Improving aeration control at the Ljubljana wastewater treatment plant

D. Vrečko, U. Zupančič and R. Babič

ABSTRACT

This paper describes an improvement to the aeration control at the Ljubljana wastewater treatment plant. Several changes were made to the existing aeration control. An adjustment to the parameters of the common air pressure controller contributes to a more responsive operation of the compressors. The introduction of the air pressure set-point controller adjusts the air pressure in the common air rail according to the changes in the plant load. The introduction of the airflow controllers reduces the variation in the oxygen concentrations in the aerobic reactors and, consequently, enables a reduction in the oxygen set-points. With the improved aeration control, savings of up to 10% in the electricity used for aeration are achieved on a yearly basis.

Key words | aeration control, air pressure control, electricity consumption for aeration, oxygen control, wastewater treatment

D. Vrečko (corresponding author)
Jožef Stefan Institute,
Jamova 39, 1000 Ljubljana,
Slovenia
E-mail: *darko.vrecko@ijs.si*

U. Zupančič
ASIT d.o.o.,
Brnčičeva ulica 5, 1000 Ljubljana,
Slovenia

R. Babič
Javno podjetje Vodovod-Kanalizacija d.o.o.,
Vodovodna cesta 90, 1000 Ljubljana,
Slovenia

INTRODUCTION

Aeration of the reactors is one of the most crucial processes in wastewater treatment plants (WWTPs). For effective wastewater treatment, a sufficiently high oxygen concentration has to be maintained in the aerobic reactors. At the same time, it is desirable to achieve the lowest possible air consumption, since this is responsible for more than half of the total electricity consumed by the plant (Olsson *et al*. 2005). The air consumption can be reduced by proper control of the air pressure in the common air rail and oxygen control in the aerobic reactors. Various control strategies have already been proposed for the oxygen control in aerobic reactors (Åmand *et al*. 2013). However, strategies for the proper control of the air pressure in the common air rail are not sufficiently elaborated. Normally, the so-called 'most opened valve' approach is proposed. A brief description of this approach can be found in (Olsson *et al*. 2005; Kandare & Reviriego 2011; Beltrán *et al*. 2011). However, details of how to apply it and what can be achieved with it are still missing. The novelty of this paper is to describe the implementation of this approach at the full scale WWTP of Ljubljana. Moreover, our experience with the introduction of the airflow control inside the oxygen controllers is also presented.

The paper is organised as follows. In the next section the aeration system of the Ljubljana WWTP is described. Then, the improved air pressure control in the common air rail is presented. After this, an upgraded oxygen control with the introduced airflow control is described. In the following section, aeration control is evaluated by calculating the consumption of electricity. Finally, the most important conclusions are drawn.

THE AERATION SYSTEM AT LJUBLJANA WWTP

The Ljubljana WWTP is the largest such plant in Slovenia and is designed for organic and ammonia nitrogen removal for 360,000 PE. The biological stage of the plant has three parallel plug-flow aerobic reactors. Each of them is divided into two reactors (inlet and outlet), which means that there are six reactors in total. The scheme of the aerobic reactors and the common air rail is shown in Figure 1. The total volume of the aerobic reactors is 39,034 m^3 and the average wastewater flow rate is around 75,000 m^3/d (Bordon *et al*. 2005). The sludge from the secondary settlers is returned to the reactors in proportion to the wastewater flow rate. The air for the aerobic reactors is provided by three HV Turbo compressors. The nominal operating power of each of the compressors is 450 kW. The compressors operate with redundancy, with two compressors always in use and the third one kept in reserve. The maximum airflow capacity of the compressors is 32,000 m^3/h. The air is

