EXTENDING ASM1 TO MODEL A TUBULAR BIOFILM REACTOR

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ABSTRACT

The world's largest tubular biofilm reactor for biological oxidation of hydrogen sulphide (H_2S) in geothermal power station cooling water was successfully commissioned in NZ in 2012. The original design of the biofilm reactor was based on pilot studies conducted over several years and an empirical model was developed to predict the biofilm reactor performance. The biofilm reactor has operated for six years and continues to perform as predicted by this model.

To enable a more rigorous evaluation of the fundamental biokinetics from first principles, and to consider the application of the tubular biofilm reactor to alternative configurations and operation, a more mechanistic design approach was required. This paper describes the development of a mechanistic biofilm reactor model based on an extension of activated sludge model 1 (ASM1) to simulate the biological oxidation of H_2S by sulphur oxidising bacteria (SOB) and the incorporation into a tubular biofilm reactor simulation using commercial software.

A review of literature identified strategies for the incorporation of SOB and sulphur reducing bacteria (SRB) kinetics into ASM1. The extension of ASM1 was carried out by adding processes for H_2S biological oxidation to elemental sulphur or sulphate endpoints with kinetic rate equations and component stoichiometry drawn from literature values.

The extended ASM1 model was incorporated into a biofilm reactor simulation using commercial software (GPS-X Hydromantis). The paper describes how the tubular biofilm reactor was simulated in GPS-X as a series of reactors that incorporate both fixed film and bulk fluid biokinetics. A total of ten reactors in series were modelled to represent individual 20m x 100mm diameter pipe sections for the total full-scale tubular length of 200m. Sulphide removal data from the pilot studies collected at 20m intervals was used to modify the model SOB kinetic and stoichiometric parameters to achieve a simulation performance fit. Model values were compared with published literature values.

The biofilm reactor's performance was simulated for different flow velocities, temperature and dissolved oxygen conditions. The evaluation of the extended model for simulation of the full-scale biofilm reactor, provided a better understanding of the biofilm reactor's performance and presents the opportunity to optimise the operating conditions to improve energy consumption and sulphide removal.

The process for incorporating further processes into the ASM models extends beyond the scope of the current biofilm reactor and could be applied within the wastewater industry to simulate the fate of contaminants in alternative biofilm reactor configurations.

KEYWORDS

ASM1; SULPHIDE; BIO-OXIDATION; BIOFILM; TUBULAR REACTOR

PRESENTER PROFILE

Caroline Hope

Last year, Caroline completed a BE (Hons) in Chemical and Materials Engineering at the University of Auckland. She currently works for Beca as a Process Engineer in the Auckland Water Team. Since the start of 2017, she has been working with Rob Fullerton, developing a sulphur model of the Wairakei Biofilm Reactor.

Rob Fullerton

Mr Fullerton is a Senior Technical Director of Environmental Engineering with Beca Ltd with over 40 years of scientific consulting experience. He has been involved at the concept process phase and commissioning for many of the industrial water and wastewater engineering projects undertaken by the Beca Group. Rob was responsible for leading the scientific and pilot plant investigations for the Wairakei Biofilm Reactor, leading to successful the full scale implementation.

NOMENCLATURE

HDPE – High Density Polyethylene
SOB – Sulphur Oxidising Bacteria
SRB – Sulphur Reducing Bacteria
H_2S – Hydrogen Sulphide
S° - Elemental Sulphur
SO_4 – Sulphate
DO – Dissolved Oxygen
CSTR – Continuously Stirred Tank Reactor
BOD – Biological Oxygen Demand
COD – Chemical Oxygen Demand
ASM1 – Activated Sludge Model 1 (Henze, Gujer, Mino, & van Loosedrecht, 2015)
GPS-X – General Purpose Simulator-X™ Hydromantis Inc. -commercial wastewater treatment process simulation software

INTRODUCTION

The world's largest tubular biofilm reactor for biological oxidation of H_2S was successfully commissioned in 2012, at Contact Energy's Wairakei Geothermal Power station. The bioreactor's purpose is to reduce H_2S content in the cooling water discharge to the Waikato River by 95%. For the last five years since commissioning, the reactor has performed as predicted by the original empirical design model based on the results of pilot testing. To gain a more comprehensive understanding of how the system works, a mechanistic design model was developed using a standard wastewater biological model (ASM1) with an extension to include sulphur oxidation. After reviewing the sulphur biokinetics of the system, the model was developed in the following stages:

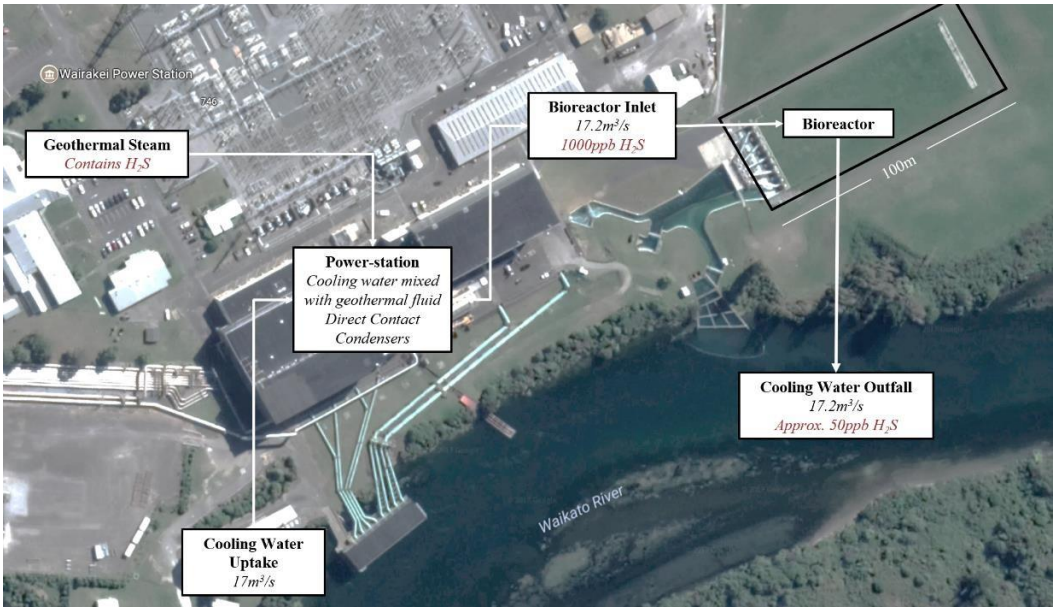
- Simulation of mechanistic model through an extension of ASM1, to simulate the biological oxidation of H_2S by SOB
- Incorporation of mechanistic model into a tubular biofilm reactor simulation using GPS-X (Hydromantis Inc.)
- Calibration using the original Wairakei Bioreactor design pilot trial data
- Performance assessment for different cooling water velocities and temperatures

1 BACKGROUND

The Wairakei Geothermal Power Station utilises water directly from the Waikato River for a 'once through' cooling water system for condensing geothermal steam from the turbines. The steam contains H_2S and this mixture of steam condensate and river water discharges H_2S into the river.

The current discharge resource consent requires that the H_2S content is reduced by approximately 95% (from 1000mg/m^3 to 50mg/m^3). Figure 1 outlines how the installation of the tubular bioreactor ensures this limit is met. The reactor comprises of 1850 x 200m parallel 100mm diameter HDPE pipes to treat up to 17m^3/s of cooling water (Bierre & Fullerton, 2015). The locally occurring SOB, create a biofilm on the inside of these pipes and oxidise the H_2S to sulphate (SO_4) and elemental sulphur (S°).

Figure 1: Current Wairakei power station cooling water system schematic

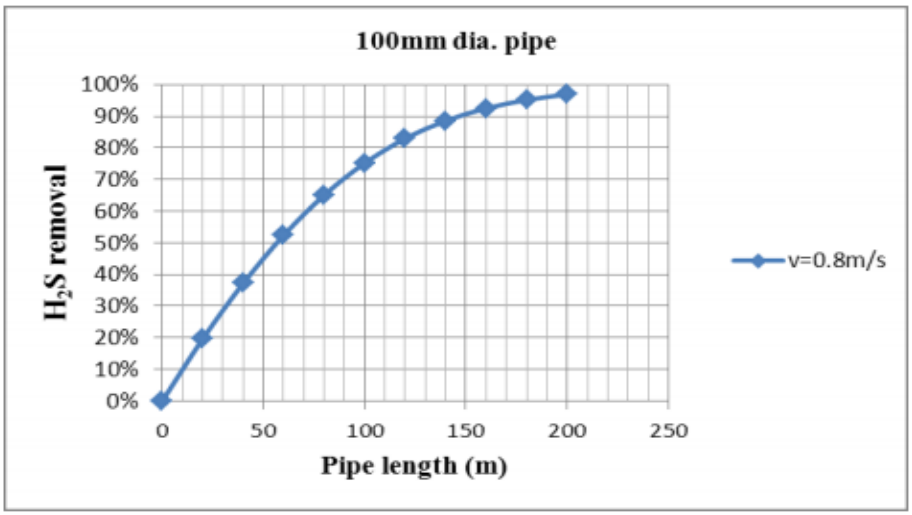


1.1 WAIRAKEI BIOREACTOR EMPERICAL MODEL

During the design phase of the Wairakei Bioreactor in 2011, a pilot trial pipe of 200m x 100mm diameter, was used to develop an empirical model to determine the design parameters.

Figure 2 shows the model design data for a single 200m x 100mm diameter pipe with a water velocity of 0.8m/s, confirming the pipe will successfully remove 95% of H_2S (i.e. reduce H_2S levels to 50mg/m^3) over 200m. This formed the design basis for the engineering of the full scale bioreactor.

Figure 2: Predicted sulphide removal vs 100mm diameter pipe length (Bierre & Fullerton, 2015)



To gain a comprehensive understanding of how the system works, a mechanistic design approach is required to evaluate biokinetics from first principles and consider the impact that disturbance variables have on operational procedures.

2 BIOKINETICS

2.1 H_2S OXIDATION PRODUCTS

SOB are naturally occurring chemolithotrophic organisms that generate energy mainly from the following redox reactions (J. Sun et al., 2017).

