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DETERMINATION OF HYDRODYNAMIC MODEL BASED ON TRACER TEST PERFORMED IN WWT PLANT IN KĘDZIERZYN KOŹLE, POLAND

Analysis results of lithium chloride concentrations, which were measured during tracer test performed in wastewater treatment (WWT) plant placed in Kędzierzyn–Koźle, Poland, are presented in the paper. The considered WWT plant operates with a five-stage Bardenpho system for organic content reduction within activated sludge process (ASP). One of the significant factors, which have an impact on the efficiency of the ASP in a biological reactor, is its hydraulic behavior. In this study theoretical and actual retention times were determined by using of mathematical modeling. Three single and multi-stream dispersion models were applied, i.e. Tanks-in-Series, Extended Tanks-in-Series and a model based on the MARTIN method. Using the last model it was possible to identify multiple wastewater flows in the reactors, which include: main flow and short circuiting flows. Furthermore, it was stated that the theoretical retention times differ from the actual values, obtained through mathematical modeling.

KEYWORDS: Bardenpho WWT plant, HRT, tracer test, RTD modeling

1. INTRODUCTION

In recent years, in Poland, modernization of wastewater treatment (WWT) plants has been performed on a large scale. Old and worn out equipment was replaced with modern devices of high electrical efficiency and the measurement systems were expanded with new sensors of the latest generation. The key element, however, is reflected to interpretation of the measured signals by the overriding control system and determination of the impact on the efficiency of the WWT plant and in particular on the activated sludge process (ASP). Simulation studies, which are preformed on a model of ASP, enable to determine the effect of oxygen concentration in the reactors on the reduction of ammonium nitrogen. From the point of view of energy consumption optimization, it is important to limit the amount of aeration, which in turns affects the level of oxygen in the biological block. The main practical aim of the

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research works is to develop a set of methodologies and scripting libraries for to create an improved overriding control system, which will be then implemented in the considered WWT plant. Prior modeling of the ASP, however, first its hydrodynamic model needs to be determined. This model will determine the effectiveness and efficiency of chemical reactions taking place in the biological block. The crucial hydraulic parameters, which affect the hydrodynamic model, are the following: geometric design of the reactor, mixing parameters, existence of aeration, bafflers, viscosity of wastewater, retention time, flow rate, existence of short-circuiting, bypass and dead zones, where there is no mixing or no flow. Although some of these values can be determined theoretically other may by gained only through experiments, e.g. using the full scale tracer test [7]. The tracer test involves adding an appropriate substance into the reactor influent and measuring its concentration at the effluent, at some given time steps. Then, based on the gathered data, identification of the actual retention time and determination of the main flow and short circuiting flows and dead volumes in the reactor is possible. Transportation of the tracer particle through the tank depicts the hydraulic behavior of the reactor. Based on this phenomenon one can give statements about positive and negative effects, thus efficiency of the ASP in reactor. Short circuiting streams and dead volumes, if present, have an unfavorable effect on the WWT performance. By highly loaded plants it can cause bad conditions for biochemical reactions and growth of desirable microorganisms.

Various types of tracer are currently used for analysis of the hydraulic parameters in WWT plants. The most important issue is that the applied substance have to be soluble in water, should not undergo chemical reactions with the wastewater, should not occur or only in negligible concentrations in the wastewater, provided to the reactor, should had low toxicity and should not affect significantly the wastewater flow in the reactor. Currently two types of tracers are applied:

1. Dye tracers. Their advantage is the low level of detection, the relatively low price and the lack of their presence in wastewater provided to the reactor. The disadvantage is their sensitivity to bio- and photo- degradation [3]. An example of readily accessible dye is rhodamine, which was applied e.g. by [3, 17, 25, 26]. Examples of other dyes are: red eriochrome acid, fluorescein and eosin [1, 22, 23].
2. Salts. The most commonly used salts are solutions of lithium and bromide: sodium hydroxide, bromine, potassium hydroxide or lithium chloride. Their advantage is immunity to degeneracy [1, 4, 6, 14, 15, 17, 23, 24, 27, 28].