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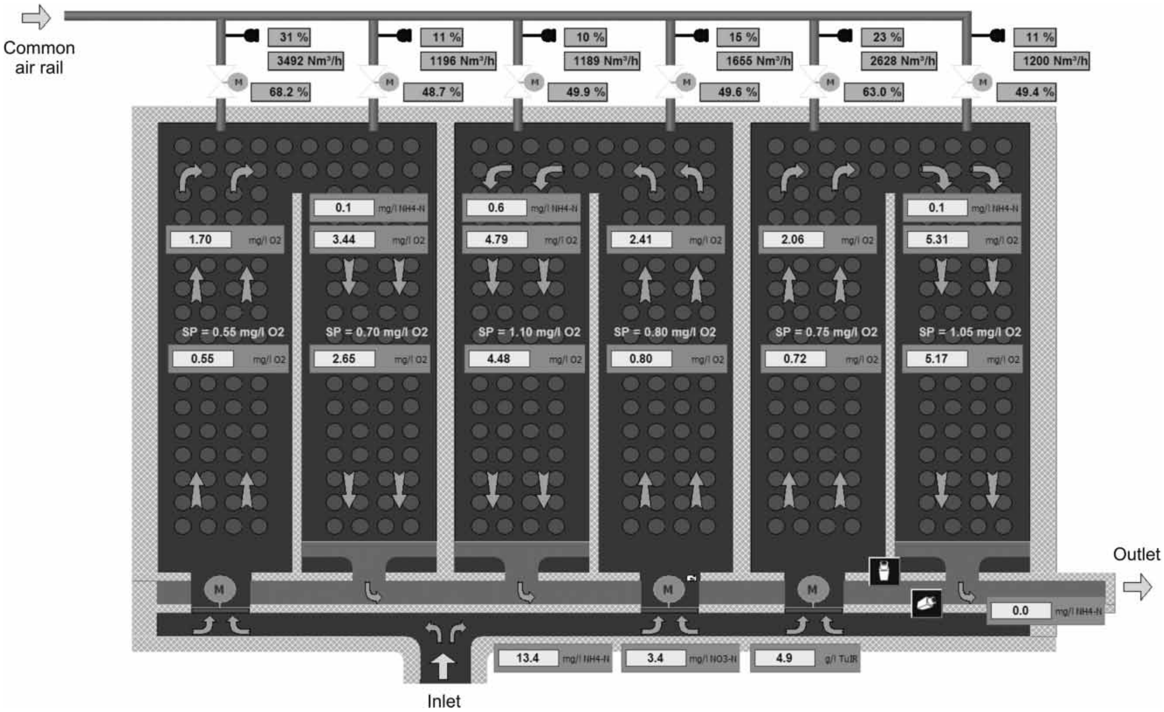

Figure 1 | Scheme of the aerobic reactors and the common air rail at the Ljubljana WWTP.

supplied into the reactors through the common air rail. The oxygen is transferred into the water by the disk membrane air diffusers. The reactors are equipped with Hach-Lange and Endress & Hauser sensors, for measuring the oxygen, airflow and ammonia, and with air valves. The oxygen is controlled in each of the six aerobic reactors.

AIR PRESSURE CONTROL

The air pressure in the common air rail is initially controlled by a Siemens SIPART DR20 controller (Siemens 2004), which adjusts the operation of the compressors. The air pressure is maintained by the local controllers of the compressors, which open and close the diffusers of the compressors and change the airflow rate. The air pressure controller works as a discrete proportional-integral (PI) controller with a three-position output. The set-point of the air pressure was constant and set to a high value of 0.68 bar so that the aeration system could provide enough air for the high load peaks. The initial behaviour of the air pressure controller is shown in Figure 2.

It is clear that the air pressure in the common air rail was varying a great deal around the selected set-point. After a careful examination of the measurement data and the controller's manual it was found that the cause of this variation lay in the improperly tuned parameters of the air pressure controller. To improve the air pressure control, two parameters of the controller were adjusted: the control region of the air pressure was set to between 0 and 1 bar and the air pressure error threshold was decreased from 1 to 0.3%. The other parameters of the controller were kept at the preselected values. These adjustments significantly increased the response of the compressors and consequently reduced the deviation of the air pressure from the set-point (see Figure 4). The parameters of the air pressure controller are given in Table 1.

