THE FORECASTING OF HYDROGEN SULPHIDE GAS BUILD-UP IN SEWERAGE COLLECTION SYSTEMS

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ABSTRACT

The presence of hydrogen sulphide gas in sewerage collection systems is a common source of odour nuisance, corrosion of sewers and toxic atmospheres. The hydrogen sulphide build-up in the sewer air may be related to sulphide concentrations in the flowing sewage and with other factors, such as turbulence, aerodynamic conditions of the ventilating air flow and roughness of the unsubmerged surfaces.

In the present work, a mathematical model is presented for forecasting hydrogen sulphide gas build-up along gravity sewers, which is based on the analysis of a differential mass balance equation applied to a sewer reach. Good correlation was obtained, comparing the results of the model with experimental information collected in the Funchal main trunk sewer. Funchal city is the capital of Madeira, a Portuguese island in the middle of the Atlantic Ocean, and its main trunk sewer was put into operation at the beginning of 1980.

KEYWORDS

Sewage; sewers; hydrogen sulphide gas; modelling.

INTRODUCTION

Hydrogen sulphide is a gas of only moderate solubility, that can escape into the air in manholes, pump-wells, and gravity sewers, or into the atmosphere above the sewerage system. Hydrogen sulphide is toxic at relatively low concentrations and is also a potential source of odour nuisance. It is corrosive to metal and it may be oxidised on moist surfaces to sulphuric acid which can attack concrete surfaces, in some cases leading to complete collapse of sewers in less than 5 years. This deadly gas, whose toxicity has been ranked with hydrogen cyanide (U.S. Environmental Protection Agency, 1985) seems to have been responsible for the death of sewer system workers at concentrations as low as 0.03% (300 ppm, or 300 parts per million in a volume basis).

The factors governing the formation of sulphide in sewerage systems have been studied intensively, and predicting equations, both for gravity sewers and pressure mains, have been proposed in the last four decades, particularly by Pomeroy (1959), Thistlethwayte (1972), Boon and Lister (1975), Pomeroy and Parkhurst (1977) and Nielsen and Hvited-Jacobsen (1988).

Concerning hydrogen sulphide build-up in the sewer atmosphere, it is related to sulphide concentrations in the sewage and with other factors, like pH, turbulence of the flow, aerodynamic conditions of the ventilating air and roughness of the unsubmerged surfaces.

In the present work, a mathematical model is presented, in order to predict hydrogen sulphide gas
build-up along gravity sewers. This model was applied, with promising results, to the Funchal city main trunk sewer, where experimental information had been previously collected.

**OCCURRENCE OF HYDROGEN SULPHIDE GAS IN SEWERS**

The serious odour and corrosion problems associated with collection, handling and treatment of domestic sewage are, in general, the result of the reduction of sulfate to sulphide under anaerobic conditions.

The distinction between the different types of sulphide compounds is significant because only the hydrogen sulphide (H₂S) can escape from solution and create odour and corrosion problems. When dissolved in water, hydrogen sulphide is partially ionised, so that it exists as a mixture of H₂S and HS⁻ (the ion S⁻ also exists in water, but not in appreciable amounts, except in solutions in which the pH is above 12). The proportions depend principally upon the pH of the solution and, to a lesser extent, on the temperature and mineral content of the water. In sewage, sulphide may be present partly in solution and partly as insoluble metallic sulphides, carried along as part of the suspended solids. If the sewage is of residential origin, the amount of insoluble metallic sulphide does not ordinarily exceed 0.2 to 0.3 mg/l (Pomeroy, 1990).

Part of the hydrogen sulphide that escapes, as a gas, from solution, may be oxidised on exposed surfaces, if the environmental conditions are adequate. Under moist conditions, a species of bacteria named *thiobacillus concretivoros* oxidises it to sulphuric acid by the reaction:

\[
H₂S + 2O₂ \rightarrow H₂SO₄
\]  

(1)

If the pipe is made of a cement-bonded material or any acid-susceptible substance, the acid may partly or entirely react. The fraction of acid remaining on the walls is then neutralised by the acid-consuming substances of the vulnerable material. The other fraction falls, under gravity action, into solution where it changes again to sulphate ion.