Equation 1 $H_2S + 0.5O_2 \rightarrow S° + H_2S$

Equation 2 $S° + 1.5O_2 + H_2O \rightarrow SO_4^{2-} + 2H^+$

Equation 3 $H_2S + 2O_2 \rightarrow SO_4^{2-} + 2H^+$

The yield ratio is dependent on the bioreactor conditions including the availability of oxygen. Table 1 outlines the measurements taken during the pilot plant trials, to determine which of the two possible end products, were produced.

Table 1: H_2S, DO and SO_4 observations during pilot plant trials

Parameter	**100 mm diameter pipe**		
	Inlet	**Outlet**	**Difference**
H_2S (g/m^3)	0.78	0.074	0.706 (decrease)
DO (g/m^3)	1.82	0.91	0.91 (decrease)
SO_4 (g/m^3)	9.72	10.12	0.4 (increase)

Based on a mass balance of oxygen the observed SO_4 increase represents approximately 25% of the expected increase for the oxygen consumed, suggesting that S° was also produced. This is supported the whitish-grey appearance of the biomass observed in the pilot trial pipes, suggesting sulphur granules are present in the SOB (Bierre & Fullerton, 2015).

2.2 BIOREACTOR INLET WATER QUALITY

The water entering the bioreactor, a combination of cooling water from the Waikato River and geothermal steam condensate, is conducive for the growth of SOB biofilm in the presence of H_2S. The inlet conditions are; a warm temperature of 25-35**°**C, pH of approximately 6.0, high levels of dissolved oxygen at $>2gO_2/m^3$, high levels of inorganic carbon as dissolved CO_2, a low level of BOD and TN at $1g/m^3$ and $0.12g/m^3$ respectively, and sufficient levels of H_2S required for SOB growth at 0.8-1 g/m^3 (Bierre & Fullerton, 2015).

2.2.1 OXYGEN LEVEL

Due to the high level of dissolved oxygen, it can be assumed that the tubular reactor biofilm only operates under aerobic and anoxic conditions. There is potential that anaerobic conditions may exist in the biofilm, due to oxygen diffusion limitations. However, for simplification, all anaerobic reactions, including those carried by Sulphur Reducing Bacteria (SRB) are not included in the extended ASM1 model.

2.2.2 BACTERIAL SPECIES COMPETITION

Due to the inlet water quality, it can be reasonably assumed that biofilm is dominated by SOB growth. Growth rates of heterotrophic and nitrifying autotrophic bacteria are likely to be limited due to the restricted organic carbon and nitrogen substrates in the process water and the less favourable pH conditions.

3 ASM1 EXTENSION METHOD

3.1 STRATEGIES FROM LITERATURE

To simulate the biological oxidation of H_2S by SOB, an extension of ASM1 was required. The following literature identified strategies for the incorporation of SOB and SRB kinetics into ASM1. Directly related investigations are:

- Sulphide Removal and Sulphur Production in a Membrane Aerated Biofilm Reactor: Model Evaluation (Sun *et al.*, 2017)

- Transport and Transformation Processes in Combined Sewers (Huisman, 2015)

- Constructed Wetland Model No. 1: a general model to describe biokinetic processes in subsurface flow constructed wetlands (CWM1) (Langergraber *et al.*, 2009)

In the model investigations carried out by Sun *et al.* (2017) and Huisman (2015), SO_4 and S° are considered products of biological oxidation of H_2S, unlike CWM1 considers the oxidation to SO_4 as a single biological process. All three papers describe aerobic, anoxic and anaerobic sulphur processes. However, as noted in 2.2.1, anaerobic processes and growth of sulphur reducing bacteria are not in this model.

Although constructed wetlands (Langergraber *et al.*, 2009) and sewers (Huisman, 2001) take a different physical form than the bioreactor, the similarities in biochemistry, provide a suitable comparison for kinetic and stoichiometric parameters.

3.2 ASM1 PROCESS MATRIX

The extended ASM1 model included the following additional processes:

- Aerobic growth of X_{SOB} on S_{H2S}: consumes S_O, S_{H2S}, S_{ALK} and S_{NH} to produce S_{S°
- Aerobic growth of X_{SOB} on S_{S°: consumes S_O, S_{S°, S_{ALK} and S_{NH} to produce S_{SO_4}
- Anoxic growth of X_{SOB} on S_{H2S}: consumes S_O, S_{H2S}, and S_{NH} to produce S_{S° and S_{ALK}
- Anoxic growth of X_{SOB} on S_{S°: consumes S_O, S_{S° and S_{NH} to produce S_{SO_4} and S_{ALK}
- Lysis of X_{SOB}: decay produces particulate organic matter

Table 2 provides the process additions in the form of a Petersen Matrix, with description of each of the associated components in the bottom row, the 4 new state variables, ($S_S{}^o$, S_{SO4}, S_{H2S} and X_{SOB}) and process rate equations.

3.3 KINETIC AND STOICHIOMETRIC PARAMETERS

The kinetic parameters described in Table 2 were set with initial values drawn from literature and adjusted during calibration. Literature values for stoichiometric values described in Table 3 were used and held constant for simplicity of the model.