It is important that the air pressure in the common air rail is kept as low as possible. This ensures that the air valves for dosing the air into the aerobic reactors are always opened as much as possible, which reduces the air resistance in the pipes and results in a reduced consumption of electricity for the aeration. This can be achieved by adjusting the air pressure in the common air rail according to the 'most opened valve' strategy (Olsson *et al*. 2005; Beltrán *et al*. 2011). The control scheme of such an air pressure control is shown in Figure 3.

The controller maintains the most opened valve of the aerobic reactors at the selected set-point. The outer PI controller determines the air pressure set-point according to

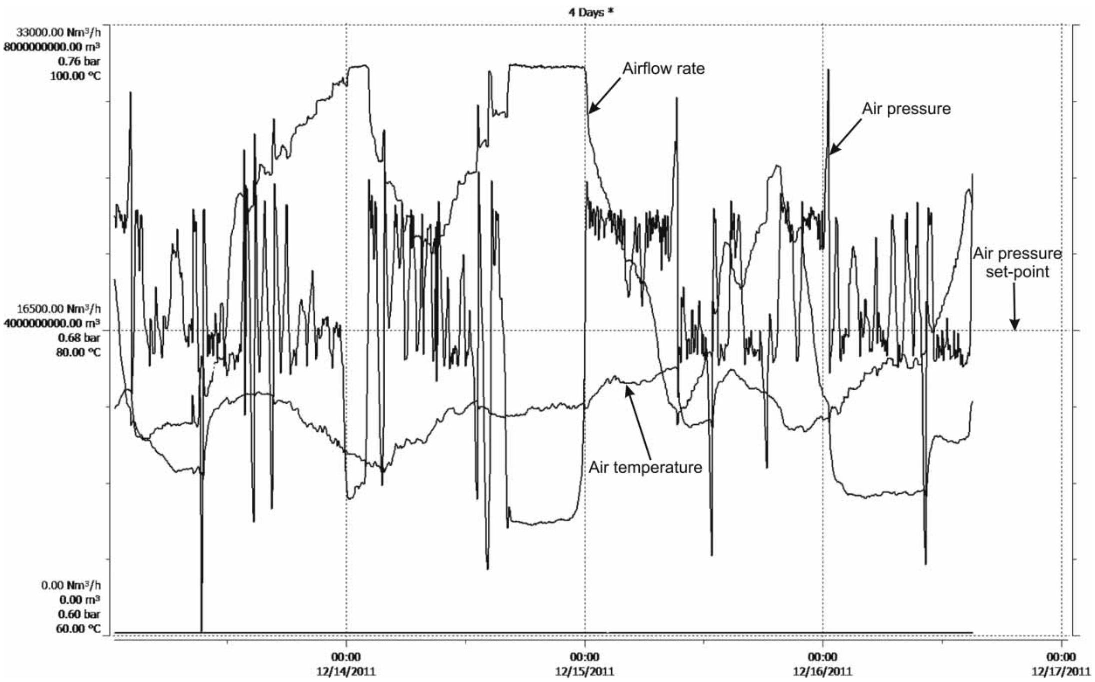

Figure 2 | Results of the initial air pressure controller for 4 days of operation. Signals shown: air pressure, airflow rate and air temperature in the common air rail.

Table 1 | The parameters of the air pressure controller

Parameter	Value
Control region from 0 to 100%	0 to 1 bar
Error threshold	0.3%
Proportional gain	1
Integral time constant	45 s
Diffuser opening/closing time	60 s
Min. control pulse length	0.04 s

the most opened valve of the aerobic reactors. This set-point is maintained by the inner air pressure PI controller, described above. The air pressure set-point controller was implemented in the ABB SCADA system (ABB 2005) by using the max function, the low-pass filter and the PI controller blocks. The sampling time for the control blocks was equal to the inner sampling time of the SCADA system, which was 0.2 s. The parameters of the air pressure set-point controller are given in Table 2.

