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Performance comparison of batch and continuous flow surface aeration systems

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Abstract−The oxygen transfer rate and the corresponding power requirement to operate the rotor are vital for design and scale-up of surface aerators. The aeration process can be analyzed in two ways such as batch and continuous systems. The process behaviors of batch and continuous flow systems are different from each other. The experimental and numerical results obtained through the batch systems cannot be relied on and applied for the designing of the continuous aeration tank. Based on the experimentation on batch and continuous type systems, the present work compares the performance of both the batch and continuous surface aeration systems in terms of their oxygen transfer capacity and power consumption. A simulation equation developed through experimentation has shown that continuous flow surface aeration systems are taking more energy than the batch systems. It has been found that batch systems are economical and better for the field application but not feasible where large quantity of wastewater is produced.

Key words: Activated Sludge Process, Continuous Flow, Geometric Similarity, Oxygen Transfer, Power Number, Surface Aerator, Two Film Theory

INTRODUCTION

One of the most common methods for wastewater treatment is the activated sludge process. An activated sludge plant is characterized by four elements (as shown in Fig. 1):

- An aeration tank equipped with appropriate aeration equipment, in which the biomass is mixed with wastewater and supplied with oxygen.
- A final clarifier, in which the biomass is removed from the treated wastewater by settling or other means.
- Continuous collection of return sludge and pumping it back into the aeration tank.
- Withdrawal of excess sludge to maintain the appropriate concentration of mixed liquor.

In a conventional activated sludge plant (Fig. 1), the primary-treated wastewater and acclimated microorganisms (activated sludge or biomass) are aerated in the aeration tank. The aeration tank receives the effluent stream and treats it with an activated mass of microorganisms maintained in suspension and capable of stabilizing the substrate aerobically [1]. Aeration is the process by which air is circulated through, mixed with and dissolved in a liquid or substance. In its broadest sense, aeration is the process by which the area of contact between water and air is increased, either by natural methods or by mechanical devices. The essential prerequisite for every aerobic treatment system, being either designated for the decomposition of liquid or solid biomass, is to maintain a sufficient air supply for the micro-organisms. Adequate aeration in liquid manure involves dissolving enough oxygen into the substrate to replace the naturally occurring anaerobic environment (devoid of oxygen) with an aerobic environment. As a result, reactive organic matter, characterized by BOD_5 (five-day biochemical oxygen demand), is rapidly oxidized to relatively harmless products such as carbon dioxide and water. Aeration is the most energy-intensive aspect of wastewater treatment that consumes as much as sixty to eighty percent of the total energy requirements in a modern wastewater treatment plant [2]. The spiraling costs of electricity and other energy forms are now causing engineers and their clients to reevaluate the design of aeration systems. It is to everyone's advantage for a community to be able to treat its wastewater in the most economical way.

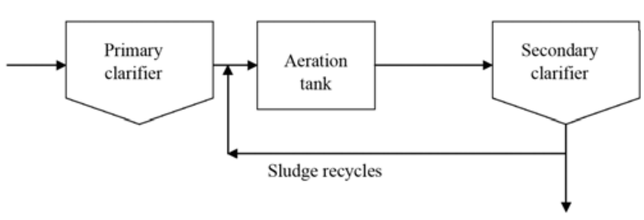

Fig. 1. Schematic diagram of activated sludge process.

Oxygen transfer and the corresponding power requirement are the two basic parameters necessary for design and scale-up of surface aerators for which it is essential to have accurate laboratory simulations governing the hydrodynamic and mass transfer in the concerned area of application [3]. Entrainment of gas from a gas-liquid surface is known as surface aeration. Stirred reactors designed for this type of gas-liquid contact are called surface aerators. For effective aeration, the impeller blades may be located near the free liquid surface [4]. When the geometric similarity conditions are maintained, the functional relationship representing the oxygen transfer coefficient and also power number is reduced to a function of dynamic similarity [5,6] for any shape of aeration tank. The relationship can be described as follows:

