MODELING OF SULFIDE EMISSION FROM THE VIRGINIA SEWER SYSTEM

by

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DECLARATION BY CANDIDATE

I, YUE LU, hereby declare that this thesis
is my own work and it has not been submitted
for a degree at another University.

March 2001

For my mother

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SYNOPSIS

In 1988, a test sewer was constructed downstream of a pump station in Virginia, South Africa, with the objective of creating a field laboratory. The field laboratory was to be used as a means of testing the response of various concrete materials to an acidic sewer environment. This field laboratory has been investigated under the control of the CSIR. Publications have arisen from observations effected on site (Kelly and Kruger, 1996). However, the majority of these have involved literature reviews and reports including listed data but very little analytical work has been effected. Recognizing that attack in the sewer environment involves five distinct processes occurring simultaneously, each with its own kinetics, any meaningful research can be effected only once the individual processes have been uncoupled and studied separately.

The principal objective of this thesis is to predict hydrogen sulfide emission from sewerage along the line of flow for the Virginia sewer field laboratory. Meeting this objective required both an understanding of the flow hydraulics in this sewer environment, and a model (kinetic equation) for hydrogen sulfide emission in terms of the flow characteristics.

The thesis presents the relevant theory for predicting hydraulic characteristics (including the velocity gradient, G) in gravity flow sewers. This was used to establish a dynamic model for the Virginia sewer line using AQUASIM as a mathematical integrator.

Regarding the kinetics of hydrogen sulfide emission, these were measured in the laboratory. A flocculation unit was used to impart a selected velocity gradient (G) into the water and sulfide concentration measured with time. This was effected for a number of G values. Regression analysis was then used to fit an equation of rate of emission against G. In the final chapter to this thesis, the hydraulic model and the kinetic model are linked (via G) to give the desired rate equation for hydrogen sulfide emission along the sewer line. On-site observations at manholes along the line of flow agreed reasonably with those predicted by the model.

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LIST OF SYMBOLS

SYMBOL	**DESCRIPTION**
A_s	Surface area of emission (m^2)
A	Cross section area (m^2)
atm	Atmosphere
°C	Degrees Celsius
C_L	Concentration in the bulk liquid (mg/*l*)
C_e	Equilibrium concentration in the gas phase (mg/*l*)
Ca	Calcium
COD	Chemical Oxygen Demand (mgO/*l*)
D_H	Hydraulic diameter or equivalent pipe diameter (m)
DO	Dissolved oxygen (mgO/*l*)
d_{mean}	Mean hydraulic depth $=A/P_w$ (m)
e.g.	For example
f	Darcy friction factor
g	Weight per unit mass on earth's surface (9.81 N/kg)
G	Gradient velocity (/s)
HS^-	Dissociated hydrogen sulfide
H^+	Hydrogen ion
H_2S_{aq}	Sulfide species in aqueous phase
H_2S	Undissociated hydrogen sulfide
H_2O	Water
H_L	Friction energy loss (m)
l	Liters
OH^-	Hydroxide ion
ρ	Sewage density (kg/m^3)
P_{H2S}	Partial pressure of H_2S in the gas phase (atm)
P_w	wetted perimeter (m)

Q	Flow rate (m^3/s)
KH_2PO_4	Potassium dihydrogen orthophosphate
K_2HPO_4	Di-Potassium hydrogen orthophosphate
K_H	Henry's law constant for hydrogen sulfide ($mg/l.atm$)
K_{La}	Overall liquid phase mass transfer rate coefficient (/s)
min	Minute
Na_2S	Sodium sulfide
n	Manning's friction coefficient
rpm	Revolution per minute
r	Unit weight of liquid ($9.81*10^3$ N/m^3)
S_f	Friction slope (m/m)
S_T	Total dissolved sulfide (mgS/l)
S	Dissolved sulfide species
S^{2-}	Dissociated sulfide
s	Sewer slope (m/m)
τ_0	Boundary shear stress (Pa)
t	Time (s)
T	Sewage retention period (s)
μ	Absolute viscosity of liquid ($N\ s\ m^{-2}$)
UCT	University of Cape Town
V	Reactor volume (m^3)
v	Mean flow velocity (m/s)
v_*	Shear velocity (m/s)
w	Water surface width (m)
W	Dissipation function ($N\ s^{-1}\ m^{-2}$)

CHAPTER 1

INTRODUCTION

Sulfuric acid attack of cement materials in the sewer environment is a common phenomenon downstream of pumping stations. Such attack arises from a number of sequential processes:

1. Biological generation of hydrogen sulfide.
2. Emission of hydrogen sulfide into the sewer environment.
3. Dissolution of hydrogen sulfide into a moisture film of the sewer surfaces exposed to the gas phase (air).
4. Oxidation of hydrogen sulfide to sulfuric acid.
5. Chemical attack by the sulfuric acid on the cement material comprising the sewer surface exposed to the gas phase (air).

Each of these processes is considered briefly below:

(1) Generation of hydrogen sulfide in the sewer environment

Hydrogen sulfide either may be discharged either directly into a sewer system or generated in the sewer environment. Generation may occur biologically provided that anaerobic conditions prevail. Such anaerobic conditions may arise either in the line of flow or in pumping systems. In the line of flow, a poorly designed sewer system may result in low sewer velocities, settlement of suspended organic material and subsequent biological sulfate reduction to form sulfides (see Figure 1.1). This has been well researched and reported for the South African environment by Kruger (1987). In the wet well of pumping systems, settlement of suspended organic solids occurs and anaerobic conditions with concomitant sulfide generation are inevitable.

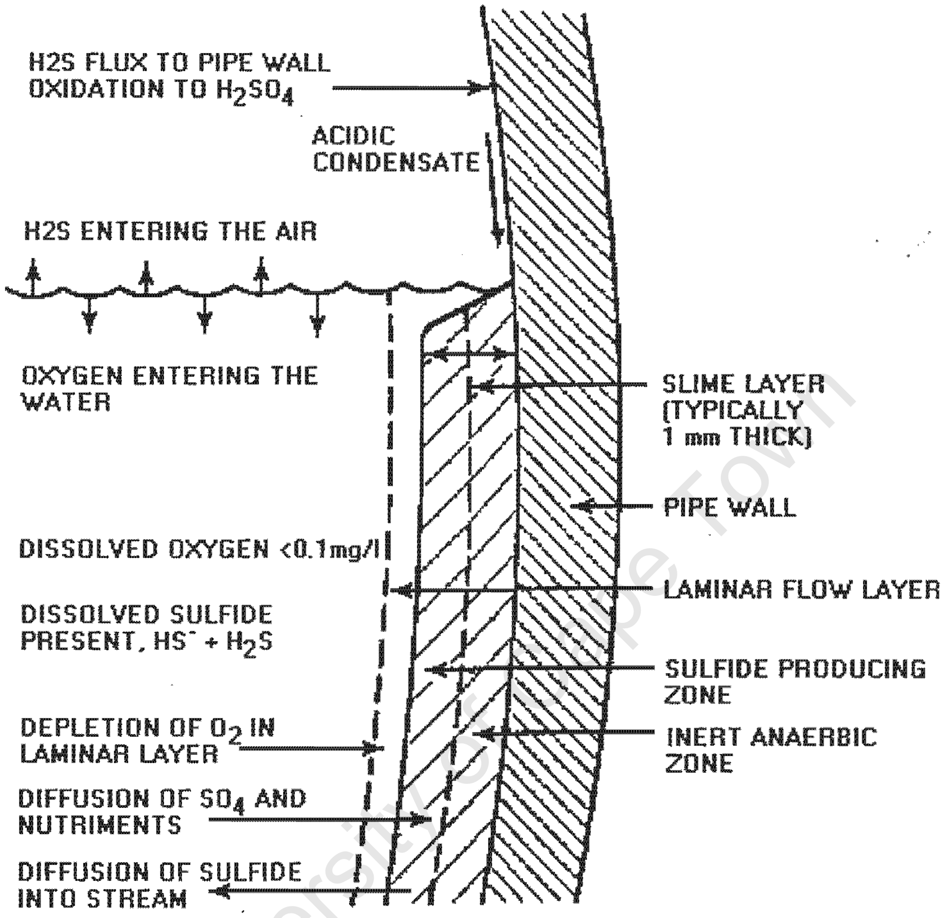


Fig 1.1: Processes occurring in sewers under sulfide build-up

Two groups of sulfide generating bacteria (i.e. sulfate reducing species) occur. Firstly, those that reduce organic sulfate material (for example: *Escherichia Coli, Proteus Vulgaris and Pseudomanas Pyocynea*), and secondly those that reduce inorganic sulfate ions (for example: *Desulphovibrio and Desulphotomaculum*). All these organisms are anaerobes, meaning they can only operate under anaerobic conditions. Such anaerobicism reflects the outcome of poor aeration of the sewage (poor sewer design) and the presence of an electron donor (organics in the sewage which is ubiquitous). Further, the bio-kinetics of sulfide generation (once anaerobic conditions are established) are strongly temperature dependant and its occurrence in cold environments is only rare (Kruger, 1991).

Various empirical equations have been presented for predicting sulfide generation in the sewer environment, including those presented in the American Concrete Pipe Association's Concrete Pipe Handbook and its Design Manual: *Sulfide and Corrosion Prediction and control* (1981), the Davy equation (Davy, 1950), its extension by Pomeroy and Parkhurst (1977) to give the so-called Z formula and various other publications. All these predictive equations take cognizance of hydraulic considerations (for example sewer slope, sewage flow, and wetted surface area), sewage characteristics (for example oxidisable organics, sulfate content and pH) and temperature.

(2) Emission of hydrogen sulfide into the sewer atmosphere

Grant (1979) states that sulfides may occur in two forms in sewage. Firstly as insoluble metal sulfides such as zinc or ferrous sulfide, and secondly in the dissolved form comprised of both H_2S and HS^-. The metal sulfides are in a solid form which cannot be volatized in the sewer environment. However, hydrogen sulfide can occur in both aqueous and gas phases, and therefore can be emitted from the liquid (whereas the ionic species HS^- can not). The relative fractions of H_2S and HS^- are strongly pH dependent. At lower pH values, H_2S dominates, and at higher pH values (greater than 7.1) HS^- dominates. Clearly the rate of hydrogen sulfide emission will depend in part on pH. Kruger (1987) lists other factors which will effect hydrogen sulfide emission, including: a) total dissolved sulfide species in sewage, b) the sewage flow and turbulence which gives arise to surface renew at the liquid-air interface, c) fresh air supply (i.e. oxygen supply) to the sewer atmosphere), d) surface area of liquid exposed, and e) the solubility of hydrogen sulfide gas in the sewage (Henry's constant). Hydrogen sulfide can escape to the gas phase until its concentration in this phase reaches approximately 300ppm. For concentrations of hydrogen sulfide in the gas phase greater than this value the reverse reaction dominates, that is overall hydrogen sulfide will be dissolved.

The most widely used predictive model is that by Pomeroy (1947). In essence, the model is empirical with the rate depending on such considerations as head loss, concentration of undissociated hydrogen sulfide and temperature. The equation however is not in the form which can be used generally and should be used with discretion bearing in mind that scientific method has advanced significantly over the past five decades since this equation was proposed.

(3) Dissolution of hydrogen sulfide into a moisture film of the sewer surfaces exposed to the gas phase (air)

An aqueous film will occur at the cement pipe - sewer gas boundary. The pH of this film should be high because of the alkaline nature of cement pipe. This means that hydrogen sulfide in the sewer atmosphere will be highly soluble in the film. At pH of 7 and a hydrogen sulfide partial pressure of 0.1atm, approximately 0.67mg/*l* H_2S can dissolve and this value will increase by approximately an order of magnitude for each unit increase in pH. The rate at which such dissolution occurs depends on a number of factors, including the pH of the water film, turbulence in sewer gas atmosphere (Kruger and Botha, 1987) and the rate at which dissolved H_2S is oxidized on the sewer wall.

(4) Oxidation of hydrogen sulfide to sulfuric acid

Kruger and Botha (1987) states that the onset of oxidation of dissolved sulfides species on a sewer wall is initiated by aerobic autotrophic bacteria which operate optimally at pH values of about 8. The byproduct of these organisms is utilized by a second group (*inter alia*, the sulfur-oxidizing bacteria such as *Thiobacillus*) which then become established on the sewer wall environment, generating sulfuric acid. This second group of organisms, also aerobic, is able to operate down to pH values below 2. Thus, for the growth of sulfide oxidizing organisms on sewer surfaces exposed to the gas phase, the following conditions need to be satisfied: a) biological seed must be present (in practice the sewage flow supplies such seed), b) the relative humidity of the sewer atmosphere must greater than 85 percent to maintain an aqueous film, c) temperature must greater than about 5

°C, d) trace nutrients must be available for bio-growth and e) oxygen must be present to act as the electron acceptor for biological catabolism and carbon dioxide and ammonia for anabolic requirements.

An empirical equation for predicting sulfide flux to the sewer wall is given by Kruger and Botha (1987) based on the work of Pomeroy (1947).

(5) Chemical attack by sulfuric acid to the cement material comprising the sewer surface exposed the gas phase (air)

It is widely known that cement material is susceptible to acid attack because of its alkaline nature. In this regard sulfide species are not directly aggressive to cement materials. However, on its bio-oxidization to sulfate, protons are released (i.e. sulfuric acid is generated) which then attack the cement surfaces. Components of the cement paste break down when exposed to acid. For example, the free lime in the cement is dissolved, i.e.:

$$Ca(OH)_2\,(solide) + 2H^+ \rightarrow Ca^{2+} + 2H_2O \qquad (1.1)$$

and the integrity of the cement breaks down. Gypsum, $CaSO_4.2H_2O$, formed from sulfate released by bacteria and the calcium from the dissolved free lime is generated. The specific volume of the gypsum is larger than the original material causing an expanding pressure and consequential disintegration.

In 1988, a test sewer was constructed downstream of a pump station in Virginia, South Africa, with the objective of creating a field laboratory. The field laboratory was to be used as a means of testing the response of various concrete materials to an acidic sewer environment. This field laboratory has been investigated under the control of the CSIR. Publications have arisen from observations effected on site (Kelly and Kruger, 1996). However, the majority of these have involved literature reviews and reports including listed data but very little analytical work has been effected. Recognizing that attack in the sewer environment involves five distinct processes occurring simultaneously, each with its own kinetics, any meaningful research can be effected only once the individual process have been uncoupled and studied separately.

The objective of this investigation firstly is to model the physical flow characteristics of the field laboratory (Virginia sewer) and secondly to model the kinetics of hydrogen sulfide emission along the line of flow. It should be noted that the study did not incorporate modeling sulfide generation because it was found that sulfide is generated outside the test site, probably in the wet well of the pumping station. Sulfide generation along the line of flow was discounted because the sewage in the test region was found to be saturated with oxygen.

CHAPTER 2

HYDROGEN SULFIDE EMISSION RATE

- LABORATORY STUDY

2.1 INTRODUCTION

The principal objective of this chapter is to establish an equation for rate at hydrogen sulfide emission rate from a batch reactor (i.e. a plug flow system simulating sewer flow) under controlled laboratory conditions. This will serve in the later formulation of a predictive model for hydrogen sulfide in the sewer environment.

With regard to the occurrence of H_2S in the sewer environment and the onset of chemical attack, three principle steps are identified.

1) Biological sulfide generation in the sewage
2) H_2S emission from the sewage
3) Aggressive/corrosive attack to sewer wall

With regard to biological H_2S generation in the sewer environment; it would appear that this occurs principally in the wet wells necessary at pumping stations and in raising mains and only minimally in the gravitational sewer system (Kelly and Kruger, 1996).

In contrast, H_2S emission from sewage effluent appears to occur principally in the gravitational flow reticulation system, probably due to the high turbulence encountered in these regions (Appendix B). A number of researchers have attempted to model such sulfide emission, most widely accepted being that of Pomeroy (1947) (Kruger and Botha, 1987). However, recognizing that his work was effected a long time ago, in a era when chemical analyses were notoriously inaccurate and quantification of mixing conditions not well established, it is necessary to revisit this aspect of sewer corrosion and possibly remodel such kinetics.

The approach to be adopted here was first to effect a laboratory scale investigation using a batch reactor configuration and a controllable mixing energy input for well pH-buffered waters with known initial total sulfide content. Total dissolved sulfide was then measured with time and such observations used to create a model of the observed kinetics (Appendix A). The fitting of the model to the observations was effected using the user-friendly program AQUASIM. This software was developed specifically for simulation purposes and is thus ideally suited to the problem in hand.

Before dealing with the experimental methods and observations effected, it is necessary to inquire into the chemistry of the sulfide system in aqueous solutions. The reason for this is that sulfides form part of a weak acid-base system in aqueous solution and consequently concentrations of species change in a complex fashion with both pH and redox potential. Furthermore, sulfide species in solution are also affected by interactions between the aqueous phase and either or both of the gaseous (H_2S) and solid phase (mineral sulfide).

2.2 AQUEOUS PHASE CHEMISTRY OF SULFIDE SYSTEM

2.2.1 Equilibrium and mass balance considerations

Sulfate species are reduced biologically to create the sulfide system in the sewer environment. In the aqueous phase the sulfide species are in the forms of H_2S_{aq}, HS^-, S^{2-} and complexes of these. The concentrations of these species in solutions are governed by both equilibrium equations and mass balance considerations.

The concentration of individual species varies with pH and the total dissolved sulfide concentration. Such variations are best described using graphical methods based on system equations derived from mass balance and equilibrium considerations.

For a fixed total dissolved sulfide species concentration, S_T, the relevant mass balance equation is:

$$S_T = [H_2S] + [HS^-] + [S^{2-}] \tag{2.1}$$

Where [X] = molarity of species X

The relevant equilibrium reactions for the sulfide system can be visualized as:

1. dissociation of $[H_2S]_{aqueous}$, i.e.

$$H_2S \leftrightarrow HS^- + H^+ \tag{2.2}$$

2. dissociation of HS^- species, i.e.

$$HS^- \leftrightarrow S^- + H^+ \tag{2.3}$$

The relevant equilibrium equations for these two reactions are:

$$\frac{(H^+)(HS^-)}{(H_2S)} = K_1 \tag{2.4}$$

$$\frac{(H^+)(S^{2-})}{(HS^-)} = K_2 \tag{2.5}$$

Where (X) = activity of species = f_x [X]

f_x = activity coefficient of species X

[X] = molarity of species X

K_1, K_2 = thermodynamic equilibrium constants

Rewriting Equation 2.4 and 2.5 with species in the more useful molar form but H^+ in the activity form- which is linked to pH:

$$\frac{(H^+)[HS^-]}{[H_2S]} = K_1' \tag{2.6}$$

$$\frac{(H^+)[S^{2-}]}{[HS^-]} = K_2' \tag{2.7}$$

Where K' = apparent equilibrium constant which has been Adjusted for the effects of the activity coefficient

Values for the equilibrium constants K_1 and K_2 are given in the literatures at 25°C:

$$pK_1 = -\log K_1 = 7.0 \tag{2.8}$$

and

$$pK_2 = -\log K_2 \cong 12.5 \tag{2.9}$$

The fact that the value of pK_2 is not well known is of little concern here as will become apparent later.

