Performance Optimization of Waste Water Treatment Plants

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TABLE OF CONTENTS

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Introduction:

In most of the time, waste water treatment plants are operated without optimization. It is normally thought that optimization is unnecessary as the system is already designed to meet our requirements. However, this is not the case. Design always has some operating margin for taking care of performance degradation. Further, waste water treatment plant design is based on the results obtained for a set of samples collected for a short time duration. The quality of waste water being treated may be significantly different from the design, and it is always essential that any waste water treatment facility is optimized after successful commissioning of the plant. This ensures that all the machines do perform well so that the treated water quality is to the expected level.

In the current situation of economic downturn, it is very much important that we focus our attention on reducing operational costs of any waste water treatment facility – irrespective of the technology in use. A well optimized system can consume around 20-30% less electrical power, reduce maintenance works by 50%, and increase life-time of the treatment units by around 10-20%. Optimization also ensures that the waste water treatment facility always meets environmental compliance (discharge norms), provided suitable treatment system is already in place.

We have developed an algorithm for detection of a shift-in the performance of any waste water treatment unit. This is essentially detecting a point from where the performance starts degrading – the *threshold*. We achieve this with the performance data for a given treatment unit. Finding both upper and lower levels of *threshold* is important. When the *threshold limit* crosses the upper limit, the performance is above average (this occurs in a new treatment unit that is designed to meet future performance degradation issues and operated with full-throttle), and when the threshold crosses the lower limit, the performance decreases (this happens when the treatment unit has operated for quite some time and its performance degraded). This fixes the *threshold limit* for starting the maintenance of the equipment such as, backwash, chemical cleaning, replacement of filtration media or, changing the entire unit if the desired performance is not attainable with any strategy. In this article, all possible applications of this algorithm for process optimization is explained.

There are other areas of applications that are unexplored in this article such as, optimization of pipelines, cooling towers, heat exchangers, boilers, *etc.*, to conserve space. Preventive maintenance is another area where this algorithm can be effectively applied.

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Equalization:

It is well known that irrespective of the system in place to treat the waste water, the equalization of the effluent determines the performance of the whole treatment system, as well as the life-time of the machineries in place. Equalization homogenizes the effluent, thereby reducing shocks to the treatment units, increasing overall efficiency and life-time.

Normally, equalization is achieved in two ways: 1) by mixing the effluent in the equalization tank using an agitator or, mixer; 2) by pumping air into the equalization tank. When the flow volume of effluent to the equalization tank, and its physico-chemical characteristics such as pH, Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD) *etc.*, remains within certain limits, best results are obtained. However, changes in flow volume and/or, the chemical nature of the effluent with time beyond a desired limit may result in insufficient equalization. This may even be a transient process of short-time duration in an otherwise normally running waste water treatment plant – thereby missing a chance for detection. These problems shall normally prevail in a Common Effluent Treatment Plant receiving effluent from diverse industries.

The size of the equalization tank is determined based on the fluctuations in the flow (input) and the design treatment capacity of the plant (output) – not fluctuations in the chemical characteristics of the effluent. And, it is normally assumed that by retaining the effluent in the equalization tank to a certain time determined by the design, the effluent shall be homogenized *i.e.*, the chemical nature of the effluent does become uniform throughout space and time. However, depending on the tank geometry, changes in flow characteristics (volume and chemical nature), placement and mixing efficiency of the agitators/mixtures/aerators, the efficiency of homogenization may vary from time to time. Thus, under normal operating conditions, variation in the physico-chemical nature of the equalized effluent is quite common. If this variation exceeds design limit, it may turn out to be detrimental to the entire waste water treatment system, as any variation beyond the allowed limit may impose performance problems.