The fraction of the hydrogen sulphide gas that is released from solution and is not condensed nor oxidised on the pipe walls, escapes from the sewerage system into the atmosphere above, or remains in the sewer air, leading to a general increase of concentration within the confined atmosphere of the system.

**HYDROGEN SULPHIDE GAS MODELLING**

For prediction of hydrogen sulphide gas balance in sewer air, the quantity of gas released from solution and the quantity of gas transferred to the unsubmerged pipe walls must be computed.

**Hydrogen Sulphide Gas Release**

In enclosed vessels containing dissolved hydrogen sulphide at equilibrium, the concentration of hydrogen sulphide gas will vary according to Henry's law. Under normal atmospheric conditions that concentration may be given to close approximation by the following empirical equation (Matos, 1991):

\[
C_{eq} = (3.79 \times 10^{-5}T^2 + 7.64 \times 10^{-3}T + 0.197) [H₂S]
\]  

(2)

where

- \(C_{eq}\) = hydrogen sulphide concentration at equilibrium in the air, g/m³,
- \(T\) = temperature, °C,
- \([H₂S]\) = dissolved hydrogen sulphide concentration, mg/l.

The emission of sulphide from the sewage is a process involving a driving force proportional to the relative concentrations of hydrogen sulphide respectively in the sewage and in the sewer air.

Under typical conditions, Pomeroy (U.S. Environmental Protection Agency 1985) has developed an equation to predict the flux of hydrogen sulphide from the stream surface in sewerage systems. That equation may be presented in the following way:
Hydrogen sulphide gas build-up in sewerage collection systems

\[ dsf = 0.69 \, CA \, (su)^{(3/8)} \, [H_2S] \, (1-q) \]  

where

- \( dsf \) = flux of hydrogen sulphide from the stream surface, g/m\(^2\)·h,
- \( CA \) = factor representing the effect of turbulence in comparison to a slow stream \((1 + 0.17 \, u^3/(g \, dm))\), dimensionless,
- \( g \) = gravitational constant = 9.8 m/s\(^2\),
- \( dm \) = mean hydraulic depth, m,
- \( s \) = slope of the energy grade line of the stream, m/m,
- \( u \) = stream velocity, m/s,
- \( q \) = relative hydrogen sulphide saturation in the air compared to equilibrium concentration, expressed as decimal fraction, equal to \( CH/CH_{eq} \), in which \( CH \) is the local hydrogen sulphide gas concentration, dimensionless,
- \([H_2S]\) = dissolved hydrogen sulphide concentration, mg/l.

**Hydrogen Sulphide Transfer to the Pipe Walls**

Above the sewage level, the surfaces are usually damp, because of condensate from the sewer atmosphere, infiltration of ground water, incidental wetting by the sewage or capillary water drawn up by walls. The gas transferred from the sewer atmosphere brings the necessary sulphur into the moisture film where it can be utilised by the acid-forming organisms to produce sulphuric acid.

When a fluid is in a state of turbulent flow in a conduit, such as ventilating air moving through a sewer, there will be a thin film of the fluid air adjoining the conduit wall or wall moisture in a state of laminar flow, so that the filaments or layers of flowing air move parallel to the wall without mixing eddies. The hydrogen sulphide in the turbulent body of the air stream passes through the laminar layer to the moisture film on the wall by molecular diffusion, as opposed to eddy diffusion in the main air stream. This laminar layer offers a resistance to the hydrogen sulphide transfer to the pipe walls that is directly proportional to its thickness, and inversely proportional to the hydrogen sulphide gas diffusivity in the air.

