Development of Model for Activated Sludge Process

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***Abstract*—Activated sludge process (ASP) has been the most common treatment method for wastewater. The first mathematical model of ASP was developed by Henze et al. in 1987. This model is called activated sludge model no. 1 (ASM1). The International Water Association (IWA) and the European Co-operation in the field of Scientific and Technical Research (COST) Action 682/624 were tasked to develop the Benchmark Simulation Model No.1 (BSM1) based on the ASM1. The motive behind the development of BSM1 was to establish a benchmark tool, so that different control schemes can be implemented for ASP. This study, aims at developing a Matlab model based on BSM1. In this paper, the model of BSM1 is developed using Matlab m-files. The obtained nonlinear model is then reduced using model reduction techniques. The steady state simulation results of full and reduced model are then compared with the simulation results obtained by COST for validation of the developed model. The aim of this study is to obtain the BSM1 model which can subsequently be used for development of control schemes.**

***Keywords*—Wastewater treatment, Activated Sludge Process, Activated Sludge model No. 1, Benchmark simulation model No. 1, Model development, Model reduction.**

I. Introduction

In their paper, "Experiments on the Oxidation of Sewage Without the Aid of Filters", Ardern and Lockett introduced the activated sludge process as the method for wastewater treatment. This method is now the most commonly used biological wastewater treatment process. The term "activated sludge" was reported for the first time in this paper. This term referred to the micro organisms that settled out of the wastewater and recycled back to the process. The activated sludge process gives an impetus to aerobic micro organisms in their flocculation process. This gives rise to formation of solids which can settle down easily and then can be removed by sedimentation and recycled back to the system. The micro organisms which are non-settleable are allowed to drain out of the system. Consequently, enough concentration of microorganisms is maintained in the aeration tank. This enhances the oxidation of organic matter in the influent. The impetus to this process is provide by the secondary settler that allows the residence time for the micro organisms to settle down.

The activated sludge process is the most popular method for providing secondary treatment of municipal wastewater. It aims to achieve, at minimum cost, a sufficiently low concentration of biodegradable matter in the effluent along with minimal production of sludge. In recent decades, the mathematical models of the activated sludge wastewater treatment process have been fully developed. IWA has been involved in development of most of the ASP models. Consequently, major portion of literature regarding ASP is available from IWA. The understanding of biological and physicochemical process, that take place in such complex and nonlinear processes, can be derived from the models developed by IWA.

The first such model was developed by Henze et al. [1], which is called the activated sludge model no. 1 (ASM1). A comprehensive description of the ASM1 is given in [2]. ASM1 describes nitrogen and chemical oxygen demand within suspended-growth treatment processes, including mechanisms for nitrification and denitrification. Gujer et al. developed the second IWA model called the activated sludge model no. 2 (ASM2) [3]. This model is an extension of ASM1 incorporating mechanisms for biological phosphorus removal at a wastewater treatment plant. The third IWA model called the activated sludge model no. 2d (ASM2d) was produced in [4]. ASM2d describes simultaneous phosphorus removal as well as nitrification- denitrification. In the ASM2d chemical phosphate removal is modelled and the behaviour of phosphate-accumulating organisms (PAO) is not described. This is the difference between ASM2d and ASM2. The latest IWA model called the activated sludge model no. 3 (ASM3) was also developed by Gujer at al. [5]. ASM3 incorporates oxygen consumption, sludge production and nitrification-denitrification processes of the ASP. ASM3 is an extension of ASM1 where the main difference is the recognition of the importance of storage polymers in the heterotrophic conversion.

ASM1 is the most used of all the IWA models. The ASM1 has been found to give a good description of the ASP provided that the wastewater has been characterised in detail. The latest summary of all the IWA models can be found in [6]. For a complete activated sludge wastewater treatment process, it includes a secondary settler after a biological treatment unit with the activated sludge. Takács double exponential settling velocity model is the internationally recognized mathematical model of the secondary settler [7].

Simulations provide a cost-effective means for the evaluation of control strategies, but the unlimited number of simulation permutations makes the need for a standardized protocol very important if different strategies are to be compared. Each control strategy must be simulated under the same conditions to ensure unbiased comparisons. Validation of the computer simulations is difficult without supporting

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experimental or full-scale data, but the value of the work is enhanced through the use of accepted ASMs. Because appropriate simulation tools for the ASP are available this approach has numerous advantages, but still there is a need for a standardized procedure. The idea to produce a standardized ‘simulation benchmark’ was first devised and developed by the first IAWQ Task Group on Respirometry-Based Control of the Activated Sludge Process. This original benchmark was subsequently modified by the European Co-operation in the field of Scientific and Technical Research (COST) 682/624 Actions in co-operation with the second IWA Respirometry Task Group [8].