Thus, any waste water treatment facility should check first whether homogenization is effective and whether the equalized effluent adhere to the treatment system design. By properly designing the equalization process, it is possible to reduce the required treatment units down the stream. For example, if an effluent with wide ranging Total Suspended Solids (TSS) is equalized efficiently, then the requirement for additional sequential filtration units (*i.e.,* for example, two Pressure Sand Filters in series) can be avoided. This is due to the fact that if the well equalized influent TSS concentration does not vary much, the effluent TSS of the first PSF shall not have wider variation, and there shall be no need to dampen this variation with another PSF. The same logic is applicable for all physico-chemical properties and the effluent and corresponding treatment units.

There are also operating cost benefits with well equalized system design. Consider an example where the BOD has to be reduced by aeration. In a well equalized effluent, the variations in BOD shall not be much. Under this scenario, the oxygen transferred to the waste water shall be completely utilized. However, if equalization is not efficient, then there shall be times in which the BOD levels might have been higher and the supplied oxygen may not be enough to attain desired level of BOD reduction. Similarly, there shall also be times in which the oxygen requirement shall be less than the supply. In this case, power shall be unnecessarily wasted for pumping the air.

Aeration:

Aeration is an energy intensive process and it consumes a significant portion of energy in any waste water treatment facility. Nowadays floating aerators are being replaced by venturi mixtures and membrane diffusers to achieve energy efficiency and better oxygen transfer. However, the depth of aeration, the location of mixtures and diffusers, the air bubble size, the energy of mixing, the air flow rate, the temperature and chemical nature of the effluent, type and level of microorganisms in the aeration tank, all determine the quantity of oxygen that is transferred and consumed. Thus, BOD reduction becomes not only a function of available oxygen, but also the factors that affect oxygen transfer and consumption.

In an aeration tank, the quantity of air flow has to be optimized to suit the prevailing environmental conditions and biological oxygen demand of the effluent. Otherwise, energy shall be wasted in pumping excess air. On the other hand, pumping lesser quantity of air may result in inefficient BOD reduction, and this shall affect the performance as well as the life time of the waste water treatment units down the line.

The one important thing often forgotten with aeration is the diurnal and seasonal fluctuations in ambient temperature. Temperature changes affect two things – i) oxygen transfer efficiency; ii) biological growth. The supply of oxygen through aeration should be tuned to suit prevailing oxygen demand of the waste water being treated and the environmental conditions. In this way, a lot of energy can be saved and operating cost can be reduced.

Aeration control is also an important aspect in recent innovations *viz.*, membrane biorector, where air is utilized both for scouring the membrane as well as to oxygenate the water column. In the anoxic chamber of membrane bioreactor (MBR), it is essential to maintain the oxygen concentration below a certain level (typically < 0.5 mg/L) to maintain the growth of anaerobic metabolism, which is essential for the degradation of recalcitrant organics. Similarly, in the aeration chamber, it is essential to maintain oxygen above certain level (typically ~ 2 mg/L) so that enough oxygen is made available for the sustenance of aerobic metabolism. In the membrane bioreactor, it is normal practice to return a certain amount of treated waste water from the membrane compartment to the anoxic compartment as given in Fig.1.

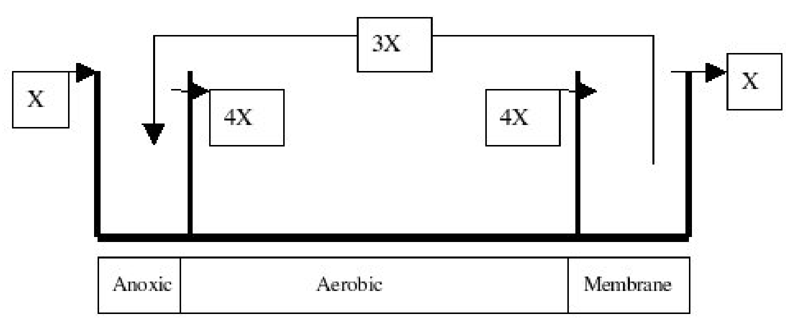

Fig.-1: Recirculation pattern inside MBR compartments.