Table 3: Stoichiometric parameters (at 20°C)

Symbol	Characterisation	Value	Units	
$Y_{SOB,H2S}$	Yield coefficient for SOB while growing on H_2S	0.26	gCOD/gS	*
Y_{SOB,S°	Yield coefficient for SOB while growing on S^o	0.09	gCOD/gS	*
I_{XBN}	N content of active biomass	0.07	gN/gCOD	#
F_U	Fraction of particulate product generated in biomass lysis	0.1	gCOD/gCOD	#
Y_H	Yield coefficient for heterotrophs	0.63	gCOD/gCOD	^
Y_A	Yield coefficient for autotrophs	0.24	gCOD/gN	^

***:**Buisman *et al.* (1995) #:Langergraber & Simunek (2005) ^:Henze *et al.* (2015)

Table 2: Kinetics and stoichiometry for additional process in Petersen Matrix Format

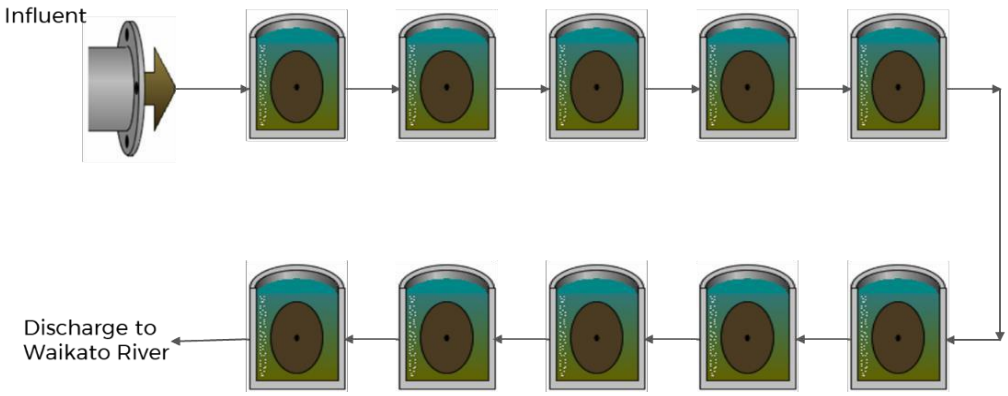
Component i → / ↓		**1** X_S	**2** S_O	**3** S_{NO}	**4** S_{S^o}	**5** S_{SO4}	**6** S_{H2S}	**7** S_{ALK}	**8** X_{SOB}	**Process Rate, p_j**
j	**Process**	gCOD	gCOD	gN	gS	gS	gS	molHCO3	gCOD	
1	Aerobic growth of X_{SOB} on S_{H2S}		-(2-$Y_{SOB,HS}$)/ $Y_{SOB,HS}$		1/ $Y_{SOB,HS}$		-1/ $Y_{SOB,HS}$	-I_{XBN}/14 +1/$Y_{SOB,HS}$	1	$\mu_{SOB} \times \left(\frac{S_{H2S}}{K_{H2SSOB} + S_{H2S}}\right) \times \left(\frac{S_O}{K_{OSOB} + S_O}\right) \times X_{SOB}$
2	Aerobic growth of X_{SOB} on S_{S^o}		-(2-Y_{SOB,S^o})/ Y_{SOB,S^o}		-1/ Y_{SOB,S^o}	1/ Y_{SOB,S^o}		-I_{XBN}/14 - 1/$Y_{SOB,\ S^o}$	1	$\mu_{SOB} \times \left(\frac{X_{S^o}}{K_{S^oSOB} + X_{S^o}}\right) \times \left(\frac{S_O}{K_{OSOB} + S_O}\right) \times X_{SOB}$
3	Anoxic growth of X_{SOB} on S_{H2S}			-(1-$Y_{SOB,HS}$)/ (0.875*$Y_{SOB,HS}$)	1/ $Y_{SOB,HS}$		-1/ $Y_{SOB,HS}$	(1-$Y_{SOB,HS}$)/ (14*2.86* $Y_{SOB,HS}$) - I_{XBN} /14	1	$\mu_{SOB} \times \left(\frac{S_{NO}}{K_{NOSOB} + S_{NO}}\right) \times \left(\frac{K_{OSOB}}{K_{OSOB} + S_O}\right) \times \left(\frac{S_{H2S}}{K_{H2SSOB} + S_{H2S}}\right) \times X_{SOB}$
4	Anoxic growth of X_{SOB} on S_{S^o}			-(1-Y_{SOB,S^o})/ (0.875* Y_{SOB,S^o})	-1/ Y_{SOB,S^o}	1/ Y_{SOB,S^o}		(1- $Y_{SOB,\ S^o}$) /(14*2.86* $Y_{SOB,\ S^o}$) - I_{XBN} /14	1	$\mu_{SOB} \times \left(\frac{S_{NO}}{K_{NOSOB} + S_{NO}}\right) \times \left(\frac{K_{OSOB}}{K_{OSOB} + S_O}\right) \times \left(\frac{X_{S^o}}{K_{S^oSOB} + X_{S^o}}\right) \times X_{SOB}$
5	Lysis of X_{SOB}	1-F_U							-1	$b_{SOB} \times X_{SOB}$
Observed Conversion Rates		$r_i = \sum_{j=1}^{R} v_{i,j} \times p_j$								
Stoichiometric Parameters: $Y_{SOB,HS}$ Y_{SOB,S^o} I_{XBN} F_U		Slowly biodegradable particulate COD	Dissolved oxygen	Nitrate and nitrite	Elemental Sulphur	Sulphate Sulphur	Hydrogen Sulphide	Alkalinity	Sulphur Oxidising Bacteria	**Kinetic Parameters:** SOB Growth μ_{SOB} SOB Saturation Constants $K_{H2SSOB}, K_{OSOB}, K_{NOSOB}, K_{S^oSOB}$ SOB Decay b_{SOB}