The set-point for the most opened valve was set to 90%. The higher value of the set-point results in more opened air valves and consequently the lowest electricity consumption for the aeration. However, a too high set-point value can cause control problems, because of the limited control error range. The parameters of the air set-point PI controller were calculated from the self-oscillation method using the Ziegler–Nichols rules (Åstrom & Hägglund 1995) and manually adjusted for weeks to obtain the desired control performance. Note that the proportional gains of the

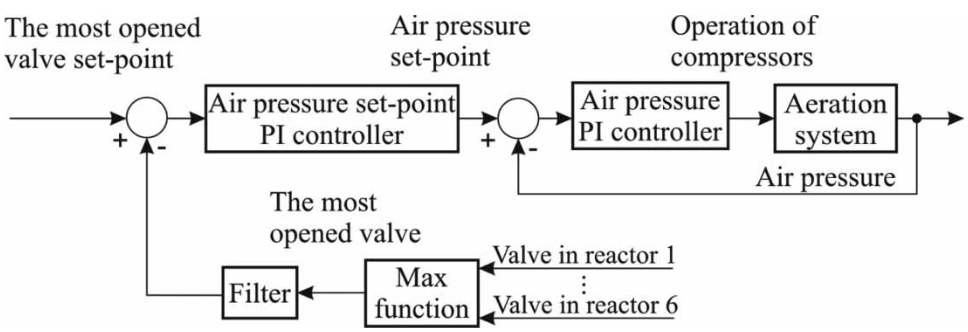

Figure 3 | Control scheme of the air pressure control.

Table 2 | The parameters of the air pressure set-point controller

Parameter	Value
Set-point of the most opened valve	90%
Proportional gain	0.0005 bar/%
Integral time constant	14,400 s
Max. air pressure	0.67 bar
Min. air pressure	0.61 bar
Time constant of the most opened valve filter	900 s
Sampling time	0.2 s

controllers have to be scaled according to the selected input and output ranges of the controllers. The maximum and minimum values of the air pressure set-point should be selected with care. The maximum value should be high enough so that the aeration system provides enough air for the high load peaks. At the same time, it should not be too high because this can cause an unnecessary consumption of electricity for the aeration. The minimum value should be low and at the same time high enough to provide sufficient overpressure in the common air rail. The low-pass filter was a first order system with a time constant. The purpose of this filter is to reduce occasional spikes in the air valves.

The results of the air pressure set-point controller are shown in Figure 4. The controller changes the air pressure set-point on a daily basis according to the changes of the plant load. During a low load the set-point is decreased, and then it is increased during a high load. It is clear that the controller quickly reduces and slowly increases the air pressure set-point. The reason for this phenomenon is that the positive valve error is usually much larger than the negative one.

OXYGEN CONTROL

Initially, the oxygen at the end of the inlet reactors and in the middle of the outlet reactors was controlled by the oxygen controllers. These oxygen controllers worked as the cascade controllers, where the outer oxygen PI controller determines the set-point for the air valve and the inner on-off controller maintains the desired valve set-point by opening and closing the valve. Such controllers resulted in oxygen oscillations or a sluggish response (see Figure 5). The oxygen oscillations were usually obtained for lower valve values, and a sluggish response at higher valve values. This indicates that the gain of the aeration process is greater at lower valve values than at higher ones. The