In the tracer test, results of which are presented in this paper, lithium chloride was applied.

There are two basic ways to provide tracer into the reactor: 1) in the form of a quite expensive step function, by which the tracer is added continuously for a period of time or 2) in form of an impulse, by which the whole tracer amount is added at once. The important parameters of the RTD curve can be determined by both methods, but the second one is more frequently used, which is mainly conditioned by lower costs associated with implementation of the experiment. A detailed description with a number of practical advices related to tracer test can be found e.g. in [7]. Description of mathematical models and analytical solutions can be found e.g. in [5, 10, 13, 16, 19]. A very good review work an interested leader can find e.g. in [12].

2. THE OBJECT UNDER STUDY

The object under study is the WWT plant in Kędzierzyn-Koźle, Poland, where a five-stage Bardenpho system is working. It consists of five reactors arranged sequentially: one anaerobic reactor, two anoxic and two aerobic. The scheme of the Bardenpho technology is presented in Fig. 1.

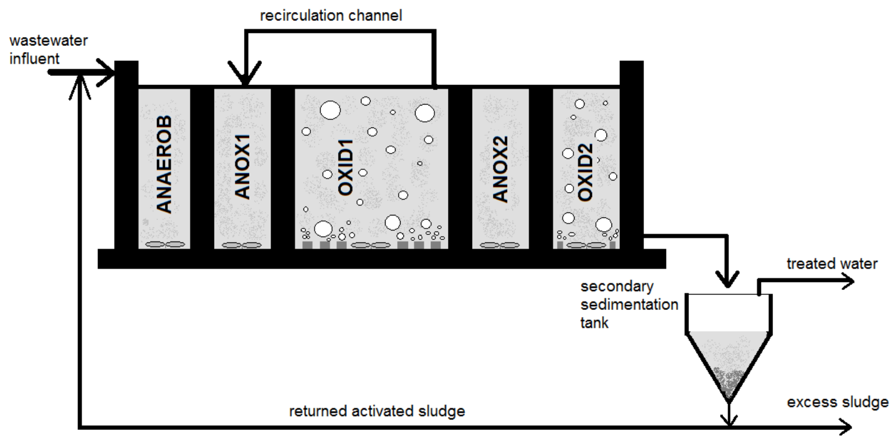

Fig. 1. Technological scheme of the 5-stege Bardenpho process, applied in the WWTP in Kędzierzyn-Koźle, Poland

Between the first anoxic and first aerobic chamber there is a recirculation of the wastewater. The first aerobic chamber allows additional denitrification of nitrate, which are produced by the nitrification processes in the anaerobic reactor. This process involves conversion of nitrates as electron acceptors with the carbon content. The second aerobic reactor, placed before the secondary settling tank, enables for reduction of nitrogen from wastewater provided to the separator. In addition, it limits the release of the phosphates in the secondary settling tank. Each of the reactors has different size. The first and fourth reactor consists of two independent chambers of the same shape. The second and third reactors are characterized by increased volumetric flow, what is related to the existence of recirculation channel, in which a mixer is mounted. In this way part of wastewater from the third chamber is recirculated to the second chamber. The mixer in the recirculation channel rotates at a speed of 300 rev/min. This value depends on the value of REDOX, which is registered in the second chamber. The first four reactors are equipped with mixers mounted inside. They rotate at speed of 150 rev/min and are designed for to maintain the mass, preventing sedimentation. The considered WWT plant is a mechanical-biological treatment plant, which occupies an area of approx. 8.2 ha. It was designed for daily average flows of 16 000 m^3/d and a daily maximum of 20000 m^3/d. The installed equipment has been dimensioned for a BOD5 load of 4000 kg O_2/d. This is an equivalent to 67 000 PE.