4 TUBULAR BIOFILM REACTOR SIMULATION

The ASM1 model only describes the mechanistic equations of bacterial growth. To model the bioreactor system, the tubular biofilm reactor must be simulated in a separate physical model incorporating the ASM1 mechanistic equations. The extended ASM1 model was transferred to simulate a tubular biofilm reactor in commercial software, GPS-X (Hydromantis, 2011). The tubular bioreactor was configured as a series of submerged biological contactor (SBC) reactors incorporating fixed film and bulk fluid biokinetics processes.

A total of ten reactors in series were modelled to simulate individual 20m x 100mm diameter pipe sections of the pilot plant for the total full-scale tubular length of 200m. Figure 3 shows the GPS-X layout for the simulated pipe. Sulphide removal data from the pilot studies collected at 20m intervals was used to modify the model SOB kinetic parameters to achieve a simulation performance consistent with the pilot trial results.

Figure 3: Schematic of simulated pipe in GPS-X



4.1 BIOFILM REPRESENTATION

Each SBC's surface area to volume ratio was set equivalent to a 20m section of the pipe, to simulate the same surface area available for SOB biofilm. The internal pipe surface area was approximately 6.2m^2, with a total liquid volume of approximately 0.16m^3. The biofilm thickness was assumed to be a constant thickness of ~1mm due to operating at quasi-steady state, where there is an equilibrium between biomass sloughing and growth.

5 EXTENDED ASM1 MODEL CALIBRATION

5.1 ASSUMPTIONS FOR THE SULPHUR MODEL

The following list summarises assumptions made for the sulphur model. Most were required due to limited amount of data available for calibration.

- *Consistent biofilm and boundary layer thickness throughout the reactor:* held constant for simplicity, even though the pipe trial measurements showed that the biofilm thickness decreases along the pipe

- *Constant biomass concentration (X_{SOB}):* assume biofilm has reached a quasi-steady state with constant thickness, hence visible growth is equal to detachment. The substrate (S_{H2S}) concentration is low hence can be assumed the growth rate of biomass will be low and substrate limited

- *Non-anaerobic environment in biofilm:* conditions are unknown hence it is assumed sufficient dissolved O_2 throughout entire biofilm

- *ASM1 Limitations:* System is operating at constant temperature and constant pH. The biomass is homogenous and does not undergo changes in species diversity with time

- *SBC Model Limitation:* SBC operate as a CSTR with the assumption that each 20m section of pipe is completely mixed, hence model outputs for each reactor represent an average concentration for the section

- *Constant biology and kinetic parameters along pipe*: although it is likely that the biology varies at different points of the pipe as H_2S levels reduce. All kinetic and stoichiometric parameters are common for the 10 reactors

5.2 INFLUENT CHARACTERISATION

The influent into the model was characterised using existing pilot trial data and data collected post commissioning of the bioreactor by Contact Energy between 2007 and 2011 outlined in Table 4.

Table 4: Average inlet parameters values used

Velocity#	**pH***#	**Sulphate Conc.**#	**H_2S Conc.**#	**Ammonium**^	**Dissolved CO_2**^	**Dissolved O_2**#
0.8 m/s	5.8	10 g/m^3	774 mg/m^3	0.07g/m^3-N	101g/m^3	1.9 g/ m^3

**pH value is median #pilot trial data ^ Contact Energy Data*

5.3 DATA FOR MODEL CALIBRATION

H_2S removal data from the pilot studies collected at 20m intervals along the 200m pipe was used for calibration. The mean H_2S concentration over five days is shown by the blue line in Figure 4. The minimum and maximum bars for this line, shows the spread of data at each 20m section over the five-day period.