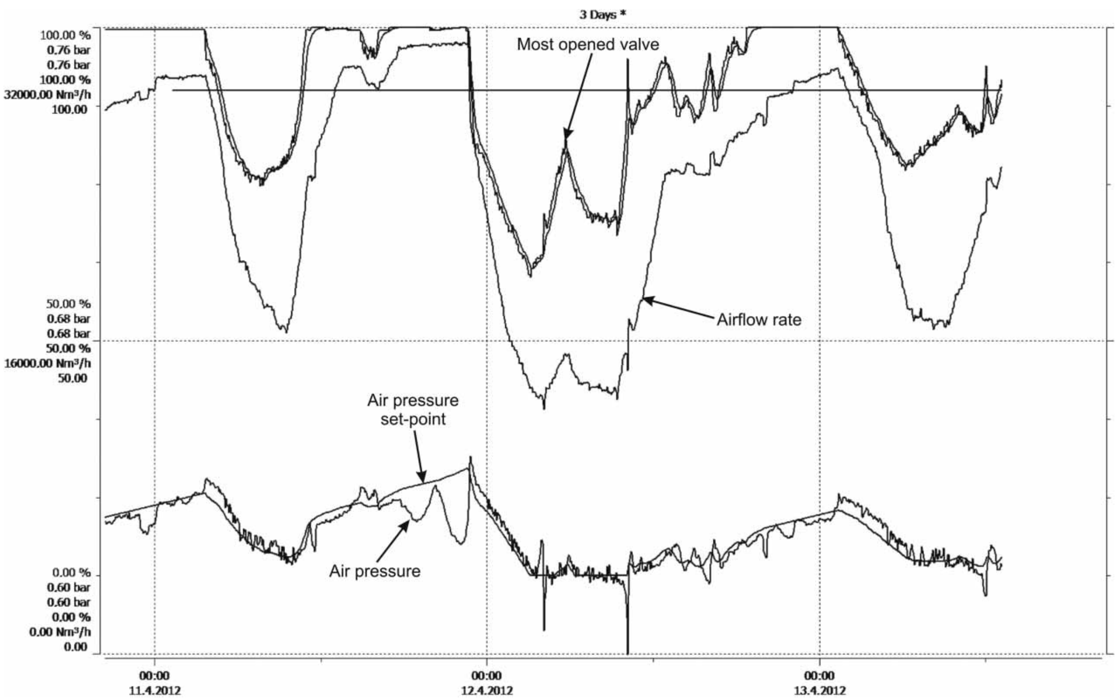

Figure 4 | Results of the air pressure set-point controller for 3 days of operation. Signals shown: air pressure and airflow rate in the common air rail and the most opened air valve (non-filtered and filtered value).

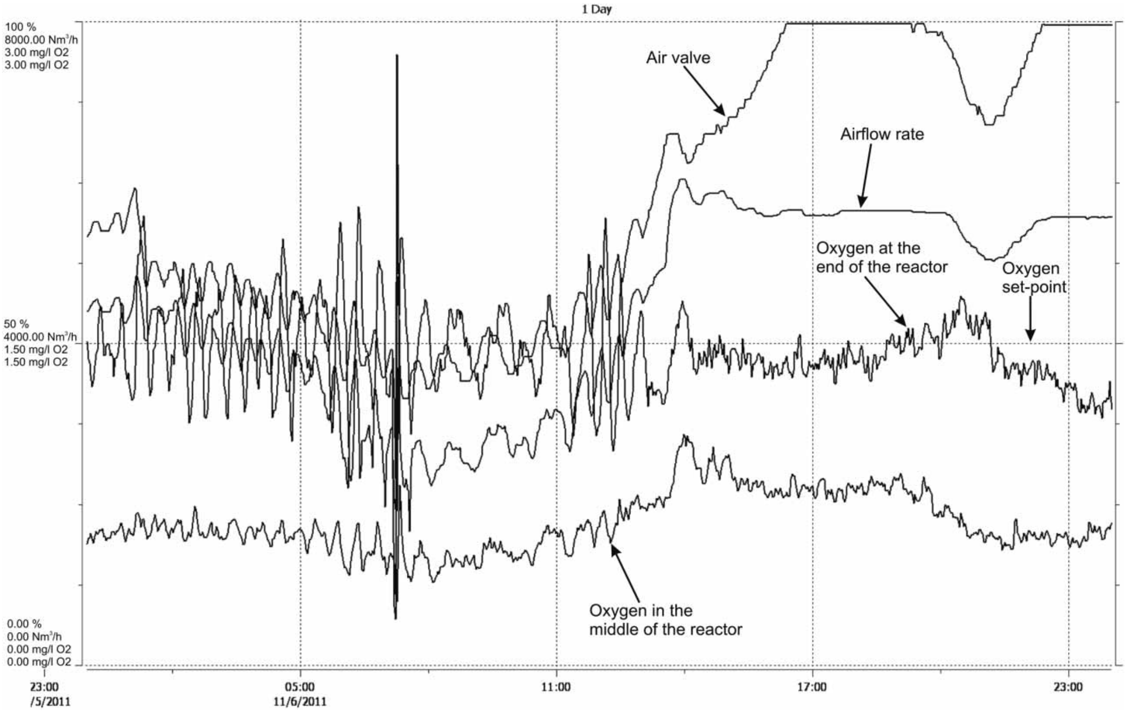

Figure 5 | Results of the initial oxygen controller in the fourth reactor (the second inlet reactor) for 1 day of operation. Signals shown: oxygen concentrations at two locations, air valve value and airflow rate.

