewater on the air is greater than the pressure difference and hence is the air flowing in the same direction as the wastewater instead of upwards.
3 Methane formation in sewer system

Methane emission in wastewater treatment facilities occurs as a result of anaerobic treatments of organic compounds. The rising mains creates a perfect environment for methanogens because they are completely anaerobic, the pH is usually around neutral, the temperature does not differ so much during the year (because the pipes lays deep in the ground), there are often high amounts of organic carbon present and the pipes are pressurised which means that the concentration of methane can get supersaturated (Guisasola et al., 2008).

Due to the fact that rising mains are pressurised the concentration of dissolved methane can get supersaturated. Most of this supersaturated dissolved methane will leave the fluid and enter the gas headspace when the pressure is released. If there is an opening (e.g. from a well) to the air the methane will leave the gas headspace in the sewer and enter the atmosphere (Guisasola et al., 2008).

There are some factors that affect the methane formation. Since the production takes place in the biofilm, it is necessary that as much water as possible is in contact with the biofilm to gain the production. Therefore the formation will decrease with increasing A/V ratio since more water will flow unperturbed through a larger pipe. It has also been shown that the higher hydraulic retention time, the higher methane concentration. Therefore the methane concentration peaks during the earliest morning just before people wake up and start taking showers etc. (Guisasola et al., 2008).

3.1 Factors for methane production

There are some factors or conditions that have to be met for methane formation to occur. First attention was paid to these parameters in order to find “hot spots” in the sewer system.

Parameters that favours the methane formation and presence are:

- High temperature
- High pressure
- Neutral pH
- High hydraulic retention time
- High COD content
- High A/V ratio

3.2 Competition between hydrogen sulphide microorganism and methanogens

The production of methane occurs in the biofilm that is formed on the pipe walls. A research group (Jiang et al., 2010) has shown that as long as the substrate is not limited, both hydrogen sulphide producing microorganism (SRB) and methanogens (MB) can coexist. But as soon as the substrate gets limited the MB will be out-competed due to their lower substrate affinity compared to the SRB. Possible coexistence is explained by their difference in penetration depth of the biofilm microorganisms e.g. the amount of SRB is very high near the surface and almost zero deeper into the biofilm. For the MB it is just the opposite, the concentration is low near the surface and high deep in the biofilm. Therefore no competition exists in the biofilm as long as there is enough substrate (Jiang et al., 2010).
3.3 Inhibition

Formation of methane in sewer systems is undesired, to overcome this, substances that inhibits the formation is injected to the sewer. Since methane formation in sewer systems recently caught researcher’s interest, not much attention has been paid to develop a method that inhibits the production. The difficulty is to find a substance and method that can be used to inhibit the formation of both hydrogen sulphide and methane. At the same time to much addition of foreign compounds into the sewer is undesireable (Jiang et al., 2010).

There are three common methods for hydrogen sulphide production inhibition used today (Jiang et al., 2010). One is injection of air, oxygen or nitrate to oxidize the sulphide. The second method consists of addition of iron, zinc, lead or copper salts to form metallic sulphides that is precipitated in the fluent and then removed somehow that is not presented in the article studied. The last method is to directly increase the pH of the wastewater. This will reduce the transfer of hydrogen sulphide between the liquid phase and the air, thus the hydrogen sulphide formation will be prevented.

3.3.1 Inhibition by nitrite addition

A research group from the University of Queensland (Jiang et al., 2010) has studied how nitrite dosage has affected the formation of methane and hydrogen sulphide. The study was performed both in the laboratory and in the field. The laboratory experiment was performed in four reactors with different amounts of nitrite added to each reactor. The amounts added were 0, 40, 80 120 mg NO₂/L, respectively. The result of the laboratory experiment is shown in Figure 7.

![Figure 7. Variation in concentrations of sulphide and methane when adding nitrite (Gutierrez, 2010). Reproduced with permission.](image)

The inhibition of hydrogen sulphide reaches its minimum value after 17 days and it is here the dosage stops. Then it takes about 60 days to reach the same level as before the nitrite dosage.
The methane reaches negligible levels within two days for all concentrations which indicates that even lower concentrations can be used to get rid of the methane in the sewer. Recovery also takes a bit longer for MB than SRB, in fact after 60 days of recovery only 60% of the pre-dosing level is reached for MB. In general certain amounts of inhibition can be reached either with high concentration and short exposure time or low concentration and long exposure time. However a minimum concentration is always needed to reach a certain inhibition level (i.e. 90% inhibition requires at least a minimum concentration which cannot be compensated with longer exposure time) (Guangming et al., 2010).

A field experiment was performed in a rising main with a three days dosing period with a concentration of 100 mg NO₂⁻/L. The nitrite was added at the pump station and the concentration measurements were performed 828 m downstream. The reason why three days were chosen is because total inhibition of hydrogen sulphide was reached after only three days.

The results from the field are shown in Figure 8. As can be seen it is similar to the laboratory experiments. The sulphide hydrogen reaches total inhibition already after three days instead of seventeen days which is explained by differences in the biofilm. Another difference is that a 50% recovery is reached after 7 days instead of 9-16 days. It took about 14 days before the pre-dosing level was reached. The lower picture in Figure 8 shows the methane concentration from 7 days before the dosing began until 13 weeks after. Also here the laboratory experiment was confirmed. The methane production ceased direct and did not recover during the 13 weeks the experiment lasted.

![Figure 8. Result of the field experiment (Gutierrez, 2010). Reproduced with permission.](image)

This two experiments shows that nitrite dosing might have a future for reduction of methane in sewer systems as it inhibits both methanogens and sulphite reduction microorganism. A researcher group (Jiang, 2011) relieveed that the quick reduction in activity of the methane producing biofilm is due to the biocidal effect of the free nitrous acid, FNA. FNA is the
protonated form of nitrite on biofilm microorganisms. Nitrite also has a relative low chemical prize compared to many other potential inhibitors (Guangming et al., 2010). Today’s existing dosing systems consider which concentrations of the two compounds that is acceptable and then measure these at the end of the pipes and then dose considering these measured values.
4 A method for methane concentration estimations in sewer systems

The final and most satisfactory method developed from trial and errors during the development of a method for sampling and analysis of wastewater from sewers is described in this section. The developing process is described in chapter 6 Development of a method for methane concentration estimations in sewer systems. Sampling was done in two different ways either from manholes in the sewer system or from pipes that ended at a wastewater treatment plant. All the laboratory work is executed in the same way as well as the calculations or determination of the methane concentration.

4.1 Sampling and data collected in the field

The sampling technique is based on a study by (Alberto et al., 2000). This sampling technique was first developed for river water for determination of dissolved methane. The technique was assumed to work also for determination of methane in sewers since it has been used by several researchers (e.g. Guissasola et al., 2008). Two different kinds of pipes were investigated, pressurised and non-pressurised. The approach for sample taking in the two kinds of pipe was a bit different because they are built up in different ways.

Sources of errors are a major risk in this work since almost no methodology existed and this study is a first draft. The strategy was to first take samples at a few sites which were potential hotspots just to see if any methane formation existed. The sites needed to be located in a way that samples easily could be taken without any danger action (e.g. no manhole in the middle of the road). To exclude outside hazards, the parameters were discussed with the sample takers at VA SYD and they took this into account when choosing the mains that were going to be examined. The idea was to locate the methane and then in the end, when the method was fully developed, return to this area and take samples again.

4.1.1 Sampling from manholes

The approach here was a screening method which means as many mains with different characteristics as possible were examined. Both the liquid and the gas phase were sampled in the sewer. Samples from manholes were taken at sites randomly scattered around Malmö. This was done to get an overview if methane production exists in many sewers and if it does at what concentrations. From this any possible typical site could be found and characteristics could be determined. Both manholes in residential areas as well as areas with a lot of industries were investigated.
4.1.2 Estimation of methane production
The methane formation rate was calculated and for this samples were taken at two different spots, in the pipes. The sampling spots was located as far away as possible from each other on the same pipe length and without interferences of any head works just as shown in Figure 9.

![Figure 9. The pipe length with the two sampling places.](image)

Non-pressurised pipe
To be able to calculate the methane production, the average instantaneous sewage velocity was measured together with the filling degree and the pipe diameter. From this, the liquid and air flows are calculated assuming an air velocity half of the wastewater (Edwini-Bonsu, 2004).

Pressurised pipe
In the pressurised pipe, the first sample was taken in the closest manhole to where the pressure begins and the second sample as close as possible to the pressure release, as there was no access directly to the pipe where it was pressurised or where the pressure was released. The average instantaneous sewage velocity was measured. Also here was the assumption made that the velocity of the air over the wastewater is half of the wastewater, this to be able to calculate how much methane that had been stripped off to the sewer air from the pressure released to the sampling place. This would not have been necessary if there were access directly to the point of the pressure release. But as soon as the pressure is released the methane will begin to leave the wastewater and therefore a gas sample is also needed for estimations in the pressurised pipe.

4.1.3 Sampling procedure in manholes
The sampling of wastewater was done in 100 ml bottles. In every manhole two bottles were filled, one was used to fill 7 or 10 ml vacuum tubes donated from BD and Labco with 4 or 6 ml sewage and the other bottle was stored refrigerated to be analysed later at the laboratory. The reason why two different kinds of vacuumed tubes were used is because the ones from Labco were sent in twenty specimens. These were the most optimal ones, since the vacuum tubes did not contain any disturbing background components, but they would not suffice through the whole Master Thesis. Therefore the second best of the tested vacuum tubes were ordered and used. The vacuumed tubes filled in the field are executed in the same way as the ones in the lab, described in section 4.3.1. The sampling session is done by climbing down the manhole, carrying the two sample bottles in the pockets, see Figure 10. The most important thing is to avoid aeration of the sample. This is done by holding the sample bottle below the
wastewater surface and wait for it to be filled before the cap is put on below the water surface. A document was filled in at each sampling site, see Appendix 1.

**Figure 10. Sampling in a manhole at Segevång, Malmö.**

The bottles were filled as much as possible to avoid any contact with oxygen when transporting them and taken at the middle depth of the pipe to get as good average value as possible. At the same sampling points as for the wastewater, sewer gas was also collected for methane analysis. This was also done in BD’s 7 ml vacuum tubes or Labco 10 ml exetainers shown in Figure 11. The device built to force the sewer air into the tubes, a needle, which was just pushed through the cap when the gas was supposed to be collected, see Figure 12. When the gas was trapped inside the tubes the device was removed by just pulling it out and the gas were no longer able to flow in or out from the tube.

**Figure 11. Vacuum tubes donated from BD and Labco where BD:s is the lower one.**
4.1.4 Procedure for sample taking from incoming pressurised pipe to Sjölunda Wastewater Treatment Plant

The wastewater treatment plant surveys were all executed at Sjölunda where the incoming pressurised pipe was investigated and tested for methane. The sampling was done by lowering a sample bottle with a rubber cap under the surface at the same level all the time, see Figure 13. When the bottle was as close to the pipe as possible, the cap was removed by pulling a string attached to the cap. When the bottle was filled it was quickly removed from the basin where the pipe had its outlet and the water was poured into a 100 ml bottle with a rubber cap that was placed refrigerated until it was analysed. Also here it was very important not to let any air inside the bottles. To be sure that the sampling was done at the same place every time the used rope was marked and an extra weight was attached to the sampling device so it would not move along with the flow.

Figure 12. Gas sampling device.

Figure 13. Sampling of sewage from a pressurised pipe.
The sampling device used is shown in Figure 14. There are two strings attached to the device, one to the sampling bottle holder and one to the rubber stopper. The extra weight can also be seen under the sampling device.

![Sampling equipment at the pressurised pipe.](image)

To see how the methane concentration varies in the pipe during the day, one sample was taken every half hour between 8 am to 5 pm. To verify the sampling method used, four bottles were filled one time during the day within a time span of 5 minutes. From these samples a confidence interval for the methane measurements was constructed.

4.1.5 Transportation of the samples
When the samples are transported they are kept refrigerated in a cooling bag to avoid any further methane production. The storing equipment is shown in Figure 15.