$$k=f(X) \quad (1)$$

$$P_O=f(X) \quad (2)$$

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where k is the non-dimensional oxygen transfer coefficient (K_La_{20} $(\nu/g^2)^{1/3}$, where K_La_{20} is the oxygen transfer coefficient at 20 °C and ν is kinematic viscosity of the water), P_O ($P/\rho VN^3D^2$, where P is the power consumed in rotating the impeller, N is the rotational speed, ρ is the density of water, V is the volume of water and D is the diameter of the impeller) is the power number and X is the theoretical power per unit volume. X is defined as $F_r^{4/3}R_e^{1/3}$, where F_r is impeller Froude number and R_e is the impeller Reynolds number. More discussion on this relationship can be found in Rao and Kumar [7].

Basically two types of aeration tank operation (batch and continuous) are used in the activated sludge plant. The precise definitions vary, but in its most basic form batch operation involves a single vessel which is filled, aerated then completely emptied. Continuous operation method of operating a biological treatment plant is characterized by a steady input stream (in terms of chemical and biological composition and flow rate), steady process conditions during the treatment steps and by a fairly consistent flow of treated material with only little variation in its composition. The flow and process dynamics of batch and continuous flow systems are different. In designing, results obtained through batch experiments cannot be applied to the continuous systems. In the present work by doing experiments, energy efficiency and suitability of both the types of surface aeration systems have been analyzed on the basis of oxygen transfer coefficient and power consumption.

EXPERIMENTAL SETUP

Experiments have been done primarily on continuous flow surface aeration systems. Experimental result and simulation equations for k and P_O of square-shaped batch surface aeration systems have been taken from Rao and Kumar [6]. Fig. 2 shows the basic layout of the continuous surface aeration systems.

The following geometric parameters have been maintained in the continuous flow surface aeration tanks during experimentation:

$$l/D=0.3,\ b/D=0.24,\ H/D=1.1,\ h/D=0.94,\ B/D=2.88,\ S/L=0.1$$

where B is the width of the tank, L is the length of the tank, H is the position of water in the tank, h is the position of the impeller, l and b is the rotor's blade length and width and S is the spacing between rotor. A six-blade rotor has been used in the experiments [8]. The experimental setup consists of three rectangular tanks of the following dimensions: a) 40 cm×60 cm×420 cm b) 20 cm×40 cm×220 cm and c) 10 cm×20 cm×120 cm. By maintaining the above-mentioned geometric parameters, experiments have been conducted to ascertain the mass transfer coefficient and power consumption. Each tank has an inlet and outlet connection for re-circulating the water. For controlling rotational speed, DC motors are connected to the control panel. A water meter is also connected to an outlet pipe to check the steadiness of the flow. First, tap water is stored in the 500 liter water tank and it deoxygenates in the tank only. After that, the inlet connection and outlet connection are opened and the desired conditions are set in the tank. Flow steadiness was thoroughly checked as shown in Fig. 3 for the two cases. DO concentration and power consumption have been measured at both inlet and outlet point.

1. Measurements of K_La_{20}

According to two-film theory [9], the oxygen transfer coefficient at T °C, K_La_T may be expressed as follows:

$$K_La_T=[\ln(C_s-C_0)-\ln(C_s-C_t)]/t \tag{3}$$

where ln represents natural logarithm and C_s, C_0 and C_t are dissolved oxygen (DO) concentrations in mg/l, C_s=the saturation DO

Fig. 2. Continuous flow surface aeration systems (40 cm×60×420 cm).