According to Thistlethwayte (1972) the flux of hydrogen sulphide to the pipe walls may be given by the following equation:

\[ dsw = D_H \, (CH - CH_p)/Tc = D_H \, CH \, (1-fp)/Tc \]  

where

- \( dsw \) = flux of hydrogen sulphide to the pipe walls, g/m\(^2\)·h,
- \( D_H \) = hydrogen sulphide gaseous diffusivity, assumed constant, 58x10\(^{-3}\) m\(^2\)/h,
- \( CH \) = concentration of hydrogen sulphide in sewer atmosphere, g/m\(^3\),
- \( CH_p \) = concentration of hydrogen sulphide in wall moisture interface, g/m\(^3\),
- \( Tc \) = thickness of the laminar layer, m,
- \( fp \) = relative hydrogen sulphide concentration in wall moisture interface, compared to concentration in the sewer atmosphere \((CH_p/CH)\). Under most circumstances of active corrosion, it is reasonable to assume \( fp = 0 \).

In equation (4), thickness may be computed according to Manzanares (1981):

\[ Tc = 32.8 \, \sqrt{air/(u_{air} \, f^{0.5})} \]  

(5)
with

\[
fn + 1 = 0.25 \log^2 \left( \frac{k}{(3.7 \, D_h) + 2.51 \, \nu_{\text{air}} \, D_h \, fn^{0.5}} \right)
\]  

(6)

where

\[
\begin{align*}
T_c &= \text{thickness of the laminar layer, m,} \\
\nu_{\text{air}} &= \text{kinematic viscosity of the air, assumed constant, } 1.5 \times 10^{-5} \, \text{m}^2/\text{s,} \\
u_{\text{air}} &= \text{velocity of the ventilating air, m/s,} \\
f &= \text{resistance factor or Darcy-Weisbach factor, iteratively computed by equation (6), dimensionless,} \\
fn, fn + 1 &= \text{values of the resistance factor in iterations } n \text{ and } n + 1 \text{ (the iterative process stops when } fn \text{ and } fn + 1 \text{ are approximately equal),} \\
k &= \text{equivalent surface roughness, m,} \\
D_h &= \text{hydraulic diameter, equal to four times the hydraulic radius, corresponding to the air flow, m.}
\end{align*}
\]

Hydrogen Sulphide Build-up Along Sewer Atmosphere

Well ventilated structures may be kept dry enough to prevent biological action from occurring. When this happens, oxidation of hydrogen sulphide will not occur and its concentration along the sewer atmosphere will increase, approaching the equilibrium concentration given by equation (2). Nevertheless, in the general situation, part of the hydrogen sulphide escaping from the sewage is simultaneously taken-up and oxidised on the sewer walls, thus initiating and maintaining corrosion activity. In those circumstances, the concentration of that gas in the sewer air has a tendency to attain a balancing condition, in which the concentration is greater than zero but lower than the equilibrium concentration given by Henry’s Law.

When the balancing concentration is reached, the quantity of gas released from the sewage equals the quantity of gas transferred to the pipe walls. If the quantity of gas escaped from solution is the bigger one, the hydrogen sulphide concentration along the sewer atmosphere will increase; the opposite occurs when the quantity of gas moving to the pipe walls exceeds the quantity of sulphide released from the sewage.

Numerous experiments have already been made in which concentrations of hydrogen sulphide in sewage and in sewer atmospheres have been determined simultaneously. As already referred by Pomeroy and Bowlus (1946), it is characteristic in all such tests that the concentration of hydrogen sulphide in the air responds promptly to changes in the sewage, but when calculations are made of the amount of gas which would be in the air if it were in equilibrium with the liquid phase, it is found that the amount actually present only corresponds generally to 2 to 20 percent of the equilibrium concentration. This indicates a rapid removal of hydrogen sulphide from the sewer atmosphere, by oxidation on the pipe walls.