main cause of this variable aeration process gain lay in the nonlinear characteristics of the air valves.

To improve the oxygen control performance, several changes were made to the existing control.

Oxygen measurements in the middle of the inlet reactors (approximately 25% of the reactor's length) instead of at the end of the reactors were used for the control. Those measurements were located closer to the start of the reactors and provided a smaller variation in the oxygen concentrations and a faster response to the load changes. On the other hand, it was assumed that they were located far enough away from the start of the reactors so that the depletion of the soluble chemical oxygen demand (COD) occurs prior to those points.

An inner airflow PI control loop was introduced in the oxygen control. The airflow controller is faster than the outer oxygen controller, which improves the disturbance rejection inside the aeration system and linearizes the nonlinear characteristics of the air valve. The oxygen and airflow controllers were implemented by the ABB cascade PI control block (ABB 2005), whereas the oxygen signal was filtered with the low-pass filter block. The cascade PI controller includes the backtracking of signals from the inner to the upper controller, which allows anti-windup protection and a bump-less switch between the manual and control modes. The control scheme of the oxygen control is shown in Figure 6.

The initial values of the parameters for the oxygen and airflow PI controllers were calculated from the step response experiments using the IMC tuning rules (Olsson & Newell 1999). The values of the parameters vary according to the position of the reactor (inlet, outlet), the operating point (valve

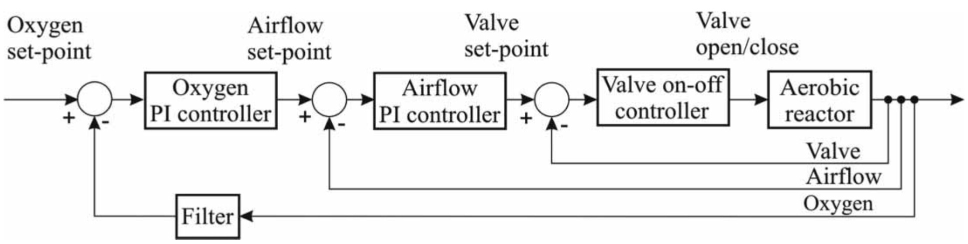

Figure 6 | Control scheme of the oxygen control.

Table 3 | The parameters of the oxygen and airflow PI controllers

Controller	Parameters	Inlet aerobic reactors	Outlet aerobic reactors
Oxygen PI controller	Proportional gain	1,100 (m^3/h)/(mg/l)	600 (m^3/h)/(mg/l)
	Integral time constant	600 s	600 s
	Time constant of the oxygen filter	50 s	50 s
	Max. airflow rate	10,000 m^3/h	10,000 m^3/h
	Min. airflow rate	1,500 m^3/h	1000 m^3/h
	Sampling time	0.2 s	0.2 s
Airflow PI controller	Proportional gain	0.019%/(m^3/h)	0.027%/(m^3/h)
	Integral time constant	500 s	400 s
	Max. valve	100%	100%
	Min. valve	10%	10%
	Sampling time	0.2 s	0.2 s

and oxygen values), the plant load, etc. It was apparent that the tuning of these controllers is a very demanding task in real plants. One of the tuning challenges was to obtain satisfactory oxygen control without disturbing the air pressure control too much. To achieve satisfactory performance for the controllers, their parameters had to be manually adjusted for several months. This indicates that the use of some sort of self-tuning control could be advantageous. The maximum values for the control outputs were set to the highest upper values, whereas the minimum values were set to values that still allow for sufficient mixing of the aerobic reactors. The filter time constant was set to a value high enough to significantly reduce the oxygen measurement noise. The parameters of the oxygen and airflow PI controllers are given in Table 3.