The above equations can be used to plot log-species concentrations with pH for known S_T. The relevant equations are as follows:

$$[H_2S] = \frac{10^{-2pH}}{10^{-K_1} * 10^{-K_2} + 10^{-2pH} + 10^{-K_1} * 10^{-pH}} * S_T \tag{2.10}$$

$$[HS^-] = \frac{10^{-2pH} * 10^{-K_1}}{(10^{-K_1} * 10^{-K_2} + 10^{-2pH} + 10^{-K_1} * 10^{-pH}) * 10^{-pH}} * S_T \tag{2.11}$$

$$[S^{2-}] = \frac{10^{-2pH} * 10^{-K_1} * 10^{-K_2}}{(10^{-K_1} * 10^{-K_2} + 10^{-2pH} + 10^{-K_1} * 10^{-pH}) * 10^{-2pH}} * S_T \tag{2.12}$$

$$[H^+] = 10^{-pH} \tag{2.13}$$

$$[OH^-] = 10^{-(14-pH)} \tag{2.14}$$

Equations 2.10 to 2.14 are shown plotted in Figure 2.1 for $S_T = 10^{-3}$ molar. Referring to Figure 2.1, one sees that in the pH region to be encountered in a sewer system, $6 < pH < 8$, the species S^{2-} are totally negligible and thus can be ignored.

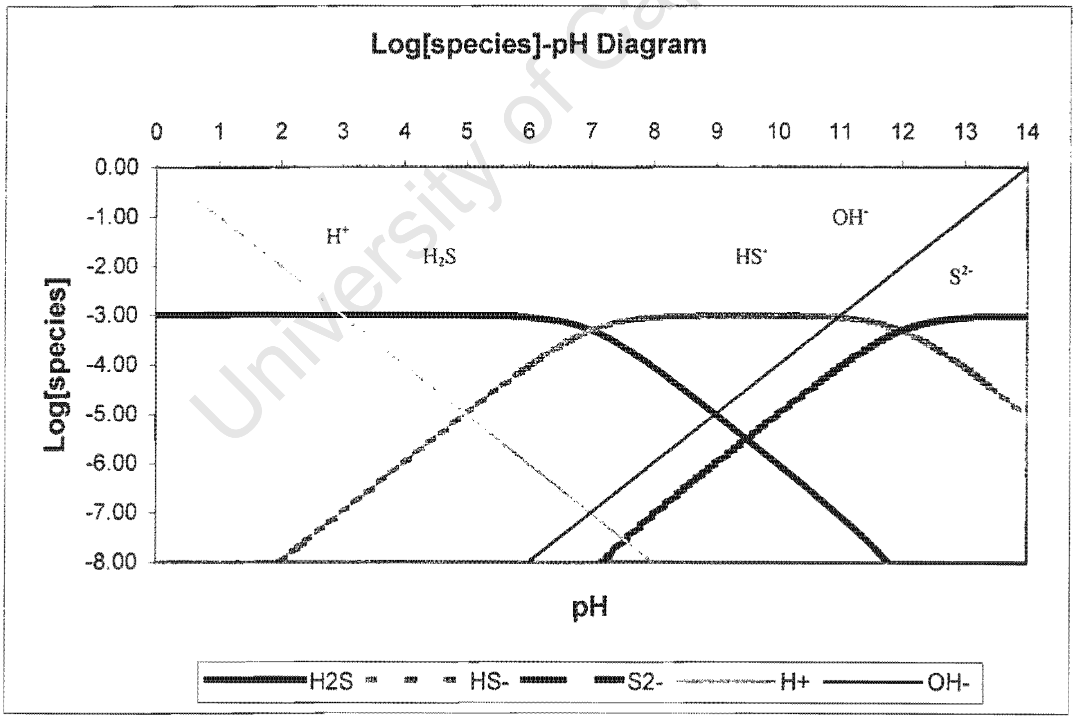


Figure 2.1: Log[species]-pH diagram

With regard to the H_2S and HS^- species concentrations, H_2S decreases with increase in pH and vice versa for HS^-. H_2S and HS^- concentrations are equal at pH equal to pK_1, and, in the normal sewer environment (pH~7) these two species will have closely equal concentrations.

2.2.2 Alkalinity and Acidity considerations

Alkalinity and Acidity are parameters considered in the aqueous environment because:

1. As capacity parameters they change in a simple stoichiometric fashion with chemical dosing.
2. They are usually easily and accurately measured in the laboratory.
3. As system parameters they can be used for characterising pH and weak acid systems in water.

In the sewer aqueous environment, the carbonate weak acid system totally dominates pH and its control. In other weak acid systems, for example phosphate, and sulfide systems, total species concentrations are at levels which make that their effects on pH are minimal. For these reason, the effect of the sulfide system on alkalinity and acidity is too small to allow accurate characterisation using these parameters. Consequently they are not considered further.

2.2.3 Characterisation of the sulfide system in sewer environment

Referring to the three mass balance and equilibrium equation for the sulfide system (Equation 2.1 to Equation 2.3), the system is comprised of two more unknowns than equations. Consequently, two independent parameters for the system need to be measured for characterisation. Only two can be sufficiently accurately measured in laboratory to effect such characterisation. These are pH and total dissolved sulfide concentration S_T. However for accurate and meaningful measurement of these, care should be taken that the highly volatile H_2S species is not lost in taking and storing samples. In this regard it should be noted that H_2S permeates certain materials, for example, silicone and these should not be used as sample storage materials.

2.2.4 Aqueous-gas phase equilibrium

Considering the sulfide system, the hydrogen sulfide species can exist in both the aqueous and gaseous phases. Consequently for water containing dissolved S species in contact with a gas phase, H_2S will be exchanged between these two phases until an equilibrium situation is attained. At this equilibrium situation, the pertinent equilibrium equation is:

$$[H_2S]_{aq} = K_H * P_{H_2S} \tag{2.15}$$

Where K_H = Harry's law constant for hydrogen sulfide (mg/l.atm)

P_{H2S} = partial pressure of H_2S in the gas phase (atm)

The rate at which such equilibrium is attained is extremely slow compared with the rate of the weak acid reactions in the aqueous phase, given by equation 2.2 and 2.3, and will depend on such factors as mixing of the aqueous solution and degree of super-under saturation existing between the two phases. In the sewer environment, such H_2S evolution from the aqueous phase occurs. However gas-aqueous phase equilibrium does not arise because the H_2S evolution is continuously oxidised by bacteria on sewer walls adjacent to the gas phase.

2.3 KINETICS

Conventionally, the rate of exchange of species between the aqueous and gas phase is considered to be equal to the product of a concentration driving force and a mass transfer rate constant.

$$-\frac{dC_L}{dt} = K_{La}(C_L - C_e) \qquad (2.16)$$

Where

K_{La} = overall liquid phase mass transfer rate coefficient (/s)
C_L = concentration in the bulk liquid (mg/*l*)
C_e = equilibrium concentration in the gas phase (mg/*l*)

Referring to Equation 2.16, the mass transfer rate coefficient will vary not only with temperature but also with the amount of mixing energy (i.e. flow characteristics, in the sewer line). Furthermore, C_L and C_e refer to concentrations of molecular dissolved aqueous sulfide in the aqueous phase and its concentration in the gas phase respectively:

$$-\frac{dC_L}{dt} = K_{La}[H_2S] - K_H P_{H_2S} \qquad (2.17)$$

Clearly, in order to predict H_2S emission rates, one needs to know the value of K_{La} in a particular environment. And, as stated before, this will depend on both temperature and mixing conditions in the water. In the sewer environment, the mixing conditions will depend on hydraulic flow characteristics, that is, on head loss along the line of flow. Usually in water treatment practice, such head loss has been linked to a parameter G. This G value is empirically linked to flow characteristics (see Chapter 3). Consequently it would be of interest to link G to the mass transfer coefficient, K_{La}, and this would enable one to formulate an equation for kinetics for hydrogen sulfide emission in the sewer environment where the velocity of flow and physical characteristics (e.g. roughness in the sewer) are known.

2.4 LABORATORY SCALE EXPERIMENT TO DETERMINE H_2S EMISSION RATE

Standard flocculation equipment exists which allows one to impart a desired G value into a water sample in the laborator. If the water contains dissolved sulfide species, H_2S

would be given off from the water at a rate dependant on the G applied. Thus, measurement of dissolved species with time gives a measure of the rate of H_2S emission. Such emission from this batch reactor simulates H_2S emission from a plug flow reactor, which in turn simulates flow in the sewer.

A series of batch experiment tests were effected in the laboratory at 20°C and the H_2S emission rates with various G values were measured. The experimental apparatus and methodology used are set out below.

2.4.1 Apparatus

- A *Spectroquant 1.14779.001 Hydrogen Sulfide* for total sulfide concentration measurement. The measuring range falls between 0.03-3.3mg/*l*.
- A pH meter
- A thermometer
- A 10ml volume adjustable pipette
- A standard flocculation batch reactor with the cross section area 115mm*115mm and the height 230mm, see Figure 2.2
- A variable speed motor for applying G
- Standard curve linking speed of mixing (rpm), i.e. revolution of the rotating blades, to G for this apparatus (Figure C.1 in Appendix C).
- Standard table linking frequency (Hz) to revolution (rpm) (Table C.1 in Appendix C).
- Test reagents (purchased with the *Spectroquant*)

2.4.2 Layout of the experiment

Figure 2.2 shows the layout for the batch reactor used. The initial concentration of H_2S was 10mgS/*l* in each test.

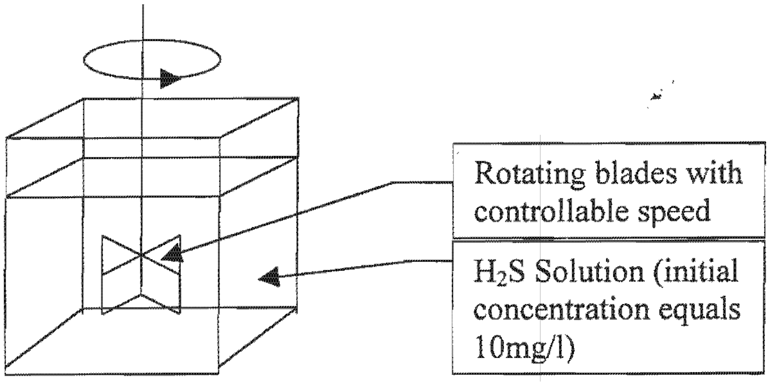


Figure 2.2: The layout of the experiment in the laboratory

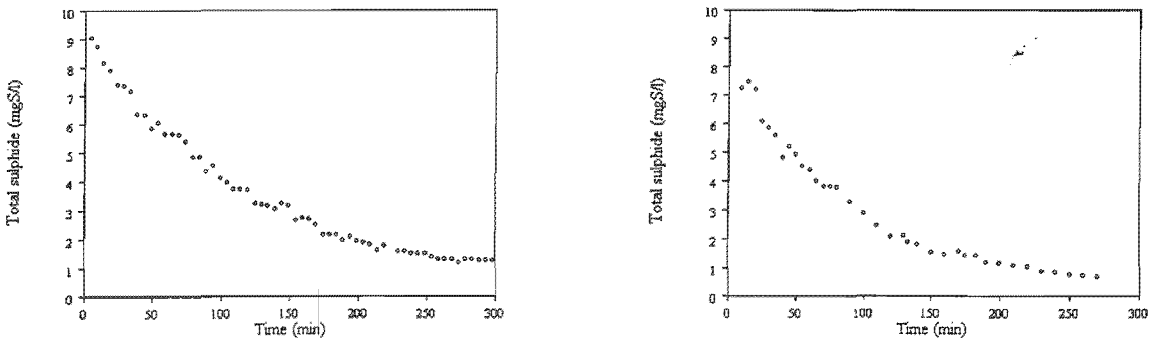
2.4.3 Experiment conditions

- In the sewer system, a typical pH value of sewage is around 7. During the experiment, the pH value was controlled at 7 by adding equal molar concentrations of KH_2PO_4 and K_2HPO_4.
- Solution temperature was in the range 18°C-20°C, which is the ambient laboratory temperature. Literature shows that the temperature is irrelevant to the hydrogen sulfide emission rate (Kruger and Botha, 1987), thus it is not necessary to control the temperature.
- Na_2S flakes were added to distilled water to give initial total dissolved sulfide concentration of 10mgS/*l*.
- The motor rotating frequency range was varied from 25Hz (120rpm) to a maximum 60Hz (275rpm).

2.4.4 Experimental procedure

1. A desired frequency of the motor was selected. The operation fell in the frequency range 25Hz-60Hz.
2. Stable mixing conditions were obtained by operating the system for one hour before addition of chemicals.
3. Buffer solution: Substances KH_2PO_4 and K_2HPO_4 with same molar masses (3.2 mg KH_2PO_4 and 2.7mg K_2HPO_4) are added to 2*l* of distilled water to give a pH of about 7 to the solution.
4. 0.72mg $Na_2S.2H_2O$ flakes are added to the 2*l* sample to give a sulfide concentration of 10mgS/*l*
5. After the $Na_2S.2H_2O$ was dissolved into the solution; a 5ml sample was taken for measurement. The testing time and pH should be recorded.
6. Sampling and measurement were repeated every 5 minutes with the mixing maintained at a constant rate. Temperature and pH were also noted.
7. The experiment was then repeated for different mixing velocities.

Figures 2.3 and 2.4 show measured dissolved sulfide concentration with time for the various batch tests effected and the corresponding velocity of mixing and G values.

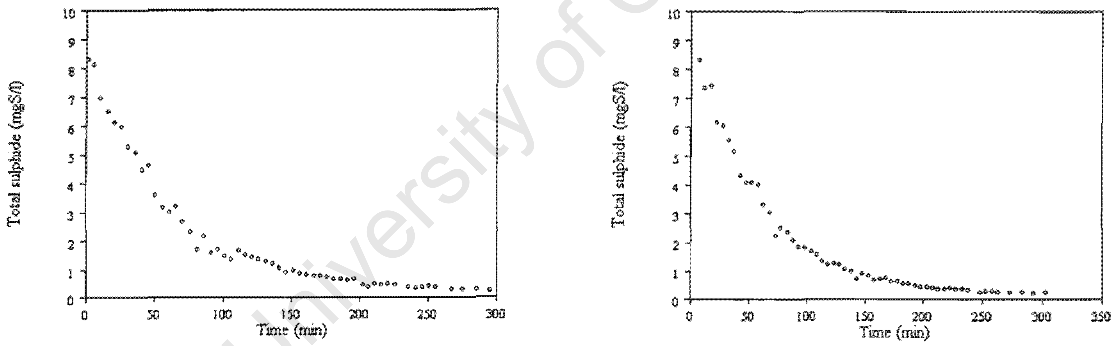


(a) frequency = 25Hz

G = 115/s

(b) frequency = 30Hz

G = 150/s



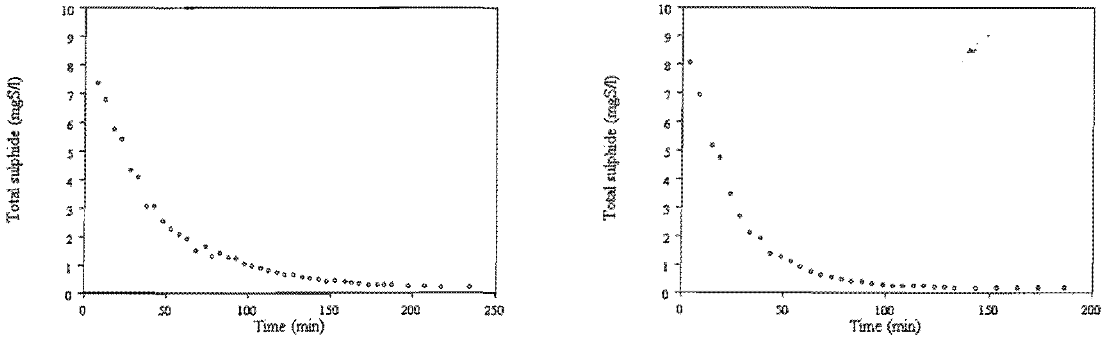
(c) frequency = 35Hz

G = 178/s

(d) frequency = 40Hz

G = 212/s

Figure 2.3: Experimental data at different motor rotating frequency and G value

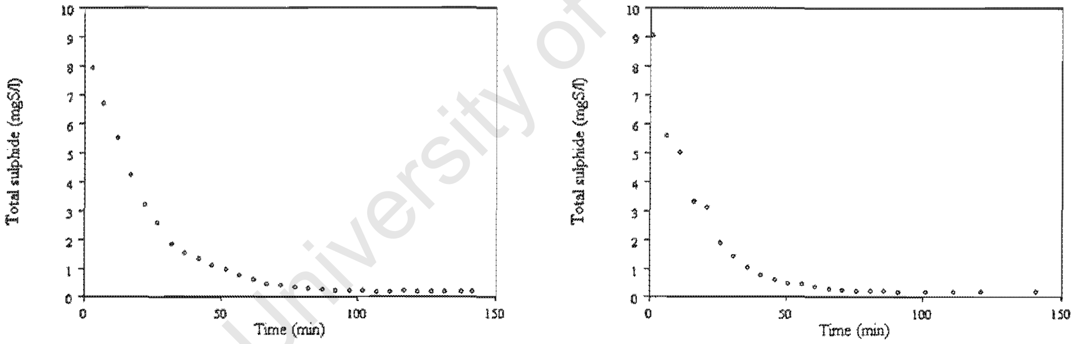


(e) Frequency = 45Hz

G = 241/s

(f) Frequency = 50Hz

G = 278/s



(g) Frequency = 55Hz

G =313/s

(h) Frequency = 60Hz

G = 350/s

Figure 2.4: Experimental data at different motor rotating frequency and G value

2.5 MODELLING OF LABORATORY DATA

For a batch mixed reactor, the rotating blades generate the solution turbulence and velocity of rotation is linked to G. Logically one expects the rate of change of total sulfide concentration to depend on mixing conditions (i.e. G, in our case G^2 was found more appropriate), the exposed area, the reactor volume, the hydraulic depth of reactor, and the concentrations of dissolved H_2S and H_2S gas.

$$-\frac{d[S_T]}{dt} \propto G^2 * \frac{A_S}{V} * d_{mean} * ([H_2S] - K_H * P_{H_2S}) \tag{2.18a}$$

Recognising that in the laboratory the H_2S concentration in the gas phase was zero, the rate of change of total sulfide concentration is as follows:

$$-\frac{d[S_T]}{dt} \propto G^2 * \frac{A_S}{V} * d_{mean} * [H_2S] \tag{2.18b}$$

i.e.

