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Research article

Statistical monitoring and dynamic simulation of a wastewater treatment plant: A combined approach to achieve model predictive control

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ABSTRACT

The on-line monitoring of Chemical oxygen demand (COD) and total phosphorus (TP) restrains wastewater treatment plants to achieve better control of aeration and chemical dosing. In this study, we applied principal components analysis (PCA) to find out significant variables for COD and TP prediction. Multiple regression method applied the variables suggested by PCA to predict influent COD and TP. Moreover, a model of full-scale wastewater treatment plant with moving bed bioreactor (MBBR) and ballasted separation process was developed to simulate the performance of wastewater treatment. The predicted COD and TP data by multiple regression served as model input for dynamic simulation. Besides, the wastewater characteristic of the wastewater treatment plant and MBBR model parameters were given for model calibration. As a result, R^2 of predicted COD and TP versus measured data are 81.6% and 77.2%, respectively. The model output in terms of sludge production and effluent COD based on predicted input data fitted measured data well, which provides possibility to enabled model predictive control of aeration and coagulant dosing in practice. This study provide a feasible and economical approach to overcome monitoring and modelling restrictions that limits model predictive control of wastewater treatment plant.

1. Introduction

Model predictive control (MPC) is considered as an advanced control scheme to optimize wastewater treatment plants (WWTPs) (Kim et al., 2014; Vega et al., 2014). The application of MPC has been reported that 25% aeration cost can be saved in an activated sludge plant (O'Brien et al., 2011). For the successfully use of MPC, real time monitoring of the treatment process and appropriate models which can describe process behaviors are required. However, the application of model predictive control in full-scale WWTPs is limited due to unavailability of capable process model and reliable online analyzers for process monitoring, especially for chemical oxygen demand (COD) and total phosphorus (TP) online measurement. Present literature reports are mainly focus on the selection of control structure (Gutierrez et al., 2014; Stare et al., 2007) and cost function and set point optimization (Vega et al., 2014). Consequently, most control scheme developed in the past is tested using simulation, but much fewer controllers have been implemented in full scale WWTPs (Olsson et al., 2014; Åmand et al., 2013).

Moving Bed Biofilm Reactor (MBBR) is a fluidized biofilm wastewater treatment system, which was widely used during last decades due to its higher treatment efficiency and lower footprint (Di Trapani et al., 2011; Ødegaard, 2006). The separation of biomass produced by MBBR system usually requires coagulant dosing to enhance biomass separation. Therefore, aeration and coagulant dosing control is essential to the performance of wastewater treatment plant with MBBR. For the purpose of improving MBBR plant performance and reduce operation cost, a MBBR model and influent wastewater characteristics are necessary to achieve model predictive control.

Although there is no standard MBBR model available as activated sludge model 1- ASM1 (Henze et al., 1987), modelling and dynamic simulation of MBBR has been carried out based on ASM1 (Mannina et al., 2011; Plattes et al., 2006), which proved that the bio-kinetic model in ASM1 are able to serve as reference for the

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modelling of MBBR system. Nowadays, fluidized biofilm model are available in simulation tools for wastewater treatment, e.g. STOAT® (WRc, Wiltshire, England), BioWin® (EnviroSim Associates Ltd., Canada). Consequently, modelling and dynamic simulation of a MBBR plant are possible to carry out for model predictive control purpose.

Principal components analysis (PCA) is a multivariable statistical method for detecting data collinearity and reduce dataset dimensions, which plays an essential role in software sensor development (Cecil and Kozlowska, 2010; Haimi et al., 2015). Recently, researchers employed PCA to determine correlation between process variables (Avella et al., 2011) and characterize water quality (Huang et al., 2012). Moreover, multiple regression coupled with PCA was used to monitor WWTP operation and predict process performance (Avella et al., 2011; Liu et al., 2014; Martín de la Vega et al., 2012). Data collected from WWTPs contain useful information and are not always explicit. Therefore, with the application of modern statistical methods, process engineers are able to obtain real-time information without the corresponding online sensors.

The objective of this work was to provide an approach to optimize full-scale WWTP performance and reduce operation cost in practice. This is achieved by a combined approach to enable model predictive control. Furthermore, the study provides wastewater characteristics of a full scale WWTP in Norway, based on which a MBBR model was built. Statistical monitoring of influent wastewater and dynamic simulation of WWTP performance based on predicted influent data was carried out. By applying the approach presented in this work, full-scale WWTPs are able to achieve model predictive control easily and economically.