3. TRACER TEST AND THE RETENTION TIME

The tracer test was conducted in April 2014, from 7am to 5pm. The weather conditions were as follows: windless, no rain, air temperature at 7am was 1.5 ºC, and at 1pm was 10.9 ºC, humidity at morning was 86% and afternoon it was 57%. The wastewater temperature was 14.1 ºC. Wastewater pH value was equal to 8.7. The solution with tracer was prepared from 20 kg of lithium chloride and 20 l tap water. At 7:20 am, 35 l of the resulting solution was injected through the grid into the chamber distributing wastewater to the reactor no 1. At specified locations, near effluent, wastewater samples were taken. The total number of samples was 100.

In the scientific literature various non-ideal models applied for description of the actual hydraulic retention time distribution are presented. The most frequently used are the Tanks-in-Series (TIS) and modified models, which regard to the Continuous Stirred Tank Reactor (CSTR) [9, 10, 11, 12]. Another example constitutes the Plug Flow Reactor (PFR) model, which takes into account the dispersion phenomenon. Other, more complex methods allow for calculation of the volume of short-circuiting and “dead" zones within the reactor [2, 21, 27]. These “black box” models describe the hydraulics at a global level manifesting the actual state in the reactor. More details on the most common modeling algorithms, an interested reader can find e.g. in [8, 10, 11, 18, 20].

The mean time τ, which a tracer molecule stays in the reactor, often designated as hydraulic retention time (HRT), is the most essential hydraulic parameter in the analysis considered in this work. It is determined based on the retention time distribution (RTD). In Table 1 the calculated theoretical values of retention time in the five particular reactors of the biological block of WWT plant in Kędzierzyn-Koźle are summarized.

Table 1. Theoretical values of nHRT, dimensions of the particular reactors and information about mixers installed inside the reactor and flow rates

Parameter name	ANAEROB	ANOX I	OXID I	ANOX II	OXID II
Flow rate [m^3/min]	13.99	21.53	21.53	13.99	13.99
Volume [m^3]	1878	3165	6330	2133	550
nHRT [min]	134.24	147	294	152.47	39.31
Length [m]	14	23	46	15.5	4
Width [m]	32	32	32	32	32
Depth [m]	4.3	4.3	4.3	4.3	4.3
No of sliding mixers	4	8	4	4	2
Nominal power [kW]	2.2	2.2	7.5	2.2	7.5
Rotor diameter [mm]	845	840	1080	845	845
RPM	150	150	150	150	150

The actual retention time may be shorter than the theoretical value of nHRT. This happens in cases where there are dead zones in the reactor. The retention time may also be longer if the wastewater volume and/or the flow rate have been estimated inaccurately. Additionally, HRT depends on weather conditions, evaporation, and the degree of mixing (of both horizontal and vertical mixers), dispersion and hydraulic inefficiency. Hence the factual value of HRT changes in time, and these variations are depicted by the RTD curve. The retention time is one of the indicators, which determine the efficiency of wastewater treatment. The RTD may be influenced by differences in distribution of flow velocities, positioned vertically or horizontally in the reactor [11]. In the mixers area and around differently oriented flows (streams) turbulences may occur, which cause additional mixing, however with a much smaller impact. Furthermore, the wind acting in the water surface in the reactor may cause recirculation of wastewater, which in turn results with additional streams on greater depth. Some other effects on mixing have animals swimming in the wastewater [7].

4. MODELS FOR HRT DISTRIBUTION ESTIMATION

The WWT plant consists of five reactors of different functions. The tracer test was performed for each reactor. Thus, five timeruns of RTD were gathered. Due to specific operation and size of the particular reactors, three most popular models [2] were applied in this study:

1. The Tanks-in-series (TIS) model [2]. This reactor model assumes *N* same CSTR chambers put in series.
2. The Extended-Tanks-in-series (ETIS) model [2]. This model is an extension of the TIS model and enables for to model a non-integer number of tanks in the reactor.
3. The MARTIN method model [2]. This model involves N separate strands through the reactor, while each of it is assumed to be a TIS reactor. This model enables for determination of the main flow, which commonly is the biggest strand, and also the short-circuiting and bypass flows, as the other, smaller strands.

For calculations the MATLAB environment and the *ga* function was applied. The evolutionary algorithm implemented in the MATLAB toolbox enables for definition of arbitrary optimization function as well as for taking into account the boundaries (limits) and the linear and nonlinear conditions.