II. ASM1 AND BSM1

ASM1 is widely accepted in the research and application of activated sludge process in biological wastewater treatment systems. The typical ASP is shown in Figure 1. The first tank in the ASM1 model is an anoxic tank followed by the aerobic tank. Oxygen is supplied in the aerobic tank to meet the oxygen demand in the process. These tanks are generally referred to as reactors. These reactors are followed by a non-reactive settler tank. In the settler tank, the solid particles settle at the bottom of the tank.

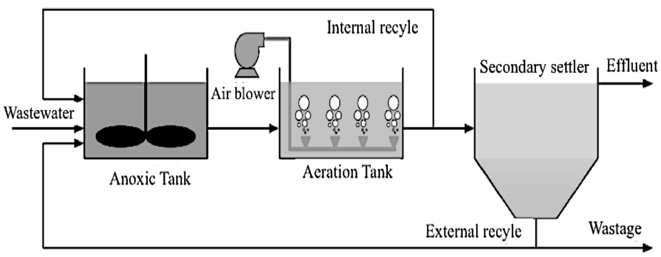

Fig. 1. Schematic representation of ASM1

There are two types of micro-organisms in the aeration tanks: heterotrophic and autotrophic bacteria. ASM1 consists of thirteen reaction components, which can be referred to as states, and eight reaction processes of the organic matter present in the influent. In each process, all the organic substances and micro-organisms have their own reaction rates and stoichiometry. The list of ASM1 state variables, with their definition and appropriate notation, is given in Table I.

It is difficult to apply a control strategy on the given model based on existing reference, process or location. To enhance the acceptance of innovative control strategies the performance evaluation should be based on a rigorous methodology that includes a simulation model, plant layout, controllers, performance criteria and test procedures. As a result, the Benchmark Simulation Model was introduced.

TABLE I
LIST OF ASM1 STATE VARIABLES

Soluble inert organic matter	S_I
Readily biodegradable substrate	S_S
Particulate inert organic matter	X_I
Slowly biodegradable substrate	X_S
Active heterotrophic biomass	X_{BH}
Active autotrophic biomass	X_{BA}
Particulate products arising from biomass decay	X_P
Oxygen	S_O
Nitrate and nitrite nitrogen	S_{NO}
$NH4^+$ + NH_3 nitrogen	S_{NH}
Soluble biodegradable organic nitrogen	S_{ND}
Particulate biodegradable organic nitrogen	X_{ND}
Alkalinity	S_{ALK}

The first Benchmark Simulation Model (BSM1), which is based on the ASM1, has relatively a simple layout and is shown in Figure 2. BSM1 plant consists of five bioreactors and a 10-layer secondary settler. The first two tanks are anoxic tanks and the later three are aerated tanks. The volume of first and second tank is 1000 m^3 and that of rest of the tanks is 1333 m^3. Volume of settler is 5999 m^3.

BSM1 incorporates thirteen reaction components (states) and eight reaction process of the organic matter present in the influent. As a result, eight process, involving thirteen states, take place in each tank. The anoxic tanks are un-aerated but fully mixed. In the open loop case, the third and fourth tank are supplied with oxygen with constant oxygen transfer coefficient. The oxygen transfer coefficient in the fifth tank is selected as control variable so as to maintain the oxygen concentration in the fifth tank at a particular level (generally 2g/m^3). As a result, the system achieves biological nitrogen removal through nitrification in the aeration tanks and pre-denitrification in the anoxic tanks.

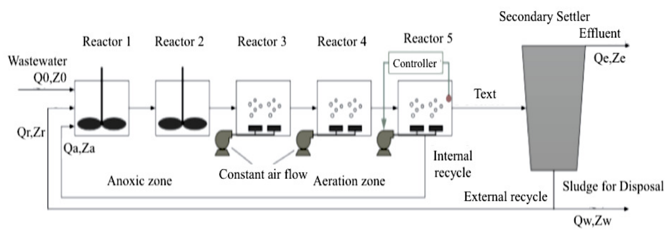

Fig. 2. Schematic representation of BSM1

According to the mass balance of the system, the biochemical reactions that take place in each compartment (reactor) can be described as follows [9]:

Reactor 1

$$\frac{dZ_1}{dt} = \frac{(Q_a Z_a + Q_r Z_r + Q_0 Z_0 + r_1 V_1 - Q_1 Z_1)}{V_1} \quad (1)$$

Reactor 2 through 5 ($k = 2\ to\ 5$)

$$\frac{dZ_k}{dt} = \frac{(Q_{k-1} Z_{k-1} + r_k V_k - Q_k Z_k)}{V_k} \quad (2)$$