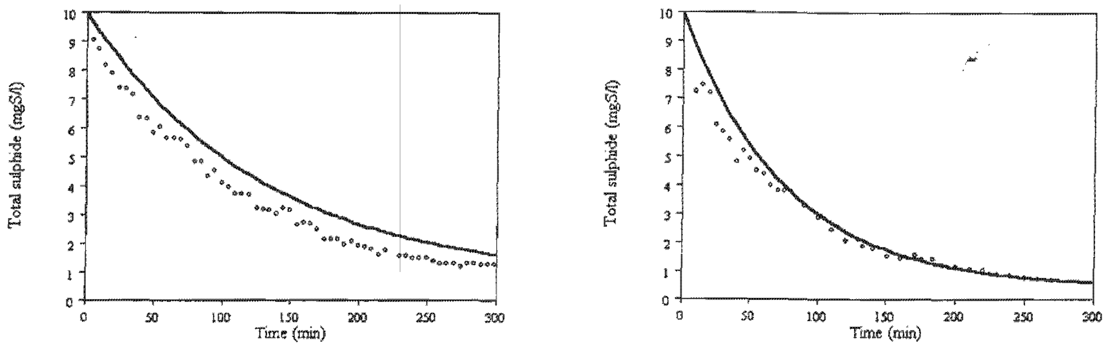
$$-\frac{d[S_T]}{dt} = K_1 * G^2 * \frac{A_s}{V} * d_{mean} * [H_2S] \tag{2.19}$$

Where:
$d[S_T]/dt$ = rate of change of total sulfide concentration (mgS/*l*.s)
K_1 = constant (s)
A_s = surface area of emission (m^2)
V = reactor volume (m^3)
d_{mean} = mean hydraulic depth (m)
$[H_2S]$ = dissolved molecular sulfides in batch reactor (mgS/*l*)
$[S_T]$ = total sulfide concentration (mgS/*l*)
G = velocity gradient (presents mixing conditions) (/s)

A mathematical integrator program (AQUASIM) was used to fit the Equation 2.19 to the experimental data. To improve the fits in the low H_2S concentration regions the rate equation was modified to a more empirical form as shown below:

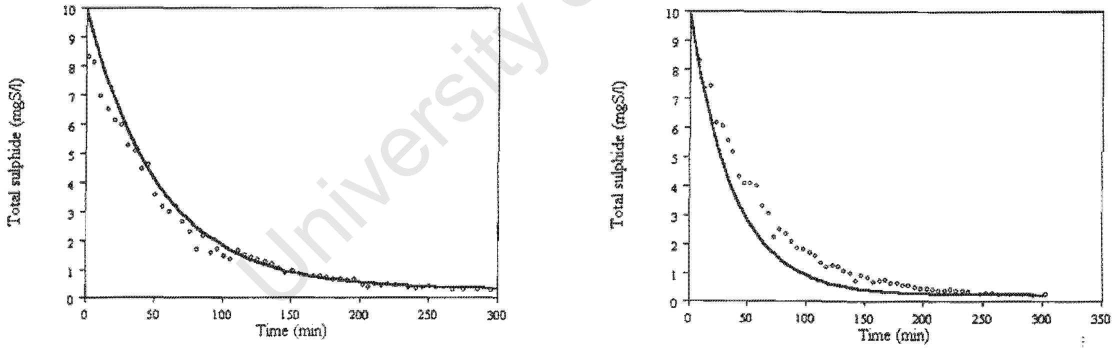
$$-\frac{d[S_T]}{dt} = K_1 * G^2 * \frac{A_s}{V} * d_{mean} * [H_2S] - K_2 \qquad (2.20)$$

Where K_2 = constant (mg/*l*.s)



(a) frequency = 25Hz
G = 115/s

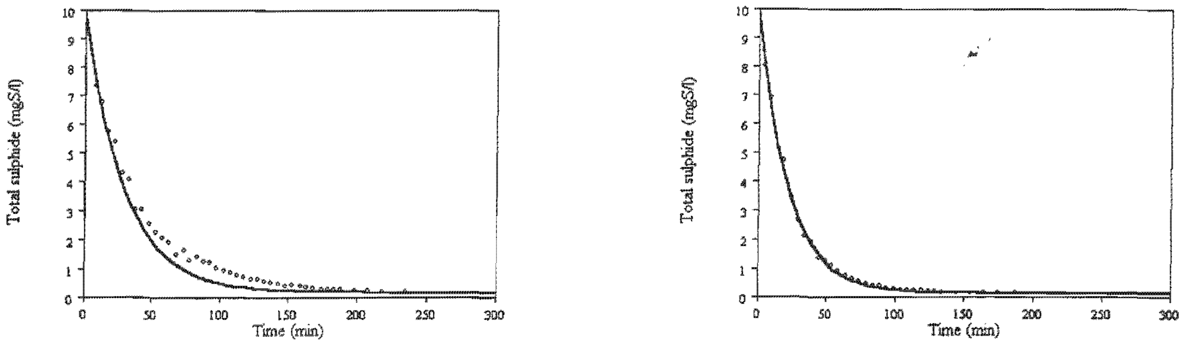
(b) frequency = 30Hz
G = 150/s



(c) frequency = 35Hz
G = 178/s

(d) frequency = 40Hz
G = 212/s

Figure 2.5: comparison between modeled results and experimental data at different motor rotating frequency and G value

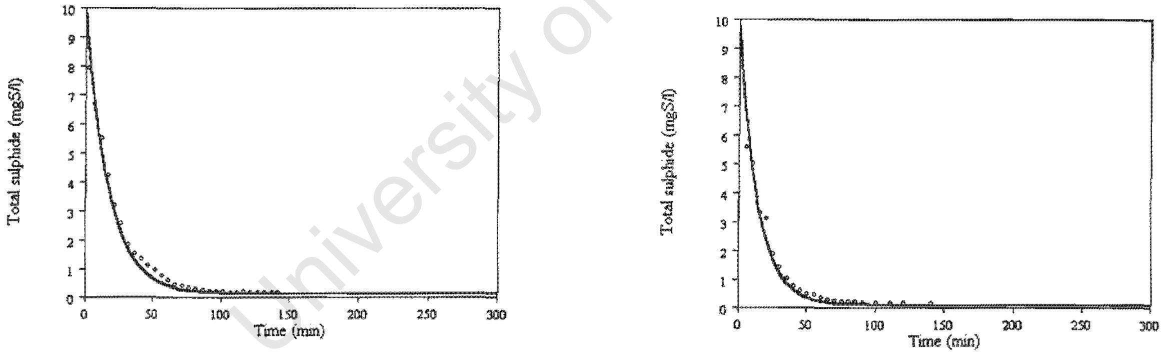


(e) Frequency = 45Hz

G = 241/s

(f) Frequency = 50Hz

G = 278/s



(g) Frequency = 55Hz

G = 313/s

(h) Frequency =60Hz

G = 350/s

Figure 2.6: Comparison between modeled results and experimental data at different motor rotating frequency and G value

Values for K_1 and K_2 were determined by regression as shown in Figure 2.5, and Figure 2.6.

The values determined for these constants at approximately 20°C are:

$K_1 = 9.33*10^{-8}$ (s)

$K_2 = 8.3*10^{-5}$ (mgS/*l*.s)

Thus the equation of change of total sulfide concentration in a batch reactor is defined as:

$$-\frac{d[S_T]}{dt} = 9.33*10^{-8}*\frac{A_s}{V}*d_{mean}*G^2*[H_2S]-8.3*10^{-5} \qquad (2.21)$$

Note that strictly speaking Equation 2.21 is valid only for total sulfide concentration between about 10 and 0.1 mgS/*l*, G from 100 to 700 units and temperature about 20°C and for low partial pressure of H_2S in the gas phase.

CHAPTER 3

HYDRAULICS OF SEWER FLOW

3.1 INTRODUCTION

Recognizing that the objective of this investigation is to model sulfide emissions in sewer systems and that such emission rate are linked to mixing conditions, it is necessary to quantify this consideration. That is, one needs to link the G value which establishes controlled mixing conditions in the laboratory to those that arise in the field due to the hydraulics of flow in the sewer.

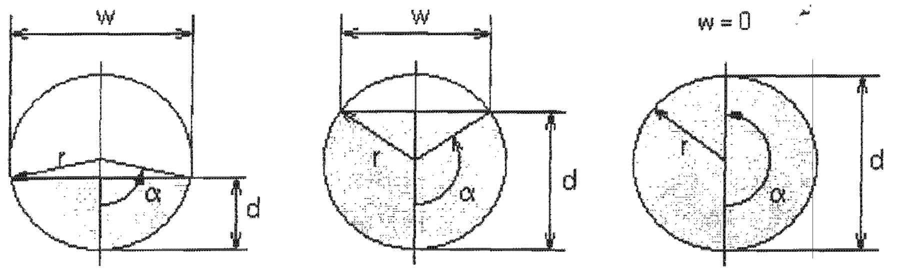
In practice, a number of semi-empirical equations have been derived to model the hydraulics. Invariably such models are in terms of both the physical characteristics of the sewer and the fluid being transported (e.g. sewer slope, wall material and its roughness, shape of cross-section, and sewage density and viscosity), and the flow characteristics (e.g. flow rate).

In this chapter, the physical characteristics of the sewer will be considered and linked to various semi-empirical equations describing the hydraulics. The link between the hydraulics of flow and hydrogen sulfide emission will be considered in Chapter 4.

3.2 PHYSICAL CHARACTERISTICS OF SEWERS

Although a wide variety of noncircular sewer sections have been employed including egg-shaped, semi-elliptical, horseshoe, baskethandle, oval, catenary, gothic, parabolic and elliptical, the majority of sewers presently constructed are of circular cross section.

Figure. 3.1 illustrates a typical circular cross section and three flow conditions: (1) under-half full flow, (2) over-half full flow, and (3) full flow.



(1) under-half full flow (2) over-half full flow (3) full flow

Figure 3.1: Standard circular cross-section of sewers

According to geometry, the α value depends on both the water depth, d, and sewer radius, r:

$$\alpha = a\cos(\frac{r-d}{r}) \qquad (3.1)$$

At any flow situation:

surface width: $w = 2*r*\sin(\alpha)$ m (3.2)

wetted perimeter: $P_w = 2*r*\alpha$ m (3.3)

cross-section area: $A = r*r*(\alpha - \sin(\alpha)*\cos(\alpha))$ m^2 (3.4)

Another important parameter that is related to the cross-section is hydraulic diameter D_H:

$$D_H = 4\frac{cross-sectional\ area}{wetted\ perimeter} = \frac{4A}{P_w} \quad m \qquad (3.5)$$

The hydraulic diameter is also called the equivalent pipe diameter, and is used often in head loss calculations.

3.3 FLOW TYPES AND THE DEFINITION OF TERMS

The following terms are basic to an understanding of both pipe and open channel flow (Metcalf and Boston, 1972).

Pipe and Open Channel Flow: The flow of liquid in a pipe may be considered to be open or closed, depending on whether or not the pipe is flowing full. For open channel flow in a pipe, a free liquid surface that is subject to atmospheric pressure must exist. For the gravity sewers researched in this project, open channel flow is the case. For open channel flows, the fluid is propelled by the weight of the flowing water resolved down a slope. Open channel flow is shown schematically in Figure 3.2.

Steady flow: Steady flow occurs when the discharge or rate of flow at any cross section is constant.

Uniform and Non-uniform Flow: Uniform flow exists when the depth, cross-sectional area, and other elements of flow are substantially constant from section to section. Non-uniform flow exists when the slope, cross-sectional area and velocity are changing from section to section.

Varied flow: Flow in a channel is considered varied if the depth of flow changes along the length of the channel. In general, the flow may be gradually varied (GVF) or rapidly varied (RVF). Rapidly varied flow occurs where the depth of flow changes abruptly.

3.4 FLOW EQUATIONS

In real fluid flow situations, energy is continuously dissipated. Considering a sewer extending over several kilometers, the friction force counterbalances exactly the weight force component in the flow direction.

The laws of flow resistance in open channels are essentially the same as those in closed pipes. In an open channel, the calculations of the boundary shear stress are complicated by the existence of the free surface and the wide variety of possible cross-sectional shapes. Another difference is the propulsive force acting in the direction of the flow. In closed pipes, the flow is driven by a pressure gradient along the pipe whereas, in open channel flows, the fluid is propelled by the weight of the flowing water resolved down a slope.

3.4.1 Friction head loss

The head loss is directly proportional to the system dissipation function, which in turn is linked to the laboratory parameter utilized in Chapter 2, that is the velocity gradient G.

The total energy of flow in any section, with reference to some datum, is the sum of the elevation head z, the pressure head y, and the velocity head $V^2/2g$. The energy from section to section is represented by a function termed the energy line or energy gradient (see Figure 3.2). When a fluid is moving along a pipe, work is being done against the frictional resistance of the wall. Consequently the energy of the fluid decreases as it moves and is termed the head loss (H_L). In Figure 3.2, H_L represents the head loss between sections 1 and 2.

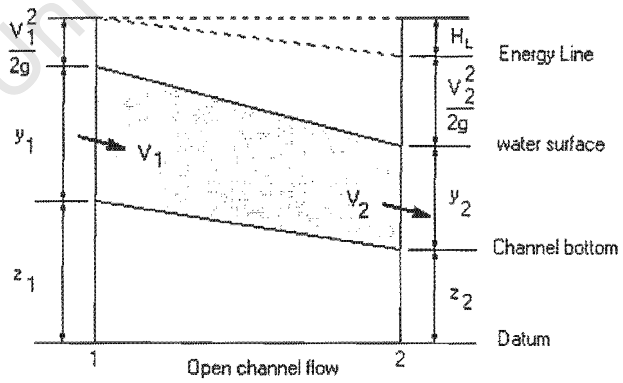


Figure 3.2: Energy loss in the sewer system

The energy loss per unit length can be equated to the work done against friction per unit length as in the Darcy-Weisbach formula:

$$H_L = f * \frac{L}{D_H} * \frac{v^2}{2g} \qquad (3.6)$$

where

H_L = friction energy loss	(m)
f = Darcy friction factor	
D_H = hydraulic diameter or equivalent pipe diameter	(m)
g = weight per unit mass on earth's surface	(9.81 N/kg)
v = mean flow velocity along the distance L	(m/s)

This equation is formulated for circular pipes.

3.4.2 Mean flow velocity, *v*

Based on work conducted during the latter part of the nineteenth century, Manning published the now well know equation for flow in open channels:

$$v = \frac{1}{n} * (\frac{D_H}{4})^{\frac{2}{3}} * s^{\frac{1}{2}} \qquad (3.7)$$

Where

v = mean flow velocity	(m/s)
n = Manning's friction coefficient	dimensionless
D_H = hydraulic diameter	(m)
s = sewer slope	(m/m)

This equation was originally intended for use in the design of open channels. It is now used for both open and closed channels. The equation is valid for both uniform and non-uniform (gradually varied) flows.

Even though Equation 3.7 is the one most widely used in the design of sewers, considerable misunderstanding exists concerning the selection of the appropriate friction coefficient n value to be used. Typical n values for various types of pipes are presented in Table 3.1. In general, n values varying from 0.011 to 0.015 are used in sewer design, and are usually assumed to be valid for all depths of flow.

Table 3.1 Values of n to be used in Manning equation (Bevan, 1949)

Surface	Best	Good	Fair	Bad
Uncoated cast-iron pipe	0.012	0.013	0.014	0.015
Coated cast-iron pipe	0.011	0.012*	0.013*	
Commercial wrought-iron pipe, black	0.012	0.013	0.014	0.015
Commercial wrought-iron pipe, galvanised	0.013	0.014	0.015	0.017
Smooth brass and glass pipe	0.009	0.01	0.011	0.013
Smooth lockbar and welded "OD" pipe	0.01	0.011*	0.013*	
Riveted and spiral steel pipe	0.013	0.015*	0.017*	
Vitrified sewer pipe	0.01	0.013*	0.015	0.017
	0.011			
Common clay drainage tile	0.011	0.012*	0.014*	0.017
Glazed brickwork	0.011	0.012	0.013*	0.015
Brick in cement mortar; brick sewers	0.012	0.013	0.015*	0.017
Neat cement surfaces	0.01	0.011	0.012	0.013
Cement mortar surfaces	0.011	0.012	0.013*	0.015
Concrete pipe	0.011	0.012	0.013*	0.016
Wood stave pipe	0.01	0.011	0.012	0.013
Plank flumes:				
Planed	0.01	0.012*	0.013	0.014
Unplanned	0.011	0.013*	0.014	0.015
With battens	0.012	0.015*	0.016	
Concrete-lined channels	1.012	0.014*	0.016	0.018
Cement-rubble surface	0.017	0.02	0.025	0.03
Dry-rubble surface	0.025	0.03	0.033	0.035
Dressed-ashlar surface	0.013	0.014	0.015	0.017
Semicircular metal flumes, smooth	0.011	0.012	0.013	0.015
Semicircular metal flumes, corrugated	0.0225	0.025	0.0275	0.03
Canals and ditches:				
Earth, straight and uniform	0.017	0.02	0.0225*	0.025
Rock cuts, smooth and uniform	0.025	0.03	0.033*	0.035
Rock cuts, jagged and uniform	0.035	0.04	0.045	
Winding sluggish canals	0.0225	0.025*	0.0275	0.03
Dredged earth channels	0.025	0.0275*	0.03	0.033
Canals with rough stony beds, weeds on earth banks	0.025	0.03	0.035*	0.04
Earth bottom, rubble sides	0.028	0.030*	0.033*	0.035
Natural stream channels:				
(1) Clean, straight bank, full stage, no rifts or deep pools	0.025	0.0275	0.03	0.033
(2) Same as (1), but some weeds and stones	0.03	0.033	0.035	0.04
(3) Winding, some pools and shoals, clean	0.033	0.035	0.04	0.045
(4) Same as (3), lower stages, more ineffective slope and sections	0.04	0.045	0.05	0.055
(5) Same as (3), some weeds and stones	0.035	0.04	0.045	0.05
(6) Same as (4), stony sections	0.045	0.05	0.055	0.06
(7) Sluggish river reaches, rather weedy or with very deep pools	0.05	0.06	0.07	0.08
(8) Very weedy reaches	0.075	0.1	0.125	0.15

3.4.3 Bottom shear stress and shear velocity

In Chapter 5, the software AQUASIM is utilized to model hydraulic flow and consequential sulfide emission along the line of flow in the sewer. Uses of AQUASIM are divided into tasks and one of these involves open channel flow, described as a river compartment. The input hydraulic requirements to this compartment include such parameters as friction slope S_f, and Darcy friction coefficient (*f*). Consequently it is necessary to link both S_f and *f* to n and other hydraulic characteristics, the values of which are known.

The link between Darcy friction coefficient *f*, the friction slope (S_f) (which form input to AQUASIM) and Manning friction coefficient (n), and physical hydraulic characteristics is obtained through the shear velocity, v_*, defined as:

$$v_* = \sqrt{\frac{\tau_0}{\rho}} \qquad \text{m/s} \qquad (3.8)$$

Where τ_0 is the boundary shear stress and:

$$\tau_0 = \rho g \frac{D_H}{4} S_f \qquad \text{Pa} \qquad (3.9)$$

Where ρ = sewage density (kg/m^3)

g = gravity acceleration value (N/kg)

S_f = friction slope (m/m)

D_H = hydraulic diameter (m).