5. EXAMPLE RESULTS AND DISCUSSION

The obtained dependencies of tracer concentration, gathered from analyses of wastewater samples taken from the particular reactors are presented in Fig. 2. The curve obtained for the reactor no 1 indicates a high concentration of tracer, as compared to the other data, and a relatively short retention time. This could be due to bypassing, which may be present in the first reactor. Other reactors are characterized by similar concentration values. In the second reactor the effect of recirculation is evident: the first peak at the time of approx. 75 min is related to the main stream, while the second peak at the time of approx. 125 min is related to the recirculation stream. Based on these RTD, it can be concluded that the duration of the recirculation is approx. 50 min. The RTD curves for the 4th and 5th reactors have a very similar course.

In Fig. 3 RTD of lithium chloride concentration as a function of time is presented. The data was collected in the anaerobic reactor (ANAEROB) and shown graphs depict the results of modeling using TIS, ETIS and Martin models. Analyses carried out were performed for different numbers of streams and tanks (s, N = 1..5), while for each value the determination coefficient r^2 was examined. All three models indicate a high value of determination coefficient $r^2 > 0.97$. The TIS model is obtained slightly worse as compared to the ETIS model. The values of parameters are very similar. The differences appear for the retention times: the ETIS model is shifted by approx. 2 min, and for the number of tanks: the ETIS model allows for rational number, which here is being close to 1. The best fit, i.e. such, for which the highest $r^2 = 0.997$ was calculated, was obtained using the Martin model, which took into account the presence of three streams in the reactor: one main and two smaller, which may be related to the internal circulation in the reactor.

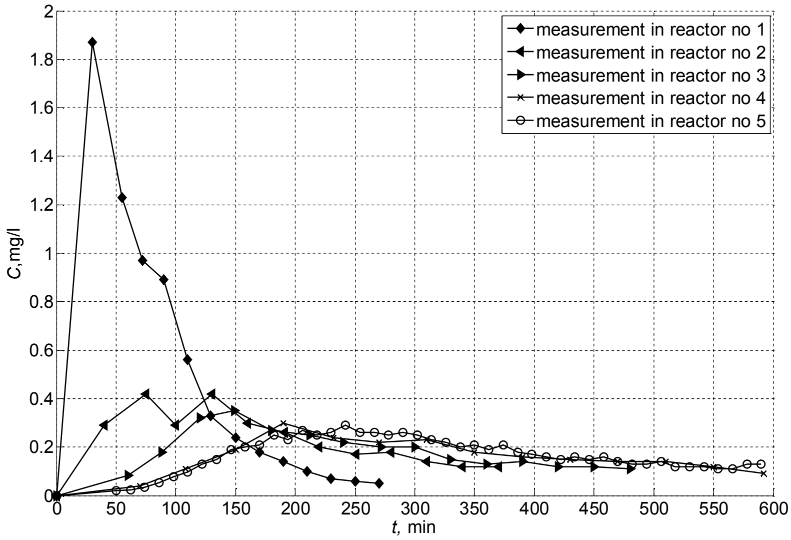

Fig. 2. Distribution of lithium chloride concenrtration contained in the samples collected from the five considered reactors

The retention time of the first major stream is $\tau_1 = 40.86$. The second stream, of a slightly smaller volume ($f_2 = 0.36$), appears at the time of approx. 92 min. The smallest, third stream ($f_3 = 0.09$) appears at the retention time $\tau_3 = 164.34$. The value of the initial concentration C_0 is slightly lower as compared with the data obtained for TIS and ETIS models. There is also a much larger number of tanks N_i for individual streams. However, these values can not be directly compared between the considered models. If we compare the theoretical retention time value nHRT=134.24 with times obtained by modeling significant differences are visible. The single stream models (TIS, ETIS) indicate twice a shorter HRT values. Similar, the first (biggest) stream of the MARTIN model, which is 55%, is more than three times shorter. The reason may be the fact that the measurement of the tracer concentration was not performed directly at the reactor effluent, but in its middle part. Another possible explanation for HRT < nHRT may be the existance of bypass (or short circuit) streams. The third stream obtaind by the MARTIN model, which was only 9%, has a retention time 30 minutes longer than the nHRT. This may be an indicator of the existence of internal circulation caused by mixing. Based on the achieved results it was also stated that the actual number of streams could be estimated differenty if the number of samples was higher.