Table 4 | The parameters of the valve on-off controller

Parameter	Value
Hysteresis	1%
Min. pulse length	0.2 s
Max. valve	100%
Min. valve	10%

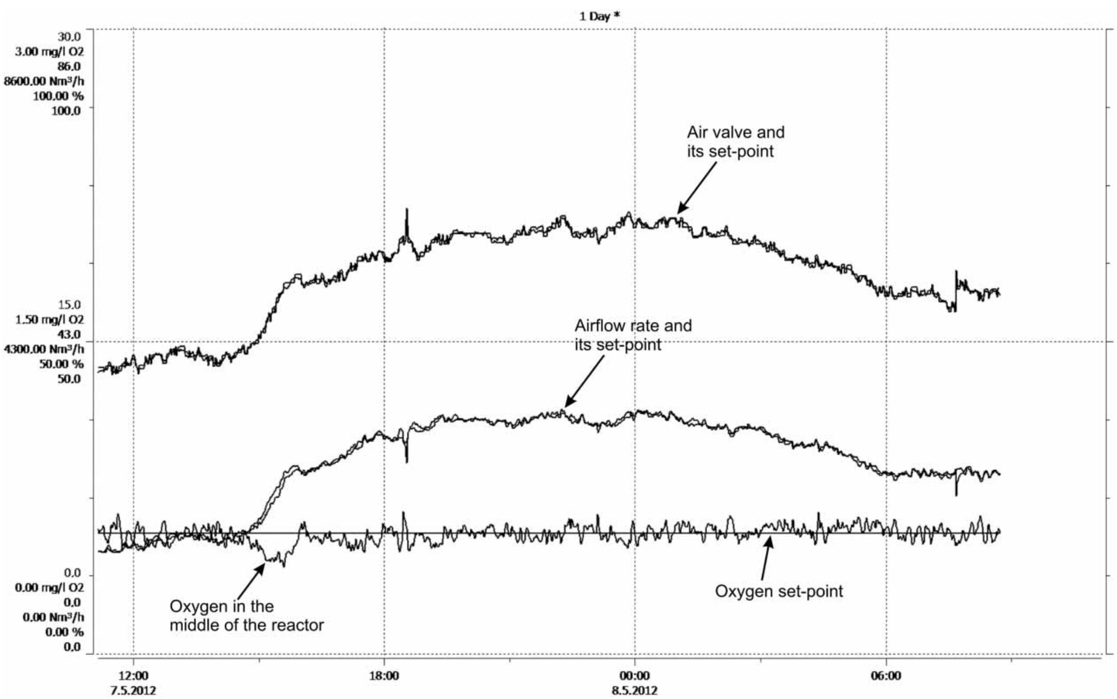

Figure 7 | Results of the improved oxygen controller in the fourth reactor (the second inlet reactor) for 1 day of operation. Signals shown: oxygen concentration, air valve value and airflow rate.