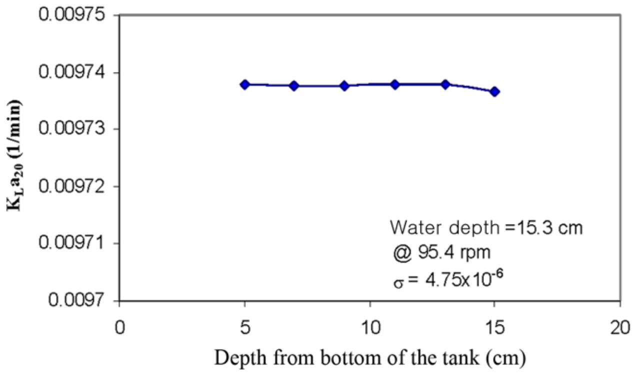

Fig. 3. Spatial uniformity in DO measurement.

at time tending to very large values, C_0 is at the beginning of time t=0 and C_t is at time t=t. The value of K_La_T can be obtained as slope of the linear plot between $\ln(C_s-C_t)$ and time t. The value of K_La_T can be corrected for a temperature other than the standard temperature of 20 ºC as K_La_{20}, using the van't- Hoff Arrhenius equation [10]:

$$K_La_T=K_La_{20}\,\theta^{(T-20)} \tag{4}$$

where θ is the temperature coefficient equal to 1.024 for pure water. At first, water in the tank was deoxygenated by adding the required amount of cobaltous chloride ($CoCl_2$) and sodium sulfite (Na_2SO_3) and thoroughly mixed water. The deoxygenated water was re-aerated by rotating the rotor at desired speeds and maintaining the variables as said earlier. When the DO concentration began to rise, readings were taken at regular intervals till DO increased to about 80% of the DO saturation value. The Lutron Dissolved Oxygen meter was used to measure the DO concentration in water. With the known values of DO measured in terms of C_t at regular intervals of time t (including the known values of C_o at t=0), a line was fitted by linear regression analysis of Eq. (3), between the logarithm of (C_s-C_t) and t. For this purpose, by assuming different but appropriate values of C_s the regression that gives the minimum "standard error of estimate" was taken and thus the values of K_La_T and C_s were obtained simultaneously. The values K_La_{20} were computed using Eq. (4) with θ=1.024 as per the standards for pure water [10]. Thus, the values of K_La_{20} were determined for different rotor speeds N of the rotor in all of the geometrically similar tanks. The rotational speed of the impeller was measured by digital tachometer. Aeration devices are conventionally evaluated in clean water [2] and the results are adjusted to process operating conditions through widely used conversion factors (α and β). The ratio of the process water K_La_{20} to the clean water K_La_{20} is also known as the Alpha Factor (α). α varies depending on the aeration process and water characteristics. Surface aerators generally have an a factor ranging from 0.8 to 1 [11-13]. Thus, tap water was used in the experimentation instead of wastewater. The primary assumption for measurement of the oxygen transfer coefficient in a surface aeration tank is that the bulk test liquid under aeration is completely mixed (of a uniform DO concentration throughout) at all times. In practice, it is not always the same. The *ASCE Standard* requires that "A minimum of four determination points shall be used." One should be at a shallow depth, one should be at a deep location, and one should be at middle depth. An experiment was conducted to investigate the impact of adjusting the location of dissolved oxygen measurement points used to evaluate the operational performance of surface aerators. The DO concentrations were measured at various depths and at regular intervals, as shown in Fig. 4. It is noted from Fig. 4 that the resultant re-aeration rates are consistent between the measurement points at each depth. Additionally, the re-aeration rates determined for the two depths are comparable.

2. Power Consumption by DC Motor

The effective power available at the shaft was calculated as follows [14]. Let P_1 and P_2 be the power requirements under no load and loading conditions, respectively, at the same speed of rotation. Then the effective power available to the shaft, $P=P_2$-P_1-Losses, is expressed as,

$$P=I_2V_2-I_1V_1-R_a\,(I_2^2-I_1^2) \tag{5}$$

where I_1 and I_2 are the currents measured in amperes under no load and loading conditions, respectively; similarly the respective voltages in volts are V_1 and V_2. Armature resistance R_a is measured in ohms.

