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Grzegorz ŁAGÓD[1], Henryk SOBCZUK[1],
Zbigniew SUCHORAB[1] and Marcin WIDOMSKI[1]

# FLOW PARAMETERS EFFECTS ON AEROBIC BIODEGRADATION OF POLLUTANTS IN SEWER SYSTEM

## WPŁYW NAPEŁNIENIA KOLEKTORA KANALIZACJI GRAWITACYJNEJ NA PRZEBIEG TLENOWYCH PROCESÓW BIODEGRADACJI ZANIECZYSZCZEŃ

**Abstract:** The interceptor of urban wastewater should be treated as a collector and transporter of sewage and also as a bioreactor, with a continuous inflow, growth and washing out of biomass. Specific sewage biodegradation processes were described by suitable mathematical models of biomass growth and decay. For given system it is possible to compose the matrix of integrated process of organic substance transformation in the gravitational sewer system. Numerical model based on described processes contains stoichiometric and kinetic parameters of sewage biodegradation appropriate to living microfauna of saprobionts as a biological processing factor in sewer pipe and a precursor of activated sewage sludge in wastewater treatment plant. Complete numerical implementation of a model includes also a module of sewer channel hydrodynamic calculation based on Saint-Venant equation. As a last part of necessary modules advection-dispersion equation is used. This kind of model, makes it possible to demonstrate the changes of pollutants load change to the wastewater treatment plant through interceptor of a sewage system. It can be also used to predict influence of combined sewer overflows on receiving waters. This paper, based on the previous achievements is a case study to create a model describing the process of self-purification of urban sewage running in gravitational sewer in the presence of saprobiontic microfauna.

**Keywords:** sewer, physico-chemical sewage parameters, microbial transformation modelling, biodegradation of pollutants in sewer system, Saint-Venant equation, advection-dispersion equation

Heretofore, the researches' attention, concerning the problem of sanitation and wastewater treatment, was first of all focused on pollutants transformation processes inside *wastewater treatment plant* (WWTP) and its hydraulic transport through the sanitation system. Sewer system, in respect of its range, is the most expensive part of a municipal system of sewage removal. Despite the fact that sanitation system is often perceived as a simple manner of hydraulic sewage transport, many various complex

[1] Faculty of Environmental Engineering, Lublin University of Technology, ul. Nadbystrzycka 40B, 20–618 Lublin, Poland, phone: +48 81 538 43 22, email: G.Lagod@wis.pol.lublin.pl

processes occur inside it. These are the physical, chemical and biochemical processes, which greatly change the properties of sewage entering WWTPs [1–10]. In respect of their mentioned range the sanitation systems have a large capacity which, on account of low hydraulic loads during the major part of day, may be used in preliminary wastewater treatment [3, 6, 8, 9]. But the precise determination of biodegradation processes rate in particular sewage systems is still problematic. However, the most important biochemical transformations occurring inside sanitation are nowadays known [4–10], though we still lack the quantitative and qualitative data concerning relations and affiliations of all occurring processes and their influence on the technological processes of WWTPs.

## Influence of sewer processes on WWTP work regime

The studies cited above show that considerable development of knowledge concerning sewage transport and technology of biological wastewater treatment and taking place during last two decades introduced the fundamental changes in understanding and perception of processes connected to sanitation systems and operation of WWTPs based on biological treatment. It was noted that the biological processes, traditionally connected to the particular parts of WWTPs occur also at different locations and even outside the treatment plants, leading to appearance of different but sometimes noticeable effects which were unintentional by the designer.

A lot of complex processes occur between the point of sewage introduction to the system and WWTP, in effect of which the treatment plant may be reached by sewage of different parameters than assumed at the stage of WWTP technology design. Even in the nineties of XXth century the concentrations changes developed during sewage flow through sanitation system were connected to dilution by infiltration water. But in this case the pollutants load should not have been changed. The following studies [1, 3–10] reported its changes, so the designing assumptions of WWTP based on *population equivalent* (PE) for the extensive sanitation network cannot be fulfilled. The introduction of applicable corrective coefficients considering these transformations seems to be advisable. Such coefficients and proper designing guidelines allowing to roughly estimate the effects of pollutants biodegradation processes may be elaborated basing on field tests and model studies.