![The samples were kept refrigerated during the day until they were analysed in the laboratory.](image)
4.2 Laboratory work

4.2.1 Laboratory analysis preparation before gas chromatography

All laboratory work was done in the laboratory of Water and Environmental Engineering at the department of Chemical Engineering at Lund University. The laboratory set-up is illustrated in Figure 16. The equipment used was:

- 100 ml glass bottle with plastic cap
- 7 and 10 ml vacuum tubes
- 10 ml syringe
- 0.22 µm filter
- Needle for the syringe, three different size
- Gas Chromatograph Agilent 6850 equipped with a FID detector and a HP-1 column (19091Z-413E) 30 m + 0.32 mm + 0.25 µm
- Hamilton syringe

The syringe was rinsed with wastewater once before the real samples were transferred from the sample bottles to the vacuum tubes. Besides clogging and destroying the GC the filter used also avoids any microorganism to come inside the sample and thereby have further methane production. The syringe was turned upside down and the air inside the syringe was ejected before the wastewater was transferred to the vacuum tubes. The vacuum in the tube was released which means that a needle was stung through the rubber cap. Hence air could flow unprevented into the vacuum tube and thus reach atmospheric pressure which was important when performing the calculations later. The vacuum in the tubes was released before the tubes were shaken and then the samples were resting for 1 hour to allow equilibrium. The equilibrium state was needed for further calculations, assuming equilibrium in the analysed gas. Samples of 0.2 ml of the gas phase were taken with a Hamilton syringe, just over the surface of the wastewater. The water sample could have been injected directly into the chromatograph instead of the gas phase, but to avoid the risk of clogging the syringe and damage the gas chromatograph the gas was prefered ahead of the liquid phase. Also, some of the GC instruments could not be used for liquid injections. Three replicate per sample was done. The procedure with equipment where wastewater is taken from the sample bottle and transferred to the vacuum tubes is shown in Figure 16.
4.2.2 Procedure for determination of Henry’s constant

A 100 ml bottle with a rubber cap was filled with methane and then the vacuum was released to reach atmospheric pressure. The bottle was then filled with 80 ml distilled water, released vacuum ones more and then shaken for 30 seconds. After one hour the gas was analysed and Henry’s constant could hence be calculated.

4.3 Calculations

The method used for calculations of the methane concentration was Henry’s law and mass balances. A computation template was constructed in MATLAB in order to make it easy to redo all calculations, in Appendix 2 and 3 the two files can be seen. Compensation for background methane was done when the tubes used contained background methane. For numbers used see Appendix 4.

4.3.1 Henry’s constant determination

Henry’s constant is dependent on pressure and temperature and in this study the constant was determined for the prevailing conditions in the lab and was assumed to be constant for all samples. When filling the bottle a syringe was used to know the exact volume of water added and therefore the volume of methane can easily be calculated.

Figure 16. Set-up for the laboratory analyses of dissolved methane determination.
Henry’s constant is determined from the following equation.

\[ H_{e,CH_4} = \frac{P_{tot} \times x_{CH_4}}{C_{CH_4}} \]

Where:

- \( H_{e,CH_4} \) = Henry’s constant for methane in water (Pascal \( \times \) L/mol)
- \( P_{tot} \) = total pressure in the bottle used for the experiment (Pascal)
- \( x_{CH_4} \) = the partial pressure of methane in the gas headspace (%)
- \( C_{CH_4} \) = concentration of dissolved methane in water (mol/m³)

The concentration of dissolved methane is calculated from the known start concentration (due to the known volume of methane) and the methane concentration after equilibrium is allowed, the following formula is used:

\[ C_{CH_4} = \frac{\left( \frac{P_{tot}}{R \times T} \right) - \left( \frac{P_{tot} \times x_{CH_4}}{R \times T} \right) \times V_{gas,flask}}{V_{liquid,flask}} \]

- \( R \) = The general gas constant (Joule/mole/Kelvin)
- \( V_{liquid,flask} \) = The liquid volume in the bottle (m³)
- \( V_{gas,flask} \) = The gas volume in the bottle (m³)
- \( T \) = The tempature in the room (K)

### 4.3.2 Methane concentration calculations

**Analysis of the vacuum tubes containing sewage:**

\[ C_{CH_4,sewage} = \frac{n_{HS} + n_{liquid}}{V_{liquid,tube}} \]

Where:

- \( C_{CH_4,sewage} \) = Total concentration of metane in the liquid from the beginning (moles/L)
- \( n_{HS} \) = moles of metane in the gas head space of the vacuum tube (moles)
- \( n_{liquid} \) = moles of metane in the liquefe phase of the vacuum tube (moles)
- \( V_{liquid,tube} \) = the liquid volume in the vacuum tube (L)

The amount of moles in the gas head space, \( n_{HS} \), is calculated from the following formula:

\[ n_{HS} = \frac{P_{tot}}{R \times T} \times x_{CH_4} \times V_{gas,tube} \]

\( V_{gas,tube} \) = Volume gas in the vacuum tube (m³)
\(n_{\text{liquid}}\) is calculated from the Henry’s constant for methane in water, using the following formula.

\[
n_{\text{liquid}} = \frac{P_{\text{total}} \times x_{\text{CH}_4}}{He_{\text{CH}_4}} \times V_{\text{liquid, tube}}
\]

\(V_{\text{liquid, tube}} = \text{Volume of gas in the vacuum tube}\)

Analysis of the vacuum tubes containing the air collected in the sewer:

\[
C_{\text{CH}_4,\text{air}} = \frac{P_{\text{tot}}}{R \times T} \times x_{\text{CH}_4}
\]

\(C_{\text{CH}_4,\text{air}} = \text{Concentration of methane in the air collected from the sewer}\)

### 4.3.3 Methane production calculations in a non-pressurised pipe

The production of methane that shall be estimated for the selected pipe is calculated using the following formulas. The vacuum tubes are analysed in the same way as before and the concentration of methane is calculated using the same formulas.

Methane that is produced and remains in the liquid between the two sampling points:

\[
\dot{m}_{\text{CH}_4, \text{liquid}} = \frac{(C_{\text{CH}_4, \text{liquid, prod}} - C_{\text{CH}_4, \text{liquid,1}}) \times v_{\text{liquid}} \times \frac{d^2 \times \pi}{4} \times \beta}{l} \times M_{\text{CH}_4}
\]

\(\dot{m}_{\text{CH}_4, \text{liquid}} = \text{The average production of methane that remains in the liquid (g/s)}\)

\(v_{\text{liquid}} = \text{The instantenious average liquid velocity (m/s)}\)

\(d = \text{The diameter of the pipe (m)}\)

\(\beta = \text{Filling factor of the pipe (\%)}\)

\(M_{\text{CH}_4} = \text{Molar mass of methane (g/mole)}\)

\(C_{\text{CH}_4, \text{liquid, prod}} = \text{The average methane concentration in the liquid between the two sampling points (mole/m}^3\text{)}\)

\(l = \text{length of the pipe (m)}\)

\[
C_{\text{CH}_4, \text{liquid, prod}} = \frac{C_{\text{CH}_4, \text{liquid,2}} + C_{\text{CH}_4, \text{liquid,1}}}{2}
\]

The index number indicates the two sampling points.

The methane production between the sampling points that has left the liquid and entered the gas headspace:

\[
\dot{m}_{\text{CH}_4, \text{gas}} = \frac{(C_{\text{CH}_4, \text{gas, prod}} - C_{\text{CH}_4, \text{gas,1}}) \times v_{\text{liquid}} \times \frac{d^2 \times \pi}{4} \times (1-\beta) \times M_{\text{CH}_4}}{l}
\]

\(\dot{m}_{\text{CH}_4, \text{gas}} = \text{The average production of methane that has entered the gas (g/s)}\)

\(C_{\text{CH}_4, \text{gas, prod}} = \text{The average methane concentration in the gas headspace between the two sampling points (mole/m}^3\text{)}\)
4.3.4 Methane production calculations in a pressurised pipe

Analysis of the vacuum tubes:

The vacuum tubes are analysed in the same way as before and the concentration of methane is calculated using the same formulas.

Calculation of the methane production rate:

\[
\dot{m}_{\text{CH}_4,\text{tot}} = \frac{\left( c_{\text{CH}_4,\text{liquid,prod}} - c_{\text{CH}_4,\text{liquid,1}} \right) \cdot v_{\text{liquid}} \cdot \frac{d^2 - d^2 + \epsilon}{4} + c_{\text{CH}_4,\text{air, end}} \cdot \frac{v_{\text{liquid}} \cdot \left( \frac{d^2}{4} - \frac{d^2 - d^2 + \epsilon}{4} \right)}{2} \cdot (1 - \beta)}{l} \cdot M_{\text{CH}_4}
\]

\[C_{\text{CH}_4,\text{air, end}} = \text{The concentration of methane in the air at the end of the pressurized pipe (mol/m}^3\text{)}\]

4.3.5 Confidential interval calculations

The confidence interval is calculated according to the following formula:

Confidence interval (Olbjer, 2000):

\[
I_\mu = \left( \overline{x} \pm t_{\alpha} \cdot \left( n - 1 \right) \cdot \frac{S}{\sqrt{n}} \right)
\]

\[\overline{x} = \text{The average value from the samples}\]

\[t_{\alpha} = \text{Quantile that depends on number of measurements and degree of safety}\]

\[n = \text{Number of measurements}\]

\[s = \text{Measurement of the breadth on the distribution, standard deviation}\]
5 Potential methane formation sites in Malmö

The sampling sites were chosen with the literature study as a basis. Location, time, number of the manhole, pipe diameter, filling degree, and maximal velocity at the sample spots was registered, see Appendix 5.

5.1 Malmö sewer system

To give the reader a deeper understanding in how Malmö’s sewer system is built it is described here. The sewer system in Malmö covers an area of just over 15000 ha (Thysell, 2009), see Figure 17. The system is divided into seven large drainage areas, Turbinen, Rosendal, Spillepengen, Södra Sallerup, Hamnen, Limhamn and Klagshamn. The 15000 ha consists of 1864 ha combined sewers, 495 ha non active duplicate sewers, 4995 ha duplicated systems and 7803 ha of non-covered surface. The characteristic for the sewer network in Malmö is that about 30% consist of combined system. This has historically reasons and the consequences are that when large precipitation occur the risk for basement flooding and stormwater overflow are high in these areas. It is important for VA SYD to minimize both types of nuisance. Around 60% of the sewage flow is wastewater from household and industries while the other part comes from spills and stormwater. Large parts of the sewer network in the central parts of Malmö, is built as a combined system. The newer parts of the sewer, mainly located at the outer parts are built in a duplicate system. In Malmö there are two wastewater treatment plants one located in Klagshamn and the other in Sjölunda, marked with an X in Figure 17 (Thysell, 2009).

![Figure 17. Drainage areas in Malmö (Thysell, 2009). Reproduced with permission.](image-url)
5.1.1 Drainage areas
All drainage areas in Malmö are described below. The characteristics of each area and how large it is are presented.

*Turbinen (2527 ha)*
Turbinen is one of Malmö’s oldest sewer network and was built between 1930-1955. About 40% consists of a combined network, 20% is non-covered and 40% is a duplicated system. The sewage is pumped to Sjöllunda Wastewater Treatment Plant and if the volume is too large, the excess is led to Malmö canal.

*Rosendal (867 ha)*
Malmö’s oldest duplicated system is located in Rosendal and it covers about 21% of the total area, 69% of the sewer system is a combined sewer and 5% is non-covered. To avoid flooding of basements during heavy rainfalls or snow melt it is broadened to Sege creek and Malmö canal. Also this drainage area is connected to Sjöllunda.

*Spillepengen (5101 ha)*
Spillepengen is the largest duplicated system in Malmö which cover a total of 49%, 45% is non-covered and 5% is combined. The sewage is pumped to Sjöllunda together with the area of Rosendal and Turbinen. The stormwater from this area is connected to Sege and Riseberga creek which also is where the broadened occurs when the system is full.

*Södra Sallerup (900 ha)*
Södra Sallerup has the smallest sewage areal in Malmö and consist of 5.5% duplicated system and 94.5% non-covered. No stormwater overflow is possible here due to the lack of sewage pipes. The stormwater is connected to Sege and the sewage is connected to another sewer network in Oxie.

*Hamnen (850 ha)*
The sewage system in Hamnen consist most of duplicated pipes, 65%. 25% is combined and 8% is non-covered. The stormwater is connected to a basin and then further to the Oresund. The sewage is treated at Sjöllunda.

*Klagshamn (4556 ha)*
Klagshamn covers a wide area but not many sewage pipes exist here. The non-covered area covers 84%, 15% is duplicated and 1% is combined. The sewage is pumped to the wastewater treatment plant in Klagshamn which also handles the sewage from Limhamn. It is believed that Klagshamn also will handle sewage from the new villages that is emerging in the neighborhood.

*Limhamn (770 ha)*
Limhamn is the smallest drainage area in Malmö and covers only a total of 770 ha. Of this 770 ha is 13% duplicated, 43% non-covered and 38% combined. When broadening is needed due to heavy rainfalls is it done to the nearby harbour.