Special case for oxygen ($S_{O,k}$)

$$\frac{dS_{O,k}}{dt} = \frac{(Q_{k-1} S_{O,k-1} - Q_k S_{O,k})(K_{La})_k (S_O^* - S_{O,k})}{V_k} + r_k \quad (3)$$

where, Q is the flow rate, Z is the mass concentration of either substrate or bacterial mass, V is the volume of the reactor, r is the reaction rate, K_{La} is the oxygen transfer coefficient, S_O is the dissolved oxygen concentration. S^* is the saturation concentration for oxygen (S_O^* = 8 g/m^3 at 15^{o}C); also Q_1 = Q_a + Q_r + Q_0 ; Q_k = Q_{k-1}

III. Model Development

In this paper, the BSM1 is developed by converting ordinary differential equations into algebraic differential equations. Thirteen algebraic differential equations are obtained in each reactor. Therefore, there are 65 equations corresponding to 5 reactors. In order to limit the number of algebraic differential equations of the process (including settler) to 65, the simplified model of secondary settler is considered [10]. For this secondary settler configuration, it is assumed that the concentration of all soluble components in the settler remains homogenous throughout, while the suspended components settle at the bottom of the settler.

The model is established in proper order according to sequence of the wastewater flow in the 5 reactors, where the 13 components are in the order of the influent file form [11]. For example, the 1^{st} component coming out from the 1^{st} reactor is S_I (indexed as 1), the second component is S_S (indexed as 2) and the last component is S_{ALK} (indexed as 13). Similarly, the first component entering the second reactor is S_I (indexed as 14), the second component is S_S (indexed as 15) and the last component is S_{ALK} (indexed as 26), and so on. The 13th component coming out from the 5^{th} reactor is S_{ALK} (indexed as 65).

In each reactor, the 13 components use eight processes and 13 component reaction rates forming 65 algebraic differential equations. Based on the ordinary differential equations brought out earlier, the corresponding algebraic differential equations are obtained. The total number of ADEs is 65. For first reactor the algebraic differential equations are given as:

$$dy(i) = \frac{Q_0 Z_0 + Q_a y(i+52) + Q_r y(i+52) - Qy(i)}{V} + r_j \quad (4)$$

$i = 1, 2, ...13,\ \ j = 1, 2, ...13\ and\ Q = Q_0 + Q_a + Q_r$ For second reactor on-wards, the algebraic differential equations are given as:

$$dy(i) = \frac{Q(y(i-13) - y(i))}{V} + r_j \quad (5)$$

$i = 14, 15, ...65\ and\ j = 1, 2, ...13$

The above algebraic differential equations for first reactor correspond to soluble components. For particulate components an additional variable λ is used as a multiplier to Q_r term above.

In accordance with the general ADEs obatined on previous slide, the ADE for soluble components like that of the first component in the first reactor, i.e. S_{I1}, is given as:

$$dy(1) = \frac{(Q_0 S_{I0} + Q_a y(53) + Q_r y(53) - Qy(1))}{V_1} + r_{1,1} \quad (6)$$

Accordingly, ADE for for second component in the first reactor, i.e. S_{S1}, is given as:

$$dy(2) = \frac{(Q_0 S_{S0} + Q_a y(54) + Q_r y(54) - Qy(2))}{V_1} + r_{1,2} \quad (7)$$

Similarly for the particulate components like third component in the first reactor, i.e. X_{I1}, the ADE is given as:

$$dy(3) = \frac{(Q_0 X_{I0} + Q_a y(55) + \lambda Q_r y(55) - Qy(3))}{V_1} + r_{1,3} \quad (8)$$

where, λ= (Q_0+Q_r)/(Q_r+Q_w), Q_w is the the waste flow (for simplified secondary settler model).

When the wastewater flows into the second reactor, the ADE for first component in the second reactor, i.e. S_{I2} is given as:

$$dy(14) = \frac{(Q(y(1) - y(14))}{V_2} + r_{2,1} \quad (9)$$

The ADE for second component in the second reactor, i.e. S_{S2} is given as:

$$dy(15) = \frac{(Q(y(2) - y(15))}{V_2} + r_{2,2} \quad (10)$$

Similarly, the ADE for last component in the second reactor, i.e. S_{ALK2} is given as:

$$dy(26) = \frac{(Q(y(13) - y(26))}{V_2} + r_{2,13} \quad (11)$$

When the wastewater flows into the fifth reactor, the ADE for first component in fifth reactor, i.e. S_{I5} is given as:

$$dy(53) = \frac{(Q(y(40) - y(53))}{V_5} + r_{5,1} \quad (12)$$

The ADE for second component in the fifth reactor, i.e. S_{S5} is given as:

$$dy(54) = \frac{(Q(y(41) - y(54))}{V_5} + r_{5,2} \quad (13)$$

Similarly, the ADE for last component in the fifth reactor, i.e. S_{ALK5} is given as:

$$dy(65) = \frac{(Q(y(52) - y(65))}{V_5} + r_{5,13} \quad (14)$$

In this work, ode15s is chosen for solving the simulation, which is designed for solving continuous stiff systems based on Gear's method.