The proper elements should be functionally related together during the development of complex model of processes occurring inside the sanitation conduit. These elements are: local model of transformations caused by an active heterotrophic biomass in aerobic conditions, hydrodynamic model of sewage flow and advection–dispersion model of pollutants transport. The model completed in such a manner should be then supplied in the input parameters, boundary and initial conditions.

## Assumption of local model of sewage biodegradation inside sanitation pipes

The gravitational sanitation systems are in many aspects identical to WWTPs with biological treatment in terms of the dominant biochemical processes [6, 7, 9, 10]. The manner of modelling of sewage transformations caused by microorganisms settled sanitation, thus may be based on the Henze's [11] description of phenomena occurring inside wastewater treatment objects, where sewage are being treated by an active sludge. Some elements may also be based on river flow and self-purification models, however some important differences concerning the system definition and occurring processes as well as different validity of its several elements should be noted [6, 7, 9, 11–15].

The direct application of *Activated Sludge Models* (ASM) group to description of sanitation processes is not advisable because:

– different hydraulic conditions,

– biochemical transformations occurring simultaneously in suspended biomass and biofilm,

– diversity of substances limiting the biomass growth,

– lack of preliminary sedimentation process,

– direct influence of rainfall event on sanitation system,

– oxygen concentration in sewage dependent to reaeration through the free surface and inflow in diluted form included in wastewater.

Taking into account models used to descript water movement and biodegradation in watercourses one should notice the following differences:

– concentration of suspended biomass is clearly higher than in natural watercourses,

– microorganisms development is not limited by nutrients according to the high COD concentration in sewage,

– nitrification rate in sanitation is slower because the nitrifying biomass coating by sooner developing heterotrophs,

– clear daily hydraulic and pollutants load diversity in sewerage,

– no primal production in most sewage systems resulted from the lack of sunlight,

– well specified sanitation pipes geometry.

In order to describe the biodegradation processes of sewage inside sanitation gravitational conduit one has to entertain the microbiological transformations of organic substance in aerobic conditions. The aerobic conditions and suspended biomass as well as biofilm incidence are the assumption taken for the presented model. Providing for the most important properties of the modelled system and interactions among its basic parts is thus possible. The mentioned interactions cover: biomass development, biodegradable substances hydrolysis and consumption of dissolved oxygen. The sewage components are considered in aspect of biomass, substrates and acceptors for the electrons incoming from liquid phase and solids suspended in it. The biomass developed beneath sewage free surface is being taken into account. Heterotrophic biomass concentration in the liquid phase of sewage is usually low in comparison with the concentration of biomass in an active sludge and the amount of nutrients available for biomass inside sanitation pipes is usually relatively high. There is an easily biologically degradable substrate available in a raw sewage, accessible in such quantities that in most cases it does not limit the development of heterotrophic organisms biomass [6, 7, 9, 10, 12, 14–16].

The *in situ* research on full scale sanitation systems showed that biofilm is a very important factor in the process of sewage biodegradation [6, 7, 9–12]. In some cases the participation of biofilm in sewage biodegradation may be higher than the suspended biomass. It is possible during the phases of flow with low shear stress and low conduit filling.

The additional element also taken into account in the presented model is temperature, which is a very important factor because it influences the enzymatic activity of microorganisms and oxygen solubility in wastewater.

## Sewage reaeration in gravitational sanitation

The degree of sewage aeration matters considerably in case of aerobic processes of pollutants biodegradation conducted by heterotrophic biomass inside the sanitation system. This degree depends on many factors, among which, the most important are: oxygen concentration in air over sewage free surface, area of contact between air and sewage and hydraulic properties of flow [17–19].