RESULTS AND DISCUSSION

The relationship between the oxygen transfer coefficients k and P_O with X for square-shaped surface aeration systems is well established by Rao and Kumar [6]. Rao and Kumar [6] formulated the relationship as follows:

$$k=\{17.32\exp[-0.3/X^{1.05}]+3.68 -0.925\exp[-750(X-0.057)^2]\}\;10^{-6}\sqrt{X} \tag{6}$$

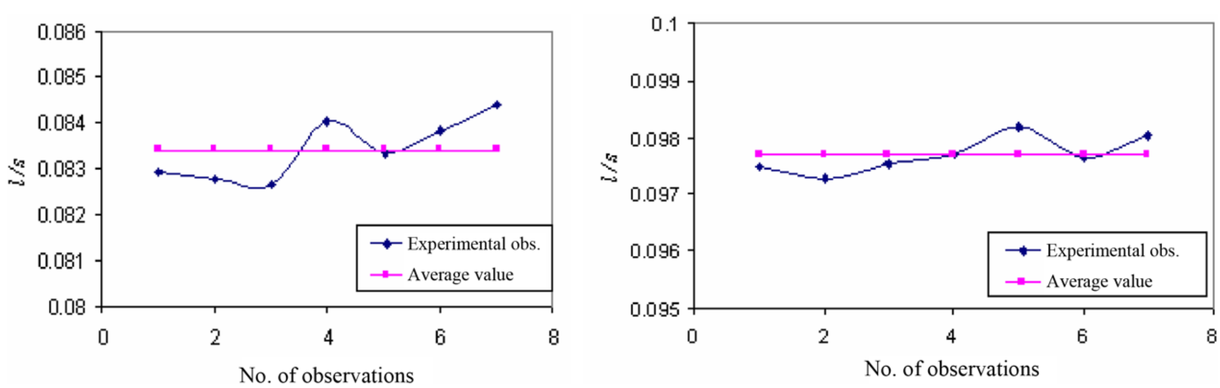

Fig. 4. Ascertaining flow steadiness.

$$P_O\sqrt{X}=0.145+0.203\sqrt{X}+0.855\sqrt{X}e^{-X} \tag{7}$$

By going back to the functional relationship described in Eqs. (1) and (2), when geometrical similarity is maintained, k is a function of both Reynolds number and Froude number (combined as X). Same can be said in the case of the power number also. Considering that the fluid medium is the same in all the experiments of different scale of tanks and the system is Newtonian, subsequent fluid hydrodynamics or relevant mass transfer phenomena can be satisfactorily described by the Reynolds number and Froude number. To know the functional relationship as described in the Eqs. (1) and (2), experimental observations of k and P_0 with X have been plotted in Figs. 5 and 6. As it can be seen, experimental observations of continuous flow surface aeration systems are merged to a single curve suggesting a unique relationship among them. The equations

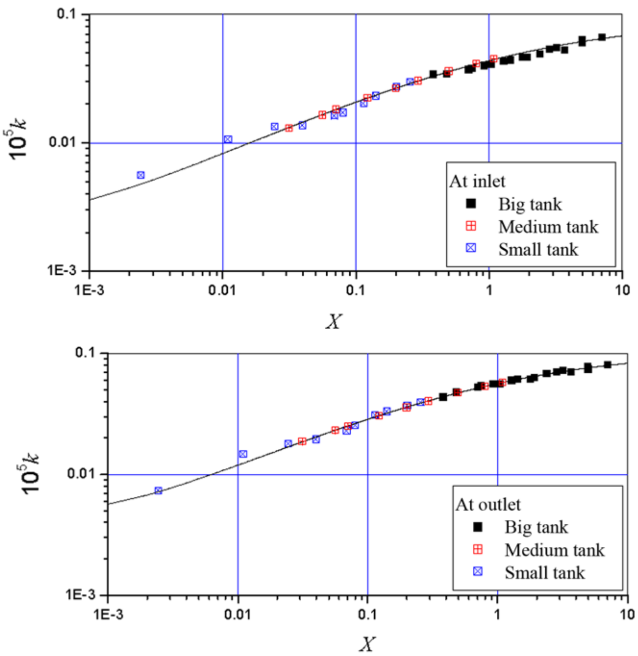

Fig. 5. Oxygen transfer rate with X in continuous flow surface aeration systems.