Substituting for τ_0 from Equation 3.9 into Equation 3.8 gives:

$$v_* = \sqrt{\frac{g * D_H S_f}{4}} \qquad (3.10)$$

and noting that the friction coefficient *f* is linked to v_* (Chanson, 1999):

$$f = 8 * (\frac{v_*}{v})^2 \tag{3.11}$$

Where *v* is the average velocity

Thus substituting for v_* from Equation 3.10 into Equation 3.11 gives one of the desired links:

$$f = \frac{8 * g * D_H * S_f}{4 * v^2} \tag{3.12}$$

and the link between S_f and Manning friction coefficient (n) is obtained through the following equation (Reichert, 1998):

$$S_f = n^2 * \frac{P_w}{A} * \frac{Q^2}{A^2} \tag{3.13}$$

Thus for a known n value and flow it is possible to determine both *f* and S_f, i.e. the input required for AQUASIM. The next objective is to link these hydraulic considerations (i.e. Equation 3.6) to the sulfide emission rate. Clearly, the link will be obtained through the velocity gradient G.

CHAPTER 4

APPLICATION OF HYDROGEN SULFIDE EMISSION RATE TO A SEWER SYSTEM

4.1 INTRODUCTION

In Chapter 2, an equation for hydrogen sulfide emission rate was established. Equation 2.21 is based on data obtained from batch tests effected in the laboratory. The fundamental objective of developing such an equation is to apply it to a sewer system. In this chapter, hydraulic considerations are dealt with enabling one to link the kinetic equation developed earlier to the flowing sewer environment.

4.2 RELATING A BATCH REACTOR TO A SEWER SYSTEM

The batch experiments effected earlier simulate plug flow conditions which arise in sewer systems. However, differences arise in the mixing regimes between the two. These factors are now considered in order to create a link.

4.2.1 Mixing regimes

There are two mixing extremes: plug flow and completely mixed.

- Plug flow regime (Figure 4.1): under plug flow mixing conditions, each downstream element (n) is not influenced by the preceding (upstream) element, i.e. no longitudinal mixing.

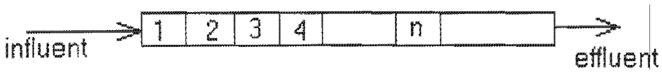


Figure 4.1: plug flow

- Completely mixed regime (Figure 4.2): Under completely mixed conditions, the influent is instantly and completely mixed throughout the reactor thus effluent and reactor concentrations are equal. In other words, the reactor contents are homogenous, and the concentrations of contents are equal throughout the reactor.

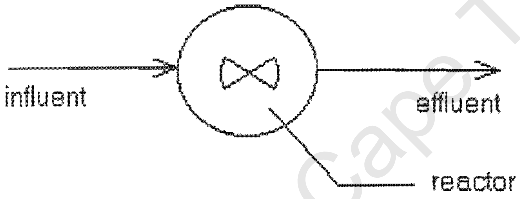


Figure 4.2: Completely mixed regime

4.2.2 Relationship between two regimes

According to the above two mixing regimes, a sewer system can be considered as a plug flow mixing regime, in which each plug is considered as a completely mixed regime with zero influent and effluent flow. That is, ***a plug flow regime can be considered as a number of completely mixed reactors in series***. This makes the H_2S gas emission equation developed from batch system applicable in sewer system.

4.3 SEWER HYDRAULICS AND THE EMISSION RATE EQUATION

In Chapter 2, the equation for the emission rate of change of total sulfide is derived from a batch reactor study, and is expressed as:

$$-\frac{d[S_T]}{dt} = K_1 * G^2 * \frac{A_s}{V} * d_{mean} * [H_2S] - K_2 \tag{4.1}$$

Where:

$d[S_T]/dt$ = rate of change of total sulfide concentration (mgS/*l*.s)
K_1 = constant (s)
K_2 = constant (mgS/*l*.s)
A_s = surface area of emission (m^2)
V = reactor volume (m^3)
d_{mean} = mean hydraulic depth (m)
$[H_2S]$ = dissolved molecular sulfide in batch reactor (mgS/*l*)
$[S_T]$ = total sulfide concentration (mgS/*l*)
G = velocity gradient (presents mixing conditions) (/s)

In the above equation, A_s, V, d_{mean} are factors related to a batch reactor configuration, and G is a factor used to measure system-mixing energy. Clearly, the sewer batch reactor and the experimental batch reactor have different system configurations and different driving forces of mixing. Therefore, for Equation 4.1 to be applicable to a sewer system, one should change surface area A_s, reactor volume V, and velocity gradient G to parameters that describe the sewer system.

4.3.1 Conversion of laboratory system configuration to a sewer system

Figure 4.3 shows a segment from a sewer system with length ΔL, and a circular cross-section with a flow surface width w, wetted perimeter P_w, cross-sectional area A, sewer radius r, depth of flow d, and angle α subtended as shown.

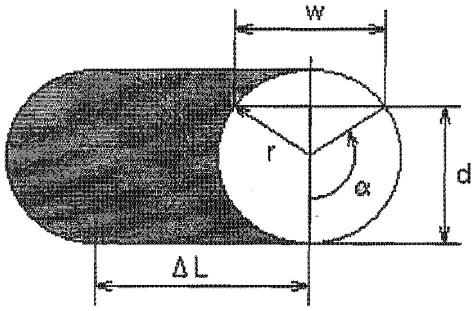


Figure 4.3: A small segment of sewer and its cross-section

According to the geometry, under any flow condition, α is linked to sewer radius and depth of flow as follows:

$$\alpha = a\cos\left(\frac{r-d}{r}\right) \qquad (4.2)$$

For any flow situation:

surface width: $w = 2 * r * \sin(\alpha)$ m (4.3)

wetted perimeter: $P_w = 2 * r * \alpha$ m (4.4)

cross-section area: $A = r * r * (\alpha - \sin(\alpha) * \cos(\alpha))$ m^2 (4.5)

and for a sewer with length ΔL:

surface area exposed to sewer atmosphere: $A_s = w * \Delta L$ (m^2)

mixed sewage volume: $V = A * \Delta L$ (m^3)

giving:

$$\frac{A_s}{V} = \frac{w * \Delta L}{A * \Delta L} = \frac{w}{A}$$

Now from Equation 4.1, for a batch system:

$$-\frac{d[S_T]}{dt} \propto \frac{A_s}{V}$$

Therefore, in a sewer system:

$$-\frac{d[S_T]}{dt} \propto \frac{w}{A} \tag{4.6}$$

Where

w = water surface width (m)

A = cross section area (m^2)

4.3.2 Velocity gradient G

Velocity gradient G is a parameter that reflects the mixing conditions in a systems. The higher the G value, the better the mixing effect in the system. Both in a batch system and in a sewer system, the velocity gradient G depends on the system dissipation function and the absolute viscosity of mixed liquid (Bratby, 1980).

$$G = \sqrt{\frac{W}{\mu}} \tag{4.7}$$

where G = velocity gradient (/s)

μ = absolute viscosity of liquid (for water = 10^{-3} N s m^{-2} at 20 $°C$)

W = dissipation function (N s^{-1} m^{-2})

For the batch reactor used in the laboratory experiment described in Chapter 2, the system dissipation function can be calculated from the torque generated by rotating blades. For a sewer system, the G value cannot be calculated directly. It is a function of system hydraulic parameters.

According to Bratby (1980), for a straight line of flow:

$$W = \frac{r * H_L}{T} \tag{4.8}$$

Where W = dissipation function ($N\ s^{-1}\ m^{-2}$)

r = unit weight of liquid ($9.81*10^3\ N/m^3$)

T = retention period (s)

H_L = head loss in a straight length of pipe (m)

Darcy-Weisbach formula defines head loss as:

$$H_L = f * \frac{\Delta L}{D_H} * \frac{v^2}{2g} \tag{4.9}$$

where f = Darcy friction factor dimensionless

D_H = hydraulic diameter or equivalent pipe diameter (m)

g= weight per unit mass on earth's surface (9.81 N/kg)

v = average flow velocity along the distance ΔL (m/s)

Combining Equation 4.7, 4.8, and 4.9, the velocity gradient G in sewer system can be expressed as:

$$G = \sqrt{\frac{r * f * \Delta L * v^2}{\mu * T * D_H * 2g}} \tag{4.10}$$

and, because $$\frac{\Delta L}{T} = \frac{flow\ distent\ length}{flow\ retention\ \ time} = flow\ velocity = v \tag{4.11}$$

Combining Equation 4.10 and 4.11:

$$G = \sqrt{\frac{r * f * v^3}{\mu * D_H * 2g}} \qquad (4.12)$$

In Equation 4.12, average flow velocity v, Darcy friction factor f, and hydraulic diameter D_H are factors only relevant to flow rate and cross-section parameters.

4.3.3 Final converted equation

Combining Equation 4.1, 4.6, and 4.12, for sewer system, the emission rate can be expressed as:

$$-\frac{d[S_T]}{dt} = K_1 * \frac{w}{A} * d_{mean} * \left(\frac{r * f * v^3}{\mu * D_H * 2g}\right) * [H_2S] - K_2 \qquad (4.13)$$

Where:

$d[S_T]/dt$ = rate of change of total sulfide concentration (mgS/*l*.s)

K_1 = constant (s)

K_2 = constant (mgS/*l*.s)

w = water surface width (m)

A = cross section area (m^2)

d_{mean} = A/P_w = mean hydraulic depth (m)

P_w = wetted perimeter (m)

$[H_2S]$ = dissolved molecular sulfide in batch reactor (mgS/*l*)

$[S_T]$ = total sulfide concentration (mgS/*l*)

G = velocity gradient (presents mixing conditions) (/s)

g = weight per unit mass on earth's surface (9.81 N/kg)

f = Darcy friction factor

D_H = hydraulic diameter or equivalent pipe diameter (m)

r = unit weight of liquid ($9.81*10^3$ N/m^3)

μ = absolute viscosity of liquid (for water = 10^{-3} N s m^{-2} at 20 °C)

CHAPTER 5

MODEL DEVELOPMENT AND VALIDATION

5.1 INTRODUCTION

The major aim of this project is to develop a kinetic model to describe sulfide emission in a gravity sewer system. In this regard it is assumed that sulfide generation occurs in the pumping section of the system and not along the line of flow in the gravity flow section (the region of interest in this investigation). This assumption would appear reasonable in sewer systems where aeration occurs along the line of flow, where dissolved oxygen is toxic to the sulfate-reducing bacteria the metabolism of sulfate reducing bacteria. Thus the work here would not be applicable to poorly designed septic sewer situation where insufficient aeration occurs due to low flow rates.

The model should be applicable to fast flowing gravity flow sewer systems where predictions depend on the sulfide concentration entering the system and the hydraulic characteristics which effect mixing. Thus, the model should

1. Describe the hydraulic characteristics of a gravity flow system, and this in turn should
2. establish the sulfide emission rate

To effect a hydraulic model, the software AQUASIM was utilized. This requires input of the physical characteristics of an "open channel" flow compartment (e.g. dimensions, gradients, and roughness of the channel), and discharge together with a model of the head loss equation to be utilized. The "open channel" compartment selected was that of the Virginia gravity sewer line. The characteristics of this sewer line are shown in Figure 5.1. The model was then used to predict flow characteristics (e.g. velocity, flow depth etc.) along the line of flow.

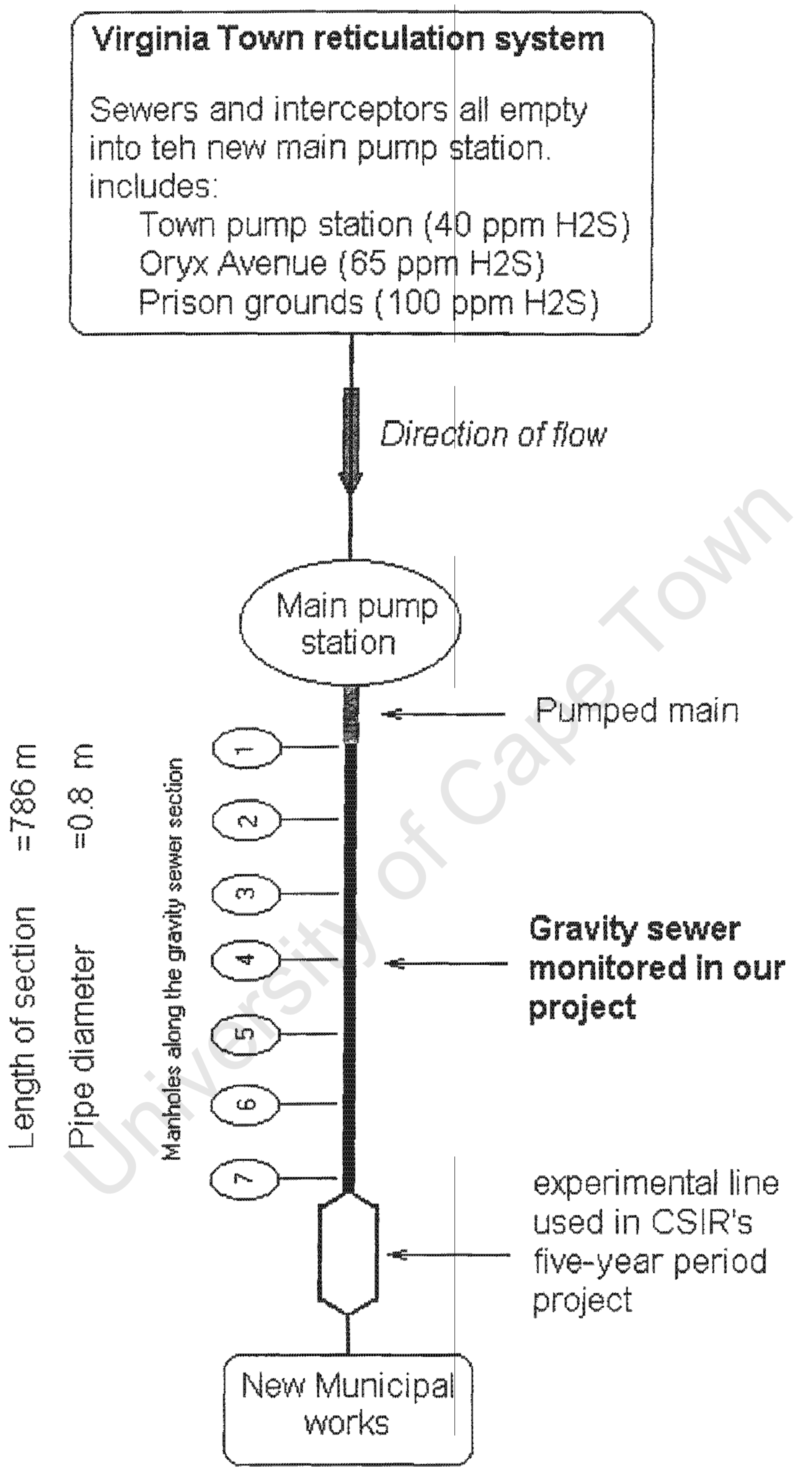


Figure 5.1a: Virginia sewer system

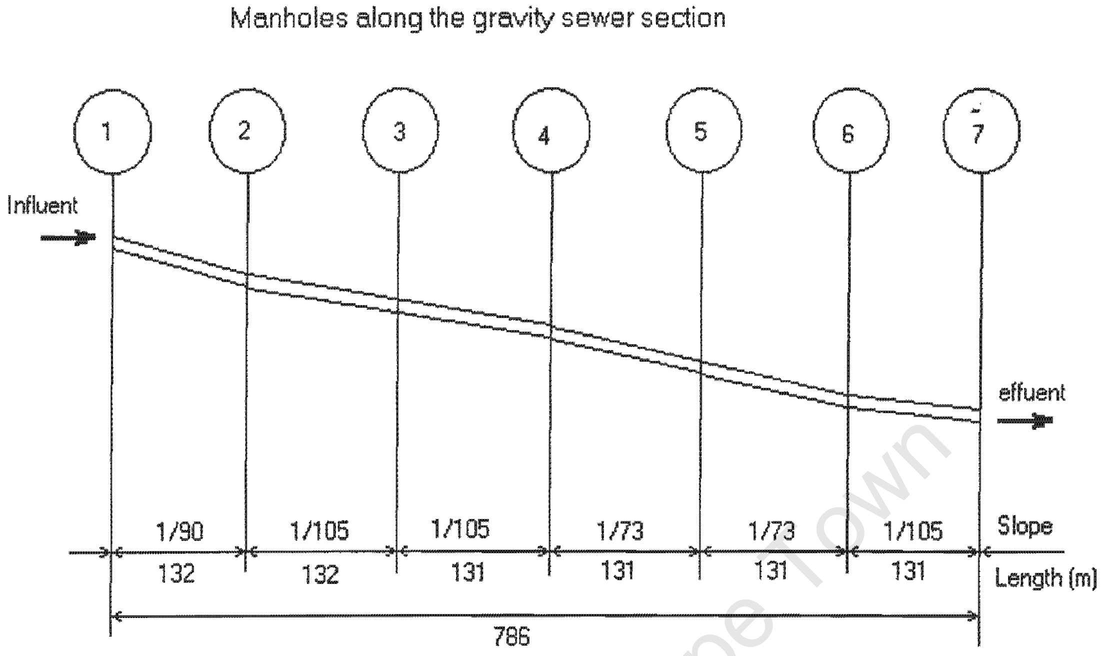


Fig 5.1b: Sewer plan

Once the hydraulic flow model was completed (for the Virginia sewer line), a model was created for the sulfide emission along the line of flow. This was effected by linking the head loss (determined from the hydraulic model) to the hydrogen sulfide emission rate equation formulated in Chapter 2 (Equation 2.21), and modified in Chapter 4 for a sewer environment. The predicted residual dissolved sulfide concentration was then compared with field observation.

5.2 MODELING HYDRAULIC CHARACTERISTICS

5.2.1 Hydraulic flow characteristics from the field

The following information is pertinent to the model development:

1. Sewer plan: The layout of the main features of the Virginia sewer system is given Figure 5.1 together with the parameters of the investigation gravity sewer. The following information can be drawn from the sewer plan:

- The overall length of the investigated gravity sewer is 786m, and the diameter is 0.8m with no junctions along the line of flow. There are seven manholes, labeled manhole 1 to manhole 7. The sewer section investigated starts from manhole 1, which is located at the outlet from the pumping main and ends at manhole 7.

- The slope of the sewer varies from 1/70 m/m to 1/105 m/m (see Figure 5.1b). A very small change in sewer direction occurs between manholes 5, 6 and 7. However, this variation was neglected in the hydraulic modeling.

2. Sewage discharge rate: A clear pumping cycle was observed and recorded. Each cycle lasted approximately 10 minutes and comprised 7 minutes pumping and 3 minutes hiatus. Onsite measurement of the discharge rate was not possible during the period of investigation. Consequently, flow discharge rate during the pumping period were assumed equal to that last measured, that is, 0.464 m^3/s.

3. Approximate measurements of sewage velocity: Recognizing that discharge rate could not be measured directly during the field investigation period, it was felt prudent to attempt to measure flow velocities and from these to determine an approximation of the flow rate. This was effected by measuring the time of the wave front between manholes at the onset of a pumping cycle (see Table 5.1).