This recirculation is effected to return the microbial population (especially slow growing ones), active extracellular enzymes that are effective in faster degradation of organics, and to dampen shocks (sudden changes in the chemical characteristics of the feed to the MBR). Recirculation of oxygenated waste water also returns a certain quantity of dissolved oxygen present in the treated effluent to the anoxic chamber. Thus, the degree of anoxicity in the anoxic chamber of the membrane bioreactor is a function of oxygen demand of the mixed effluent, the level of dissolved oxygen in the recirculating waste water, the quantity of recirculating fluid, and finally the level of dissolved oxygen in the feed. For proper functioning of the MBR, especially when it is used for the treatment of recalcitrant organics typical of waste water from textile dyeing and petroleum industries, it is very essential that the dissolved oxygen in the anoxic chamber is always monitored, controlled and maintained below the required level in order to promote the growth of anaerobic bacteria that is capable of breaking recalcitrant organics in the effluent. Thus, optimizing oxygen level in the membrane bioreactor (MBR) is an important aspect of achieving better degradation of recalcitrant organics.

Further, a lot of energy is consumed when air is pumped to scour the membrane surface for the prevention of rapid fouling. There are several ways in which this can be achieved; 1) scouring and filtration are concurrent and continuous; 2) scouring and filtration cycles are alternated; 3) scouring and filtration are concurrent with intermittent no-activity period. Each of these methods advocate certain advantages, while they themselves have some inherent problems. The decision to operate the membrane bioreactor (MBR) in any one of the above mode is decided by the design engineer of the manufacturer. But, after a suitable process has been chosen for operating the membrane bioreactor, it is essential that the system should be optimized – taking into consideration all the factors that are likely to have an impact on the performance.

The most important factors that are to be optimized here are the scouring time, filtration time, and the inactivity period. The *scouring time* is defined here as the period in which scouring of the membrane is carried out by aeration through coarse bubble diffuser[2]. The *filtration time* is the period in which water permeates through the membrane; the *inactivity period* is the time in which neither scouring nor filtration takes place. Continuous scouring may thought to thwart off particles away from the membrane surface thereby enhancing filtration. However, this shall consume more energy. Pulsed scouring operation may result in declining filtration with time in each cycle as particles tends to accumulate over the membrane surface – but this consumes less energy. By suitably optimizing the scouring time, filtration time and inactivity period, it is possible to utilize pulsed scouring and reduce the energy required for operating membrane bioreactor. A better design not only decides the duration of each process, but also the timings of each operation. Hereby I mean that an optimized overlapping of scouring time and filtration time shall give better results than their being run separately.

2 Air bubble size and air pressure inside each air bubble are important factors to be considered for effective scouring. While an increase in air bubble size shall increase the number of particles being hit by it for a given time frame, an increased pressure gives more energy for each bubble to effectively scour the membrane surface. It should also be noted here that there is an optimum air bubble size, beyond which the effectiveness of scouring declines. This can be found by plotting the air bubble size against the suspended load concentration for a given depth (though trivial, variations in depth shall result in a change in air bubble size with a reduction in water column pressure. And, suspended solids shall tend to be concentrated near the bottom due to the effect of gravity. These effects could be nullified if we fix the depth).

Maintenance of pH:

Acid/alkali dosing to maintain pH of the effluent is an another area of importance since the efficiency of the treatment system largely depends on it. It is a normal practice to set the dose based on an initial assessment of the chemical characteristics of the effluent to be treated, and this dose level is incorporated at the plant design stage itself. However, while the waste water treatment plant is operated, the effluent pH may vary, and it is essential to continuously monitor the pH of the effluent to be treated with the use of a pH sensor, and dynamically adjust the required dosing depending on the observed pH. This is easily said than done.

Effluent pH is sensitive to many factors such as the nature of ions present in the effluent, alkalinity, buffering capacity, temperature, *etc.* Taking all these things into consideration in the design of a system for dynamic control of pH shall require a lot of computing power.