The sanitation networks designing guidelines [17] show that relative depth of filling should not exceed 0.8 ratio of the total pipe inner diameter to prevent sewage from rotting. The incomplete filling of conduit asserts the appearance of air zone in the upper part of canal cross-section which makes the reaeration of sewage possible.

As a results of theoretical studies supported by experimental data, the formulas describing sewage reaeration inside gravitational sanitation conduits were developed.

The basic equation is presented as [6, 7, 9, 10]:

$$\rho_{rea} = aK_L a(20)\,(\beta S_{OS} - S_O)\,a_r^{(T-20)},$$

where:
- $\rho_{rea}$ – oxygen transfer rate [g m$^{-3}$d$^{-1}$],
- a – coefficient providing for detergents impact, usually about 0.95 [-],
- $a_r$ – coefficient providing for temperature impact on reaeration, usually about 1.024 [-],
- $\beta$ – coefficient of different oxygen solubility in sewage and clear water, usually between 0.8–0.95 [-],
- $S_O$ – dissolved oxygen concentration [g m$^{-3}$],
- $S_{OS}$ – saturation concentration of dissolved oxygen in sewage, in equilibrium to atmosphere [g m$^{-3}$].

The empirical formula developed to term the general oxygen transfer coefficient $K_L$ a(20) in gravitational sanitation may be written as follows [6, 7, 9, 10]:

$$K_L\,a(20) = 0.86\,(1 + 0.2Fr^2)\,(sU)^{3/8}\,H^{-1},$$

where:
- Fr – Froude number [-],
- U – mean velocity [m s$^{-1}$],
- s – conduit bottom inclination [m m$^{-1}$],
- H – mean hydraulic depth = A/B [m].

## Processes connected to heterotrophic biomass activity

The researches conducted on real working objects showed that biofilm is a very important factor in discussed process [6, 7, 10, 12]. In some cases its share in sewage biodegradation may be higher than the part of suspended biomass, eg during the flow of low shear stress and low filling of the sewage conduit. The additional factor considered in presented model is temperature which is very important because its influence on enzymatic activity of microorganisms.

In order to describe the biofilm heterotrophic biomass development rate in aerobic conditions, the deterministic model based on information contained in [4, 7, 9] may be used:

$$\rho_{Bf} = k_{1/2} S_O^{1/2} \frac{Y_{Hf}}{1 - Y_{Hf}} \frac{S_S}{K_{Sf} + S_S} \frac{A_{Bf}}{V} a_f^{(T-20)},$$

where: $k_{1/2}$ – half-order rate constant [g $O_2^{1/2}$ $m^{-1/2}$ $d^{-1}$],
$S_O$ – dissolved oxygen concentration [g $O_2$ $m^{-3}$],
$Y_{Hf}$ – yield constant for $X_{Bf}$ [g COD g $COD^{-1}$],
$K_{Sf}$ – saturation constant for readily biodegradable substrate in biofilm [g COD $m^{-3}$],
$A_{Bf}/V$ – wetted biofilm surface area divided by the water volume = $R_h^{-1}$ [$m^{-1}$].

The development of heterotrophic biomass suspended in sewage is limited by the quantity of available biodegradable diluted fraction and dissolved oxygen in sewage. Basing on ASM No. 1 model the rate of development $\rho_z$ may be written as follows:

$$\rho_z = \mu_H \frac{S_S}{K_S + S_S} \frac{S_O}{K_O + S_O} X_{Bz} a^{(T-20)},$$

where: $\mu_H$ – maximum specific growth rate of heterotrophic biomass [$d^{-1}$],
$S_S$ – readily biodegradable substrate [g COD $m^{-3}$],
$K_S$ – saturation constant for readily biodegradable substrate $S_S$ [g COD $m^{-3}$],
$K_O$ – saturation constant for dissolved oxygen [g $O_2$ $m^{-3}$],
$X_{Bz}$ – heterotrophic active biomass in suspension [g COD $m^{-3}$],
a – temperature coefficient for the water phase process [-],
T – temperature [$^oC$].