2. Materials and methods

2.1. Description of the wastewater treatment plant

Solumstrand wastewater treatment plant locates in Drammen, in the south of Norway with the treatment capacity of serving 130 000 person equivalent. As is shown in Fig. 1, the influent wastewater passes through the screen and grit trap to remove large solid and sand. The outlet of grit trap enters MBBR system for biological treatment. The biological treatment of this WWTP is consisted of four parallels, and each parallel has two aerobic MBBRs in series. The MBBR system is filled with bio-carriers with filling rate of 59%, and the specific surface area of bio-carriers is greater than 500 m^2/m^3. The MBBR system only has aerobic zone with short nominal hydraulic retention time (1.6 h), which enables organic matter removal, but ammonia and soluble nitrogen removal are not required in this plant. The outlet of MBBR system carries detached biological particles and enters ballasted flocculation tank for solid separation. The ballasted flocculation and separation, also known as Actiflo (Plum et al., 1998), separates solid and water within a short period due to high settling velocity caused by micro-sand and coagulant dosing. Besides, coagulant dosing should secure phosphorus removal ratio larger than 94%.

2.2. Wastewater characteristics

Influent and effluent wastewater was continuously collected by automatic samplers and the wastewater characteristics was analyzed following Standard Methods for chemical oxygen demand (COD), ammonia, total nitrogen (TN), total phosphorus (TP), soluble phosphorus, and suspended solids (SS) (APHA et al., 2012). The total sample collection period was 120 h. Table 1 lists the average influent wastewater characteristic, which are also the input values of the steady state model.

2.3. Multivariate statistical analysis

Two multivariate statistical methods were applied to achieve statistical monitoring of the WWTP: Principal components analysis (PCA) and multiple regression. The mathematical procedure of PCA for statistical monitoring of WWTP was well explained in literature (Liu et al., 2014). In this work, we applied PCA to study the collinearity and correlation between influent variables, i.e., COD, soluble COD (SCOD), Flow, SS, ammonia (NH_4-N), PH, total nitrogen (TN), orthophosphate (OP) and total phosphorus (TP). The results of PCA were visualized in form of two types of plot: explained variances plot and loading plot. The explained variances plot indicates the proportion of total variance explained by each component, while the loading plot visualizes the correlation between original variables. In addition, if a small amount of principal components explains most variance of the data, it indicates high collinearity of original variables. Moreover, the original variables located closely on the loading plot indicates positive correlation, and variables are negatively correlated if they locate on the opposite of the origin. To verify the PCA model, cross validation method was applied.

Because it is expensive and slow to measure COD and total phosphorus by online analyzers, we applied multiple regression to predict influent COD and total phosphorus based on easily measured variables, e.g. flow rate and PH. Leverage correction method are used to validate the multiple regression model. The Unscrambler® software (Camo software company) was used for all the statistical analysis.

2.4. Model development

As stated above, a steady state model of the MBBR system was developed based on Activated Sludge Model 1 (Henze et al., 1987). The function of the steady state model was to determine model parameters. Average influent wastewater characteristic of 120

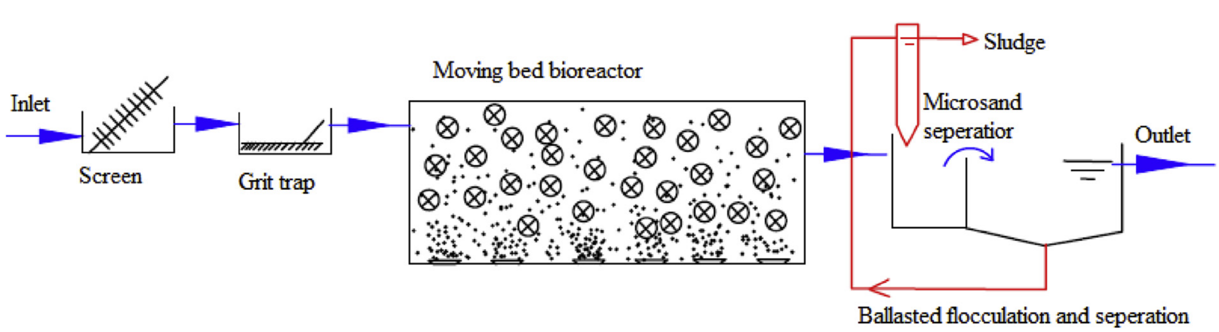

Fig. 1. Schematic diagram of the wastewater treatment plant.