5.1.2 Pressurised sewer system
The percentage of how much of the Swedish sewer system that is pressurised was calculated to get more knowledge of the distribution between non pressurised and pressurised pipes. 36 municipalities in Sweden are included in the calculations that are based on reported numbers
to Svenskt Vatten, 2013, see Appendix 6. Approximately 9.6% of the Swedish sewer system is pressurised, either consisting of so called LPS (Low Pressure Sewer) (0.5%) or of vacuumed pipes (0.02%) or of conventional pressurised pipes (9.1%). These values are approximately estimated since not all municipalities in Sweden has reported their amount of pressurised sewer system to the source used.

During the last years has the interest for building pressurised sewer systems increased. This because of that the sewer system is expanding in areas that is less urban or where it is a hilly topography (Svenskt Vatten, 2013).

In Malmö only few pressurised pipes exist. Most of them are located in the north of Malmö, they come from Turbinen, Rosendal, Spillepengen and some minor pump stations in the harbour. When there is a heavy rainfall or snow melt a total amount of 8 cubic meters per second can be pumped (Thysell, 2009).

5.2 Sites for the first sampling occasion

For the first sampling session eight manholes scattered around Malmö was chosen. The manholes are stated in point form below together with a small explanation of why they were chosen. A map over the manholes is presented in Figure 18. This sampling took place the 23nd of November 2012.

![Figure 18. Map over sampling sites for the first sampling session (two of the sampling points are marked with the same sign since they were taken almost at the same place).](image-url)
• Segevång, SNB322
Is a pipe that lays 300 meters downstream from an apartment area. The pipe has a small
diameter and therefore a high A/V ratio.

• Skånemejerier (dairy), SNB5639
This is a potential hot spot because they have just applied to expand their production and with
larger production comes larger emissions. Since it is a dairy company it is believed that their
emissions contain high amounts of fat, protein and carbohydrates. This is also an interesting
site because of the temperature that the sewage that leaves the industry has since it is heated
up in their process.

• Heleneholm 1, KNB4231
This pipe is of interest because it collects wastewater from a big area and thereby covers a
broad range of wastewater from different origins. Analysis of pipes like this is a good way to
see if methane exists in the sewer. At least if all the possible formed methane has not been
stripped to the atmosphere through the manholes along the way.

• Heleneholm 2, SNB2974
This pipe is chosen because it lies just beside the first one but collect sewage from a different
area

• Turbinen, KNB659
Turbinen is of interest because this is the last manhole before the stream enters the pump
station that will pump the water up to Sjölunda wastewater treatment plant.

• Limhamnsvägen, SNB2364
Limhamnsvägen is chosen because of its extremely short hydraulic retention time and large
amount of biomass. It is also well known that this manhole contains high concentration of
hydrogen sulphide.

• Strandvägen/Skåneg, SNB2655
Strandvägen is of interest because of its high filling degree and thus lower chance to aerobic
conditions.

• Oxie, ARV, SNB6066
Oxie is of interest since the village does not have any food waste collection which is quite
common nowadays. Hence is there a large chance that food ends up in the sink and then in the
sewer which increases the presence of carbon matter in the pipes.

5.3 Sites for the second sampling occasion
On the second field trip, samples from four places were collected. On this trip was the flows
and filling factors also registered. Two sites were chosen because they were connected to each
other in a pressurised pipe. The other two sites were chosen because methane was found in
these areas on the first sampling occasion. The sites are listed in point form below and the
position of the manholes examined is shown in Figure 19. The second sampling occasion took
place the 6th of February 2013.
Figure 19. Map over sampling sites for the second sampling session.

- **Skumparp, SNB6878, SPU70**
  The reason that Skumparp was chosen was because it was a pressurised pipe with a small A/V ratio. It was also possible to take samples on the sewage in two different manholes on the same pipe length and hence it was possible to calculate the methane production rate here.

- **Skånemejerier2, SNB5932**
  Skånemejerier2 was chosen because it was believed that the pipe coming from the dairy company had great potential on methane formation even though nothing was found on the first sampling occasion. On the first field trip a pipe that laid about 50 meters after the dairy company was examined and this was might too close to the emission source, therefore the same pipe was examined ones more but further downstream.

- **Oxie2, SNB6067**
  Oxie2 was chosen because of the simple reason that methane was found in the sewage on the first field trip. Another manhole in the same area was chosen to confirm the first result.

### 5.4 Sites for the third sampling occasion

On the third field trip samples were taken from three different manholes. The first two were chosen because they were connected to the same gravity pipe. The last manhole was chosen
because it is connected to a tank for collection of organic waste from household grinder and thus possibilities of presence of a high amount of organic matter. The sites are listed in point form and their locations can be seen in Figure 20. The third sampling occasion took place the 15th of February 2013.

Figure 20. Map over sampling sites for the third sampling session.

- Jägersro, SNB5932, SNB5933
  These manholes were of interest because they were connected to the same pipe without any headwork between. The production rate could hence be calculated in this gravity main.

- Turning Torso, SNB7979
  Turning Torso in Malmö is very interesting from a methane formation point of view. All the sinks in the building are connected to disposers which grinds the food. The grinded food is then separated from the water stream and stored in a large tank. The principle of the separation can be seen in Figure 21, where the arrows describe the directions of the different compounds. The system works similar to a sedimentation process, the food is too heavy to follow the water stream and falls to the bottom due to the gravity. The tank is then emptied every fourth week. This in itself is not a problem but when the tank is emptied and not cleaned properly there will be some residues on the bottom and on the walls of the tank.
When the food (carbonhydrates, protein and fat) lays in the tank for a longer time it begins to decompose too smaller compounds as sugars and fatty acids. These sugars and fatty acids are then converted to simpler acids like acetic acid. This acetic acid is a substrate for methanogens when producing methane (Ek, 2007). A study has been performed on this organic matter (Davidsson et al., 2007) next to Turing Torso. This study showed a positive methane formation potential when feeding it to the digesters and therefore they will most likely produce methane in the sewers as well if it enters that, since methanogens exists there.

*Figure 21. The separation of water and food at Turning Torso, Malmö.*
6 Development of a method for methane concentration estimations in sewer systems

The development of the method is built up stepwise. The workflow is constructed in the following way.

- A strategy is constructed with the literature and the author’s knowledge as a base.
- The method is tested and improved before the next session.
- The procedure starts over again for each sampling session and finally the most optimal strategy is described in the section “4 A method for methane concentration estimations in sewer systems”.

The workflow was created in different stages where each consisted of laboratory work or/and sampling from the field or at a wastewater treatment plant. The stages are described in Figure 22, which also describes in which order the different sessions were performed.

![Figure 22. Description of how the developing is built up chronologically. F stands for field sampling round, WWTP for wastewater treatment plant and LA for laboratory analysis, the number indicates the order of execution.](image)

The number of sampling sessions were decided as the project was proceeding and based on the output of the achieved results. Each step in each stage contains the following subtitles, Ideas and performance, Result, Problems that occurred and Improvements.

Typical sites chosen for sample taking:

- Pressurised pipes
- Non-pressured pipes
- Wastewater treatment plants
- A certain distance in the sewage (with identifiable parameters which made it possible to estimate the formation rate)
6.1 Laboratory analysis

6.1.1 LA 1, Control of vacuum tubes

Ideas and performance

The vacuum tubes that were supposed to be used was 7 ml vacutainers donated from BD manufacturing in Sweden, see Figure 23.

![Image of a vacutainer](image)

Figure 23. 7 ml vacutainer from the manufactory BD.

To control if the vacutainers met the requirements a couple of simple experiments were set up. First a washed tube was filled with water, the vacuum was released, then the tube was shaken and compared with a non-washed tube that was filled with water, the vacuum was released and then shaken. This was performed to see if the vacutainers contained any unknown substance that interfered with the water. In the next experiment a vacutainer with released vacuum was analysed in the GC and compared with an injection of 100% methane to see if the vacuum tubes contained a compound with the same retention time as methane. To make sure that there was no interaction from the air when aerating the tubes, pure air was injected in the GC as well. Finally an experiment was set up where one vacutainer was injected with 4 ml water and then the vacuum was released before it was opened, washed and then filled with 4 ml water. It was assumed that equilibrium was allowed in the tubes after one hour and the gas headspace over the surface was then analysed.

Results

The results from the first experiment are shown in Figure 24. As can be seen some kind of chemical substance exists inside the tube due to the foam formed on the water surface.
The chromatograms from the analysis with a vacuumed tube, with released vacuum, together with 100% methane injection, is shown in Figure 25. As can be seen, the GC indicated for some component in the vacuumed tube with atmospheric pressure that has the same retention time as methane, about 1.253 min, also another peak turned up right after the possible methane peak. The GC chromatogram for an injection with pure air is shown in Figure 26.

Figure 24. Two vacutainer tubes with water, one washed (the left one).

Figure 25. Chromatogram, vacuumed tube to the left and pure methane to the right.
The chromatogram from the injection with pure air gave no indications of methane presence even though methane exists in air. Probably was the amount of methane in air to low since it only contains 0.000177 vol% methane (Guisasola et al., 2008). Hence it can be excluded that it was the air that interfered with the vacuum tubes.

The result from the final experiment established that two different compounds existed in the vacuum tubes where one had the same retention time as methane, and probably also was methane. The chromatograms are shown in Figure 27 where the washed tube gave no indications for foreign substances while the non-washed did which can be seen in the boxes below the chromatogram where the right box indicates for nothing. In the left box it can be seen that the GC had found two substances. The vertical scale in the right chromatogram is 40 times smaller.

The area under the methane peak in Figure 28 lies around 54 au (area units) which indicates for a very small amount methane presence since 100% methane gives an area of 100 000 au.
But because of the small amounts that were measured in the sewers it can have major effects when analyzing the field samples.

**Problems that occurred**

The main issue in the first laboratory analysis was the discovery of background methane in the tubes that were used. Another problem was the other substance that was detected in the GC right after the compound that had the same retention time as methane, but as long as this compound stay at the same concentration all the time it is of minor interest since it will probably not interact with the sewage and affect the methane concentration. The same applies for the foam, as long as it does not interact with the methane it is of minor interest.

**Improvements**

If the vacuum tubes shall be able to be used in the future work, the background methane concentration has to be estimated. The results were sent to the manufactures to see if they knew what the different substances was. Also attempts were done to find out if it would have any affect when measuring the methane concentration (i.e. the substance that created the foam clearly affected the water but will it interact with the amount of methane as well).

6.1.2 LA 2, Background methane in vacuum tubes

**Ideas and performance**

Since it was found that the vacuum tubes contained a small amount of background methane, this amount has to be estimated. This was done by filling three vacutainers of the two different sizes that was donated from BD manufacturing (5 and 7 ml) with 3 and 4 ml respectively, aerate them, shake them for 30 seconds and rest them for one hour to allow equilibrium. The gas head space was then analysed in the GC. The result from the GC is transferred to the same calculations as presented in section 4.3 in Chapter 4 to calculate the methane concentration.
Result

The results are summarized in two graphs. The analysis of the 5 ml tubes is shown in Figure 28.

![Methane concentration in the 5 ml vacuum tubes.](image)

Due to the known volumes and Henry’s constant for methane and water (Villadsen, 2011) at atmospheric pressure the amount of background methane could easily be calculated with Henry’s law and mass balances using MATLAB, for detailed calculations see Chapter 4.3 or the M-file used which is shown in Appendix 2. The average concentration from the first analysis of the 5 ml tubes became 0.27 mg CH₄/L water.
The results from the 7 ml tubes are shown in Figure 29.

![Figure 29. Methane concentration in 7 ml vacuum tubes.](image)

For these calculations was a reconstructed MATLAB file with other volumes and area used, otherwise it was the same calculations. The background methane concentration was calculated to 0.25 mg CH₄/L in the 7 ml tubes.

To establish the result another experiment was executed in the same way with 3 new 7 ml vacutainers and 3 new 5 ml vacutainers. The analysis showed similar results with the same background methane concentration.

**Problems that occurred**

Sample taking affects the methane concentration inside in the tubes which indicated lower methane concentrations in the second and third analysis. This led to poor reproducibility. The explanation to this is that every time a sample is taken the amount of methane decrease. The total pressure in the tubes is also decreased when a sample is taken. These two reasons together make a small noticeable decrease in methane concentration when the next sample is taken from the tubes. Another issue was that the background concentration of methane varies from tube to tube. Also the foam that was created on the water surface in the tubes (shown in LA1) has been identified as silicon, but not examined if it will have any effect on the methane in the waste water. The unknown substance was also still there and not identified.