This problem can be circumvented if acid/alkali addition is switched on and off by setting a *threshold level* for the pH controller that adjust the pH by acid/alkali addition. The *threshold limit* should be set in such a way that whenever there is a shift in the optimum pH, then the system should take necessary intervention to adjust the pH. Then, we have to think about what is the suitable *threshold level*? Is it the pH range within which the system can operate properly – surprisingly no!

The problem with this methodology is that the system takes action only after the pH crosses the *threshold limit*. For example, after acid/alkali addition is started, the system switches off only after the pH in the effluent exceeds the desired limit. Meanwhile, it takes some time for the effluent to stabilize to the required pH as feed supply and mixing continues. These two processes are transient, and results in delayed action as well as oscillations in the pH of the treated effluent. Therefore, it is almost impossible to control the pH to high levels of accuracy. Therefore, the treated effluent pH shall not be within the limits always.

So, we have to narrow down this gap. And, how much – a difficult question to answer. Setting an arbitrary limit within the design limit is not sensible as it shall impose unnecessary load on the controlling system if the gap between upper and lower limits are too low. It may result in faster wear and tear of the pH controller, thereby reducing the life-time. It should also be noted that the performance of the pH controller may vary with long time operation[3]. Thus, a threshold level that suits the prevailing conditions should be chosen.

Implementation of *iterative algorithm*[4] may prove to be useful in many ways, but it shall have its own *learning curve* – meaning that the algorithm takes its own time to adjust to modified conditions. As waste water pH may vary from time to time depending on the chemical nature of the feed, the system may consume some test cycles to choose optimum dose level. Thus, whenever the feed characteristics fluctuate significantly, another cycle of *learning curve* shall be under progress. This is not a so good process as some quantity of chemicals (acid/alkali) shall be wasted during each *learning curve* phase, and we shall never be sure that only optimum quantity of acid/alkali is added if feed characteristics are not stable.

3 Hereby I mean that the quantity of acid/alkali added by a pH controller may change with long time operation due to wear and tear.

4 In iterative algorithm, a certain quantity of acid/alkali is added and a corresponding change in pH is measured by a pH probe. The results are analyzed by a micro processor, and that gives the quantity of acid/alkali that has to be added in the next cycle. This process goes on continuously until a suitable solution is found.

Therefore, setting a pre-determined *threshold level* seems better than invoking highly complex and, expensive to implement, *iterative algorithm*. The *threshold limit* should then be chosen in such a way that treated waste water pH does not violate the desired lower and upper pH limits at any time – or, at the least, in most of the times (a confidence level, say 95%, can be set for this purpose). Finding this *threshold limit* is a very difficult but crucial problem.

We have developed an innovative algorithm, which help us to find the *threshold limit* by using the historical *performance data*[5].

Using the performance data of pH auto controller, we are able to identify the suitable "*threshold*" at any given point in the entire life-span of an auto controller. This meas that the existing pH controller need not be replaced or, newly installed – even if its performance has worsened but remain within acceptable limits required by our algorithm. The ability to optimize the pH controller that has already attained a certain level of performance degradation over a period of time, is an important step in industrial process control[6] - as already existing waste water treatment plants can take this to their advantage to accrue cost benefits. And, any action taken by the system is *preemptive* – so the system is always under control. By knowing exactly the *threshold limit*, the trigger for the control circuitry to switch on and off acid/alkali addition can be set very accurately[7]. Thus, changes in pH can be accurately controlled, performance and life-time of the total waste water treatment system can be augmented, and benefits can be accrued. Such benefits of pH control in process control are:

1) Physico-chemical processes which are very sensitive to changes in pH such as flocculation, adsorption, gas exchange, scale formation, are very well controlled. Therefore, it improves the performance of the waste water treatment system.
2) Wastage of acid/alkali chemicals are heavily reduced.
3) The life expectancy of the waste water treatment units such as reverse osmosis (reduction in fouling) and evaporator (corrosion control) can be increased. In addition, due to reduction in number of cleaning cycles, the performance as well as operating costs are reduced.
4) There is no need to replace an existing auto controller – thereby additional costs are reduced.