Table 5.1 Average velocity estimation (test date: 15/12/2000)

flow wave front started at		flow wave front arrived at		water detention time between two manholes	distance between two manholes	average velocity
manhole	time	manhole	time	(s)	(m)	(m/s)
1	13:17:15	3	13:19:00	105	262	**2.50**
1	14:52:45	3	14:54:30	105	262	**2.50**
1	17:50:00	3	17:51:45	105	262	**2.50**
1	12:53:30	4	12:56:00	150	393	**2.62**
1	15:16:00	4	15:18:30	150	393	**2.62**
1	12:29:15	6	12:33:30	255	655	**2.96**
1	15:27:15	6	15:31:30	255	655	**2.96**
1	15:38:45	6	15:43:00	255	655	**2.96**
1	16:23:00	6	16:27:15	255	655	**2.96**
1	18:31:00	6	18:35:15	255	655	**2.96**
1	16:01:00	7	16:06:00	300	786	**2.62**
1	18:41:00	7	18:46:00	300	786	**2.62**

4. Flow depth: During a pumping cycle this was estimated as the difference between a reference level on two sticks - one stick immersed to the sewer base and the other to the flow surface.

5.2.2 Modeling of hydraulic characteristics using AQUASIM

A model describing the hydraulic characteristics of the investigated gravity sewer, was established using the fundamentals set out in Chapter 3 and the Virginia sewer characteristics set out above.

5.2.2.1 Flow cycle

The flow cycle observed in the field (described in section 5.2.1) is utilized as input data to the model. The interval of the flow cycle is set at 10 minutes. Within this cycle, the highest flow (0.462m^3/s) is set for a period of 6 minutes and the lowest flow (0.05m^3/s) for 4 minutes. Figure 5.2, 5.3, 5.4 and 5.5 present the flow cycle at different manholes. Note that the differences arise in cycle between manholes from both the spatial separations of manholes and variations in gradient between manholes.

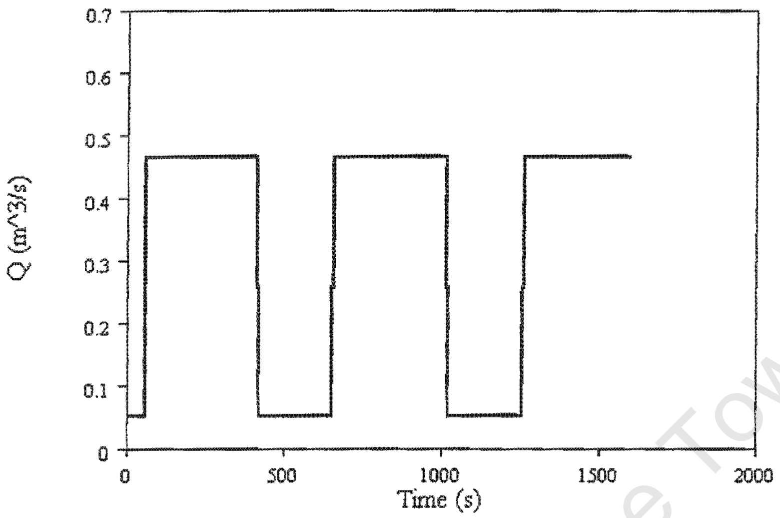


Figure 5.2: Modeled flow cycle at manhole 1

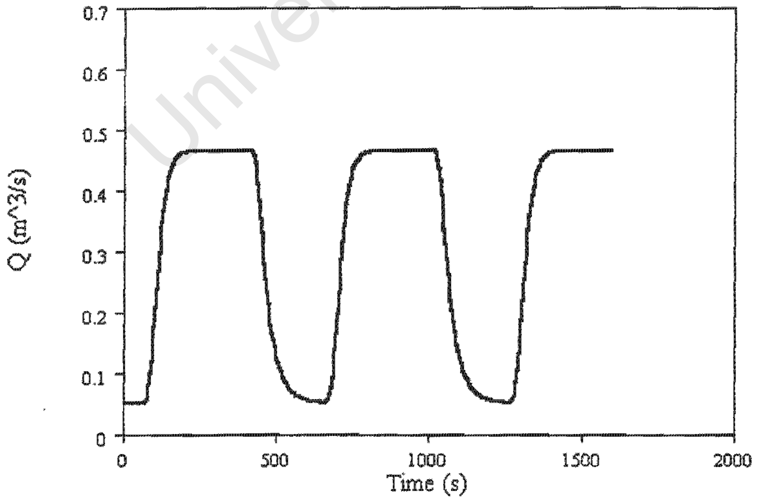


Figure 5.3: Modeled flow cycle at manhole 2

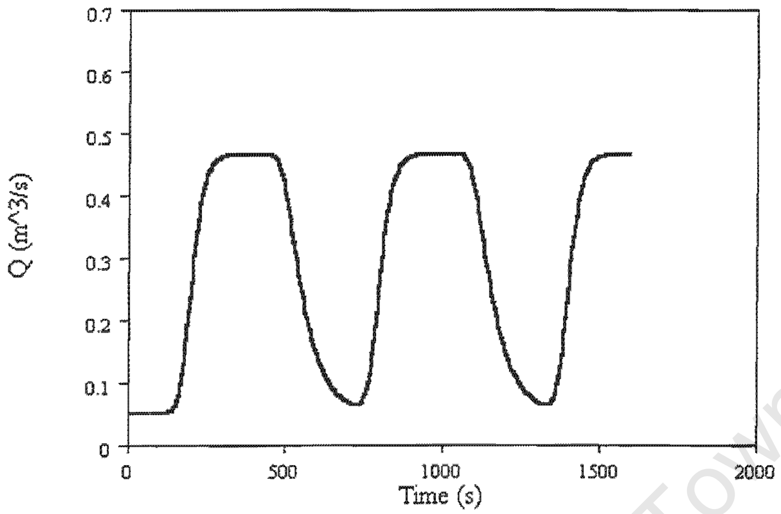


Figure 5.4: Modeled flow cycle at manhole 4

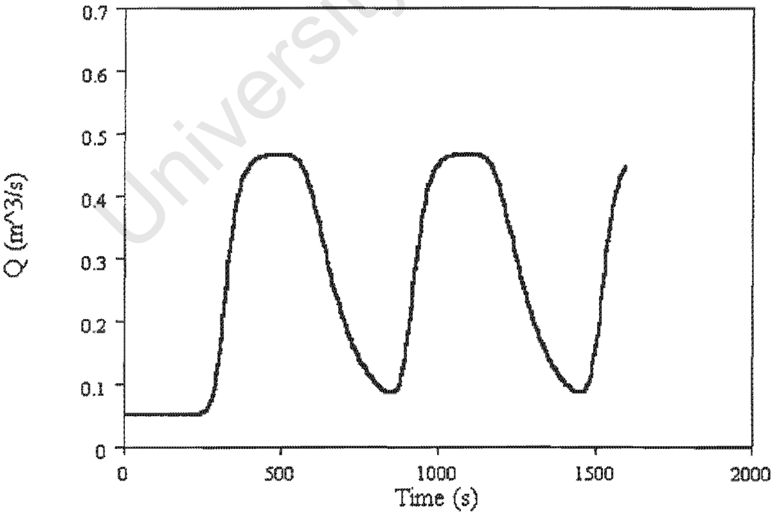


Figure 5.5: Modeled flow cycle at manhole 7

5.2.2.2 Sewage velocity

Development of the model requires utilizing the basic hydraulic flow equations set out in Chapter 3 - *inter alia*, this requires accepting a value for the Manning friction coefficient, n. Referring to the literature (Bevan and Rees, 1949; White, 1970) it would appear reasonable to assume that the n value lies between 0.011 and 0.013. It is not possible *a priori* to select which is 'the best' value, consequently, both are investigated.

Figure 5.6 shows a plot of the modeled sewer velocity along the line of flow from manhole 1 to manhole 7. Other outputs from the model include plots of velocity gradient G, sewer bed and water level elevation, and flow depth along the line of flow as shown in Figures 5.7, 5.8, and 5.9 respectively, for a Manning n value of 0.0115.

Some verification of the hydraulic model can be obtained by comparing predicted and measured flow depth at manholes 1 and 4 using the predicted data shown plotted in Figure 5.9. For manhole 1, predicted versus measured gives 0.430m versus 0.450m, and for manhole 4, gives 0.312m versus 0.320m. These results are well within experimental accuracy and form the basis for accepting the model with a Manning n equal to 0.0115.

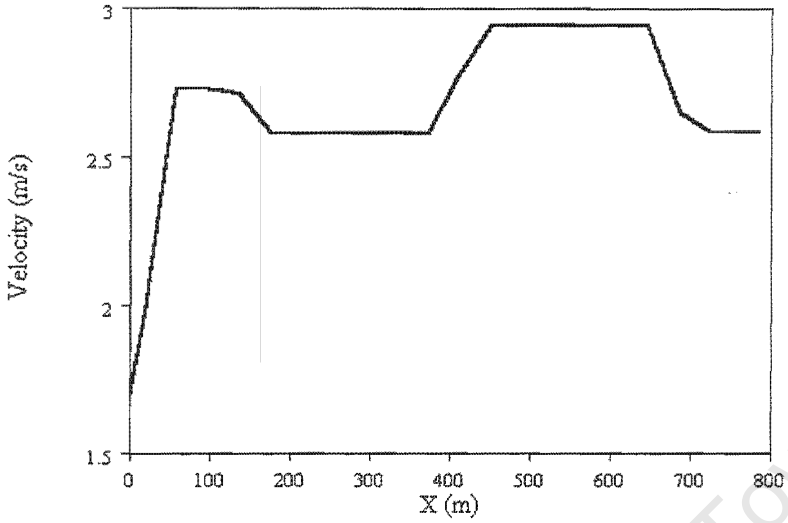


Figure 5.6: Longitudinal profile of sewage velocity along the pipe (obtained at stable flow rate 0.464 m^3/s)

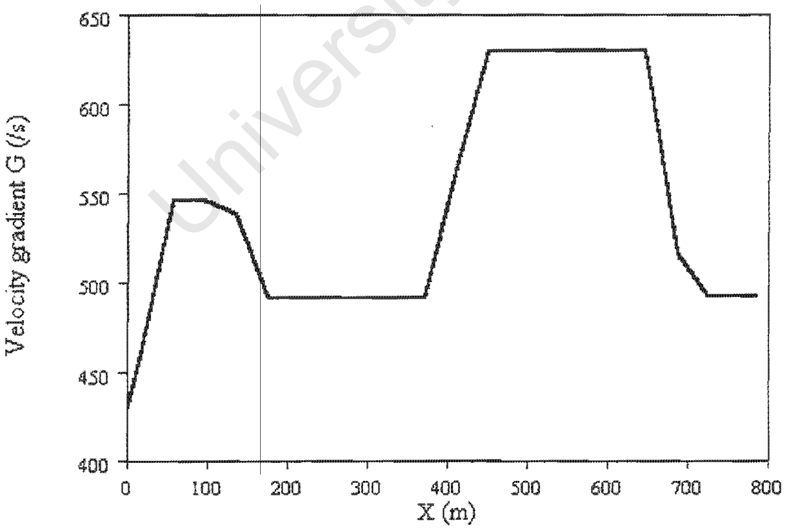


Figure 5.7: Longitudinal profile of Velocity gradient G along the pipe (obtained at stable flow rate 0.464 m^3/s)

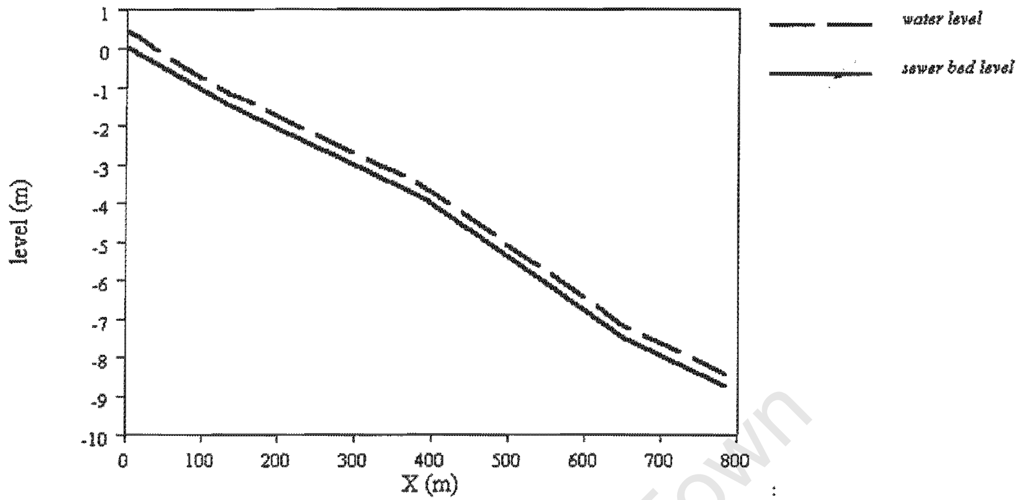


Figure 5.8: Longitudinal profile of sewer bed and water level elevations along the pipe line (obtained at stable flow rate 0.464 m^3/s)

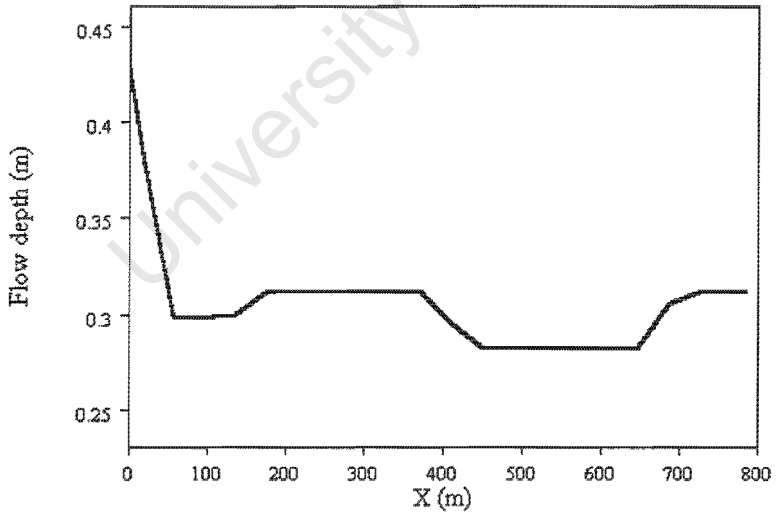


Figure 5.9: Longitudinal profile of flow depth along the pipe line (obtained at stable flow rate 0.464 m^3/s)

5.3 MODEL OF SULFIDE EMISSION

Modeling of the results was effected using the theoretical kinetic equation developed in Chapters 2, and 4, i.e. Equation 4.13, together with the initial sulfide concentrations and the flow characteristics dealt with in the previous section.

$$-\frac{d[S_T]}{dt} = K_1 * \frac{w}{A} * d_{mean} * \left(\frac{r * f * v^3}{\mu * D_H * 2g}\right) * [H_2S] - K_2 \qquad (4.13)$$

Integration of the differential equation describing sulfide change with flow was effected using AQUASIM, and considering flow to be that in an open channel with characteristics set out in previous sections. Appendix D lists the types and values of variables utilized in this equation, the characteristics (both physical and spatial) of the sewer system, the compartment type (i.e. a "batch reactor" or "river" compartment), and the process and state variables (i.e. sulfide emission rate reaction).

Figures 5.12 to 5.15 show the theoretical prediction of sulfide concentrations along the line of flow (clearly, the sulfide emitted between any two points along the line of flow is given by the decrease in total sulfide concentration between the points).

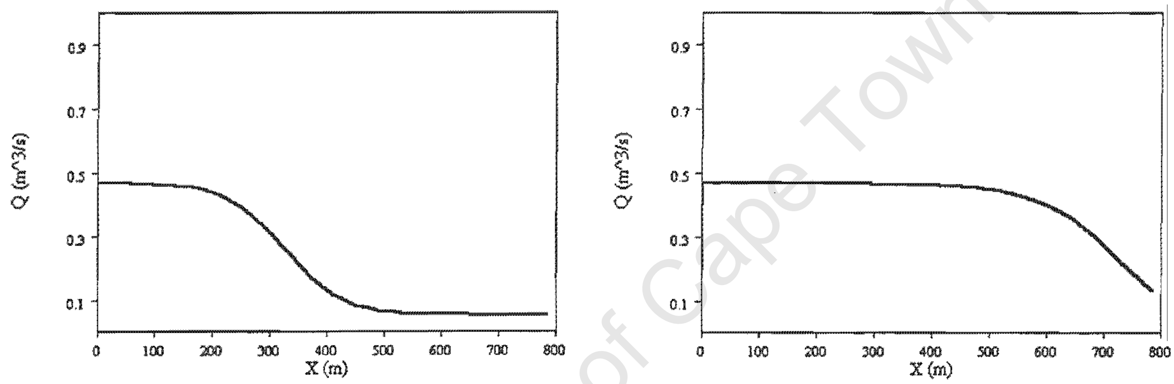
5.4 ASSESSMENT OF THE MODEL FOR SULPHIDE EMISSION RATE

Sulfide concentrations were measured on the sewer system at Virginia described in previous section. The particular section of the sewer where measurements were effected is shown in Figure 5.1. Seven manholes were utilized for sampling. The sampling methods are set out below.

5.4.1 Sampling protocol

- **Sampling times at manholes**

Recognizing that sulfide entering the system can vary with time, that flow at manholes varies both temporally and spatially, and that inflow occurs over a short pumping period (about 7 minutes) along the line of flow, it is necessary to apply stringent sampling methods in order to obtain meaningful observations (samples) to assess a model of sulfide emission rate along the line of flow. The significant temporal and spatial affects are highlighted in Figure 5.10.



a) Sewage discharge after 2 minutes

b) Sewage discharge after 4 minutes

Figure 5.10: Modeled sewage discharge along the gravity sewer at various times after initiation of the pumping cycle

Clearly, samples cannot be drawn simultaneously. To assess the model samples should be obtained from the same specimen of sewage, termed a 'slug' (Figure 5.11), as it passes the various sampling stations. To sample the same 'slug', the exact time of arrival of the 'slug' at the different sampling stations should be calculated and samples should be taken accordingly. This was effected as follows: Sampling personnel were sited at each manhole. Samples at each manhole were taken relative to the appearance of the frontal wave at each manhole.

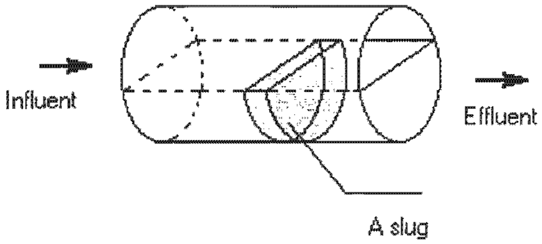


Figure 5.11: A slug in the sewage flow

- **Sampling method**

Small buckets with ropes were dropped down from the manhole to take samples. A sample from the bucket was obtained in 50ml glass bottles (filled to overflow and then secured). Sample bottles were then stored in iced cooler boxes for analyses to be conducted in the laboratory at the end of the sampling day.