**Improvements**

When the field samples are analysed only the first measurements are going to be used, it is believed that this result mirrors the true result most satisfactory. The problem with different amounts of background methane was hard to do something about since the tubes cannot be opened without destroying the vacuum. Therefore, the only thing to do was to measure the tubes continuously and use an average value or try to find methane free tubes from other manufactures. To get rid of the foam one must probably get rid of the silicon and that possibility will be investigated.
6.1.3 LA 3, Survey of new vacuum tubes

Ideas and performance

Since the first developing stages were done using BD:s 7 and 5 ml vacuum tubes which was not totally satisfactory. Three new kinds of tubes, all in different sizes (5, 10 and 11 ml), was donated from the manufactory and thus investigated. The 5 ml tube was made of glass and the other two of polytetereftalat (PET). Besides vacutainers donated from BD another two kinds of PET vacuum tubes were donated from two other manufactories, Kruuse and Vacuette. The sizes were of 9 and 6 ml respectively. The analysis of the vacuum tubes were performed in the exact same way as for the first kind of vacutainers that was described in section 6.1.1 and is hence not described again.

Result

The results for the three BD vacuum tubes investigated are shown in Figure 30. As can be seen, all three vacutainers gave indications for background methane in the GC. The results are a bit misleading since the production information sheet did not say anything about additives at all in any of the tubes. The concentration of background methane in the tubes are about the same for the 5 and 11 ml tubes and lays almost on the same level as the first ones donated. This tells that they probably have been treated in the same way and that some organic compound has been used somewhere in the production cycle. The 10 ml vacutainer indicated for almost the double concentration of background methane compared to the 5 ml and thus make this to the less favourable alternative in future work. No foam was created on the surface in any of the new vacuum tubes from BD and this establishes that it was the silicon in the first tubes that created the foam.

The results from the analysis of the tubes donated from Kruuse and Vacuette is shown in Figure 31. Also these vacuum tubes showed presence of background methane. The tubes donated from Kruuse showed the highest amount encountered so far while the tubes donated from Vacuette reached about the same level as the best tubes donated from BD. Foam was created on the surface in both these tubes which indicates that their tube walls had been treated with silicon which also could be read in the production information sheet.
Figure 30. Background methane concentrations for the three kinds of vacuum tubes donated from the manufactory BD.

Figure 31. Background methane concentrations for the two kinds of vacuum tubes donated from the manufactories Kruuse and Vacuette.

Problems that occurred

The only problem detected during this laboratory session was the usual, presence of background methane. The major problem was that every company uses methane somewhere in their manufacturing process.
Improvement

Since a total number of seven different vacuum tubes from three different companies have been tested and all of them contained background methane the conclusion was to deliberate the pros and cons for the different tubes and choose the best one and use these in the final field and WWTP sampling sessions.

6.1.4 LA 4, Different sampling volumes

Ideas and performance

One thought that arose during laboratory work was that different methane concentrations of the wastewater was might achieved for different sampling volumes. The reason that different sampling volumes were used was that the volume of the tubes differed along the developing way plus that it was known that the sampling volume should not have any effect on the final amount of methane. Also, different vacuum tubes were used during the Master Thesis to make them suffice the whole project. To overcome this, an experiment was set up. The idea was to add different volumes of water to the tubes and then measure the background methane to see if the total amounts of methane varied in the tubes due to the different methane concentrations achieved. This would show if the volume added mattered or not and also if the results from GC was affected in some way if the concentrations was high or low. The volumes added were 2-6 ml in five vacuum tubes.

Results

The tubes donated from Kruuse were the ones that this experiment was executed on since the result was believed to have been the same no matter of which vacuum tubes used. The result is shown in Figure 32. As can be seen the amount of methane in µg per tube does not vary much either depending on which tube that is tested nor what sample volume used, the amount of methane is about 3 to 4 µg per tube and the GC is hence not either affected of which concentration the methane fed had from the beginning.

![Figure 32. Result of background analysis in Kruuse tubes.](image-url)
Problems that occurred

No problems were detected within this area.

Improvement

Since it turned out that the amount of sample does not matter in this context no further work is needed in this area.

6.1.5 LA 5, Survey of vacuum tubes used for field sampling

Idea and performance

When executing the last sampling occasions it was decided that BD vacutainers were going to be used. These were hence ordered and the background methane was analysed on this new delivery to be sure that the field results were compensated for the right amount of background methane. Both analyses with distilled water as well as analysis with only air were done, in the same way as before except that this time was 5 ml water added instead of 4.

Result

The methane concentrations in the three examined tubes where water was added are shown in Figure 33.

![Figure 33. Analysis of background methane](image)

The average methane concentration was calculated to 0.40 mg CH₄/L, and it did not vary much between the tubes which means that the tubes can be satisfactory used in the last sampling occasions.
Problems that occurred
No new problems, than those who were already known, came up.

Improvements
No improvements regarding the tubes were needed.

6.1.6 LA 6, Survey of vacuum tubes with no background methane

Idea and performance
At a late stage in the project twenty vacuum tubes were donated from the manufactory Labco Limited located in the United Kingdom. These tubes and manufactures were recommended from the co-supervisor in Spain, performing the same kind of investigations. One tube was hence examined by filling 6 ml water, released vacuum, waited for equilibrium and then analysed.

Result
When the tube was shaken no foam arose at the surface of the water, like it did on several other tubes examined, see Figure 34.

Figure 34. 10 ml vacuumed exetainers donated from Labco.

As can be seen in the box under the chromatogram the GC gave no indications for any foreign substance like the other tubes did when examined, see Figure 35. The scale on the vertical axis is 25 times less than the chromatograms for the other tubes presented.
Figure 35. Chromatogram for Labco vacuum extainer chromatogram, no indications for methane.

Problems that occurred

Since the tubes met all the requirements there were no problems detected with the tube except that they were very expensive compared to the other tubes investigated and could not be delivered in time for the last sampling occasions.

Improvements

No improvement was needed, only the budget and delivering time was setting the limit. These tubes are going to be used together with the ones from BD for the last sampling occasions. Primarily the ones from Labco.

6.2 Field sampling

6.2.1 F 1, Random manholes

Ideas and performance

The first field sampling occasion consisted of sample taking where methane was believed to be formed. Two bottles were filled at each sampling point where one was saved and analysed back in the laboratory and one was used directly to fill one 7 ml vacuum tube and one 5 ml with 4 and 3 ml respectively. This session focused on readily available manholes. The main focus was to get a first overview of where methane was formed, if it was, to enlarge the author’s knowledge about how the sewer looks like in reality and to get an overview of how the method works.
Result

When the vacutainers prepared in the field were analysed in the GC it indicated that every sample contained a small amount of methane, some more than others. In Figure 36, results of the concentrations are summarized in a plot.

![Figure 36. The methane concentration from the 7 ml vacutainers prepared in the field.](image1)

As can be seen methane exists in every sewer that were analysed. Highest concentration from this analysis was found in the sewer at Limhamsvägen. The results from the same sewages, except for Segevång, but prepared on the laboratory instead are shown in Figure 37.

![Figure 37. The methane concentration from the 7 ml vacutainers prepared in the laboratory.](image2)

Since the analysed wastewater was collected from the same manholes at the same time, should the estimated concentrations be equal. This is not the case and the plots do not conform. This can be explained by measuring errors and the differences in the way the samples have been treated during the day. Figure 38 shows the results of the analysis made for the 5 ml vacuum tubes.
Figure 38. The methane concentration from the 5 ml vacutainer prepared in the field.

A comparison of the field samples taken in 5 and 7 ml vacutainers showed that the 5 ml vacutainers gave generally higher concentrations. This could be seen since every sample gave higher concentrations and the trends were still remaining. The trends can still be compared. Limhamnsvägen showed a high concentration while Skånemejerier did not show particularly much methane.

A summarize of the concentrations are shown in Table 2. For the detailed calculations see Appendix 3. The same file was used for all calculations but the adjustable parameters were changed in every concentration calculation. The adjustable parameters were the area from the GC, volume of the vaccum tube used, volume of liquid injected to the tube and amount of background methane (depends on the size of the tube).

Table 2. A summarize of the results from the first field sampling occasion.

<table>
<thead>
<tr>
<th>Site</th>
<th>Concentration, 7 ml, field (mg/L)</th>
<th>Concentration, 7 ml, laboratory (mg/L)</th>
<th>Concentration, 5 ml, field (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segevång</td>
<td>0.1503</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Skånemejerier</td>
<td>-</td>
<td>0.1411</td>
<td>0.1858</td>
</tr>
<tr>
<td>Oxie</td>
<td>0.3255</td>
<td>0.4366</td>
<td>0.3414</td>
</tr>
<tr>
<td>Brandstation 1</td>
<td>0.136</td>
<td>0.1819</td>
<td>0.352</td>
</tr>
<tr>
<td>Brandstation 2</td>
<td>0.2362</td>
<td>0.2708</td>
<td>-</td>
</tr>
<tr>
<td>Strandvägen</td>
<td>0.2736</td>
<td>0.2871</td>
<td>-</td>
</tr>
<tr>
<td>Limhamnsvägen</td>
<td>0.5163</td>
<td>0.216</td>
<td>0.6038</td>
</tr>
<tr>
<td>Turbinen</td>
<td>0.3143</td>
<td>0.6015</td>
<td>-</td>
</tr>
</tbody>
</table>

The results show that the concentration in general was higher in the samples prepared in the laboratory than the field samples. This can be explained by the higher concentration of methanogens in the sampling bottle than in the vacutainer which allows a faster continuing methane production. The field sample was filtered and thereby did not contain any methanogens. This results in a higher methane concentration when taking the sample later in
the laboratory than in the field. No certain explanation exist to the miss matching results from the 5 ml vacutainer other than that the smaller samples the larger the errors get when not performing the analysis. Another reason could be that the tubes had different background concentration of methane.

Problems that occurred

One problem during the first sampling occasion was filling the sampling bottle, since locations with for instance low flow was of interest, manholes that fulfilled this requirement was tested, which lead to that the bottles was hard to fill properly without getting biofilm and waste material inside them. The most interesting issue detected during this occasion was more a thought than a problem. It was that when taking samples from non-pressurised pipes, the methane that have been formed will most likely leave the wastewater and enter the gas headspace in the sewer. It was also noticed that during the laboratory analysis methane was accumulated in the GC when pure methane was injected. This resulted in a measuring error when injecting the samples right after. The injection of pure methane was done twice during this laboratory session, before analyzing the samples from Skånemejerier field and Segevång lab. Therefore there are no results from these samples presented. About the difference of the different vacutainer volumes it was stated that the 7 ml vacutainer gave more stable results.

Improvements

The first problem was avoided the next time, by training the technique and tilt the bottle in an appropriate way. The accumulation problem was avoided by injecting air every time after a methane injection and repeat it until the GC gave no indications for methane. The only way to know if the gas in the sewer contains any methane is to build a device that traps the gas inside a tube down in the manhole. This is done by a needle that is attached in the vacutainer, when the gas is supposed to be collected the needle is pushed down through the cap and removed when the tube is full. A sketch over how the device is supposed to work is shown in Figure 39. In further work the 7 ml vacutainers will be used.

![Figure 39. The left picture shows how the collection tube works when taking the sample and the right picture shows how to do when the gas is inside the vacutainer.](image-url)
6.3 Wastewater treatment plant

6.3.1 WWTP 1, Inlet analysis

Ideas and performance

To get a perception of how large proportion of the incoming methane that is released at the wwtp, a sample was taken from one of the centrifuges.

Result

The analysis of the samples collected at Sjölunda wastewater treatment plant showed the highest methane concentration so far, was found in the sample taken from the basin where the wastewater ends up after it has been pumped from Turbinen. The results for the sample taken in the basin are shown in Figure 40.

![Concentration of methane (mg/L) vs Test number graph](image)

Figure 40. The methane concentration for the sample from the basin at Sjölunda wastewater treatment plant.

As can be seen in Figure 40 the average concentration was 0.83 mg CH₄/L in the basin. It can also be said that this value is the absolute minimum amount of methane that the wastewater treatment plant emits from the amount that arrives at the inlet.

Problems that occurred

A problem during sampling was that the site for sampling was not that close to the inlet as wanted from the beginning.

Improvement

To improve the method a map over the incoming pipe was studied and a better site for sampling was found in order to get a sample before any methane has been stripped of to the atmosphere.
6.3.2 WWTP 2, Centrifuge analysis

Ideas and performance

One sample was taken on the sludge liquor from one of the centrifuges. This was done in order to estimate how much methane that has been emitted from the incoming pipe until the waste water reaches the centrifuge.

Result

The result for the sample taken in the centrifuge is shown in Figure 41.