Assuming that no significant hydrogen sulphide quantities escape from the sewerage system, which is usually reasonable to accept, and considering a “slug” of air moving along a reach, a mass balance can be made as follows:

\[
Q_r = Q_{\text{ox}} + Q_{\text{inc}}
\]  

(7)

where

\[
\begin{align*}
Q_r &= \text{quantity of hydrogen sulphide gas released from the sewage, g,} \\
Q_{\text{ox}} &= \text{quantity of hydrogen sulphide transferred to the pipe walls, g,} \\
Q_{\text{inc}} &= \text{quantity of hydrogen sulphide that remains within the sewer atmosphere, leading to a general concentration increase, g.}
\end{align*}
\]

Developing equation (7), may be obtained,
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\[ \text{dsf} \frac{dl}{b dt} = \text{dsw} \frac{dl}{p_1 dt} + \text{dCH} A_1 \frac{dl}{dt} \]  

or

\[ \text{dsf1} (1-C_H/\text{Ceq}) \frac{dl^2}{u_{air}} = \text{dsw} \frac{dl^2}{p_1 u_{air}} + \text{dCH} A_1 \frac{dl}{dt} \]

or

\[ \frac{dl}{dt} = A_1/b \frac{u_{air}}{\text{dCH} ([\text{dsf1}(1-C_H/\text{Ceq})-\text{dsw} p_1/b]} \]

where

- \( \text{dsf} \) = flux of hydrogen sulphide escaped from solution, \( g/m^2\cdot h \),
- \( \text{dsf1} \) = flux of hydrogen sulphide that would escape from solution, if the hydrogen sulphide concentration in the air, were zero, \( g/m^2\cdot h \),
- \( dl \) = infinitesimal length of the reach, \( m \),
- \( b \) = surface width of the stream, \( m \),
- \( dt \) = travel time of the air along the reach, \( h \),
- \( \text{dsw} \) = flux of hydrogen sulphide to the pipe walls, \( g/m^2\cdot h \),
- \( p_1 \) = unsubmerged perimeter, \( m \),
- \( u_{air} \) = velocity of the ventilating sewer air, \( m/h \),
- \( \text{dCH} \) = (\( \text{CH}_2-\text{CH}_1 \)) = increase of hydrogen sulphide concentration in the sewer air along the reach,
- \( A_1 \) = unsubmerged area of the sewer, or ventilating area, \( m^2 \)

As the "slug" of air moves along the sewer, the hydrogen sulphide build-up can be obtained by integration of the differential equation (10). That equation has the following analytical solution:

\[ \text{CH}_2 = (\text{CH}_1 \text{aux1} - \text{dsf1}) \exp (-\text{aux2}) + \text{dsf1}/\text{aux1} \]  

\[ \text{aux1} = (\text{dsf1}/\text{Ceq}) + \text{DH} p_1 (1-\text{fp})/(\text{Tc} b) \]  

\[ \text{aux2} = (L b \text{aux1})/(A_1 u_{air}) \]

where \( \text{CH}_1 \) (\( g/m^3 \)) and \( \text{CH}_2 \) (\( g/m^3 \)) are the gaseous hydrogen sulphide concentrations respectively upstream and downstream of the reach, \( L \) (\( m \)) is the length of the reach and \( \text{aux1} \) and \( \text{aux2} \) are calculation functions. The others symbols \( \text{dsf1} \) (\( g/m^2\cdot h \)), \( \text{Ceq} \) (\( g/m^2 \)), \( \text{DH} \) (\( m^7/h \)), \( p_1 \) (\( m \)), \( \text{fp} \) (-), \( \text{Tc} \) (\( m \)), \( b \) (\( m \)) and \( A_1 \) (\( m^2 \)) were already defined in this paper.