5.4.2 Wastewater characteristics measured

The following wastewater characteristics were measured:

- *Sulfate Concentration:* Ideally, sulfate measurement along the line of flow should be effected (with due cognizance of spatial and temporal considerations) so that assessment can be made on whether biological sulfate reduction occurs along the flow. However, this was not possible because changes in sulfate concentration are outside the accuracy of the measurement method. However, a few sulfate measurement were made for the sake of completeness.
- *Chemical oxygen demand*: As with sulfide observation, only a limited number of COD measurements were effected again more for completeness sake.
- *pH*: The pH of the wastewater will influence the relative proportions of dissolved hydrogen sulfide (H_2S) and hydrogen sulfide ion (HS^-) and this consequently forms

an important aspect to kinetics of emission (see Chapter 2). This was measured as set out in Chapter 2.

- *Temperature*: From a modeling stand point, temperature affects the pK value for the sulfide weak acid system and thus the concentration of dissolved hydrogen sulfide and the kinetics of emission.
- *Dissolved Oxygen (DO) Concentration.* The DO was measured in order to assess whether biological sulfate reduction is to be expected along the line of flow. The DO concentrations along the line of flow all showed that the sewage was aerobic in the flow region (DO~8mg/*l*)
- *Sulfide concentration*: Sulfide analyses of samples were effected as set out in Chapter 2.

5.4.3 Experimental results

Appendix B lists observations of total dissolved sulfide species concentrations over a number of flow cycles during the three day period of investigation. The results reported in Table B.1 and Table B.2 were not used because of the high dilutions due to heavy rain which affected the first two days of the period of investigation. Only results in Table B.3 and Table B.4 are considered.

It is to be noted that (1) experimental data could not be obtained from manhole 5 as this could not be opened due to corrosion and (2) data from manhole 6 consistently showed a significant increase in sulfide concentration from manhole 4. The only way such an increase can be explained is either via generation of sulfide along the line of flow, or via a second unmarked sewer line joining the mainline at manhole 5 or H_2S from the sewer atmosphere dissolved back into the sewage. Generation of sulfide online is unlikely because the sewage is aerated in the line of flow (i.e. the dissolved O_2 content is approximately 8 mg/*l*) and the sewage retention time is very short. Sewer plans shows no sewer line joining the system at manhole 5. The possibility of redissolution of hydrogen was not assessed because gas measurements were not effected in synchrony with aqueous phase sample taking. For these reasons, data from manhole 6 was not considered in the analyses.

Figures 5.16 to 5.19 show comparisons of theoretical versus observed sulfide concentration along the line of flow. Comparing theoretical with practice, the results indicate that there is good reason to believe that the theoretical model can be developed which adequately predicts sulfide emission for a given flow rate and initial sulfide concentration entering a particular sewer.

5.5 CONCLUSIONS

The following conclusions can be drawn from this project:

1. It would appear that a reasonable model describing sulfide emission rate has been obtained in terms of a hydraulically defined parameter G (velocity gradient). This was obtained from laboratory scale investigations.
2. *Inter alia*, a hydraulic model describing the Virginia gravity sewer system is presented. This model could not be tested directly because of a lack of instrumentation on site. However, an indirect assessment was obtained by measuring sulfide emission rates (which are linked to the G value and hence the hydraulic model along the line of flow) and comparing these with theory. Such comparison showed reasonable agreement.
3. Laboratory data on sulfide emission rate (i.e. regarding 1 above) was linked to the hydraulic model (i.e. 2 above) to give a spatial and temporal model of sulfide emission rate along the line of flow for the Virginia sewer. This work was assessed by measuring dissolved sulfide concentration along the line of flow in a particular flow cycle and comparing these with values predicted. The model gives a reasonable description of observed data.
4. Perhaps the most onerous aspect of the research reported here relates to the field laboratory at Virginia. This is isolated and a great distance from the research headquarters (University of Cape Town). This create logistical problems in effecting

fieldwork. Furthermore, the chemical laboratory to effect the chemical analyses (situated at the local sewage works) is primitive. It would appear more practical to select a sewer system closer to Cape Town as the field laboratory.

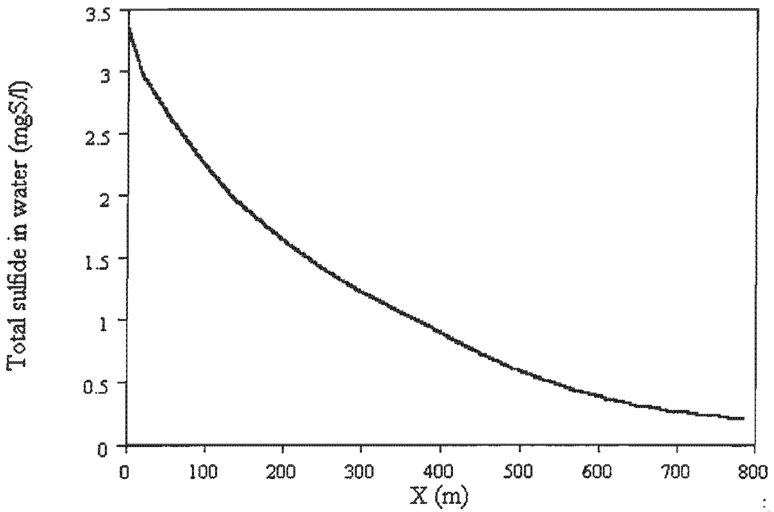


Figure 5.12: Predicted residual sulfide in the sewer line with initial sulfide concentration of 3.36 mgS/*l* (the initial sulfide concentration of test 1, Table B.4)

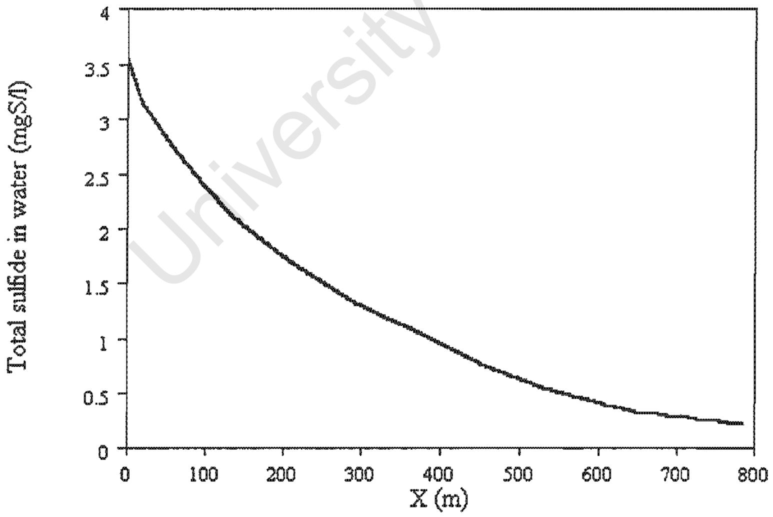


Figure 5.13: Predicted residual sulfide in the sewer line with initial sulfide concentration of 3.56 mgS/*l* (the initial sulfide concentration of test 3, Table B.4)

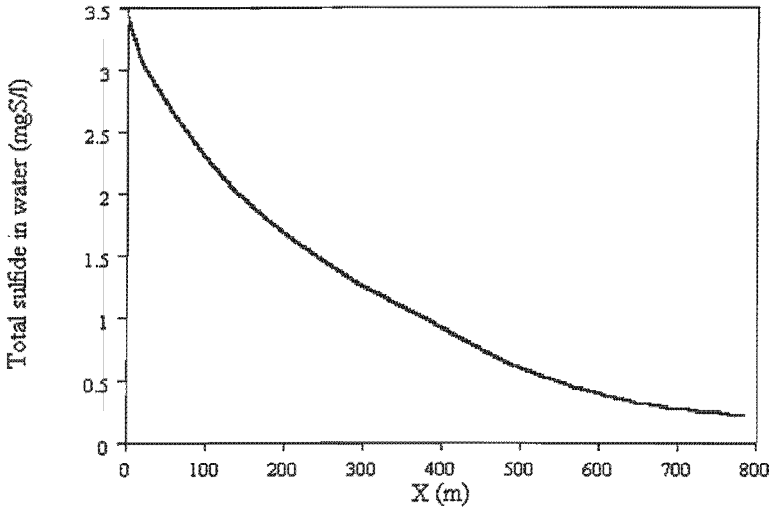


Figure 5.14: Predicted residual sulfide in the sewer line with initial sulfide concentration of 3.44 mgS/*l* (the initial sulfide concentration of test 5, Table B.4)

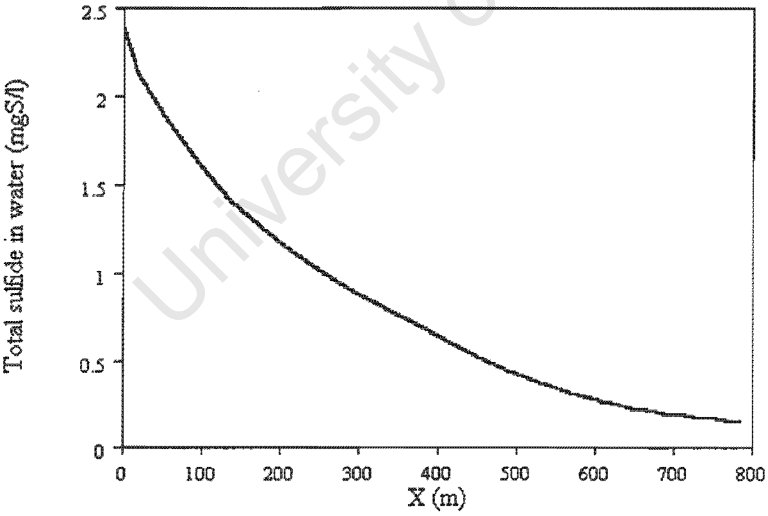


Figure 5.15: Predicted residual sulfide in the sewer line with initial sulfide concentration of 2.4 mgS/l (the initial sulfide concentration of test 7, Table B.4)

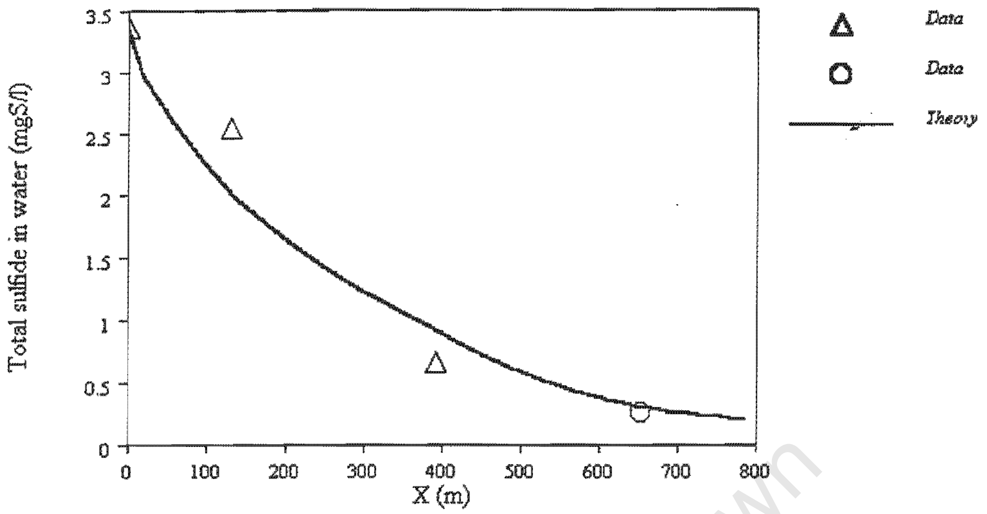


Figure 5.16: Comparison of residual sulfide in the sewer line, measured versus predicted, for data of test 1 from Table B.4. Date o refers to mean data of manhole 6.

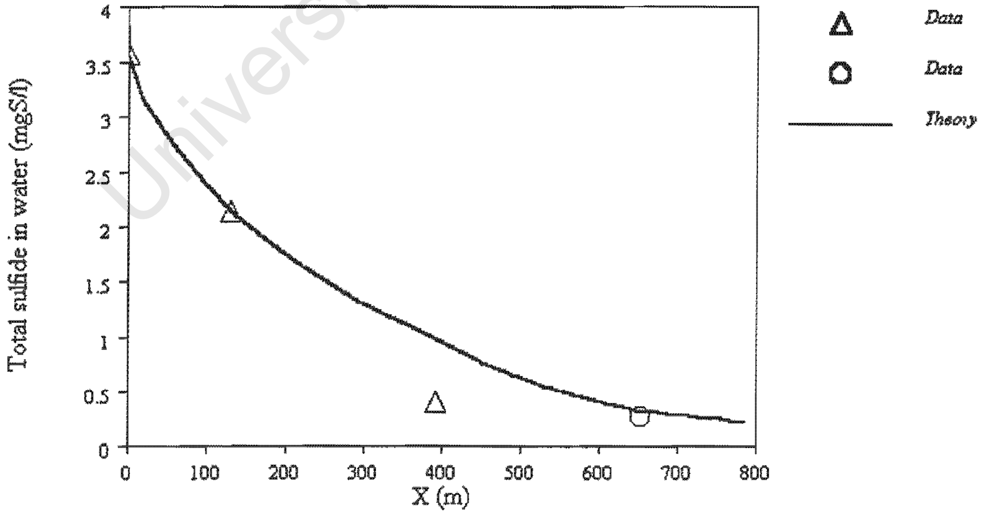


Figure 5.17: Comparison of residual sulfide in the sewer line, measured versus predicted, for data of test 3 from Table B.4. Date o refers to mean data of manhole 6.

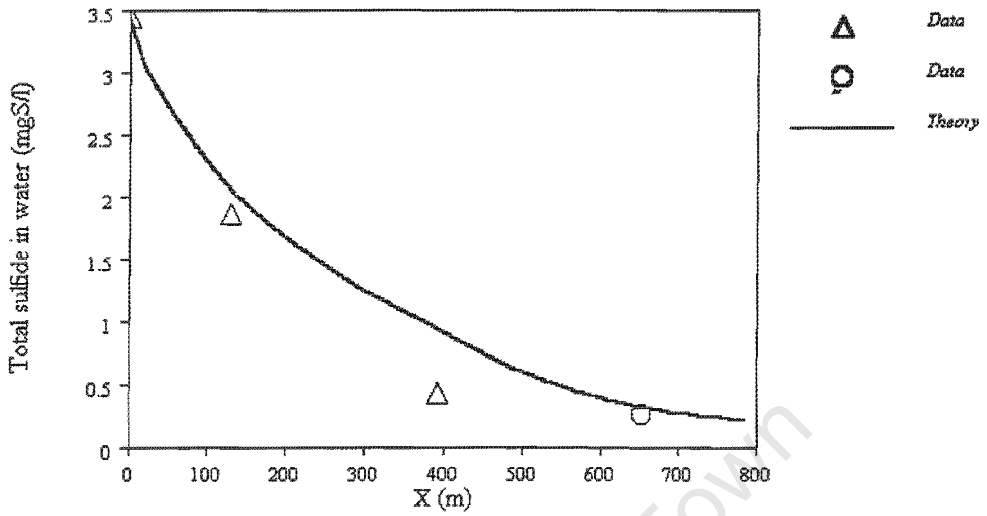


Figure 5.18: Comparison of residual sulfide in the sewer line, measured versus predicted, for data of test 5 from Table B.4. Date o refers to mean data of manhole 6.

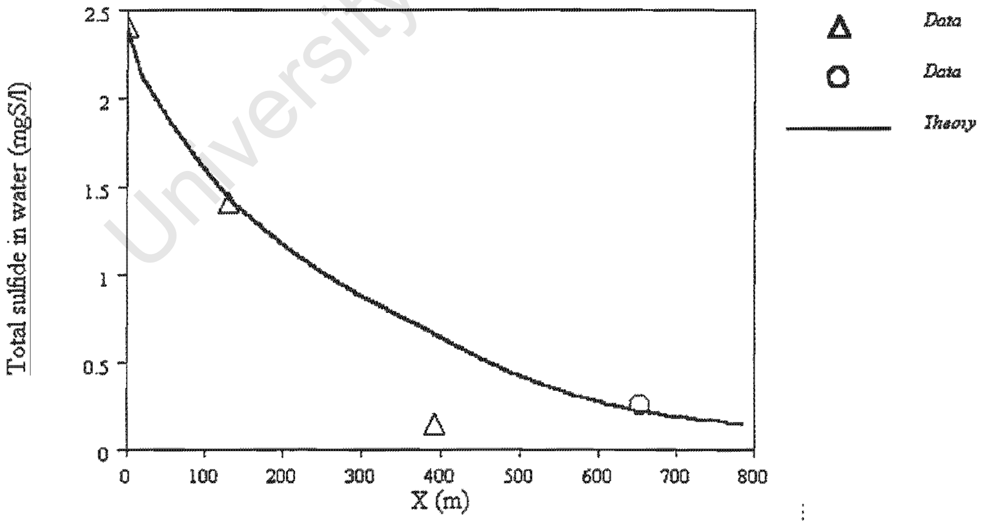


Figure 5.19: Comparison of residual sulfide in the sewer line, measured versus predicted, for data of test 7 from Table B.4. Date o refers to mean data of manhole 6.

REFERENCES

1. Amiantus Centre, 1979. Fibrecement sewer pipes: *Design criteria to prevent H_2S/H_2SO_4 corrosion.* Amiantus Centre Information 75. CH-8867 Niederurnen. Switzerland, 30
2. American Concrete Pipe Association. *Concrete Pipe Handbook.* ACPA (Publisher), 412
3. Barnard, J.L., 1967 *Corrosion of sewers.* CSIR Research Report 250, 1-16
4. Bevan, B.V., Rees, B.T., 1949. *Sewers: theory, design, specification and construction; a reference book for civil, municipal, and sanitary engineers and a test-book for student.* 2nd ed., 3rd reprint. London: Chapman & Hall, 1-21
5. Bratby, J., 1980. *Coagulation and Flocculation.* Croydon, England: Uplands Press, 173-232
6. Carne R., Clough G. F. and Newcombe S., 1982. *Oxygen injection into a rising main: Its effect on pumping.* Water Pollut. Control, 399-409
7. Chanson, H., 1999. *The Hydraulics of Open Channel Flow.* London: Arnold; New York: Wiley.
8. Condon, R L Cooper, R A and Egnglande, A J., 1973. *Instream aeration to control dissolved sulfides in sanitary sewers.* NTIS No 223342. US APE
9. Davy, W.J., 1950. *Influence of velocity on sulfide generation in sewers.* Sewage and Industrial Wastes, Vol. 22 N 9, 1132
10. Estoup J.M. and Cabrillac R. 1997. *Corrosion of Biological Origin Observed On Concrete Digestors* , Construction and Building Materials, Vol. 11, No.4.pp. 225-232. Elsevier Science Ltd.
11. Grant A. 1979. *Sulphide Corrosion of Concrete Sewers.* Bulletin No.76. The Institution of Corrosion Science and Technology.

12. Kelly, M, J, Kruger, J, E, 1996. *Consolidated Report on Phase 1 of Sewer Corrosion Research: The Virginia Sewer Experiment and Related Research.* Division of Building Technology, CSIR, South Africa

13. Kienow, K., 1978. *Computer predicts pipe corrosion.* Water and Sewage Works, 78-98

14. Kruger, J. E. and Botha, J., 1987. *Sewer Corrosion and its control: a literature survey of the status quo.* National Building Research Institute, CSIR, South Africa

15. Laughlin, J.A., 1964. *Studies in forced main aeration.* Journal ASCE: SED 90 (SA6), 13-24

16. Metcalf, Boston, B., 1972. *Wastewater Engineering: collection, treatment, disposal.* New York: McGraw-Hill, 4-99

17. Milde K., Sand W., Wolff W., and Bock E., 1982. *Thiobacilli of the Corroded Concrete Walls of the Hamburg Sewer System.* Journal of General Microbiology (1983), 129, 1327-1333. England.