![Figure 41](image)

Figure 41. The methane concentration for the sample from the centrifuge at Sjölunda wastewater treatment plant.

The concentration of methane became 0.18 mg /L for the centrifuge. These two values establish that 0.65 mg CH₄ /L incoming water is released to the atmosphere.

Problems that occurred

The problem with tanking sample at the centrifuge was that the sample was mixed with air since the flow was heavy.

Improvement

No improvements were needed since the sample site was not interesting for further investigations.

6.3.3 WWTP 3, Inlet pipe analysing

Ideas and performance

Samples were collected from Sjölunda during the day between 8am to 5pm. One time during the day, 4 bottles were filled within a time period of 5 minutes. The reason for the first experiment was to see how the methane concentration varies during the day. It was also
believed that the results from this occasion would give a time dependent scaling factor which can be used when estimating the total emission from a chosen pipe according to the average value from the samples at Sjölunda.

*Result*

The concentration varied between 0.43 – 0.68 mg CH\(_4\)/L during the day. The highest concentration was encountered in the morning, probably because the flow was at the lowest then and therefore the retention time at the highest. The whole methane concentration variation curve is shown in Figure 42.

*Figure 42. Variation in methane concentration during the day at the inlet to Sjölunda WWTP.*

The flow also varied during the day, the highest measured was 1412 L/s and was encountered at 16.00. The whole variation of mass flow is shown in Figure 43.
Figure 43. Shows how the flow varies during the day.

By combining Figure 42 with 43 the amount of methane that arrives to Sjölund can be calculated. Even though the concentration was highest in the morning, the total amount of methane in the wastewater was highest at the end of the day. This can be explained by the 43% larger flow but only 18% less methane concentration. The whole amount of methane can be seen in Figure 44.

Figure 44. Amount of methane arriving to Sjölund.  

Figure 44. Amount of methane arriving to Sjölund.
The analysis of the measurements from the samples taken within a 5 minutes timespan gave the concentrations 0.51, 0.46, 0.46 and 0.47 mg/L. For calculations for confidence interval see Appendix 7.

Confidence interval:
\[ I_{\mu} = [0.437, 0.513] \]

The average value divided with the confidence interval gave a deviation of 8% for the for samples analysed.

Problems that occurred

Some problems were detected during this sampling occasion, the flow was too strong or the sampling device not heavy enough which resulted in that as soon as the sampling device touched the surface it started to move along with the flow instead of sink at the spot. This made it impossible to take the samples at the same depth all the time since the flow varied over the day and therefore collected the device water at different levels even if the rope used was of the same length all the time. A further problem with the large flow was that the more the device flowed along, the further it got from the end of the pressurised pipe and thus more methane could have been stripped of before the samples were taken, due to the turbulence in the water. Another problem, which easily could have been avoided, was that the bottles used when storing the water was larger than the sampling device, this resulted in that two samplings were needed to fill one bottle and thus water from two different spots were mixed each time. In the bottles, an air bubble at the top were unavoidable since there was a gap between the cap and the top of the bottle and therefore methane could be stripped of to this air bubble while stored during the day.

Improvement

Since all the problems detected concerning the sampling was rather simple all of them were corrected to the next sampling occasion at Sjölunda. To avoid that the sampling device was moving along with the flow instead of sinking at the spot where it was dropped a heavy weight was attached at the bottom of the sampling device. The bottles used were exchanged to 100 ml instead of 250 ml and rubber caps were used instead of a plastic cap which eliminated the air bubble at the top.

About the samples taken within a 5 minutes timespan the confidence interval constructed deviates with approximately 8% from the mean value. This is an acceptable deviation since the samples were not taken at the same time and it was hence possible that the concentration varied little during the sampling session. The measured concentrations all lays inside a small concentration span. Therefore is it also possible that the concentrations were the same but they have been affected by some errors in the laboratory, either from the GC or by the human factor.
7 Results

In this chapter the results from the experiments described in the Chapter 4, “A method for methane concentration estimations in sewer systems” is presented. For all calculations MATLAB is used and the file can be found in Appendix 3. The concentration of methane is calculated in the same way all the time and is hence not shown, the exact description of how it is done with explanations can be found in the sub chapter calculations.

7.1 Sample taking from Sjölunda wastewater treatment plant

The results from the sampling occasions at Sjöunda are shown in Figure 45. This gives a good overview and the results can easily be compared.

Figure 45. Amount of methane emitted from two sampling occasions at Sjölunda.

The amount of emitted methane (assuming that the arrived methane will be emitted somewhere at the WWTP) was slightly higher on the 24th of January than on the 19th of December. The average methane flow became 1.89 kg/h and 1.76 kg/h respectively. The trend on the curves is quit equal, especially between 9 am - 15 pm. Appendix 8 shows the flows, temperature and concentrations for the two sample occasions.

7.2 Methane production calculations in a pressurised pipe

Here are the measurements and calculations for estimation of the methane production rate in a pressurised pipe presented, for calculations see Appendix 9. The concentration of methane was calculated in the same way as described in the other results and hence not presented. For detailed concentration calculations MATLAB file used shown in Appendix 3 and the calculations are shown in the Chapter 4.

\[ m_{CH_4, tot} = 1.2 \text{ mg/m/min} \]

The estimated production rate became 1.2 mg/m/min and is quite a low value according to the measurements presented in different articles around the world for instance Guisasola (2008).
The concentration measured in the end of the pressurised pipe is, even if it is low compared to other articles, the highest value encountered in this study and strengthens hence the theory about pressurised pipes contra gravity.

### 7.3 Estimation of total amount of methane emission from Malmö Sewer system

The total amount of methane formed in Malmö was calculated from the formation values estimated for a pressurised and a non-pressurised pipe. The total length of the sewer and how large part of it that is pressurised in Malmö was given by Svenskt Vatten, 2013. The length of non-pressurised pipes could hence be calculated. For methane formation calculations, see Appendix 10.

\[ E_{\text{non-press}} = 0.177 \, \text{kg/min} \]

\[ E_{\text{press}} = 0.029 \, \text{kg/min} \]

\[ E_{\text{tot}} = 0.206 \, \text{kg/min} = 12.4 \, \text{kg/h} \]

### 7.4 Methane concentration from manholes scattered around Malmö

The measurements from water samples collected from three different manholes scattered in Malmö presented together with the methane concentration calculations.

#### 7.4.1 Oxie2

Oxie2 was a pipe with a diameter of 0.5 m and the filling factor was 22%. The instantaneous sewage velocity was 0.76 m/s. For calculations of the methane concentration, see Appendix 11.

\[ C_{CH_4,\text{wastewater}} = 0.223 \, \text{mg/L} \]

\[ C_{CH_4,\text{air}} = 0.021 \, \text{mg/L} \]

The concentration of methane became 0.223 and 0.021 mg/L for the wastewater and sewer air respectively. As can be seen, the concentration of methane in the wastewater is about ten times higher but the volume is also one fourth of the total volume in the pipe and thus is the volume of air four times bigger.

#### 7.4.2 Skånemejerier2

Skånemejerier2 was a pipe with a diameter of 1 m and the filling factor was 27%. The instantaneous sewage velocity was 0.74 m per second. Equations and calculation for estimating the methane concentration are presented in Appendix 12.

\[ C_{CH_4,\text{wastewater}} = 0.150 \, \text{mg/L} \]

\[ C_{CH_4,\text{air}} = 0.021 \, \text{mg/L} \]

In this pipe the concentrations became 0.151 and 0.021 mg/L for the wastewater and the sewer air respectively. The methane concentration in the wastewater is slightly lower
compared to the results from Oxie2 which strengthen the theory about the A/V ratio.

7.4.3 Turning Torso
The sewage tested at Turning torso flowed in a pipe with a diameter of 0.275 m, the velocity and filling factor became 0.25 m/s and 18% respectively. The sampling spot was placed about 60 meters downstream from the food tank. Calculations for estimation of the methane concentration can be seen in Appendix 13.

\[
C_{CH_4,\text{wastewater}} = 0.339 \text{ mg/L}
\]

\[
C_{CH_4,\text{air}} = 0.009 \text{ mg/L}
\]

The concentration of methane became 0.339 and 0.009 mg/L for the sewage and sewer air respectively. The concentrations are high concerning that the methane have only been produced on such a short distance (the pipe between the households and the sampling spot was short).

7.5 Methane production calculations in a non-pressurised pipe
The concentration of methane was calculated in the same way as described in the results above and hence not presented here. For detailed concentration calculations in MATLAB see Appendix 3. For methane formation rate calculations see Appendix 14.

\[
m_{CH_4,\text{liquid}} = 0.12 \text{ mg/m/min}
\]

\[
m_{CH_4,\text{gas}} = -10.62 \text{ mg/m/min}
\]

The results showed that methane in the wastewater is formed while it was a negative formation in the gas phase. The formation rates became 0.12 and -10.62 mg/m/min for the sewage and air respectively.
8 Discussion

About the model developed for methane concentration estimations in the sewer, a final procedure was presented. It was to collect wastewater in sampling bottles and at the same time avoid air to enter the bottles. A known amount of wastewater was transferred to a vacuum tube. Equilibrium was reached and the gas phase was analyses with a gas chromatograph. The origin methane concentration was calculated with Henry’s law.

The first samples taken during the two occasions at Sjölunda both showed a high amount of methane compared to the rest of the measurements during these days. If the flows, temperatures and concentrations are compared, see Appendix 8. It can be seen that the temperatures was almost equal and that the flow was lower on this day (the 24th of January) and the concentration was higher. Higher concentration and slightly lower flow on the 24th resulted in a higher amount of emitted methane per time unit at this time. Between 9 am to 15 pm the flow was slightly higher on the 24th of January while the difference in concentration was negligible. This resulted in a higher methane emission rate on the 24th. It could be established that marginal differences in flows does not affect the concentration of methane in the wastewater and hence the day with the highest flow will emit most methane per time unit. The temperature difference between the two days was marginally and hence can the conclusion be drawn that marginally temperature differences does not matter for the formation of methane. From 15:30 pm until 17 pm is the two plots very different were the one from the 19th of December continues to increase from its lowest value while the one from the 24th goes up and down. It is hard to say why the amount varies back and forth without any further investigation. It can be said that the methane amount does not rise to the highest level, like it did for the samples from the first sampling occasion. The reason for this is that the flow does not increase notably on the 24th of January like it did on the 19th of December.

The average amount of carbon dioxide emitted from a car driven in Sweden 2011 was 144 g CO₂/km (Hägglund et al., 2011) which becomes 14.4 kg CO₂/h when a car is driven in 100 km/h. As described in the theory one methane equivalent equals twenty-five carbon dioxide equivalents which makes 14.4 kg CO₂/h equals 0.576 kg CH₄/h. If this is compared to the average amount that was measured it results in that the inlet at Sjölunda equals about 3 cars, in a GHG emission point of view, driving in 100 km/h. This is a very low number and is hence not a large environmental issue, at least not during the winter. The conditions in this pipe length do not favour the formation of methane (high flow and cold water) and that is probably the explanation to the low methane concentration even though the pipe was pressurised.

About the methane formation rate in the pressurised pipe the value became 1.1 mg methane per minute and meter pipe which was calculated from the measured concentrations in the end and beginning of the pipe. These became 2.36 and 0.07 mg methane/l respectively. The lower value is not much to say about since it was taken at a pump station where the sewage comes from a gravity pipe plus that it was ventilated and thus it was aerobic conditions. The upper value is the highest encountered, but still low for being methane dissolved in wastewater coming from a pressurised pipe. To compare it with the concentration that has been measured in a pressurised pipe in Australia, this is somewhere between saturated and supersaturated, about 22 mg methane/L (Guisasola et al., 2008). This value is about 9 times higher than 2.36. The differences in concentrations occurred due to the different conditions in the two pipes.
The A/V ratio differed with approximately 2 per meter since the diameter differed with 0.01m. This is not very much and is definitely not the reason to the nine times higher concentration in the Australian pipe since it is in favour of the Swedish pipe. One of the reasons could instead be the much higher HRT for the pipes in Australia which was between 1-10 hours while the pipe in Sweden had a HRT of 15 minutes. Also the Australian wastewater temperature was slightly over 26°C. Unfortunately was the wastewater temperature on the sampling occasion not measured but it was most likely around the same temperature as the one measured from the previous sampling session at Sjölunda (14°C). Among other things these two reasons explain why the encountered concentration in Sweden is lower than the ones measured in Australia, but it does not explain why the one in the Swedish sewer is so very low. This can only be described with one explanation. Due to varying physical barrier, the sample taker could not climb down in the manhole where the pressure was released and thus was the concentration measured in another manhole, 85 meters after the pressure release. This would not have been any problem if there would not have been any ventilation between the pressure release and the sampling place since a gas sample also was taken. But since there was a manhole in between it was possible for the methane to enter the atmosphere here before it was measured. The pressurised pipe was also connected to this main about 1.6 meters above the bottom of the manhole which resulted in a free fall for the wastewater from this height. When the wastewater lands on the bottom of the manhole, most of the methane will leave the liquid phase and enter the air and since this appears in a well will the methane enter the atmosphere here through the pick holes in the manhole instead of go further in next pipe. This is also the reason to why the gas sample indicated for no presence of methane.