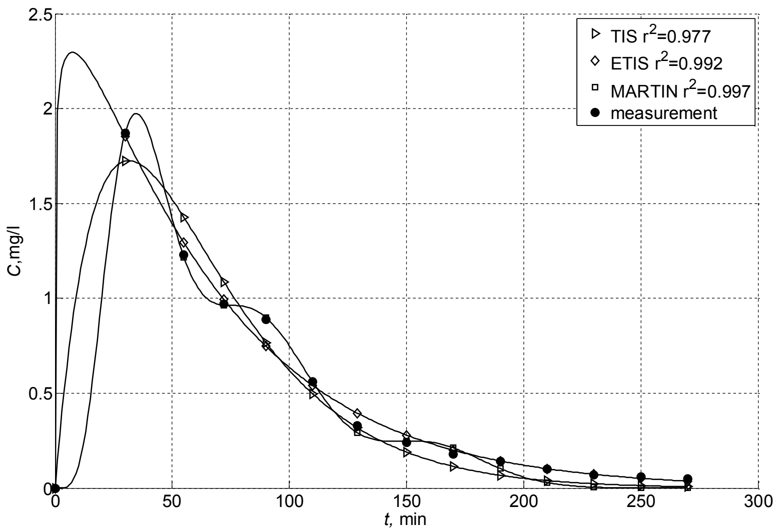

Fig. 3. Distribution of lithium chloride concenrtration and the RTD curves modeled with the TIS, ETIS and the Martin models, obtained for the anaerobic reactor (ANAEROB)

6. CONCLUSIONS

For investigation of the hydrodynamic behavior in activated sludge reactor tracer test may be very informative. Based on tracer concentration values obtained from sampled wastewater at the reactor effluent it is possible to determine the actual retention time, which in turn is significant for estimation of the ASP efficiency. A full-scale tracer test requires difficult and time-consuming work and a large staff. In contrast, mathematical modeling enables for to quantify the hydraulics in the reactor. In this study hydraulic parameters were measured within a tracer test, which was performed in a 5-stage Bardenpho WWT plant, operating in Kędzierzyn–Koźle, Poland.

Based on the obtained lithium chloride concentrations the actual retention times were determined using the Tanks-in-Series, the Extended Tanks-in-Series and the MARTIN models. Although all three models indicated high values of determination coefficient $r^2 > 0.84$, for each of the five reactors, best fit parameters were obtained always for the MARTIN model. Application of the MARTIN model enabled to identify multiple wastewater flows in the reactors, which include: main flow and short circuiting flows. In the short circuit stream or in dead volumes, there is a reduced denitrifying capacity, since the wastewater retention time is much shorter. According to the level of nitrate concentration in the effluent, bypassing may have positive or negative impact on the treatment process. Example, by high nitrate concentrations in the reactor, the retention time in the main volume is increased what may be compensated by reduced reaction time in the short circuit streams. Analyses carried out for different numbers of streams (s = 1..5) resulted with the statement that there are three streams in each of the reactor. However, one needs to take into account that the actual number of streams could be estimated differently if the number of samples was higher. The TIS and ETIS model estimates were in all cases very similar. Differences were observed for retention times and number of tanks. It was also stated that the theoretical retention times differ from the actual values, obtained through mathematical modeling.

The obtained result will be used for design and implementation of a simulation model, which will be integrated with an adaptive-predictive overriding control system that is installed on the considered WWT plant. By controlling of chosen process parameters it is possible to reduce the operational const of the WWT plant and to increase the effectiveness and performance of the treatment process by the up to 25%. Beyond the reduction the demand for electric energy, application of optimization methods in the automatic control process may reduce also water and chemicals, which in turn may have a positive ecological effect on the natural environment.

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