IV. Model reduction

Behaviour of activated sludge process is predicted by full model. The full model also predicts the variation in the effluent quality during dynamic operations. The activated sludge processes are time varying and highly nonlinear. These processes also involve significant instability and high dimensions in terms of the number of state variables (wastewater components), processes and parameters. Hence a need arises for reduction of model variables. Besides, some of the parameters can not be observed due to unavailability of sensors. In order to accurately predict the behaviour of a plant, activated sludge models require online modifications based on available data from sensors. The model reduction techniques have been discussed in [10] and [12]. The process reduction techniques are carried out as discussed below:

a) Biological simplifications: The alkalinity in the activated sludge process changes as a result of reaction of other variables. Further, the dynamics of other states (components) is not affected by S_{ALK}. Hence, S_{ALK} mass balance is eliminated from the model equations.

The states corresponding to dissolved oxygen in first two tanks, i.e. $S_{O,1}$ and $S_{O,2}$, are not considered, since these two tanks are anoxic tanks. Oxygen concentrations in the aerobic tanks, i.e. $S_{O,3}$, $S_{O,4}$ and $S_{O,5}$, are state variables. K_{La3}, K_{La4} and K_{La5} are inputs to the aerobic Tank 3, Tank 4 and Tank 5, respectively. Reduction of oxygen concentration below a reference level severely affects the reaction rates. In such cases, K_{La5} is used as manipulated variable, while K_{La3} and K_{La4} are kept constant.

b) Singular perturbation Method: The activated sludge process is a stiff process, that is, some variables are changing faster than others. The time scales vary from slow (weeks) to medium (hours) to fast (minutes). The variables which change slowly can be assumed in quasi steady state. Thus, the variables can be eliminated from the system of algebraic differential equations. Analytic elimination is, however, quite tedious and prone to errors. Therefore, a numerical solution procedure is preferred (for instance using the index 1 DAE solver ode15s of MATLAB). The models are reduced on the basis of different time scales separation.

The following components are considered as fast variables:

- No reaction takes place for the inert materials S_I and X_I.
- The mortality processes gives rise to X_P.
- During the process of ammonification the S_{ND} and X_{ND} emerge in transient phase.
- During the hydrolysis process i aerobic reactors X_S is an intermediate.

In light of the above, the state vector in each reactor included following components:

- S_S, X_{BH}, X_{BA}, S_{NO} and S_{NH} (in anoxic reactors)
- S_S, X_{BH}, X_{BA}, S_O, S_{NO} and S_{NH} (in aerobic reactors)

and the input vector is

- S_{S0}, X_{S0}, X_{BH0}, S_{ND0}, X_{ND0}, X_{I0}, K_{La}, Q_0, Q_r, Q_a

The reduced model obtained using above mentioned methodology has 28 states.

V. Simulation Results and Discussion

A. Steady State Response

The 100-days steady state simulation is carried out in Matlab for both full and reduced model. Oxygen transfer coefficients for 3^{rd} & 4^{th}tank K_{La3} and K_{La4} are kept at constant rate of 10 h^{-1}. The oxygen coefficient for fifth tank K_{La5} is kept at 3.5 h^{-1}. The values of constant input parameters have been taken from [9]. Internal feedback flow, Q_a and external feedback flow, Q_r, are kept at constant values of 55338 m^3/day and 18446 m^3/day, respectively. BSM1 represents the stiff dynamic systems, i.e. the time constants for the different processes involved vary significantly. Such systems are quite difficult to solve numerically unless special numerical solvers are used, which have been developed especially to deal with these difficulties. In this study, ode15s was chosen for solving the simulation, which is designed for solving continuous, stiff systems based on Gear's method.