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5 The term *performance data* here means the continuously measured values of pH after acid/alkali addition. The measurement can be in two modes: i) with *regular intervals*; ii) with *irregular intervals*. We are able to provide the solution under both the scenarios and also suggest a suitable time interval to monitor the pH. We do this by finding an optimum time interval through our model calculations with long-term historical data. We are also able to find this optimum *time interval* for measuring pH or, any other process parameter such as temperature, pressure, *etc.* Setting an optimum *time interval* is in many ways useful as given here: i) it reduces the storage space on the data logger; ii) increases the number of sensors that a data logger can handle simultaneously for a given period of operation; iii) decreases the required band width if the data is transmitted over internet, cellular network, or, wireless instruments.

6 Implementing the *Six Sigma* concept may seems useful in process control – but still it has some peculiar problems associated with it. One of the main impediment is that the variations in process parameters, up to 4.5 σ (*i.e.*, standard deviation – not six σ as the name implies), should be tolerated by suitable system design to deliver desired output. Designing such a system shall increase initial capital costs, and sometimes even operational costs. The focus here is to pin-point at which point in time the performance of the system starts deviating from normal – so that necessary remedial measures can be taken in advance before the system crosses the design limit. This is like preventive maintenance. The current algorithm that we have developed is more sensitive to process variations, easy to implement, and less expensive.

7 Instead of switch on/off, progressive controllers can also be set-up. But, to reduce confusion and for ease of understanding, here I use only switch on/off model.

Filtration:

In filters, such as Pressure Sand Filter (PSF) and Activated Carbon Filter (ACF), the filtered waste water has to be regularly checked for quality (such as total suspended solids, trace elements, and residual chlorine) so that backwashing can be effected at the right time. Since regular sampling and analysis may not be possible in a large treatment facility, backwashing is automated with regular time intervals when the filtration flow is expected to decrease to a certain level. The chosen time interval for backwash operation is normally fixed arbitrarily based on the experience and expertise of the plant operator. Choosing an arbitrary backwash interval may not be a perfect decision. It is possible that the planned time interval for backwash operation may either be longer or, shorter than it is actually necessary in most of the cases – as the feed quality and the condition of the treatment unit changes continuously. If frequent backwash is carried out, it may increase the downtime and reduce overall treatment capacity. Since backwash operation is normally conducted with water recovered from the reverse osmosis system down the line, frequent backwash can also result in overall decrease in the output of reusable water. Instead, if the backwash is delayed, it may reduce the operating capacity and filter efficiency. Thus, it is vital to optimize the filters for better performance to increase operating efficiency and reduce the maintenance cost.

The time within which the PSF and ACF were unable to sustain a design critical flow rate is basically different from the time frame within which their capacity to remove the contaminants decrease significantly. However, the basis for choosing the flow rate as the controlling factor is largely vested with the fact that when the flow decreases, the capacity of PSF and ACF to remove contaminants is also decreased – as void pore spaces are blocked. A real optimization, however, implies designing a system with the level of contaminants removed as the design factor – rather than the flow rate of the waste water. With some test-runs in a fully functioning PSF and ACF in a waste water treatment plant, we are able to find the right time interval for backwash operation that is specific to each filtration unit[8]. As the performance of any treatment unit degrades with time, optimization may have to be planned at regular intervals or, when frequent problems are faced with the treatment unit. This may improve the overall performance of the waste water treatment system, reduce the operating costs, and also expand the usable life-time.