About the value estimated for the total amount of methane formed in the sewer system, this is just a rough approximation. This because the value estimated is based on calculations from just two pipe types with certain characteristics and then generalized for the whole sewer system. The formation depends on many different factors, individual of each section-part pipe and should hence not be used in other cases than just rough approximations. It is also based on only two measurements executed in the middle of the winter. To make a fair estimation of the concentrations, samples should be taken during every season. As described earlier in the discussion, the formation rate in pressurised pipe is probably higher than the one calculated due to various complications that arose. This also applies for the formation rate in non-pressurised pipes and by taking this into account when making a conclusion it can be said that 12.4 kg CH₄/h is absolute lowest formation rate that will occur within the sewer.

About the non-pressurised pipes examined the fact that the air in the sewer actually contains methane and hence validates the theory that the methane will leave the wastewater and enter the gas headspace if the pipes are non-pressurised. The concentration is much lower than in the wastewater but many pipes, like the ones that have been examined, have a filling degree of a maximum 30%. This shows that if the total methane concentration in the sewer shall be estimated it is important to take the sewer air into account since most of the sewers contain mostly air. If this sewage air is added up to each other there will be lots of cubic meters and hence a noticeable amount of methane even though the concentrations are low.

A noteworthy matter detected after the field sampling session was that Skånemejerier2 and Oxie2 had a higher and lower methane concentration respectively than Skånemejerier and Oxie had on the first sampling occasion, presented in development of a method. Skånemejerier2 was the same pipe but half a kilometer further away from the dairy company. Also, Oxie2 lays a few hundred meters up streams from Oxie. Even if it cannot be established
does it look like there was some methane formation between the examined manholes even if the pipes were non-pressurised. Unfortunately it was necessary to take samples in all four wells on the same day to exclude that it was a coincidence.

About Turning Torso, analysis of this sewage showed a quite high value for being a pipe that close to its source. It can be compared to the pipe tested when the method was developed, Segevång, which was a pipe 300 meters downstream from the buildings that gave no indications for methane. Unfortunately it is hard to say if the formation of methane occurs in the food tank or in the pipe with just this measurement. What can be said is that the formed methane ends up in the sewer system anyway and will hence be emitted somewhere. The concentration in the sewer air was very low which can have different explanations. It is possible that the methane is formed in the tank and when enters the sewer air it is oxidized. It is also possible that the measurement was too close to the source and hence the methane has not left the wastewater yet.

About the methane formation rate in the non-pressurised pipe the value became 0.12 mg/m/min in the liquid (based on the concentrations measured in the wastewater). This value itself indicates that there is a methane formation also in non-pressurised pipes, a formation rate that is about ten times smaller than the rate calculated in pressurised pipes. Hence it strengthens the theory that one should include the non-pressurised pipes when estimating the total methane formation. The measured concentrations were very low which did not come as a surprise since the diameter of the pipe was 1 meter and the velocity varied between 0.61 to 1.7 m/s which resulted in a higher flow than most of the other manholes examined. This variation in velocity lowers the credibility since it is known that the lower the flow is the higher the formation of methane per volume wastewater flowed. To avoid this credibility lowering, samples should be taken in the pipe length at the same time and when the flow is equal throughout the pipe. Under this sampling occasion was the flow lower downstream and hence the concentration should be higher which it also was. It is hence hard to say if the concentration was higher due to the lower flow or actually formation. But how much the flow variation affects the formation in this pipe length and during this time is impossible to say without further investigations. In this investigation should also the filling factor be included etc.

The results from the gas samples showed a negative formation on about 10 mg/min/m. This value means that the methane formed will disappear in the sewer when entering the sewer air. The most likely way for the methane to be destroyed is by oxidation. But oxidation by air requires a certain kind of microorganism that will most likely not be formed in the sewer pipes. Therefore this negative value is most likely a measuring error or some other disruption. For instance the manhole up streams was examined first and it was hence possible that the pipe was ventilated when the manhole was opened. If the experiment shall be executed in a proper way should gas samples be taken at the same time without opening the manholes, which in practical is impossible. Therefore it is hard to draw any conclusions from this since only one measurement on a non-pressurised pipe length was executed. Hence can the calculated negative value in the sewer air not be established and further investigations are necessary.

One of the goals was to develop a method that enabled estimations of the methane concentration in the sewer system. From the results from the samples taken from manholes scattered around Malmö it can be seen that the manholes analysed contains methane in both the liquid and the gas phase. This confirms that the sampling method had been developed
successfully from the first sampling sessions. It is hard to say anything about the sampling of wastewater since it was not same manholes that have been tested as during the development of a method. How well the gas sampling device worked is hard to say but the measurements showed that the device constructed is better to use than skip sewer air measurements since methane was found.

The analysis method used is also fast, easy and cheap (apart from the instrument). One thing though that can be discussed is if GC is the right method to use when measuring so small concentrations as presented. Hard to say without any further investigation but it can be said that the calculations are very sensitive and dependent on the area from the GC. The laboratory work also showed that it is important to test all the equipment that is going to be used.

Something that has not reached as much attention as it should is the weird results when calculating the background methane. In Appendix 4 it can be seen that the amounts of background methane depends on how much volume that was added. Appendix 4 clearly shows that the amount of background moles of methane rises as the volume water added decreases. This was kind of strange since one test was performed during the development of method to exclude this which it also did. But when it was performed again, twice, right before the last sampling session was the result in Appendix 4 achieved. Since not much attention was paid to this it is hard to say what is wrong. The possibility that equilibrium wasn't reached could at least be excluded. This since the tests were left resting for several hours during the second test, but still giving the same results. It might have been the GC since the background methane was a very low amount and as discussed earlier, the calculations are sensitive and a small deviation can have a major effect on the result. But then it is strange that the amount rises as the volume added decreases. This is something that needs to be further investigated. This was also the reason that different samples were compensated for different amount of methane at different sampling volumes.
9 Conclusion

The amount of methane formed in the pressurised pipe that arrives at Sjölunda vary during the day but is very low and does not have a higher impact on the environment than four cars driving in 100 km/h. The amount should be taken into account when estimating the carbon footprint for the WWTP but it only plays a minor part if the total formation of methane in Malmö’s sewer system shall be estimated and is hence as important as all other sewer pipes in the system. A small difference in temperature and flow does not affect the methane formation rate and hence the concentration.

The methane formation rate in a small pressurised pipe in Sweden during the winter is about 1.2 mg methane per minute and meter pipe. The encountered concentrations in the examined pipe are much lower than the ones measured in other countries with a warmer climate. However this is the minimum formation rate in this pipe since most of the methane most likely already has been stripped of. Pressurised pipes are the most potential methane formation places.

Methane formation exists in small concentrations in every sample spot analysed, Segevång, Skånemejerier, Heleneholm 1, Heleneholm 2, Turbinen, Linhamnsvägen, Strandvägen/Skåneg, Oxie ARV, Oxie2, Skånemejerier 2, Turning Torso, Skumparp and Jägersro. If the total amount should be fairly estimated analysis of the sewer air is necessary.

Methane in non-pressurised pipes exists. If it actually is formed here or just emitted is not established.

The method was successfully developed since it worked for methane measurements. The vacuum tubes from Labco fulfilled its purpose since they did not indicate for background methane. At the same time they are easy to use and are in workable volumes. The drawback is that they are produced in United Kingdom and the price is over the budget for this Master Thesis.

The method used when taking samples at Sjölunda gave an error of 8% with 95% certainty. Also, the difference in the measured concentrations was 0.05 mg/L between the lowest and the highest.

Methane formation in the sewer system could be minimized by actions in the field. Methane formation does not cause any direct problems, like corrosion or odour. This have led to that methane is not detected and hence no actions for prevention in Sweden exist at the moment. Injection of air could be done to prevent the anaerobic condition and thus prevent methane formation.

When discussing options for minimising the methane production it is important to consider the consequences. Inhibition alternatives as injection of chemicals as well as cleaning of the pipes or injection of air could be energy consuming actions. It is important to consider that those actions not exceed the problems with methane formation in sewer systems in a globing warming perspective.
10 Future work

Since this Master Thesis concerns a much unexplored subject and presents the first methane concentrations measurements executed in the sewer system in Sweden there is a lot of work left that needs to be done to make it an explored subject instead. As been noticed it was very hard to find any vacuum tubes that met the requirements and when it eventually was, they were very expensive. One focus can thus be to either find or develop vacuum tubes that are cheap and do not contain any background methane. This would make it easy to repeat the experiments presented in the report but with higher credibility since in most of the experiments was done with vacuum tubes containing background methane used.

The method presented is cheap, fast and easy for collecting, storing and analysing the sewage, thus probably not much can be done here to make it better.

About the estimation of methane in the sewer system should the total amount of methane be charted. For this, more pipes needs to be analysed. Especially pipes with different characteristics so they can be used as a generalization for all pipes when making the total estimation. It must also be known how much methane that is emitted through every manhole, one way could be to set up a mass balance for the methane when it is charted. Another approach could be to only investigate the pipes with the highest methane formation potential. The experiments should also be performed both during the winter and summer to see how the seasons affect the formation. When the methane is charted improvements should be investigated, if it is shown that the methane is formed in such amounts that it have an impact on the environment.

Since the pressurised pipes are the most interesting concerning methane production this could be a large focus for a future study. For example a laboratory-scale sewer system consisting of a pressurised pipe with conditions like those in reality could have been set up. This would make deeper studies of how methane formation occurs easier. Sample taking under controlled conditions would then be possible.

Further work could also include work for minimization of the methane production in the sewer. This could for example be to induce some chemical as it is done to prevent sulphide production in sewer system. It could also be to investigate how cleaning of the sewer system affect the methane formation since flushing of the pipe could possible prevent biofilm formation and hence methane production.

If the total methane emissions from the sewer shall be estimated properly, a lot of parameters are needed. Below these parameters are listed and described together with parameters that affect the formation. Not all of them are needed since some can complement others. Parameters that affects the methane formation:

- Temperature
The temperature in each sewer pipe is good to know since the methane formation is strongly dependent on the temperature. It may be a bit difficult to estimate the exact temperature in each pipe but mostly the temperatures in the pipes are the same with only small variations during the year. This because they are well isolated in the ground.
Biomass
The amount of biomass in the pipe is also good to known since it is here the methane formation occurs. If a pipe is free of biomass, no methane will be formed.

Internal diameter
The diameter must be known to be able to calculate how large the pipe is. If only the biomass depth is known, the internal diameter can be used together with the filling degree to calculate the amount of biomass.

Filling degree
Since most of the pipes are so called gravity pipes the filling degree must be known. This because, if a gas headspace exists (the pipe is not pressurised) methane will leave the wastewater and enter the gas headspace. If the filling degree is known together with the diameter one can calculate the area of the liquid and the area of the sewer gas.

Pipe length
The length of the pipes is one of the most important parameters to know. This cannot be replaced with any other since the methane formation occurs along the pipes.

Volumetric flow of the liquid
If the concentration of methane is known in the liquid the total emissions from the liquid part can be estimated if it is assumed that all the methane at some point will leave the wastewater. If the average flow and the average concentration are known the average amount of methane released per second can be calculated.

Ventilation
The ventilation is also an important parameter. The methane that has entered the gas phase will leave the sewers through the manholes and will therefore disappear unnoticed. If the amount of methane that leaves the manholes is known it could be taken into account when calculating the total emissions.

Volumetric gas flow
If the concentration in the gas headspace is known the average gas flow can be used to estimate the total emissions from the gas if it is assumed that this will leave the sewer and enter the atmosphere somewhere.