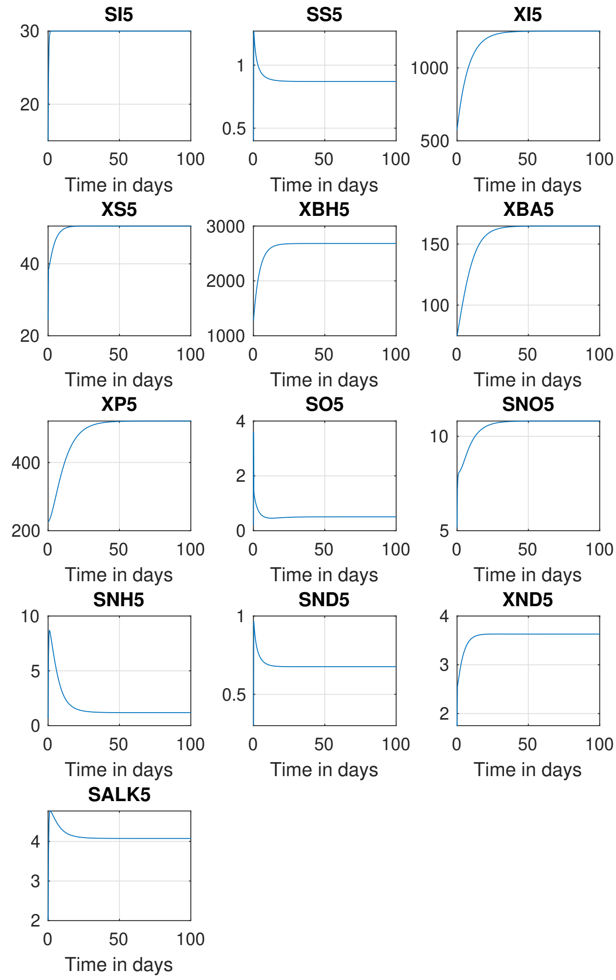

Fig. 3. Open loop steady state plots in Tank 5- Full model case

Figure 3 shows the variation of sate variables over a period of 100 days for full model in Tank 5. Similarly, Figure 4 shows the variation of state variables for a 100 days period for reduced model in Tank 5. The steady state plots have been obtained corresponding to the constant inputs as brought out above.

Table II shows the steady state simulation results obtained for the full model developed in this study. The corresponding simulation results obtained by COST Benchmark Group for the Benchmark Simulation Model No. 1 are also given in Table II. It can be observed that the results obtained in this study are very close to that of the COST Benchmark Group. This indicates that the full model developed is correct.

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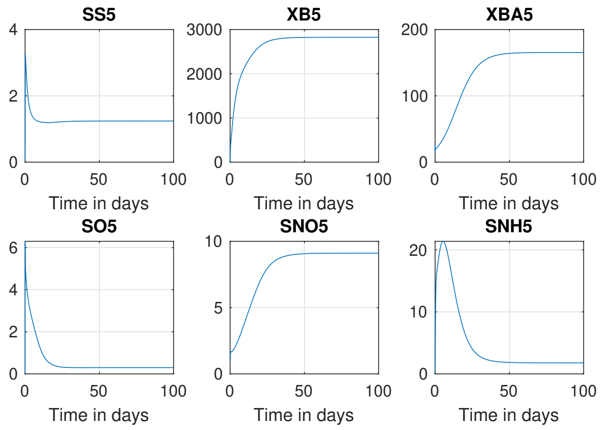

Fig. 4. Open loop steady state plots in Tank 5- Reduced model case

The steady state results of reduced model are given in Table III. Table III also shows the comparison between steady state results achieved for reduced model and the results by the COST Benchmark Group for the corresponding state variables. Similar to the full model case, It can be noticed that for reduced model the results obtained are very close to that of the COST Benchmark Group. This indicates that the reduced model developed is also correct.

From table II and III , it can be noticed that the trend of the results of the results obtained for all the states under observation (S_S, X_{BH}, X_{BA}, S_O, S_{NO} and S_{NH}) for full, reduced and COST benchmark model is similar, that is to say that the trend of decrease or increase of values from one tank to another is similar in all cases.