The required maintenance energy covers the energy necessary to conduct life processes of biomass in wastewater. It shows that consumption of nutrients and oxygen do not cause the increase of microorganism mass.

The described energy is collected from dissolved biodegradable fraction of COD and in case of its absence by endogenic respiration. The presented relations ma be written as follows [7, 9]:

$$\rho_m = q_m \frac{S_O}{K_O + S_O} X_{Bz} a^{(T-20)},$$

where: $q_m$ – maintenance energy requirement rate constant [$d^{-1}$].

Considering the hydrolysis of n suspension fraction (individual hydrolysis at different rate) in sewage under the influence of suspended biomass and biofilm enzymes at given temperature, the following equation for rate of this process r may be written [7, 9]:

$$\rho_{h,n} = k_{hn} \frac{X_{Sn} / X_{Bz}}{K_{Xn} + X_{Sn} / X_{Bz}} \frac{S_O}{K_O + S_O} \left( X_{Bz} + \varepsilon X_{Bf} \frac{A_{Bf}}{V} \right) a^{(T-20)},$$

where: $k_{hn}$ – hydrolysis rate constant, fraction n [$d^{-1}$],
$K_{Xn}$ – saturation constant for hydrolysis, fraction n [g COD g $COD^{-1}$],
$X_{Sn}$ – hydrolysable substrate, fraction n [g COD $m^{-3}$],
$X_{Bf}$ – heterotrophic active biomass in biofilm [g COD $m^{-2}$],
$\varepsilon$ – efficiency constant for the biofilm biomass [-].

## Integrated process matrix

The presented equation of sewage reaeration rate, along with description of the other processes resulting in pollutants biodegradation with corresponding stoichiometric coefficients may be written as a processes matrix [9, 15, 20]. This matrix organizes and presents in clear manner the description of biochemical transformations occurring in the unit volume of gravitational sanitation conduit. This integrated process matrix contains the set of first order differential equations written in form of matrices and vectors.

The specific sewage biodegradation processes were described by suitable mathematical models of biomass growth and decay. For presented system it is possible to compose the matrix of integrated process of organic substance transformation in the gravitational sewer system. Numerical model based on the described processes contains stoichiometric and kinetic parameters of sewage biodegradation appropriate to living microfauna of saprobionts as a biological processing factor in sewer pipe and a precursor of activated sewage sludge in WWTP.

Table 1

Integrated process matrix – model concept, process kinetics and stoichiometry for sewage biodegradation caused by biofilm and suspended biomass [6, 7, 9, 10]

| | Process | Component | | | | | Process rate $\rho j$ |
|---|---|---|---|---|---|---|---|
| | | 1 ($S_S$) | 2 ($X_{S1}$) | 3 ($X_{S2}$) | 4 ($X_B$) | 5 ($-S_O$) | |
| 1 | Reaeration | | | | | –1 | $\rho_{rea}$ |
| 2 | Biofilm biomass growth | $-1/Y_{Hf}$ | | | 1 | $(1-Y_{Hf})/Y_{Hf}$ | $\rho_{Bf}$ |
| 3 | Suspended biomass growth | $-1/Y_{Hz}$ | | | 1 | $(1-Y_{Hz})/Y_{Hz}$ | $\rho_z$ |
| 4 | Maintenance energy requirement | –1 | | | –1* | 1 | $\rho_m$ |
| 5 | Hydrolysis, n = 1 | 1 | –1 | | | | $\rho_h$ n = 1 |
| 6 | Hydrolysis, n = 2 | 1 | | –1 | | | $\rho_h$ n = 2 |

* If $S_S$ is not sufficiently available to support biomass needs maintenance energy requirement is taken from $X_B$.