18. Parker, D., 1945. *The corrosion of concrete.* Austr. J Exptl. Biol. and Med. Sc. Vol 23. pp81-91

19. Pearson, J. 1959. *A note on the 'Dankwerts' boundary conditions for continuous flow reactors.* Chemical Engineering Science, 10: 281-284

20. Pomeroy, R. D., and Bowlus, F. D. 1947. *Progress report on sulfide control research.* Sewage Works Journal. Vol 18. No4. 597-640

21. Pomeroy, R. D.,1970. *Sanitary sewer design for hydrogen sulfide control.* Public Works, Vol. 101 No 10:93

22. Pomeroy, R. D., and Parkhurst, J. D., 1977. *The forecasting of sulfide buildup rates in sewers.* Progress in Water Technology. Vol. 9 No 3 621-628

23. Pomeroy, R. D., Parkhurst, J.D., Livingston, J and Bailey, H H.,1985. Sulphide occurrence and control in sewage collection systems. US EPA, EPA600/X-85-052

24. Reichert, P., 1994. *AQUASIM-A tool for simulation and data analysis of aquatic systems.* Water Sci. Technol., 30 (2), 21-30

25. Reichert, P., Schultness R. and Wild D., 1995. *The use of AQUASIM for estimating parameters of activated sludge models.* Water Sci. Technol., 30 (2), 135-147

26. Reichert, P., 1998. *AQUASIM 2.0-Tutorial: computer program for the identification and simulation of aquatic systems.* Swiss Federal Institute for Environmental Science and Technology (EAWAG), CH-8600 Dbendorf, Switzerland.

27. South African CSIR, 1959. *Corrosion of concrete sewers.* Series DR 12. 236

28. The American Society of Civil Engineers and the Water Pollution Control Federation, 1994. *Gravity Sanitary Sewer Design and Construction.* American Society of Civil Engineers, New York.

29. Thornton, H.T., 1978. *Acid attack of concrete caused by sulfur bacterial action.* ACI Journal, 577-584

30. United States Environmental Protection Agency, 1985. *Design manual: Odor and corrosion control in sanitary sewerage systems and treatment plants.* EPA (Publisher), 132

31. White, J.B., 1970. *The Design of Sewers.* London: Arnold, 7-26

APPENDIX A

LABORATORY SCALE BATCH TESTS FOR DETERMINING THE HYDROGEN SULFIDE EMISSION RATE

This appendix tabulates the results of the batch test experiments under different motor frequencies. Samples were taken after the initial addition of the sulfide.

Table A.1 Experimental data from batch tests (motor frequency = 25 Hz)

Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)	Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)
5	7.01	19.8	9	154	--	--	2.59
9	--	--	8.71	159	7.00	19.8	2.70
14	--	--	8,11	164	--	--	2.63
19	--	--	7.84	169	--	--	2.44
24	7.01	19.7	7.34	174	--	--	2.12
29	--	--	7.3	179	7.01	19.7	2.12
34	--	--	7.12	184	--	--	2.09
39	--	--	6.3	189	--	--	1.93
44	--	--	6.28	194	--	--	2.01
49	7.01	19.5	5.83	199	7.01	19.7	1.86
54	--	--	5.99	204	--	--	1.82
59	--	--	5.63	209	--	--	1.74
64	--	--	5.63	214	--	--	1.58
69	7.00	19.6	5.58	219	7.01	19.8	1.70
74	--	--	5.33	229	--	--	1.54
79	--	--	4.79	234	--	--	1.54
84	--	--	4.8	239	--	--	1.43
89	7.01	19.6	4.32	244	--	--	1.43
94	--	--	4.48	249	6.98	19.8	1.46
99	--	--	4.09	254	--	--	1.35
104	6.98	19.6	3.93	259	--	--	1.27
109	--	--	3.67	264	--	--	1.27
114	--	--	3.67	269	6.99	19.8	1.27
119	--	--	3.65	274	--	--	1.12
125	6.98	19.8	3.17	279	--	--	1.24
130	--	--	3.13	284	7.01	19.8	1.24
134	--	--	3.12	289	--	--	1.23
139	--	--	3.00	294	--	--	1.22
144	6.99	19.8	3.20	299	7.01	19.8	1.22
149	--	--	3.10	--	--	--	--

Table A.2 Experimental data from batch tests (motor frequency = 30 Hz)

Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)	Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)
10	7.03	20.0	7.2	120	--	--	2.02
15	--	--	7.44	130	7.00	19.8	2.06
20	--	--	7.15	133	--	--	1.82
25	7.03	20.1	6.05	140	--	--	1.74
30	--	--	5.8	150	7.01	19.7	1.48
35	--	--	5.55	160	--	--	1.4
40	7.03	20.0	4.77	170	--	--	1.51
45	--	--	5.15	175	7.01	19.8	1.37
50	--	--	4.9	183	--	--	1.38
55	7.01	20.1	4.45	190	--	--	1.15
60	--	--	4.35	200	--	--	1.1
65	--	--	3.96	210	7.01	19.8	1.01
71	7.00	20.0	3.75	220	--	--	0.97
75	--	--	3.78	230	--	--	0.82
80	--	--	3.72	240	--	--	0.8
90	7.01	19.9	3.21	250	7.01	19.8	0.71
100	--	--	2.85	260	--	--	0.66
110	--	--	2.42	270	--	--	0.62

Table A.3 Experimental data from batch tests (motor frequency = 35 Hz)

Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)	Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)
2	7.05	19.7	8.3	141	7.04	19.7	0.99
6	--	--	8.1	146	--	--	0.83
11	--	--	6.93	151	--	--	0.91
16	--	--	6.48	156	--	--	0.81
21	7.05	19.8	6.08	161	7.04	19.6	0.77
26	--	--	5.92	166	--	--	0.73
31	--	--	5.25	171	--	--	0.72
36	--	--	5.04	176	--	--	0.69
41	7.05	19.8	4.44	181	7.04	19.5	0.61
46	--	--	4.56	186	--	--	0.58
51	--	--	3.55	191	--	--	0.55
56	--	--	3.1	196	--	--	0.61
61	7.04	19.7	2.96	202	7.04	19.5	0.41
66	--	--	3.16	206	--	--	0.31
71	--	--	2.61	211	--	--	0.44
76	--	--	2.25	216	--	--	0.42
81	7.04	19.7	1.66	221	7.05	19.5	0.43
86	--	--	2.1	226	--	--	0.4
91	--	--	1.54	236	--	--	0.32
96	--	--	1.64	241	--	--	0.29
101	7.03	19.7	1.4	246	--	--	0.34
106	--	--	1.3	251	7.05	19.5	0.36
111	--	--	1.6	256	--	--	0.34
116	--	--	1.45	268	--	--	0.27
121	7.03	19.7	1.36	276	--	--	0.25
126	--	--	1.28	286	7.05	19.4	0.24
131	--	--	1.22	296	--	--	0.22
136	--	--	1.12	--	--	--	--

Table A.4 Experimental data from batch tests (motor frequency = 40 Hz)

Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)	Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)
8	6.97	19.5	8.3	148	6.98	19.5	0.87
13	--	--	7.3	153	--	--	0.79
18	--	--	7.38	158	--	--	0.65
23	--	--	6.12	163	--	--	0.68
28	6.95	19.4	6	168	6.98	19.6	0.7
33	--	--	5.52	173	--	--	0.61
38	--	--	5.11	178	--	--	0.61
43	--	--	4.27	183	--	--	0.53
48	6.95	19.5	4.02	188	--	--	0.53
53	--	--	4.02	193	6.98	19.4	0.43
58	--	--	3.95	198	--	--	0.42
63	--	--	3.25	203	--	--	0.39
68	6.96	19.4	3	208	6.98	19.5	0.36
73	--	--	2.2	213	--	--	0.33
78	--	--	2.46	218	--	--	0.32
83	--	--	2.31	223	--	--	0.37
88	6.96	19.5	2.04	228	6.97	19.6	0.31
93	--	--	1.78	233	--	--	0.31
98	--	--	1.74	238	--	--	0.3
104	--	--	1.64	248	--	--	0.2
108	6.97	19.5	1.52	253	--	--	0.24
113	--	--	1.28	258	6.97	19.6	0.26
118	--	--	1.18	263	--	--	0.22
123	--	--	1.23	273	--	--	0.21
128	6.97	19.5	1.16	283	--	--	0.22
133	--	--	1.04	293	6.97	19.6	0.19
138	--	--	0.93	303	--	--	0.23
143	--	--	0.69	--	--	--	--

Table A.5 Experimental data from batch tests (motor frequency = 45 Hz)

Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)	Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)
3	7.00	19.5	7.3	108	--	--	0.76
8	--	--	6.72	113	--	--	0.68
13	--	--	5.7	118	--	--	0.6
18	--	--	5.35	123	--	--	0.58
23	--	--	4.26	128	7.01	19.5	0.54
28	7.00	19.5	4.02	133	--	--	0.47
33	--	--	2.98	138	--	--	0.46
38	--	--	3	143	--	--	0.36
43	--	--	2.48	148	--	--	0.39
48	--	--	2.22	154	7.00	19.4	0.35
53	7.00	19.4	2.02	158	--	--	0.32
58	--	--	1.88	163	--	--	0.3
63	--	--	1.46	169	--	--	0.27
69	--	--	1.61	174	--	--	0.25
73	--	--	1.24	178	7.01	19.5	0.24
78	7.01	19.5	1.37	183	--	--	0.25
83	--	--	1.2	193	--	--	0.21
88	--	--	1.16	203	--	--	0.22
93	--	--	0.97	213	--	--	0.17
98	--	--	0.91	230	7.01	19.5	0.17
103	7.01	19.5	0.84	--	--	--	--

Table A.6 Experimental data from batch tests (motor frequency = 50 Hz)

Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)	Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)
4	7.01	19.3	8	84	--	--	0.38
9	--	--	6.9	89	--	--	0.37
15	--	--	5.1	94	--	--	0.28
19	--	--	4.7	99	--	--	0.24
24	--	--	3.42	104	7.00	19.3	0.22
29	7.01	19.2	2.64	109	--	--	0.23
34	--	--	2.08	114	--	--	0.22
39	--	--	1.86	119	--	--	0.2
44	--	--	1.34	124	--	--	0.18
49	--	--	1.21	129	7.01	19.3	0.16
54	7.00	19.2	1.08	134	--	--	0.15
59	--	--	0.86	144	--	--	0.14
64	--	--	0.72	154	--	--	0.14
69	--	--	0.61	164	--	--	0.13
74	--	--	0.52	174	7.01	19.3	0.13
79	7.00	19.2	0.46	187	--	--	0.13

Table A.7 Experimental data from batch tests (motor frequency = 55 Hz)

Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)	Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)
3	7.00	19.5	7.9	77	6.99	19.6	0.3
7	--	--	6.66	82	--	--	0.24
12	--	--	5.45	87	--	--	0.21
17	--	--	4.2	92	--	--	0.18
22	--	--	3.15	97	--	--	0.18
27	6.98	19.6	2.52	102	6.99	19.6	0.16
32	--	--	1.8	107	--	--	0.15
37	--	--	1.5	112	--	--	0.14
42	--	--	1.31	117	--	--	0.16
47	--	--	1.07	122	--	--	0.13
52	6.98	19.6	0.9	127	6.99	19.7	0.13
57	--	--	0.71	132	--	--	0.13
62	--	--	0.57	138	--	--	0.13
67	--	--	0.4	142	--	--	0.13
72	--	--	0.36	--	--	--	--

Table A.8 Experimental data from batch tests (motor frequency = 60 Hz)

Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)	Sampling time (min)	pH	Water temperature (°C)	Residual total sulfide (mgS/l)
1	7.00	19.5	9	61	--	--	0.33
6	--	--	5.55	66	--	--	0.27
11	--	--	4.95	71	--	--	0.21
16	--	--	3.25	76	6.99	19.3	0.18
21	--	--	3.08	81	--	--	0.17
26	7.00	19.4	1.84	86	--	--	0.16
31	--	--	1.38	91	--	--	0.15
36	--	--	0.99	101	--	--	0.13
41	--	--	0.7	111	7.00	19.3	0.13
46	--	--	0.55	121	--	--	0.13
51	6.99	19.4	0.44	141	--	--	0.12
56	--	--	0.4	--	--	--	--

APPENDIX B

SULFIDE CONCENTRATION PROFILES ALONG THE VIRGINIA GRAVITY SEWER

Table B.1: Data for 11 December, 2000 (data not used due to excessive dilution from rain)

Test number	Manhole 1		Manhole 4		Manhole 7	
	sulfide (sulfate)	flow starting time	sulfide (sulfate)	flow arriving time	sulfide (sulfate)	flow arriving time
1	0.15	--	0.21	09:58	0.14	--
2	0.16	--	0.22	10:25	0.22	--
		--		10:38:18		--
3	0.14	--	0.15	10:53:48	0.15	--
		--		--		--
		--		--		--
		--		14:50:30		--
4	0.14	--	0.38	15:00:36	--	--
		--		15:10:51		--
5	0.14	--	--	15:21:22	0.12	--
6	0.16	--	0.14	15:42:40	0.17	--
		--		15:53:02		--
		--		16:04:25		--
7	0.13 (130)	--	0.21(130)	16:15:56	0.18 (130)	--
		--		16:26:47		--
		--		16:38:12		--
8	0.13	--	0.2	16:48:30	0.22	--
		--		16:59:03		--
		--		17:08:52		--
9	0.16 (137)	--	0.2 (137)	17:19:12	0.21 (127)	--
		--		17:28:56		--
		--		17:39:10		--
10	0.13	--	0.23	17:48:54	0.18	--
		--		17:58:54		--

Note:

1. Samples were taken from manhole 1, 4, and 7 three minutes after the arrival of the wave front of the flow.
2. COD: 528 mgO/*l*; DO: 8mg/*l*
3. Weather condition: After heavy rain, the flow had been diluted.
4. The water temperature was around 23 °C
5. Data in brackets indicates sulfate concentration in $mgSO_4/l$.

Table B.2 Data for 12 December, 2000 (data not used due to excessive dilution from rain)

Morning:

Test number	Manhole 1		Manhole 4		Manhole 6		Manhole 7	
	sulfide (mg/*l*)	flow starting time	sulfide (mg/*l*)	flow arriving time	sulfide (mg/*l*)	flow arriving time	sulfide (mg/*l*)	flow arriving time
		--		7:11:18		--		--
1	0.13	--	0.18	7:22:39	--	--	0.14	--
		--		7:32:47		--		--
2	0.15	--	0.15	7:43:40	0.15	--	--	--
		--		7:53:40		--		--
		--		8:04:29		--		--
3	0.19	--	0.21	8:14:09	--	--	0.19	--
		--		8:25:44		--		--
4	0.34	--	0.25	8:35:49	0.13	--	--	--
		--		8:45:11		--		--
5	0.39	--	0.15	8:55:52	--	--	0.17	--
		--		9:06:45		--		--
6	0.51	--	0.22	9:17:45	0.14	--	--	--

Afternoon:

Test number	Manhole 1		Manhole 4		Manhole 6		Manhole 7	
	sulfide (mg/l)	flow starting time	sulfide (mg/l)	flow starting time	sulfide (mg/l)	flow starting time	sulfide (mg/l)	flow starting time
7	1.15(223)	--	0.13(157)	--	--	--	0.18(165)	--
8	1.8	--	0.28	--	0.15	--	--	--
9	2.5	--	1.57	--	--	--	0.3	--
10	2.05	--	0.17	--	0.13	--	--	--
11	2.06(160)	--	1.3(175)	--	--	--	0.17(164)	--
12	2.47	--	0.96	--	0.33	--	--	--
13	1.61	--	1.55	--	--	--	0.18	--
14	2.22	--	1.68	--	0.16	--	--	--
15	2.24	--	0.88	--	--	--	0.15	--
16	2.96(185)	--	2.01(145)	--	0.48(117)	--	--	--

Note:

1. Samples were taken from manhole 1, 4, 6,and 7 three minutes after the arrival of the wave front of the flow.
2. COD: 750 mgO/*l*; DO: 10mg/*l*
3. Weather condition: clear, not very hot.
4. The water temperature was around 23 °C
5. Data in brackets indicates sulfate concentration in $mgSO_4/l$.

Table B.3 Data for 13 December, 2000

Test number	Manhole 1	Manhole 2	Manhole 3	Manhole 4	Manhole 6	
	sulfide(sulfate)	sulfide(sulfate)	sulfide (sulfate)	sulfide(sulfate)	sulfide (sulfate)	flow arriving time
• 1	2.2		0.13		1.11	11:57:58
• 2		1.18(179)		0.13 (180)	1.37(155)	12:09:32
						12:20:49
• 3	1.54		0.24		0.85	12:30:07
						12:43:11
• 4		1.56		0.14	1.25	12:54:12
• 5	2.44		0.14		1.75	13:15:50
• 6		2.34		0.18	2.18	13:26:47
• 7	2.76		0.17		2.04	13:37:27
• 8		2.88(180)		0.35(182)	2.64(217)	13:48:31
• 9	2.97		0.35		2.54	13:58:49
• 10		2.64		0.19	3.26	14:09:26
• 11	3.54		0.16		2.58	14:20:05
• 12		2.91		0.15	1.56	14:30:32
• 13	3.21		0.14		2.04	14:41:25
• 14		2.62(200)		0.19(138)	2.44(126)	14:51:17

Table B.4 Data for 13 December, 2000

Test number	Manhole 1	Manhole 2		Manhole 3	Manhole 4
	sulfide (sulfate)	sulfide (sulfate)	flow arriving time	sulfide (sulfate)	sulfide (sulfate)
* 1	3.36(164)	2.54(136)	15:38:03		0.65(166)
• 2	3.2	1.78	15:48:30	0.6	
* 3	3.56	2.12	15:59:04		0.39
• 4	2.88(178)	1.82(161)	16:08:33	0.13(200)	
* 5	3.44	1.86	16:18:18		0.42
• 6	2.12	1.5	16:27:55	0.18	
* 7	2.4(126)	1.4(130)	16:37:47		0.14(141)
• 8	0.64	0.48	16:47:31	0.59	
• 9	0.9	0.77	16:57:40		

Note:

1. Samples were taken from manhole 1, 2, 3,4, 6,and 7 two and half minutes after the arrival of the wave front of the flow.
2. COD: 1120 mgO/*l*; DO: 10mg/*l*
3. Weather condition: clear, temperature more than 30°C.
4. The water temperature was around 23 °C
5. Data in brackets indicates sulfate concentration in mgSO$_4$/*l*.

* Indicates data used for comparing theory and observation

• Indicates data considered insufficient for testing theory.

APPENDIX C

CHARACTERISATION AT MOTOR FOR BATCH TEST

Table C.1: Standard table linking speed of mixing (rpm) to G for the variable speed motor.