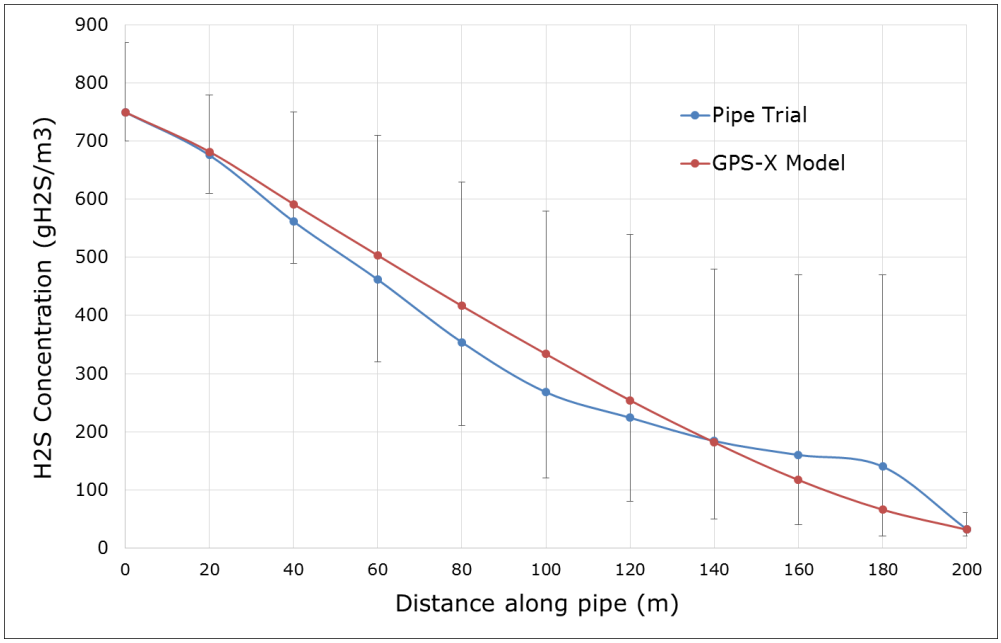
The difference in initial H_2S concentration is due to the changing H_2S concentration from the power station as generation rates change. The increased variation in the measured values along the pipe is in part due to the limitations of the H_2S test method (methylene blue - titration) as very low H_2S levels at the end of the pipe approach the test limit of detection.

5.4 RESULTS

The GPS-X Model was run to steady state several times with adjustment of the model kinetic parameters. A predicted curve, shown in red in Figure 4, was obtained as the "best fit" to the measured data. The points on this line correspond to the exit concentration of H_2S from each of the 10 SBCs.

The primary performance measure is that the H_2S discharge level from the outlet of 10^{th} SBC, meets the outlet concentration from the pilot trial data of 30 mg/m^3. Figure 4 demonstrates that the model could achieve this concentration.

Figure 3: Pipe trial calibration results



Further calibration and tuning was carried out in attempt for the predicted values from the model to match shape of the Pipe trial curve. Although this objective was not fully achieved, the predicted values from GPS-X model lie comfortably within the maximum and minimum values from the pilot trial data. High trial data variability at the 160m – 180m sample points distorts the mean value curve which is not possible to fit with the model parameters.

5.5 FINAL CALIBRATION PARAMETERS

The system was very sensitive to adjustment of kinetic parameters. It is desired that the growth rate of SOB is limited by substrate (H_2S) only. Therefore, saturation coefficients were adjusted to ensure that oxygen concentration did not impede the rate of reaction.

The concentration of SOB biomass in the influent was unknown, through calibration it was found that a concentration of 8gCOD/m^3 (~12g/m^3 of X_{SOB}) was required to ensure that the desired exit concentration of 30mg/m^3. Table 5 compares the kinetic parameters that were tuned during calibration, to their respective values from literature.

Table 5: Final model kinetic parameters compared to literature (values at 20°C)

Symbol	Parameter	Model	Literature	Units	
μ_{SOB}	SOB specific growth rate	5.28	5.28**	1/d	Remain unchanged from literature value.
b_{SOB}	Rate constant for lysis	0.15	0.15+	1/d	Typical lysis value for autotrophic bacteria
K_{OSOB}	SOB saturation for O_2	0.1	0.2+	gO_2/m^3	A lower K_{OSOB} ensures SOB growth is not inhibited by oxygen level, to maintain assumption of completely aerobic conditions. K_{OSOB} must be lower that minimum O_2 conc.
K_{NOSOB}	SOB saturation coefficient for NO	0.01	0.5+	gN/m^3	Low concentration of NO hence require a low value to ensure the system is not limited by NO.

K_{H2SSOB}	SOB saturation coefficient for H_2S	0.06	0.24[%]	gS /m^3	A lower K_{H2SSOB} is required due to very low concentrations of H_2S in system (as low as 0.03gS/m^3). In order for system to be substrate limited, value must be above minimum H_2S conc.
$K_{S°SOB}$	SOB saturation coefficient for S°	0.09	3.2[*]	gS /m^3	Significantly lower S° concentration than in the literature sewer models, hence lower value is appropriate. Section 2.1 shows equation 2 is less likely to occur, hence $K_{S°SOB}$ will be more limiting than K_{H2SSOB}.

[**]: de Wit *et al.* (1995) [+]: Rousseau (2005) [*]: Huisman (2015)

6 PERFORMANCE EVALUATION AND DISCUSSION

The performance of the full scale Wairakei Bioreactor was evaluated using the calibrated model of the trial pipe on the assumption that the full reactor configuration is many "trial pipe" reactors in parallel. Different flowrates and temperatures were modelled to predict H_2S removal under different conditions.

The maximum concentration of H_2S at 1000mg/m^3 was used as the inlet concentration for the GPS-X model. To meet the consent limit of 630kgH_2S/week the outlet concentration discharged to the river must not exceed 50mg/m^3.

6.1 EFFECT OF FLOWRATE

The Wairakei Bioreactor and its associated pumps were designed for an operational velocity at 0.8m/s and a maximum velocity of 1.2m/s. The system was not designed for a velocity of less than 0.6m/s to avoid pumice settling/blocking the pipe and risk of air pocket creation.