## Sewage flow and biodegradation in gravitational sanitation conduit

Simulations of sewage biodegradation processes require the suitable input data considering hydraulic conditions of sewage transport in sanitation conduit. The calculations are conducted for already existing or designing pipe, thus its shape, diameter, inclination and material are already known. It is possible, basing on the mentioned data, to assign sort of movement and calculate sewage flow velocity for assumed or measured sewage filling in case of different degree of channel deterioration and to relate obtained values to the flow rate. The introduced data allow to obtain information about the value of shear stress, dimensionless quantity (eg Froude number) describing the type of movement and area of contact between flowing sewage and pipe material. These variables, along with the others, which may be determined for the object presented at schematic Fig. 1, allow to run the simulation based on constructed by the Authors calculating module.

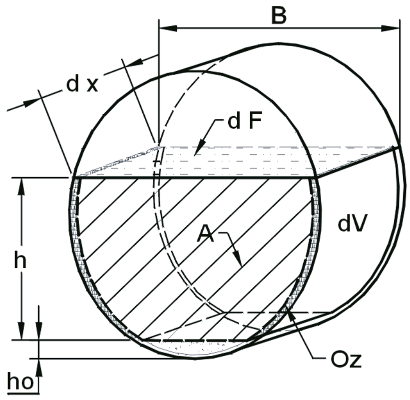


Fig. 1. Parameters connected to geometry and hydrodynamics of sewage conduit, influencing wastewater biodegradation [9, 15]

One of the most interesting cases possible to simulate with the presented model is the influence of mean sewage depth H on the process of aerobic sewage biodegradation. This case is so interesting because H considered as a border condition influences on flow velocity, decreasing the time of pollutants transport, and changing the relation between biofilm to the volume of flowing sewage. At the case of high sewage filling the relatively small area of wastewater free surface falls to the huge sewage volume, thus the rate of sewage reaeration is decreased.

## Model of gravitational conduit

The numerical model developed on the basis of matrix presented in Table 1 uses kinetic and stoichiometric process parameters of sewage biodegradation, reflects the saprobes biomass settled sanitation system. The mentioned biomass is being treated as a biological process factor of transformations occurring inside the sanitation conduits and as a progenitor of an active sludge in WWTP.

The complete numerical implementation of a model includes also a module of sewer channel hydrodynamic calculation based on Saint-Venant equation system:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + g\frac{\partial H}{\partial x} = g(s - S)$$
$$\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}(UH) = 0.$$

The S parameter included in the above set, describing waves propagation in open channels at their unit width, may be written as follows:

$$S = \frac{n^2}{H^{4/3}}|U|U.$$

However, in engineering practice the other independent variables are commonly used. The flow rate and free surface coordinates are used instead of flow velocity and sewage depth. Considering the influence of velocity distribution diversity at cross section β, and marking the cross section area as A, flow rate as Q, we must notice that considered variables refer to the whole cross section of a pipe and are properly interpreted. So, U is a mean flow velocity at given cross section and S is an inclination of energy line reflected to the whole cross section – connected to the hydraulic radius $R_h$ and roughness coefficient of inner side pipe walls material, which may be presented as [9, 18, 19]:

$$U(x,t) = \frac{1}{A}\iint_A u(x,y,z,t)\,dA = \frac{Q}{A}$$
$$S = \frac{n^2}{R_h^{4/3}}|U|U,$$

where: $R_h$ – hydraulic radius, which is a relation of cross-section area A to the wetted perimeter $O_Z$ – the peripheral length of contact between transported sewage and pipe material.

The results of hydrodynamic calculations allow to obtain the necessary data to simulate the dynamical processes described by the advection–dispersion equation with source element. The source element contains the described above integrated bio-chemical processes matrix.