Retention time
The hydraulic retention time is of importance if the productivity shall be calculated. The retention time must then be known since the longer time the water is in contact with the biomass the more methane is produced per volume water flowed. The production rate of methane depends on the presence of substrate and amounts of metanogens.
11 References


# 12 Appendix

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1 Document that was filled in on every sample place

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<thead>
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<th>Samp nr.</th>
<th>Time</th>
<th>Place</th>
<th>Nr gas samp</th>
<th>Velocity A (m/s)</th>
<th>Velocity B (m/s)</th>
<th>Gas alert (yes/no)</th>
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2 Calculations of background methane

%Variables
Vtot=5*10.^-6  %m3 total
Vl=3*10.^-6  %m3 liquid face
Agas=58.7/100000  %Area of sample

%Konstanter
T=295  %Temperature
R=8.3145  %Gas constant
Vg=Vtot-Vl  %m3 Gas face
He=75538  %Henry's constant in pascal m3/mol
Ptot=101325  %Pascal
Cren=Ptot/(R*T)  %concentration of pure methane
Aren=1  %Area of pure methane
Xch4=Agas/Aren  %Procent of pure methane

%Calculations
ngas=(Cren*Xch4)*Vg  %Amount of molar in the gas face
nl=(Ptot*Xch4/He)*Vl  %amount of molar in the liquid face

%Methane concentration
Ch4tot=(ngas+nl)/Vg  %Total concentration of methane in mol/m3
Ch4totmg=Ch4tot*16  % total concentration in mg/l
3 Calculations of amount of methane in the liquid

%Beräkning av total bildad metan

%Ändringsbara variabler
Vtot= %m³ total
Vl= %m³ vätskefas
Agas= /100000 %Area of sample
nch4back=

%Konstanter
T=295
R=8.3145
Vg=Vtot-Vl %m³ gasfas
He=75538 %Henrys konstant i pascal m³/mol
Ptot=101325 %Pascal
Cren=Ptot/(R*T) %mol/m³
Aren=1 %Area of pure methane
Xch4=Agas/Aren %andel metan i gasfas

%Beräkningar
ngas=(Cren*Xch4)*Vg-(nch4back) %total antal mol ch4 i gasen
nl=(Ptot*Xch4/He)*Vl %total antal mol ch4 i vätskan

%Metanhalt
ntot=ngas+nl
Ch4tot=(ngas+nl)/Vl %total koncentration, antar att allting kommer att lämnavätskefasen i avloppet
Ch4totmg=(Ch4tot*16) %mg/l
4 Amount of background methane in different tubes

Result from random analysing of different tubes, used for background methane estimations.

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5 Data for sampling sessions

Sampling 23\textsuperscript{th} of November 2012

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Sampling 6\textsuperscript{th} of February 2013

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Sampling 15\textsuperscript{th} of February 2013

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## 6 Pressurised sewer systems in Sweden

Source: Svenskt Vatten, 2013

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7 Confidence interval

\[ s = \sqrt{\frac{1}{4-1} \cdot \sum_{i=1}^{M} (x_i - 0.475)^2} = 0.0238 \]

\[ l_{\mu} = \left( 0.475 \pm 3.18 \cdot \frac{0.0238}{\sqrt{4}} \right) = (0.437, 0.513) \]

\[ \frac{\bar{x}}{l_{\mu}} = \frac{0.475}{0.437} \text{ and } \frac{0.475}{0.513} \approx 8\% \]
### 8 Parameters from sample taking at WWTP

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9 Methane production calculations in a pressurised pipe

\[ C_{\text{CH}_4, \text{liquid}, 1} = 0.064 \text{ mg/L} = 0.004 \text{ mol/m}^3 \]

\[ C_{\text{CH}_4, \text{liquid}, 2} = 2.36 \text{ mg/L} = 0.148 \text{ mol/m}^3 \]

\[ C_{\text{CH}_4, \text{liquid, prod}} = \frac{0.148 + 0.004}{2} = 0.076 \text{ mol/m}^3 \]

\[ \nu_{\text{liquid}} = 2.64 \text{ m/s} \]

\[ d = 0.14 \text{ m} \]

\[ \beta = 0.2 \]

\[ C_{\text{CH}_4, \text{air, end}} = 0 \]

\[ M_{\text{CH}_4} = 16 \text{ g/mole} \]

\[ l = 2400 \text{ m} \]

\[ \dot{m}_{\text{CH}_4, \text{tot}} = \frac{(C_{\text{CH}_4, \text{liquid, prod}} - C_{\text{CH}_4, \text{liquid}, 2}) \nu_{\text{liquid}} d^2 \pi r^2 + C_{\text{CH}_4, \text{air, end}} \frac{\nu_{\text{liquid}} d^2 \pi r^2 (1 - \beta)}{l} \times M_{\text{CH}_4} = 1.2}{mg/m/min} \]
10 Emission estimation

1 494 kilometers sewer in Malmö (Svenskt Vatten, 2013).
16+6+2 km pressurised (Appendix 6)
1470 km non pressurised

\[
Emission_{\text{non-press}} = 0.12 \cdot \frac{mg}{m\cdot min} \cdot 1478 \cdot 10^3 m = 0.177 \text{ kg/min}
\]

\[
Emission_{\text{press}} = 1.2 \cdot \frac{mg}{m\cdot min} \cdot 24 \cdot 10^3 m = 0.029 \text{ kg/min}
\]

\[
Emission_{\text{tot}} = 0.206 \text{ kg/min} = 12.4 \text{ kg/h}
\]
11 Calculations for methane concentration Oxie2

\( P_{tot} = 101325 \text{ Pa} \)

\( x_{CH_4,\text{liquid}} = 4.8 \times 10^{-4} \)

\( x_{CH_4,\text{gas}} = 3.2 \times 10^{-5} \)

\( H e_{CH_4} = 75538 \text{ Pa} \ast \text{m}^3/\text{mole} \)

\( V_{\text{liquid,tube}} = 6 \times 10^{-6} \text{m}^3 \)

\( V_{\text{gas,tube}} = 4 \times 10^{-6} \text{m}^3 \)

\( R = 8.3145 \text{ J/mole/K} \)

\( T = 295K \)

\( M_{CH_4} = 16\text{g/mole} \)

\[ n_{\text{liquid}} = \frac{P_{tot} \ast x_{CH_4}}{H e_{CH_4}} \ast V_{\text{liquid,tube}} = 3.88 \times 10^{-9} \text{ moles} \]

\[ n_{HS} = \frac{P_{tot}}{R \ast T} \ast x_{CH_4} \ast V_{\text{gas,tube}} = 7.98 \times 10^{-8} \text{ moles} \]

\[ C_{CH_4,\text{sewage}} = \frac{n_{HS} + n_{\text{liquid}}}{V_{\text{liquid,tube}}} \ast M_{CH_4} = 0.223 \text{ mg/L} \]

\[ C_{CH_4,\text{air}} = \frac{P_{tot}}{R \ast T} \ast x_{CH_4} = 0.021 \text{ mg/L} \]
12 Calculations for methane concentration

Skånemejerier2

\[ P_{\text{tot}} = 101325 \text{ Pa} \]
\[ x_{\text{CH}_4, \text{liquid}} = 3.3 \times 10^{-4} \]
\[ x_{\text{CH}_4, \text{gas}} = 4.5 \times 10^{-5} \]
\[ H_{e_{\text{CH}_4}} = 75538 \text{ Pa} \cdot \text{m}^3/\text{mole} \]
\[ V_{\text{liquid, tube}} = 6 \times 10^{-6} \]
\[ V_{\text{gas, tube}} = 4 \times 10^{-6} \]
\[ R = 8.3145 \text{ J/mole/K} \]
\[ T = 295 \text{ K} \]
\[ M_{\text{CH}_4} = 16 \text{ g/mole} \]
\[ n_{\text{liquid}} = \frac{P_{\text{tot}} \cdot x_{\text{CH}_4}}{H_{e_{\text{CH}_4}}} \cdot V_{\text{liquid, tube}} = 2.62 \times 10^{-9} \]
\[ n_{\text{HS}} = \frac{P_{\text{tot}}}{R \cdot T} \cdot x_{\text{CH}_4} \cdot V_{\text{gas, tube}} = 5.39 \times 10^{-8} \]
\[ C_{\text{CH}_4, \text{sewage}} = \frac{n_{\text{HS}} + n_{\text{liquid}}}{V_{\text{liquid, tube}}} \cdot M_{\text{CH}_4} = 0.150 \text{ mg/L} \]
\[ C_{\text{CH}_4, \text{air}} = \frac{P_{\text{tot}}}{R \cdot T} \cdot x_{\text{CH}_4, \text{gas}} = 0.021 \text{ mg/L} \]
13 Calculations for methane concentration
Turning Torso

\[ P_{tot} = 101325 \text{ Pa} \]

\[ x_{CH_4, liquid} = 3.3 \times 10^{-4} \]

\[ x_{CH_4, gas} = 0 \]

\[ He_{CH_4} = 75538 \text{ Pa} \cdot \text{m}^3/\text{mole} \]

\[ V_{liquid,tube} = 5 \times 10^{-6} \]

\[ V_{gas,tube} = 2 \times 10^{-6} \]

\[ R = 8.3145 \text{ J/mole/K} \]

\[ T = 295 \text{ K} \]

\[ M_{CH_4} = 16 \text{ g/mole} \]

\[ n_{liquid} = \frac{P_{tot} \cdot x_{CH_4}}{He_{CH_4}} \cdot V_{liquid,tube} = 1.28 \times 10^{-8} \]

\[ n_{HS} = \frac{P_{tot}}{R \cdot T} \cdot x_{CH_4} \cdot V_{gas,tube} = 9.31 \times 10^{-8} \]

\[ C_{CH_4, sewage} = \frac{n_{HS} + n_{liquid}}{V_{liquid,tube}} \cdot M_{CH_4} = 0.339 \text{ mg/L} \]

\[ C_{CH_4, air} = \frac{P_{tot}}{R \cdot T} \cdot x_{CH_4, gas} = 0.009 \text{ mg/L} \]
14 Methane production calculations in a non-pressurised pipe

\[ C_{\text{CH}_4,\text{liquid},1} = 0.066 \text{mg/L} = 0.004 \text{mol/m}^3 \]

\[ C_{\text{CH}_4,\text{liquid},2} = 0.094 \text{mg/L} = 0.006 \text{mol/m}^3 \]

\[ C_{\text{CH}_4,\text{liquid,prod}} = \frac{0.006 + 0.004}{2} = 0.005 \text{mol/m}^3 \]

\[ v_{\text{liquid}} = \frac{1.7 + 0.61}{2} = 1.16 \text{ m/s} \]

\[ d = 1 \text{ m} \]

\[ \beta = \frac{0.15 + 0.23}{2} = 0.19 \]

\[ M_{\text{CH}_4} = 16 \text{ g/mole} \]

\[ l = 100 \text{ m} \]

\[ C_{\text{CH}_4,\text{gas},1} = 0.114 \text{ mg/L} = 0.007 \text{ mol/m}^3 \]

\[ C_{\text{CH}_4,\text{gas},2} = 0.013 \text{ mg/L} = 0.001 \text{ mol/m}^3 \]

\[ C_{\text{CH}_4,\text{gas,prod}} = 0.004 \text{ mol/m}^3 \]

\[ \dot{m}_{\text{CH}_4,\text{liquid}} = \frac{\left( C_{\text{CH}_4,\text{liquid,prod}} - C_{\text{CH}_4,\text{liquid},1} \right) \cdot v_{\text{liquid}} \cdot \frac{d^2 \pi}{4} \cdot \beta}{l} \cdot M_{\text{CH}_4} = 0.12 \text{ mg/m/min} \]

\[ \dot{m}_{\text{CH}_4,\text{gas}} = \frac{\left( C_{\text{CH}_4,\text{gas,prod}} - C_{\text{CH}_4,\text{gas},1} \right) \cdot v_{\text{liquid}} \cdot \frac{d^2 \pi}{4} \cdot (1 - \beta) \cdot M_{\text{CH}_4}}{l} = -10.62 \text{ mg/m/min} \]
Methane formation in sewer systems

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Abstract

Methane formation in sewer system is an unexplored subject. This study is the first measuring methane formation in Swedish sewer systems. A method for taking samples in the sewer system and at a wastewater treatment plant (WWTP) is presented, as well as how to store the samples and analyse the methane content. All field sampling was done in Malmö, Sweden, in collaboration with the municipal joint authority VA SYD. It is shown that methane formation exists in the sewer as all samples analysed contained methane. The highest concentrations were detected in the samples right after a pressurised pipe, both at the WWTP and in the sewer. The highest methane concentration of 2.4 mg CH₄/L was measured at the end of a rising main in Skumparp in Malmö. The production rate for gravity mains and rising mains was calculated to 72 * 10⁻⁶ kg/m/h in total and 7.2 * 10⁻⁶ kg/m/h for the liquid phase respectively. A method for sampling of the gas headspace in the pipes of the sewer is also presented. The result from this indicated that the headspace in a non-pressured pipe did not contain high concentrations of methane. All field studies were executed during the winter season and this will most likely also affect the results. For a fairly estimation and validation of the climate impact emissions of methane from the sewer more knowledge and studies in the area is needed.