TABLE II
STEADY STATE RESULTS ACHIEVED IN THIS STUDY AND THOSE ACHIEVED BY COST BENCHMARK GROUP- FULL MODEL

Component	Tank1	Tank2	Tank3	Tank4	Tank5
SI- Study	30	30	30	30	30
SI- COST	30	30	30	30	30
SS- Study	2.676	1.397	1.112	0.9662	0.8648
SS- COST	2.81	1.46	1.15	0.995	0.889
XI- Study	1252	1252	1252	1252	1252
XI- COST	1149	1149	1149	1149	1149
XS- Study	82.92	77.06	65.61	56.53	49.3
XS- COST	82.1	76.4	64.9	55.7	49.3
XBH- Study	2676	2677	2681	2682	2682
XBH- COST	2552	2553	2557	2559	2559
XBA- Study	164	163.9	164.6	165.1	165.4
XBA- COST	148	148	149	150	150
XP- Study	518.2	518.9	519.8	520.8	521.7
XP- COST	449	450	450	451	452
SO- Study	0.0051	7.1e-5	1.679	2.519	0.5722
SO- COST	0.0043	6.3e-5	1.72	2.43	0.491
SNO- Study	6.087	4.33	7.428	10.24	11.31
SNO- COST	5.37	3.66	6.54	9.3	10.4
SNH- Study	7.369	7.805	4.791	2.179	1.037
SNH- COST	7.92	8.34	5.55	2.97	1.73
SND- Study	1.193	0.8636	0.8097	0.7496	0.6761
SND- COST	1.22	0.882	0.829	0.767	0.688
XND- Study	5.362	5.099	4.468	3.958	3.605
XND- COST	5.28	5.03	4.39	3.88	3.53
SALK- Study	4.853	5.01	4.574	4.186	4.028
SALK- COST	4.93	5.08	4.67	4.29	4.13

TABLE III
STEADY STATE RESULTS ACHIEVED IN THIS STUDY AND THOSE ACHIEVED BY COST BENCHMARK GROUP- REDUCED MODEL

Component	Tank 1	Tank 2	Tank 3	Tank 4	Tank 5
SS- Study	2.491	1.36	1.084	0.9388	1.242
SS- COST	2.81	1.46	1.15	0.995	0.889
XBH- Study	2723	2723	2727	2728	2732
XBH- COST	2552	2553	2557	2559	2559
XBA- Study	149.5	149.4	150.1	150.6	150.8
XBA- COST	148	148	149	150	150
SO- Study	NA	NA	1.886	2.716	0.4429
SO- COST	0.0043	0.0000631	1.72	2.43	0.491
SNO- Study	4.064	2.448	5.342	8.007	8.576
SNO- COST	5.37	3.66	6.54	9.3	10.4
SNH- Study	6.93	7.481	4.776	2.382	1.15
SNH- COST	7.92	8.34	5.55	2.97	1.73

This point plays an important role in validating the results obtained during simulation in this study for both full and reduced models. Further, the order of the values is also similar, e.g. the concentration of dissolved oxygen (S_O) in all five tanks changes from the order of 10 $^{-3}$ in 1^{st} tank to the order of 10 $^{-5}$ in 2^{nd} tank. The values remain near to 1.5 g COD m^{-3} to 2.5 g COD m^{-3} in 3^{rd} and 4^{th} tanks, respectively. The values obtained in 5^{th} tank are near to 0.5 g COD m^{-3}. The variation in reduced model case from that of COST benchmark case is of the order of 2% and 9%. This variation can be attributed to simplified settler model model, numerical method being implemented in the simulation process and deviation due to omission of seven states from the equations. Considering the complexity of the process, smaller values of S_O in all tanks and the simplification applied in this process, this much of variation can be accepted.

B. Openloop Dynamic Response

After running the plant in steady state for 100 day period and obtaining the steady state results, which are satisfactory so as to move further in the course of this study, next step is to run the plant in dynamic mode. The idea is to observe the open loop behavior of the process. The dynamic inputs for the dynamic simulation of the full and reduced model are available at IWA website $http : //www.iea.lth.se/WWTmodels\_download/$. The dynamic input consists of three different files. The first one being the dry weather file. The dry weather file consists of routine wastewater flow without any major variation in wastewater flow or input components. The second one is the rainy weather file. This differs from the dry weather file for the period between 8^{th} and 12^{th} day, when there is an increase in flow due to rain. The third file is and stormy weather files. In stormy weather file, there are two spikes at 9^{th} and 11^{th} day. These spikes in input data are attributed to storms.

The open-loop dynamic response for the developed full state model to all the three input files is shown in figures 5, 6 and 7. Figure 5 gives the dynamic response of the developed full state model corresponding to the dry weather file. Figure 6 shows the response of the full state model corresponding to the rainy weather file. And, finally. figure 7 indicates the response of the full state model corresponding to the the stormy weather file. The oxygen transfer coefficients of the third and fourth tank (K_{La3} and K_{La4}) are kept at a constant rate of 10 h^{-1}, each. The oxygen transfer coefficient for the fifth tank (K_{La5}) is kept at 3.5 h^{-1}. The internal recycle flow rate, Q_a and external recycle flow rate, Q_r, are kept at constant values of 55338 m^3/day and 18446 m^3/day, respectively.