To measure the effect of flowrate the model was run to steady state at 0.6m/s, 0.7m/s, 0.8m/s, 1m/s and 1.2m/s, as these values lie within the design flowrate range. An average temperature of 30°C was selected as a typical annual mean for the power station operation. Each point on Figure 5, represents the outlet H_2S concentration of the 10th SBC (end of pipe).

Figure 5: Effect of flowrate on outlet H_2S concentrations (at 30°C)

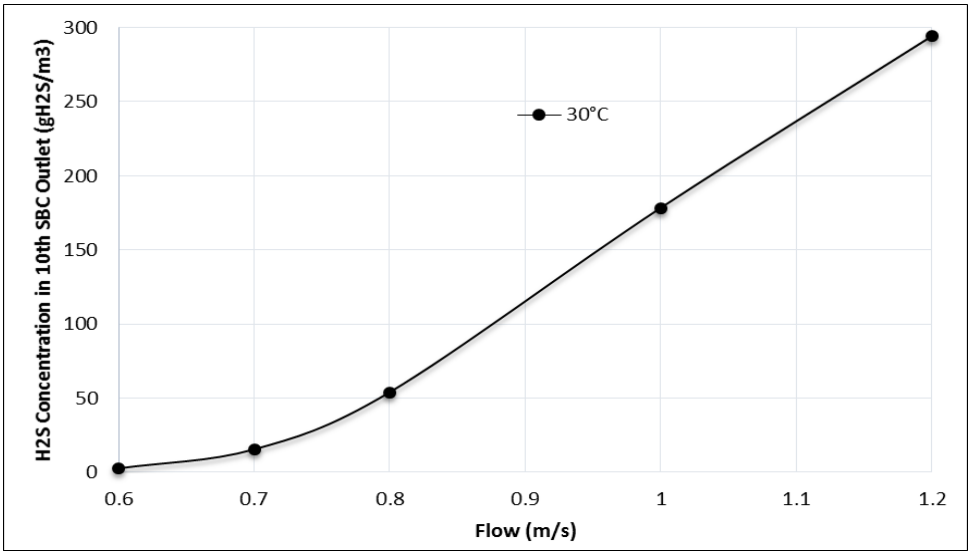


Figure 5 shows that the model predicts:

- At 0.8m/s the Wairakei Bioreactor achieves an outlet H_2S concentration of 50mg/m^3, meeting a 95% reduction in concentration.

- At flowrates less than 0.8m/s more H_2S is removed due to the longer residence time of the cooling water in the bioreactor. The H_2S has more time to diffuse into the biofilm where the SOB converts it to SO_4.

- The declining removal rate at lower flows is considered due to the low concentrations of H_2S approaching the H_2S half saturation coefficient value for SOB. The H_2S removal rate equation tends towards zero as the concentration of H_2S approaches the half saturation constant.

- At higher flows, greater than 0.8m/s, the cooling water residence time is less in the bioreactor, therefore the H_2S may not have sufficient time to diffuse into the biofilm. The linear slope is because the half saturation function does not influence the rate of the sulphide removal when the concentration of H_2S is high.

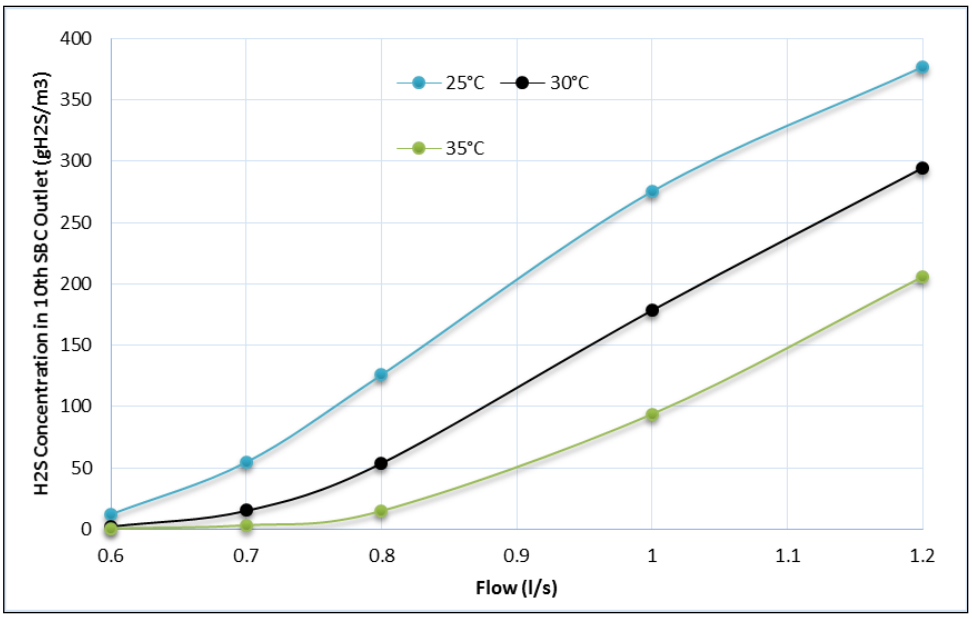
6.2 EFFECT OF FLOWRATE AND TEMPERATURE

The temperature of the water entering the bioreactor fluctuates over the course of the year. 30°C is considered an average temperature, while 35°C and 25°C, sit at the extremes of the temperature range. The growth of SOB in the biofilm increases with temperature. The model growth rates are temperature corrected through the Arrhenius temperature coefficient.