RELIABILITY OF THE MODEL

Case studies comparing the results predicted by sulphide generation and hydrogen sulphide gas build-up with observed conditions in sewers establish the reliability of forecasting models. Because the factors controlling sulphide generation in sewers are so complex, it would be unrealistic to expect that sulphide concentrations can be accurately predicted on an hour-by-hour basis (American Society of Civil Engineers, 1989). As for hydrogen sulphide gas balance in sewers, prediction is even more complex, because it depends not only on sulphide build-up in sewage but also of other factors difficult to determine, such as turbulence conditions and natural ventilation. Nevertheless, the results may be adequate for many design and operation purposes, and for identifying critical reaches or predicting the effect of corrective measures on the overall behaviour of the sewerage collection systems.

In this paper, the Funchal "case study" is presented. Funchal is the capital of the island of Madeira, a piece of Portuguese land in the middle of the Atlantic Ocean.

The city and its suburbs together have nowadays some 100,000 inhabitants. After the great part of its
main trunk sewer was placed into operation, at the beginning of 1980, problems with hydrogen sulphide have arisen and odour complaints became frequent in certain areas. The Funchal main trunk sewer is approximately 10 km long, and consists of protected concrete pipe varying from 700 mm to 1500 mm in diameter. The sewer is essentially gravitational, but receives sewage from two pumping stations, and includes two inverted siphons. The Funchal main trunk sewer is schematically presented in Figure 1.

![Diagram of Funchal main trunk sewer]

**Fig. 1.** Schematic representation of the main trunk sewer of Funchal city.

During the last decade a survey of the Funchal sewerage collection system was made, and temperature, pH, electrical conductivity, redox potential, dissolved oxygen and sulphide concentrations were measured along the main trunk sewer. Measured values were used to calibrate the predictive models for subsequent use in the design of corrective procedures and hydrogen sulphide gas in the sewer air was also evaluated, particularly under Rua Carvalho Araújo, an area where odours were more intensive and complaints were more frequent. In the trunk sewer atmosphere under that area, concentrations of hydrogen sulphide gas between 5 and 15 ppm were measured. Upstream of those critical reaches the measured concentrations were lower, and downstream, because of the entry of fresh flows and because of reaeration caused by some significant falls, dissolved sulphide and hydrogen sulphide gas concentrations in sewer air decreased to zero.

For modelling hydrogen sulphide build-up, equations (11) to (13) were included in a general model developed as follows.

1) Sulphide build-up in the two pressure mains were predicted according to Pomeroy (1959), with the empirical coefficient of the equation calibrated to the local conditions.

2) Sulphide build-up in the gravity sewer was predicted according to Pomeroy and Parkhurst (1977), using the less conservative empirical coefficients in the equation developed by those authors.

3) Oxidation of dissolved sulphide in the septic sewage caused by oxygen carried by fresh sewage and falls was evaluated, assuming that 50 percent of the available oxygen might be used by the sulphide.

4) Velocity of sewer air in the gravity sewer was evaluated according an empirical equation calibrated with experimental data obtained by Pescod and Price (1982).

The results, which are presented in Figure 2, represent qualitatively well hydrogen sulphide gas build-up in the sewer atmosphere, principally in what concerns the identification of the critical reaches and the effect of rapid decrease of gas concentrations downstream of section 7.
CONCLUSIONS

The emission of hydrogen sulphide into the sewer atmosphere and into the atmosphere above the sewerage system is an essential step in the overall chain of processes associated with sulphide problems, particularly occurrence of odour nuisance, health hazards and corrosion of sewers. It is important, therefore, to have adequate models to predict sulphide build-up in the sewage, corrosion of the conduits and gaseous hydrogen sulphide concentrations in the sewer atmosphere. A lot of experimental and theoretical work has already been done for forecasting sulphide build-up and corrosion, and experimental studies indicate that those models are, in certain circumstances, relatively accurate. Forecasting hydrogen sulphide concentrations in the sewer air is even more complex, and much less work has been developed on this topic.

In this paper, a mathematical model is presented, in order to predict hydrogen sulphide gas build-up along sewer atmospheres. The original model is based on the integration of a mass balance differential equation, and was applied, with promising results, to the Funchal city main trunk sewer, where a survey and experimental data had been previously collected.

REFERENCES


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