Frequency (rpm)	Velocity gradient G (/s)		
	22 °C	16 °C	10 °C
18	12.5	11.5	10.5
20	14	13	12
22	16	15	13.5
24	18	16	15
26	19.5	18	17
28	21.5	19.5	18.5
30	23	21	20
32	25	23	21.5
34	27	25	23
36	29	27	25
38	31	29	26.5
40	33	30	28
42	35	32	30
44	37	34	32
46	39	36	33.5
48	41	38	35
50	43	40	37.5
52	46	42	39
54	48	44	41
56	50	46	43
58	52	48	44.5
60	54	50	47
65	60	55	51
70	65	60	56
75	70	65	62.5
80	77	70	67.5
85	82.5	77.5	72.5
90	87.7	82.5	77.5
95	95	87.5	82.5
100	100	97.5	92.5
120	125	117.5	100
140	155	140	135
160	180	165	150
180	210	190	180
200	235	215	205
220	265	245	230
240	295	270	250
260	330	300	280
280	360	330	305
300	390	355	330

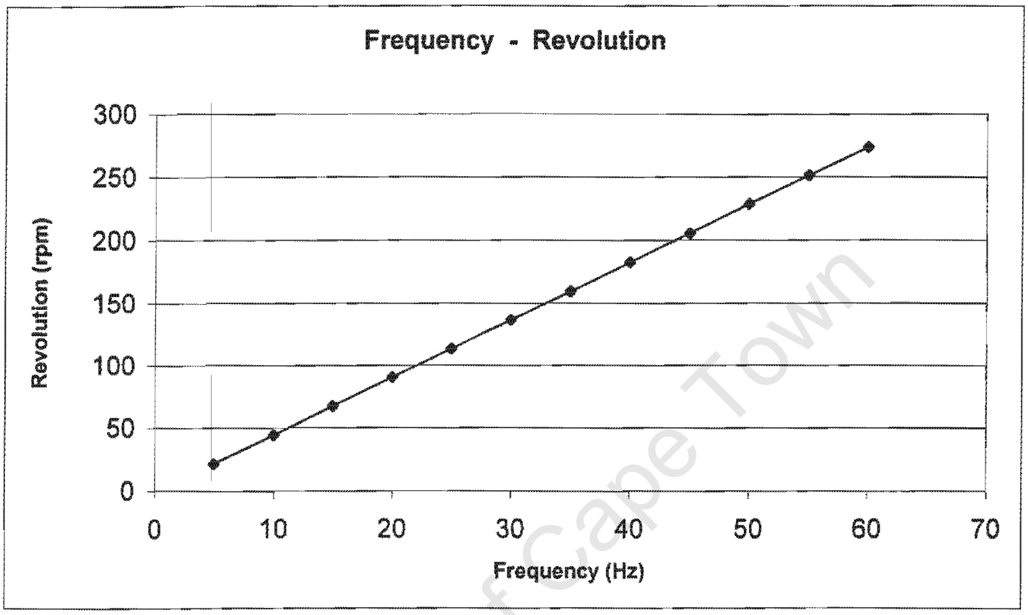


Figure C.1: Standard curve linking frequency (Hz) to revolution (rpm)

APPENDIX D

THE INTEGRATED PHYSICAL, AND CHEMICAL MODEL PROGRAMMED INTO AQUASIM

This appendix lists the integrated physical and chemical model as it was programmed into AQUASIM. Table D.1 shows the code for the integrated model of the batch reactor from which the equation of sulfide emission rate was derived (relevant to Chapter 2). Table D.2 shows the code for the integrated model of the Virginia gravity sewer system (relevant to in Chapter 5).

TABLE D.1

LISTING OF THE INTEGRATED MODEL OF THE BATCH REACTOR

****

AQUASIM Version 2.0 - Listing of System Definition for the Batch Reactor

****

D.1.1 VARIABLES

S_25:	Description:	Concentration of residual total sulfide in reactor with motor frequency of 25 Hz: varies with time
	Type:	Dynamic Volume State Variable
	Unit:	mgS/l
	Relative Accuracy:	1e-006
	Absolute Accuracy:	1e-006
S_30:	Description:	Concentration of residual total sulfide in reactor with motor frequency of 30 Hz: varies with time
	Type:	Dynamic Volume State Variable
	Unit:	mgS/l
	Relative Accuracy:	1e-006
	Absolute Accuracy:	1e-006
S_35:	Description:	Concentration of residual total sulfide in reactor with motor frequency of 35 Hz: varies with time
	Type:	Dynamic Volume State Variable
	Unit:	mgS/l

	Relative Accuracy:	1e-006
	Absolute Accuracy:	1e-006
S_40:	Description:	Concentration of residual total sulfide in reactor with motor frequency of 40 Hz: varies with time
	Type:	Dynamic Volume State Variable
	Unit:	mgS/l
	Relative Accuracy:	1e-006
	Absolute Accuracy:	1e-006
S_45:	Description:	Concentration of residual total sulfide in reactor with motor frequency of 45 Hz: varies with time
	Type:	Dynamic Volume State Variable
	Unit:	mgS/l
	Relative Accuracy:	1e-006
	Absolute Accuracy:	1e-006
S_50:	Description:	Concentration of residual total sulfide in reactor with motor frequency of 50 Hz: varies with time
	Type:	Dynamic Volume State Variable
	Unit:	mgS/l
	Relative Accuracy:	1e-006
	Absolute Accuracy:	1e-006
S_55:	Description:	Concentration of residual total sulfide in reactor with motor frequency of 55 Hz: varies with time
	Type:	Dynamic Volume State Variable
	Unit:	mgS/l
	Relative Accuracy:	1e-006
	Absolute Accuracy:	1e-006
S_60:	Description:	Concentration of residual total sulfide in reactor with motor frequency of 60 Hz: varies with time
	Type:	Dynamic Volume State Variable
	Unit:	mgS/l
	Relative Accuracy:	1e-006
	Absolute Accuracy:	1e-006
G_25:	Description:	Velocity gradient at motor frequency of 25 Hz
	Type:	Constant Variable
	Unit:	/s
	Expression:	115
G_30:	Description:	Velocity gradient at motor frequency of 30 Hz
	Type:	Constant Variable
	Unit:	/s

	Expression:	150
G_35:	Description:	Velocity gradient at motor frequency of 35 Hz
	Type:	Constant Variable
	Unit:	/s
	Expression:	178
G_40:	Description:	Velocity gradient at motor frequency of 40 Hz
	Type:	Constant Variable
	Unit:	/s
	Expression:	212
G_45:	Description:	Velocity gradient at motor frequency of 45 Hz
	Type:	Constant Variable
	Unit:	/s
	Expression:	241
G_50:	Description:	Velocity gradient at motor frequency of 50 Hz
	Type:	Constant Variable
	Unit:	/s
	Expression:	278
G_55:	Description:	Velocity gradient at motor frequency of 55 Hz
	Type:	Constant Variable
	Unit:	/s
	Expression:	313
G_60:	Description:	Velocity gradient at motor frequency of 60 Hz
	Type:	Constant Variable
	Unit:	/s
	Expression:	350
pH:	Description:	pH of solution
	Type:	Constant Variable
	Unit:	-
	Expression:	7.0
A:	Description:	Surface area of reactor
	Type:	Formula Variable
	Unit:	m^2
	Expression:	L*L
V:	Description:	Reactor volume
	Type:	Constant Variable
	Unit:	m^3
	Expression:	0.002

L:	Description:	Width of square surface area of the reactor
	Type:	Constant Variable
	Unit:	m
	Expression:	0.115
H:	Description:	Water height in the reactor
	Type:	Formula Variable
	Unit:	m
	Expression:	V/A
dmean:	Description:	Mean hydraulic depth
	Type:	Formula Variable
	Unit:	m
	Expression:	A/(L+2*H)
J:	Description:	J factor: H2S species faction in solution
	Type:	Formula Variable
	Unit:	-
	Expression:	10^(-2*pH)/(10^(-K1)*10^(-K2)+10^(2*pH) +10^(-K1)*10^(-pH))
K1:	Description:	Thermodynamic equilibrium constant of sulfide system at 20°C
	Type:	Constant Variable
	Unit:	-
	Expression:	7
K2:	Description:	Thermodynamic equilibrium constant of sulfide system at 20°C
	Type:	Constant Variable
	Unit:	-
	Expression:	12
K_1:	Description:	Constant K1 in equation 2.21, chapter 2
	Type:	Formula Variable
	Unit:	s
	Expression:	9.33*10^(-8)
K_2:	Description:	Constant K2 in equation 2.21, chapter 2
	Type:	Constant Variable
	Unit:	mgS/l/s
	Expression:	8.3*10^(-5)
S_ini:	Description:	Initial dissolved total sulfide concentration in reactor

Type: Constant Variable
Unit: mgS/l
Expression: 10

Time:
Description: Modeling time
Type: Program Variable
Unit: min
Reference to: Time

****

D.1.2 PROCESSES

emission_25:

Description: Decreasing of sulfide concentration in reactor (due to H2S emission at motor frequency of 25Hz)
Type: Dynamic Process
Rate: (K_1*A/V*dmean*J*G_25^2*S_25-K_2)*60
Stoichiometry:
Variable: Stoichiometric Coefficient
S_25: -1

emission_30:
Description: Decreasing of sulfide concentration in reactor (due to H2S emission at motor frequency of 30 Hz)
Type: Dynamic Process
Rate: (K_1*A/V*dmean*J*G_30^2*S_30-K_2)*60
Stoichiometry:
Variable: Stoichiometric Coefficient
S_30: -1

emission_35:
Description: Decreasing of sulfide concentration in reactor (due to H2S emission at motor frequency of 35 Hz)
Type: Dynamic Process
Rate: (K_1*A/V*dmean*J*G_35^2*S_35-K_2)*60
Stoichiometry:
Variable: Stoichiometric Coefficient
S_35: -1

emission_40:
Description: Decreasing of sulfide concentration in reactor (due to H2S emission at motor frequency of 40 Hz)
Type: Dynamic Process

Rate: (K_1*A/V*dmean*J*G_40^2*S_40-K_2)*60
Stoichiometry:
Variable: Stoichiometric Coefficient
S_40: -1

emission_45:
Description: Decreasing of sulfide concentration in reactor (due to H2S emission at motor frequency of 45 Hz)
Type: Dynamic Process
Rate: (K_1*A/V*dmean*J*G_45^2*S_45-K_2)*60
Stoichiometry:
Variable: Stoichiometric Coefficient
S_45: -1

emission_50:
Description: Decreasing of sulfide concentration in reactor (due to H2S emission at motor frequency of 50 Hz)
Type: Dynamic Process
Rate: (K_1*A/V*dmean*J*G_50^2*S_50-K_2)*60
Stoichiometry:
Variable: Stoichiometric Coefficient
S_50: -1

emission_55:
Description: Decreasing of sulfide concentration in reactor (due to H2S emission at motor frequency of 55 Hz)
Type: Dynamic Process
Rate: (K_1*A/V*dmean*J*G_55^2*S_55-K_2)*60
Stoichiometry:
Variable: Stoichiometric Coefficient
S_55: -1

emission_60:
Description: Decreasing of sulfide concentration in reactor (due to H2S emission at motor frequency of 60 Hz)
Type: Dynamic Process
Rate: (K_1*A/V*dmean*J*G_60^2*S_60-K_2)*60
Stoichiometry:
Variable: Stoichiometric Coefficient
S_60: -1

****

D.1.3 Compartment

Reactor:

Description: Batch test reactor
Compartment Type: Mixed Reactor Compartment
Reactor Type: Constant Volume
Volume: 0.002
Active Variables: S_25, S_30, S_35, S_40, S_45, S_50, S_55, S_60
Active Processes: emission_25, emission_30, emission_35, emission_40, emission_45, emission_50, emission_55, emission_60
Initial Conditions:

Variable(Zone): Initial Condition
S_25(Bulk Volume): S_ini
S_30(Bulk Volume): S_ini
S_35(Bulk Volume): S_ini
S_40(Bulk Volume): S_ini
S_45(Bulk Volume): S_ini
S_50(Bulk Volume): S_ini
S_55(Bulk Volume): S_ini
S_60(Bulk Volume): S_ini

Input:

Water Inflow: 0

****

TABLE D.2

LISTING OF THE INTEGRATED MODEL OF THE VIRGINIA GRAVITY SEWER

****

AQUASIM Version 2.0 - Listing of System Definition for the Virginia Gravity Sewer

****

D.2.1 VARIABLES

S_residual:	Description:	Concentration of residual total sulfide in sewage
	Type:	Dynamic Volume State Variable
	Unit:	mgS/l
	Relative Accuracy:	1e-006
	Absolute Accuracy:	1e-006
pH:	Description:	pH of sewage
	Type:	Constant Variable
	Unit:	-
	Expression:	7.0
A:	Description:	Cross section area
	Type:	Program Variable
	Unit:	m^2
	Reference to:	Cross section area
Sf:	Description:	Friction slope
	Type:	Program Variable
	Unit:	-
	Reference to:	Friction slope
z0:	Description:	Water level elevation
	Type:	Program Variable
	Unit:	m
	Reference to:	Water level elevation
zB:	Description:	Sewer bed elevation
	Type:	Real List Variable
	Unit:	m
	Argument:	x
	Std. Deriva.:	global
	Rel. Std. Dev.:	0
	Abs. Std. Dev.:	1

Minimum: -1000
Maximum: 5000
Interpolation: linear

Argument	Value
0	0
132	-1.4667
393	-3.95
655	-7.54
786	-8.79

---

n:

Description: Manning friction coefficient
Type: Real List Variable
Unit: -
Argument: x
Std. Deriva.: global
Rel. Std. Dev.: 0
Abs. Std. Dev.: 1
Minimum: -1000
Maximum: 5000
Interpolation: linear

Argument	Value
0	0.022
50	0.0115
786	0.0115

Qin:

Description: Sewage inflow rate
Type: Real List Variable
Unit: m^3/s
Argument: t_fract
Std. Deriva.: global
Rel. Std. Dev.: 0
Abs. Std. Dev.: 1
Minimum: 0
Maximum: 1e+009
Interpolation: linear

Argument	Value
0	0.05
60	0.05
61	0.464
420	0.464
421	0.05
600	0.05

t:	Description:	Time
	Type:	Program Variable
	Unit:	s
	Reference to:	Time
t_fract:	Description:	Periodic input function (returns the fraction of 600s)
	Type:	Formula Variable
	Unit:	s
	Expression:	t mod 600
K_1:	Description:	Constant K1 for the emission rate equation
	Type:	Formula Variable
	Unit:	s
	Expression:	9.33*10^(-8)
K_2:	Description:	Constant K2 for the emission rate equation
	Type:	Formula Variable
	Unit:	mgS/l.s
	Expression:	8.3*10^(-5)
E:	Description:	Dispersion coefficient
	Type:	Formula Variable
	Unit:	m/s
	Expression:	1
S_in:	Description:	Total sulfide concentration entering the sewer line
	Type:	Formula Variable
	Unit:	mgS/l
	Expression:	3.5
x:	Description:	Space coordinate along the sewer
	Type:	Program Variable
	Unit:	m
	Reference to:	Space coordinate X
w:	Description:	Water surface width
	Type:	Program Variable
	Unit:	m
	Reference to:	Surface width
wslot:	Description:	Width of Preissmann slot
	Type:	Formula Variable
	Unit:	m/s
	Expression:	0.001

P:	Description:	Wetted perimeter length
	Type:	Program Variable
	Unit:	m
	Reference to:	Perimeter length
Q:	Description:	Sewage discharge
	Type:	Program Variable
	Unit:	m^3/s
	Reference to:	Discharge
u:	Description:	Absolute viscosity of liquid
	Type:	Formula Variable
	Unit:	Ns/m^2
	Expression:	10^(-3)
r:	Description:	Radius of the sewer pipe
	Type:	Formula Variable
	Unit:	m
	Expression:	0.4
r_w:	Description:	Unit weight of liquid
	Type:	Formula Variable
	Unit:	N/m^3
	Expression:	9.81*10^3
dpress:	Description:	Water pressure in full pipe
	Type:	Formula Variable
	Unit:	m
	Expression:	if dmax<2*r then 0 else dmax-2*r endif
dmax:	Description:	Maximum water depth
	Type:	Formula Variable
	Unit:	m
	Expression:	z0-zB
dmean:	Description:	Mean water depth
	Type:	Formula Variable
	Unit:	m
	Expression:	A/P
v:	Description:	Average sewage velocity
	Type:	Formula Variable
	Unit:	m/s
	Expression:	Q/A

v_star:	Description:	Shear velocity
	Type:	Formula Variable
	Unit:	m/s
	Expression:	sqrt(9.81*dmean*Sf)
f:	Description:	Friction coefficient
	Type:	Formula Variable
	Unit:	-
	Expression:	(v_star/v)^2*8
G:	Description:	Velocity gradient
	Type:	Formula Variable
	Unit:	/s
	Expression:	(r_w*Hf/u)^0.5
DH:	Description:	Hydraulic diameter
	Type:	Formula Variable
	Unit:	/s
	Expression:	4*A/P
Hf:	Description:	Head loss along the sewer line
	Type:	Formula Variable
	Unit:	m
	Expression:	f/DH*v^3/(2*9.81)
alpha:	Description:	Angle between the vertical and the border of the water surface
	Type:	Formula Variable
	Unit:	rad
	Expression:	if dmax<0 then 0 else if dmax>2*r then pi else acos((r-dmax)/r) endif endif
J:	Description:	J factor: H2S species faction in solution
	Type:	Formula Variable
	Unit:	-
	Expression:	10^(-2*pH)/(10^(-K1)*10^(-K2)+10^(2*pH) +10^(-K1)*10^(-pH))
K1:	Description:	Thermodynamic equilibrium constant of sulfide system at 20°C
	Type:	Constant Variable
	Unit:	-
	Expression:	7
K2:	Description:	Thermodynamic equilibrium constant of

sulfide system at 20°C
Type: Constant Variable
Unit: -
Expression: 12

****

D.2.2 PROCESSE

H2S_emission:

Description: H2S emission from sewage
Type: Dynamic Process
Rate: K_1*(w/A)*dmean*G^2*J*S_residul-K_2
Stoichiometry:
Variable: Stoichiometric Coefficient
S_residual: -1

****

D.2.3 Compartment

Sewer:

Description: Virginia gravity sewer line
Compartment Type: River Section Compartment
Comp. Index: 0
Grav. Accel.: 9.81
Start Coord.: 0
End Coord.: 786
Cross Sect.: r*r*(alpha-sin(alpha)*cos(alpha))+dpress*wslot
Perimeter: 2*r*alpha
Width: 2*r*sin(alpha)
Frict. Slope: n^2*(P/A)^(4/3)*(Q/A)^2
Dispersion: Without dispersion
Method: Kinematic
Num. Grid Pts.: 22
Resolution: Low
Active for calculation

Active Variables: S_residul
Active Processes: H2S_emission

Initial Conditions:

Variable(Zone):	Initial Condition
S_residul(Water Column):	S_in
Q(Water Column):	Qin

Input:

Input type: Upstream Inputs

Variable:	Loading
S_residual:	Qin*S_in

****