Membrane Filtration:

Membranes are widely used for water and waste water treatment purposes. They can be classified under four different categories depending on the nominal pore size of the membrane – i) micro filtration; ii) ultra filtration; iii) nano filtration; iv) reverse osmosis. In water recovery from waste water or desalination systems employing ultra filtration, nano filtration and reverse osmosis, it is very much essential to optimize the plant for the following reasons:

1) The pressure at which the reverse osmosis system is operated not only decides the recovery percentage, but it also decides energy consumption, the frequency of fouling of the membrane requiring chemical cleaning and, how fast the membrane has to be replaced.

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8 This factor is often ignored in PSF and ACF design. The physical nature (particle size distribution) and chemical characteristics (nature of organics and inorganics) present in the effluent shall have a serious impact on the removal and adsorption capacity of the PSF and ACF, respectively. Thus, it is vital to conduct experiments with real waste water to optimize the operation of PSF and ACF.

2) Cleaning of the reverse osmosis membrane is normally carried out after the system reaches the threshold differential pressure between the feed and the permeate. Though this technique is useful in automating membrane cleaning, it has some difficulties and problems associated with it. At first, the warning to clean the membrane is obtained only after the membrane goes down in its performance to a certain level, and the permeate level has reduced significantly. In this mode of operation, some of the pore blockages in the membrane are not completely restored[9]. Thus, after a number of cleaning cycles, the membrane has to be replaced to attain initial level performance. Secondly, cleaning of the membrane after a certain level of blockage also reduces the overall water recovery for a given time – as the system has been under performing for quite some time due to pore blockage. These two factors results in the necessity to design a system that incorporates additional membrane modules to ensure that the reverse osmosis output remains at a certain level as per client specification. All these things lead to increased capital and operating cost.

3) The feed water quality to the membrane filtration system has to be stabilized within certain limits. This limit is often specified by the membrane manufacturer, and easily ignored by the operator. If the membrane filtration system is not operated within given specifications, it may result in serious ramifications *viz.*; i) the treated water output may not meet required standards; ii) the membrane shall be damaged once for all. Thus, it is customary to have in place a Programmable Logical Controller (PLC) or, SCADA (Supervisory Control And Data Acquisition) system so that when ever the threshold limits are exceeded, the feed is by-passed or, the system is halt. But, as discussed under the section "M*aintenance of pH*", choosing this *threshold* level is critical for successful operation. Any action taken by PLC or SCADA based on *threshold trigger* should be preventive – it should not be *at the end of the pipe* operation. And, this is were we specialize.

Evaporators – when they do start to fail with reject:

Evaporators are another additional treatment units utilized for treatment of reject generated from the reverse osmosis system. The evaporators depend on the steam supplied to the system for evaporating the water in the reject. The design and performance of the evaporator is solely based on the total solids in the feed and the amount of water that has to be evaporated to finally separate out salts and crystallize them.

It is quite possible that the total solids in the feed to the evaporator can vary significantly and it may affect the performance of the evaporator. Monitoring the total feed to the evaporator and setting the *threshold level* for the given operating conditions is an essential part of maintenance. Choosing the *threshold level* is the decision to be made by the design engineer, and it is normally fixed at the design operating total solids level. But this may not be the case when the evaporator is set to operate where, fluctuations in the quality of the feed is normal. Knowing the threshold range under the given operating condition is essential and optimization achieves this objective.

Another area of concern is that as the evaporator continues to operate, scale forms on the tube surfaces, retarding heat transfer and operating efficiency of the evaporator. The scales, if not removed in time,

9 The reason being that well clogged pore spaces are difficult to be opened up even after thorough chemical cleaning. Thus, a certain percentage of pore spaces remain clogged for ever and this increases with time.

may pose several problems including i) increased down time for maintenance; ii) decline in recovered water; iii) corrosion of the materials; iv) reduced water recovery and crystallization rate of the salt; v) increase the overall operating cost. We are able to identify the exact time to start cleaning the evaporator, just by monitoring the quantity of condensate. Thus, we are able to improve overall efficiency, reduce downtime, and save on cleaning chemicals – all of them resulting in cost reduction.