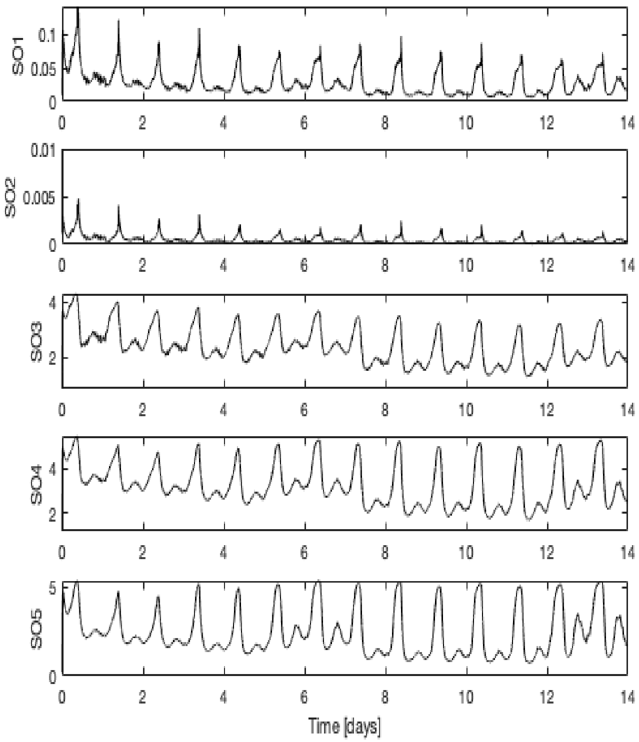

Fig. 5. DO variations corresponding to dry weather in full model case

The open-loop dynamic response for the developed reduced state model to all the three input files is depicted in figures 8, 9 and 10. Figure 8 gives the dynamic response of the developed reduced state model corresponding to the dry weather file. Figure 9 shows the response of the reduced state model corresponding to the rainy weather file. And, figure 10 indicates the response of the reduced state model corresponding to the stormy weather file. Like in case of full model, the oxygen transfer coefficients of the third and fourth tanks (K_{La3} and K_{La4}) are kept at a constant rate of 10 h^{-1}, each. The oxygen transfer coefficient for the fifth tank (K_{La5}) is kept at 3.5 h^{-1}. The internal recycle flow rate, Q_a and external recycle flow rate, Q_r, are kept at constant values of 55338 m^3/day and 18446 m^3/day, respectively.

The aim of this work as brought out elsewhere is to control the oxygen concentration in the fifth tank so as to keep it closer to a reference value irrespective of changes in influent flow. The oxygen concentrations obtained in the reduced model are close to those obtained in the full model besides are smoother.

VI. Conclusion

In this study a method for modeling of Benchmark Simulation Model is proposed. As a result, a full state model