To measure the effect of temperature and flowrate the model was run to steady state for various flows (0.6m/s, 0.7m/s, 0.8m/s, 1m/s and 1.2m/s) at 35°C, 30°C and 25°C. The concentration of H_2S at the outlet of the 10^{th} reactor was recorded.

Figure 6 shows the effect that temperature has on various flowrates. H_2S removal is most effective at higher temperatures and lower flow.

Figure 6: Effect of flowrate and temperature on outlet H_2S concentrations



At higher (summer) temperatures the bioreactor operates more effectively and the H_2S consent limit can almost be met at a flowrate of 0.9m/s. Conversely at the lower (winter) temperature condition, the bioreactor flow would need to be reduced to meet consent requirements.

6.3 EFFECT OF DISSOLVED OXYGEN CONDITIONS

The dissolved oxygen concentration in the inlet to the operating bioreactor varies with seasonal temperature changes in the river water intake and the degassing effect of the power station condenser vacuum. Variation is typically over a range of 1.5 – 3.5mgO_2/L.

The ratio of sulphide to dissolved oxygen consumption (mol/mol) has been shown to control the biological oxidation formation of either partial oxidation to elemental sulphur (equation 1) or complete oxidation to sulphate (equation 2). Buisman (1991), found that a ratio of <0.5H_2S/O_2 favoured the formation of sulphate. Increasing ratios favoured elemental sulphur formation. At a ratio of >2:1 essentially 95+% of elemental sulphur is formed.

The model results were unable to demonstrate any progressive increase to elemental sulphur formation with the reduction of inlet dissolved oxygen set to the low operating condition of 1.5mgO_2/L. This may be due to the extreme low operating sulphide levels in the bioreactor where the ratio cannot increase sufficiently to substantially favour elemental sulphur formation or the formation of sulphur within the biomass is not adequately transferred to the bulk water discharge due to the model process of biofilm detachment. Further evaluation of the biofilm model parameters and stoichiometry would be required to resolve this sulphide/oxygen effect.

7 MODEL APPLICATION

For a practical application of the model the results could be used to determine how the cooling water flowrate and temperature affect the performance of Wairakei Bioreactor and provide suggestions for how to optimise the operating conditions to improve energy consumption (pumping) and maximise H_2S reduction.

The optimal performance of the Wairakei Bioreactor is constrained by the operational requirements of the power station:

1. The H_2S inlet concentration to the bioreactor cannot be closely controlled as the mass of H_2S from the power station depends on the steam demand (electrical demand) and the combination of geothermal steam bores in use at the time as sulphide levels vary between bores.
2. The temperature of the inlet water varies with seasonal temperatures in the Waikato River and with the power station generating demand (more or less steam).

The suggested application described below assumes that inlet concentration of H_2S is held constant at 1000mg/m^3 as a conservative estimate. The predicted results generated by the Model suggest that the flowrate could be adjusted according to inlet temperature and still meet compliance, while holding all other variables constant.

The model predicts that when the temperature of the cooling water is approximately 25°C, the cooling water flowrate should not exceed 0.7m/s, as this flowrate corresponds to a H_2S discharge of 50mgH_2S/m^3. However, during colder months when the river

temperature is low, more power generation is required to meet the country's electricity demand. This would typically result in an increase in steam production hence temperature of the cooling water and a higher water velocity target. The model suggests that the power station operation managers could consider an optimisation by balancing generating power production with bioreactor flow, while remaining within the resource consent limit. The test results suggest that during warmer months, the pumps could be operating at lower rates. The energy required could be less and consent requirements would still be met.

8 CONCLUSIONS

- The extension of the ASM1 water model to include sulphur bio-oxidation reactions was successfully implemented. The model was simplified to include aerobic biofilm processes only; additional anaerobic sulphur reducing processes were not considered.
- An implementation of a simulation model of the Wairakei pilot pipe reactor using GPS-X with the extended ASM1 model was successful.
- The predicted curve from the model, was calibrated against pilot trial data and fits within the observed limits. Improved calibration could be achieved by addressing assumptions from Section 5.1 and validating using current power station performance monitoring data.
- The bioreactor performance was simulated for different flow velocities and temperatures and the results align with fundamental engineering principles regarding residence time and effect of temperature on bacteria growth rate.
- Theoretically the model suggests that the Wairakei Bioreactor could be run at higher rates when the temperature is increased. Alternately the flowrate through the bioreactor could be reduced during higher water temperature, allowing a saving in pumping energy.
- The performance of the reactor could also be evaluated for change in biofilm thickness (detachment rate) and disturbance variables such as alkalinity/pH/dissolved CO_2 to determine how levels of CO_2 in the non-condensable gases that mix with the cooling water affect the rate of reaction.
- Additional evaluation of the biofilm model is required to further understand the biokinetics of the sulphur transformations and to investigate the diffusion of soluble components into and out of the biofilm and their impact on the observed bulk water composition at the end of the bioreactor
- Further research should determine how this model can be applied to alternative biofilm reactor configurations.

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