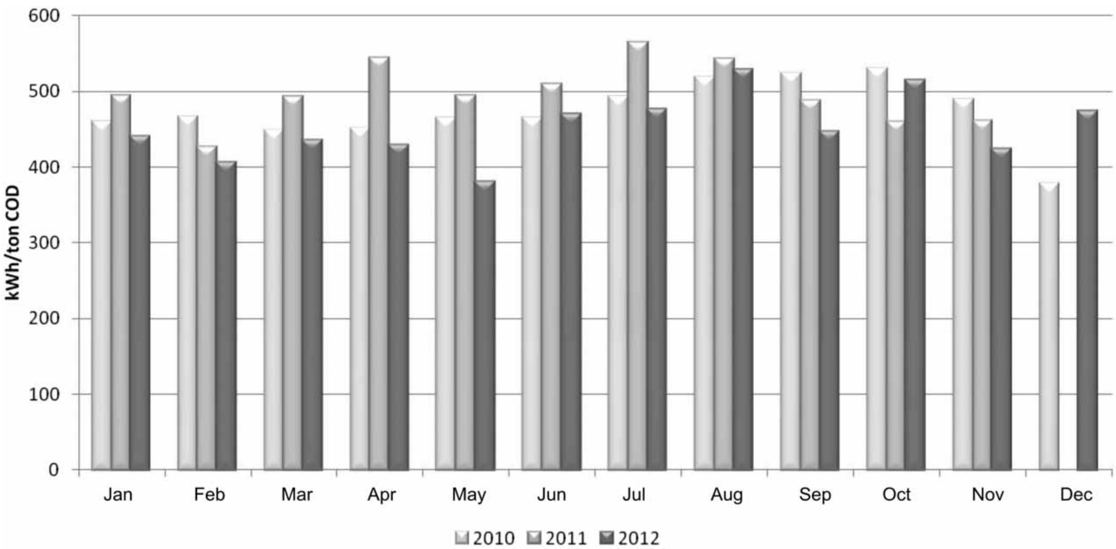

Figure 8 | Monthly electricity consumption for aeration at the Ljubljana WWTP in 2010, 2011 and 2012.

The proportional gain of the oxygen PI controllers in the inlet reactors is around twice as large as in the outlet reactors. This indicates that the gain of the oxygen process in the inlet reactors is around two times lower than in the outlet reactors.

The parameters of the valve on-off controller were also slightly adjusted. The hysteresis of the controller was reduced from 3 to 1% to achieve more accurate valve control. However, it was shown that this had no impact on the noise of the valve. Note that the number of valve position changes per hour did not exceed the limit imposed by the manufacturer. The parameters of the valve on-off controller are given in Table 4.

The results of the improved oxygen control are shown in Figure 7. This improved control results in much smaller deviations of the oxygen concentration from the set-points, so enabling a reduction of the oxygen set-points, which lowers the consumption of electricity used for aeration. The oxygen set-points were reduced to around 0.6 and 1.1 mg/l in the inlet and outlet reactors, respectively.

Table 5 | Average electricity consumption for aeration at the Ljubljana WWTP in 2010, 2011 and 2012

		Average electricity consumption for aeration per ton of COD removed	
Year	**COD removed per year (ton)**	**kWh/ton**	**%**
2010	12,357	475	105
2011	14,068	500	110
2012	15,507	453	100

ELECTRICITY CONSUMPTION FOR AERATION

The improvement in the aeration control was evaluated in terms of the electricity consumption for aeration. The consumption was calculated as the electrical energy (kWh) needed to remove a ton of COD. Note that the nitrogen was not taken into account in the evaluation because of the missing measurements of the ammonia nitrogen. The calculation was performed for the year 2012, when the improved aeration control was in use, and for the previous two years (2011 and 2010). The monthly electricity consumption for aeration at the Ljubljana WWTP in 2010, 2011 and 2012 is shown in Figure 8.

Table 5 shows the average electricity consumption at the Ljubljana WWTP in 2010, 2011 and 2012. It is clear that the amount of COD removed per year has increased in recent years. Compared to 2012, in 2011 approximately 10% more and in 2010 approximately 5% more electricity was consumed for aeration to remove a ton of COD. With the improved aeration control a certain amount of savings is achieved on a yearly basis. It should be mentioned that the return on investment for improving the aeration control was shorter than one year.

CONCLUSIONS

Attempts to improve the aeration control at the Ljubljana WWTP exposed the problem of excessive variation of the air pressure in the common air rail. To mitigate this variation the air pressure controller needed to be properly tuned. The reduction of electricity consumption for aeration was achieved by introducing the air pressure set-point controller and the air-flow controllers. With the improved aeration control a certain amount of savings for aeration is achieved on a yearly basis. In addition, a more stable operation of the plant is obtained.

Further improvements to the aeration control could result from adjusting the oxygen set-points according to the ammonia measurements in the reactors. Aeration control could be also improved by controlling the solids in the aerobic reactors.

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