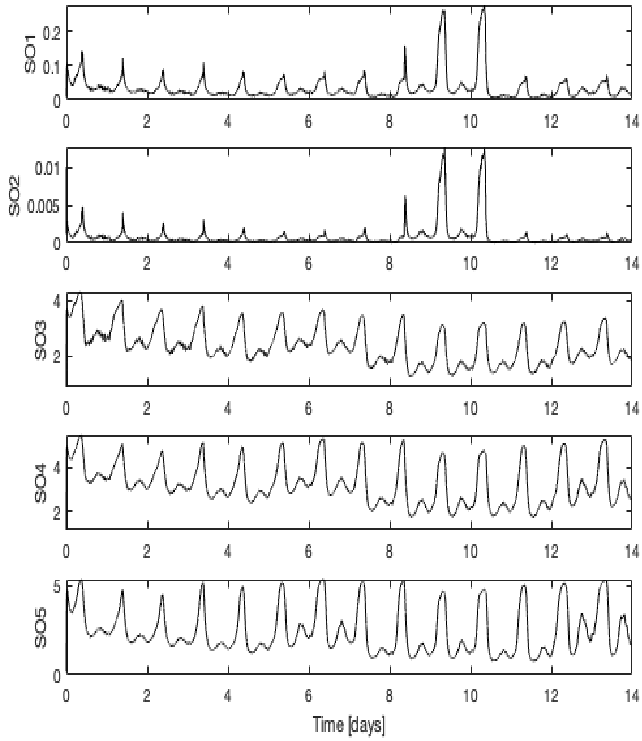

Fig. 6. DO variationscorresponding to rainy weather in full model case

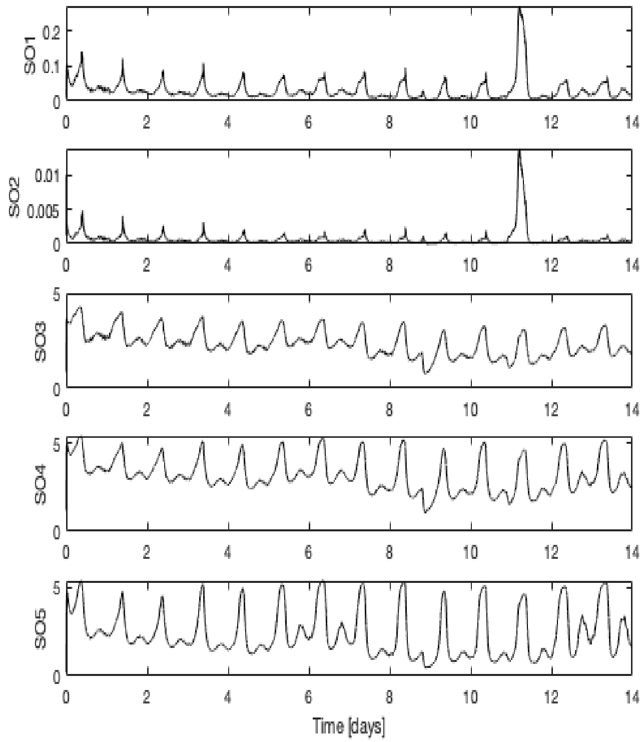

Fig. 7. DO variations corresponding to stormy weather in full model case

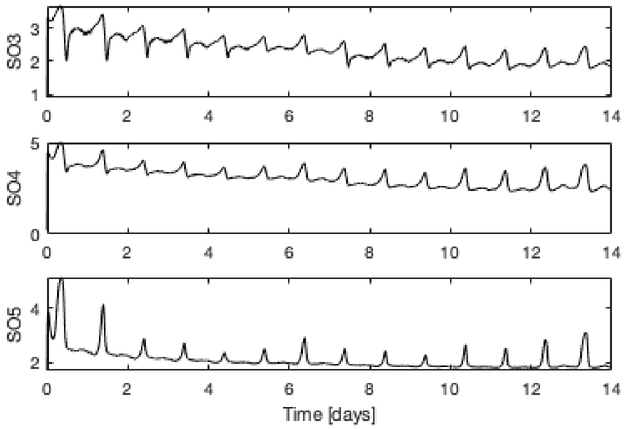

Fig. 8. DO variations corresponding to dry weather in reduced model case

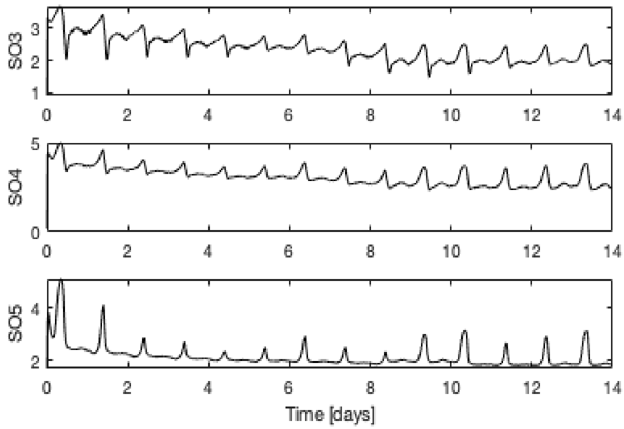

Fig. 9. DO variations corresponding to rainy weather in reduced model case

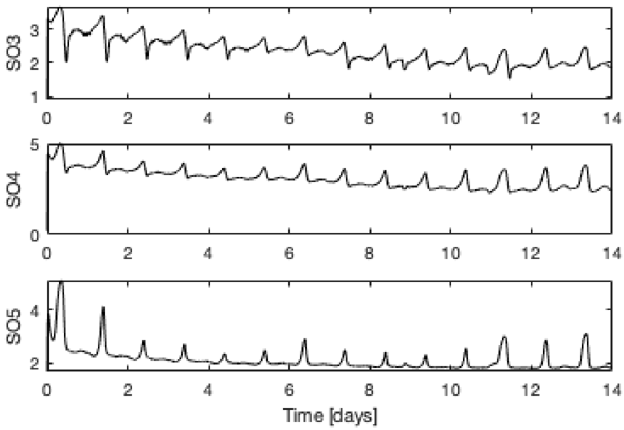

Fig. 10. DO variations corresponding to stormy weather in reduced model case

is established. The reduction techniques are implemented to obtain reduced model. Both the models are simulated for 100-days period and the results obtained are compared with the results obtained by COST Benchmark Group for BSM1 model. It is observed that the results obtained are very close to the results obtained by COST Benchmark Group. The models developed in this study can be used as a basis for development of control scheme for control of dissolved oxygen concentration in the fifth reactor of BSM1.

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