The general form of advection-dispersion transport equation of passive substances for the variable cross-section of the canal can be described in the following way [9, 18, 19]:

$$\frac{\partial}{\partial t}(AC)+\frac{\partial}{\partial x}(QC)-\frac{\partial}{\partial x}\left(AD^{D}\frac{\partial C}{\partial x}\right)+A\delta=0,$$

where: $C(x,t)=\int_A c\,dA/A$ – cross section mean pollution concentration,

$U(x,t)=\int_A u\,dA/A$ – cross section mean flow velocity,

$Q = UA$ – volumetric flow rate,

$A$ – surface of the active cross section,

$D^D$ – coefficient of longitudinal mass dispersion,

$\delta$ – source part determining the intensity of generation or pollution decline in sewage.

Assuming that no side inflows occur it is possible to write:

$$\frac{\partial C}{\partial t}+U\frac{\partial C}{\partial x}-\frac{1}{A}\frac{\partial}{\partial x}\left(D^{D}A\frac{\partial C}{\partial x}\right)+\delta=0,$$

where: $\delta$ – in presented model could be represented by processes described in Table 1.

To present results of simulations in understandable form it is necessary to chose only the most important parameters which we want to analyze. In the described numerical model it is possible to examination influence more than 20 input parameters on biodegradation processes in sewer. During the results visualization the most convenient way of data presentation is to plot pollutants fraction changes in the function of sewer pipe length or other process parameter.

## Summary and conclusions

The presented model, makes possible demonstration of the dynamics of pollutants load change delivered to the wastewater treatment plant through interceptor of a sewage system. It can be also used to predict influence of combined sewer overflows on receiving waters.

The simultaneous modelling of sewage flow and biochemical processes allows to get more precise determination of heterotrophic microorganisms development conditions, both in suspended biomass and biofilm attached to pipe walls.

The determination of pollutants transformations degree due to known conduit shape and length as well as flow parameters, is thus possible.

This property enables an easy adaptation of the presented numerical model to simulation of biodegradation processes of sewage characterized by the different physical and chemical parameters and transported through sanitation conduits of known geometry.

This paper, basing on the previous achievements, is a case study to create a model describing the process of aerobic biodegradation of urban sewage running in gravity sewer in the presence of saprobe biomass.

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**WPŁYW NAPEŁNIENIA KOLEKTORA KANALIZACJI GRAWITACYJNEJ NA PRZEBIEG TLENOWYCH PROCESÓW BIODEGRADACJI ZANIECZYSZCZEŃ**

Wydział Inżynierii Środowiska
Politechnika Lubelska

**Abstrakt:** W grawitacyjnych systemach kanalizacyjnych zachodzą procesy zarówno fizyczne, chemiczne, jak i biologiczne. Biodegradacja ścieków, prowadząca do rzeczywistego ubytku ładunku zanieczyszczeń podczas ich przepływu w kanalizacji, jest ważnym procesem zmieniającym ilość i jakość niesionych zanieczyszczeń. Stąd też kolektor grawitacyjny powinien być traktowany zarówno jako tlenowo-beztlenowy reaktor biologiczny, jak i urządzenie do zbierania i transportu ścieków. W prezentowanej pracy proces biodegradacji ścieków opisano za pomocą modelu matematycznego wzrostu i rozwoju populacji mikroorganizmów, który stanowi człon źródłowy w równaniu adwekcji-dyspersji. Parametry hydrodynamiczne powiązane z wysokością napełnienia kolektora grawitacyjnego systemu kanalizacyjnego, wykorzystywane w symulacjach, są obliczane za pomocą równania Saint-Venanta. Prezentowany model może być pomocny podczas określania dynamiki zmian ładunków zanieczyszczeń dopływających do oczyszczalni poprzez kolektory systemu kanalizacyjnego oraz prognozowania oddziaływania przelewów burzowych na wody odbiornika.

**Słowa kluczowe:** błona biologiczna, kanalizacja grawitacyjna, biodegradacja ścieków w kanalizacji