Keywords: Methane formation, sewers, sampling in sewers, wastewater, global warming

Introduction

Production of methane in sewers contributes to global warming since methane is a potent greenhouse gas. One molecule of CH₄ traps about 25 times more heat than a CO₂ molecule on a Global Warming Potential scale and methane contributes to about 20% of the total global warming. It is estimated that about 50% of global methane emissions are related to human activities (El-Fadel et al., 2001).

The amount of methane formed per volume wastewater depends on the ratio between the inner surface wall area (A) covered with biofilm and the volume (V) of the pipe (Reference). Biofilm, containing methanogens, is created on the pipe walls in the sewer. The higher the A/V ratio the more organic carbon matter is in contact with the methanogens and thus contributes to a higher methane formation. Hydrogen sulphide in sewer systems is a well-known problem (Reference). However, formation of the potent greenhouse gas methane has not received as much attention. A few studies have been done on rising mains (i.e. Guisasola et al., 2009) since these are theoretically the ones with the highest potential for methane formation. Gravity mains are the most common kinds of pipes but are still poorly investigated. Investigations of these are necessary if methane formation in sewer systems will be evaluated in this study. Factors that affect methane formation are among other things the presence of organic carbon together with
anaerobic conditions. Both requirements need to be met since the methane producing archaebacteria are strictly anaerobic and degrade the organic matter for energy production ending up with formation of methane. The main aim of this work was to develop a sampling method for determination of dissolved methane in wastewater samples and to find out whether any methane in gravity mains with high potential is present in Malmö, Sweden.

**Material and methods**

**Sampling sites**

The sampling session was divided into three different sampling sections, sampling from manholes scattered around Malmö, sampling from the inlet pipe at a wastewater treatment plant and estimation of the methane formation rate in two specific pipes. A rising main as well as a gravity main were selected.

**Sampling from manholes in Malmö**

Samples were taken in scattered manholes in the sewer system of Malmö, Sweden. Sampling in manholes was executed by climbing down and filling sampling bottles, see Figure 1. Sampling of the liquid phase was done by keeping the collection vials under the surface, let wastewater flow through them before the cap was put on under the water surface (Alberto et al., 2000).

![Sampling in a manhole at Segevång, Malmö.](image1)

Sampling of the methane in the air was done on samples from gravity mains. The sampling was done with a special gas sampling device which consisted of a vacuum tube with a needle attached, where the needle was pushed down when the sample was taken. Then the sewer air starts to flow into the tube and when it was full, the needle was removed. The device is shown in Figure 2.

![Device for gas sampling, vacuum tube with needle attached.](image2)

For the methane concentration calculations based on, equation (1), (2), (3) and (4) was used.

\[ C_{CH_4, sewage} = \frac{n_{HS} + n_{liquid}}{V_{liquid, tube}} \]  

(1)

\[ n_{HS} = \frac{P_{tot} * x_{CH_4} * V_{gas, tube}}{R * T} \]  

(2)

\[ n_{liquid} = \frac{P_{tot} * x_{CH_4} * V_{liquid, tube}}{H_e_{CH_4}} \]  

(3)
Sampling from the inlet at Sjölunda WWTP

Samples were collected from the inlet, downstream a pressurised system at Sjölunda WWTP in Malmö, Sweden. Wastewater sampling at the WWTP was executed by lowering a sampling bottle as close as possible to the incoming pressurised pipe, the devise used to sample wastewater is shown in Figure 3. The rubber stopper was released when the bottle reached a certain level.

![Figure 3. Device for wastewater collection from incoming pipe at WWTP.](image)

The wastewater was transferred from the sampling device to the same kind of bottles used for manhole sampling, 100 ml glass sample bottles, and kept refrigerated until analysis. The same equations were used here except for (4) since no gas sample was taken.

Methane formation rate in the selected pipes

The methane formation rate was calculated in two selected pipes and for this, necessary parameters needed for calculations was registered such as the filling degree of the pipe and flow of the wastewater. The formation rate was calculated in both a pressurised and non-pressurised pipe to compare the different kinds of pipes and thus make a good validation of where methane possibly could be formed. The strategy is illustrated in Figure 4, and consisted of taking samples at two different places with no ventilation between. The flow was registered at the same time as the samples were collected. The airflow over the wastewater surface in the non-pressurised pipe was assumed to be half of the wastewater rate (Edwini-Bonsu et al., 2004). In the non-pressured pipe, a gas sample was taken as well. For the pressurised pipe, equations (1), (2), (3), (4) and (7) were used and for the non-pressurised, (1), (2), (3), (4), (5) and (6).

![Figure 4. Sketch over sampling for methane production calculations.](image)

Equations used for methane formation rate calculations in the pressured pipe:

\[
\dot{m}_{CH_4,liquid} = \left( (C_{CH_4,liquid,prod} - C_{CH_4,liquid,i}) \cdot \frac{d^2 \pi}{4} \beta \right) \cdot v_{liquid} \cdot l \cdot M_{CH_4} \tag{5}
\]

\[
\dot{m}_{CH_4,gas} = \left( (C_{CH_4,gas,prod} - C_{CH_4,gas,o}) \cdot \frac{d^2 \pi}{4} (1 - \beta) \cdot M_{CH_4} \right) \tag{6}
\]

Equation used for methane formation rate calculations in the non-pressured pipe:

\[
\dot{m}_{CH_4,\text{tot}} = \left( (C_{CH_4,liquid,prod} - C_{CH_4,liquid,i}) \cdot \frac{d^2 \pi}{4} \right) \cdot v_{liquid} \cdot l + \left( C_{CH_4,\text{air,end}} \cdot \frac{d^2 \pi}{4} (1 - \beta) \right) \cdot \frac{d^2 \pi}{4} (1 - \beta) \cdot M_{CH_4} \tag{7}
\]
Laboratory analysis

From the sampling occasions all laboratory analysis were performed within 24 hours. The sampling analyses were done by filling about half of a vacuum tube with wastewater, release the vacuum and then allow equilibrium which was assumed to be reached after one hour. The methane content was determined with a gas chromatograph, the gas phase just over the liquid surface was analysed. The GC used was Agilent 6850 equipped with FID and a HP-1 column. Every sample was analysed three times. This was done to establish the measured values. The amount of methane was calculated with Henry’s law using MATLAB for easy replication.

Result and discussion

Sampling from manholes in Malmö

The methane analysis showed that methane formation exists. The concentration varied in every manhole and the highest and lowest encountered was 0.58 and 0.11 mg CH₄/L respectively. Since none of the examined sewers were pressurised and only the wastewater was analysed, the emitted amount was probably higher than the encountered as the methane formed will leave the wastewater and enter the air. The result is shown in Figure 5.

Sampling from the inlet at Sjölunda WWTP

The methane from the incoming pipe at Sjölunda WWTP was examined twice, the method was similar with just slight a few changes, the result is presented in Figure 6.

The wastewater temperature differed about 0.4°C at the two days. At the 19th of December the sewage temperature was in average +14.6°C and at the 24th of January it was +14.2°C. In average the methane concentration was the same for the two days, this probably because that the temperature did not differ so
much. Differences in concentration can depend on many factors, for instance if the sewage is diluted by rainfalls or snowmelt. The trend is that the wastewater contains most methane in the earliest sample hours and then the tendency is that the methane concentration decreases until 3 pm and then increases again. The methane amount varies during the days and the average amount released during the two days was about 2 kg methane/h. The executed pipe has a large diameter, which does not favour the methane concentration in the wastewater since a very small volume of the wastewater is in contact with the walls were the formation occurs. The samples were taken in the middle of the winter and this does not favour the methane production either since the water is colder than during summer. It can at least be noted that this is the absolute minimum amount that will arrive to the WWTP and probably emits here since the amount of methane will rise as the temperature does.

**Methane formation rates in the selected pipes**

The formation rate was calculated for the pressurised and non-pressured pipe. For the pressurised pipe the result became,

\[ n_{CH_4,\text{tot}} = 72 \times 10^{-6} \text{ kg/m/h} \]

And for the non-pressurised pipe the result became,

\[ n_{CH_4,\text{liquid}} = 7.2 \times 10^{-6} \text{ kg/m/h} \]

\[ n_{CH_4,\text{gas}} = -637 \times 10^{-6} \text{ kg/m/h} \]

The result shows that the formation rate in the pressurised pipe is the highest. It is not established that the production in the non-pressurised pipe actually takes place and maybe is it just emitted here while it is formed in the pressurised pipes. The methane concentration in the pressurised pipe is low compared to other pressurised pipe measurements worldwide, for instance (i.e. Guisasola *et al.*, 2008) found a concentration equal to 22 mg CH\(_4\)/L in the end of their examined pipe. This value is about 9 times higher than 2.4 mg CH\(_4\)/L. If the conditions are compared, the reason to the differences can be explained. The HRT differed a lot in the two pipes investigated. Another probable reason for the large variation is that the Australian wastewater temperature was slightly over 26°C which was warmer than the sewage collected in Sweden. Unfortunately, the sewage temperature was not measured but it was most likely much colder than 26°C. It can also be compared with the sewage temperature measured at Sjölunda two weeks earlier which was around 14°C.

These two reasons explain why the encountered concentration in Sweden is lower than the ones measured in Australia, but it does not explain why the one in the Swedish sewer is that low. Due to varying physical barriers could the sample taker not climb down in the main were the pressure was released and thus was the concentration measured in another main downstream, close to where the pressure was released. This affected the result since the methane is released as the pressure is.

The methane formation in the non-pressurised pipe became \( 7.2 \times 10^{-6} \) and \(-637 \times 10^{-6} \) kg/m/h for the liquid and gas phase respectively. The value \( 7.2 \times 10^{-6} \) indicates that there is a methane formation also in gravity pipes but it is hard to establish since the flow and thus filling factor changed during the sampling. Also the negative value in the gas phase indicates that methane is destroyed in the sewer. If both the values are trusted the net production in the chosen pipe will become negative and thus is more methane destroyed than formed. If that is true is kind of hard to say because just one non pressurised pipe length has been examined. The most believable way that methane is destroyed in would be by oxidation. But oxidation by air requires a certain kind of
microorganism that most likely will not be formed in the sewer pipe. Therefore this negative value is most likely a measuring error or some other disruption and hence can formation of methane in gravity pipes not be established.

**Conclusion**

Methane formation in Malmö sewer system does exist. The highest methane concentration encountered was from the inlet at Sjölunda WWTP together with the end of the pressurised pipe at the field. Pressurised pipes are the most potential methane formation places since those are filled with sewage and thus completely anaerobic. The highest and lowest encountered methane concentrations were 0.58 and 0.11 mg CH₄/L respectively. The methane formations rates in the liquid became 7.2 * 10⁻⁶ kg/m/h and 72 * 10⁻⁶ kg/m/h for the non-pressurised and pressurised pipe respectively.

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**Nomenclature**

The following symbols are used in this paper:

\[
R = \text{ideal gas constant (Joule/mole/K)} \\
T = \text{temperature (K)} \\
x_{\text{CH}_4} = \text{fraction of methane in gas phase} \\
V_{\text{gas, tube}} = \text{volume of gas in tube (m}^3\text{)} \\
H_{\text{e,CH}_4} = \text{Henry's constant for methane in water (Pascal * L/mol)} \\
\dot{m}_{\text{CH}_4,\text{liquid}} = \text{production rate of methane in the liquid phase (mg/m/min)} \\
\dot{m}_{\text{CH}_4,\text{gas}} = \text{production rate of methane in the gas phase (mg/m/min)} \\
\dot{m}_{\text{CH}_4,\text{tot}} = \text{total production rate of methane in the pipe (mg/m/min)} \\
C_{\text{CH}_4,\text{liquid prod}} = \text{average concentration of methane in the liquid phase (mole/m}^3\text{)} \\
C_{\text{CH}_4,\text{gas prod}} = \text{average concentration of methane in the gas phase (mole/m}^3\text{)} \\
v_{\text{liquid}} = \text{voulum of liquid (m}^3\text{)} \\
d = \text{diameter of pipe (m)} \\
\beta = \text{filling factor} \\
M_{\text{CH}_4} = \text{molar mass of methane (g/mole)} \\
C_{\text{CH}_4,\text{gas,1}} = \text{concentration of methane in the gas phas in the beginning of the pipe (mole/m}^3\text{)} \\
C_{\text{CH}_4,\text{gas,2}} = \text{concentration of methane in the gas phase in the end of the pipe (mole/m}^3\text{)}
\]

**References**