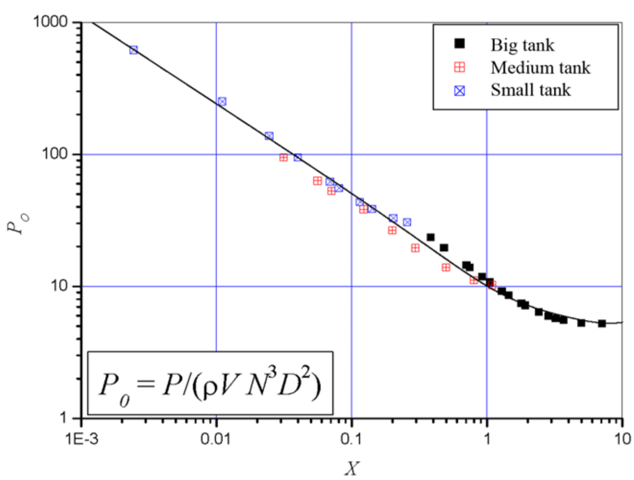

Fig. 6. Power number with X in continuous flow surface aeration systems.

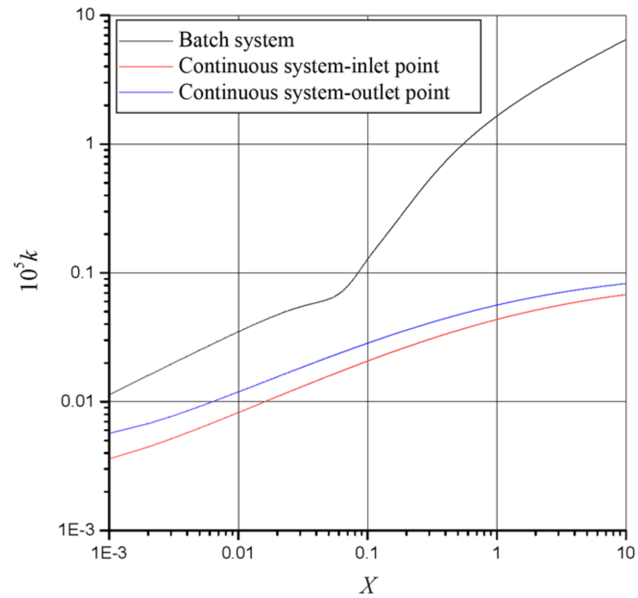

Fig. 7. Comparison of oxygen transfer rate in batch and continuous flow surface aeration systems.

representing those curves are given below:

$$10^5k=\frac{X}{-0.12+10.85X+12.22\sqrt{X}} \quad \text{(At inlet)}$$

$$10^5k=\frac{X}{-0.10+9.43X+8.432\sqrt{X}} \quad \text{(At outlet)} \tag{8}$$

and

$$P_0=X^{-0.671}e^{(2.4+0.083X)}-5.03\sqrt{X}e^{-X} \tag{9}$$

Eqs. (6) and (8) relate the oxygen transfer coefficient with X for batch and continuous surface aeration systems. Fig. 7 shows the combined graph of oxygen transfers of both the systems. As can be seen from Fig. 7, batch systems show high k which means lower time to aerate the wastewater, whereas continuous systems show higher time. To compare the performance of both these systems, an energy consumption parameter has been used to substantiate the energy consumption. As k is a nondimensional form of K_La_{20} and P_0 is the nondimesional form of P, the energy consumption (ε) may be defined as follows: $\varepsilon=P_0/k$. ε versus X has been plotted in Fig. 8 for both the systems.

As can be seen from Fig. 8, continuous flow surface aeration systems take more energy than batch systems. This indicates that batch systems are economical and better for the field application. However, batch systems are not feasible where a large quantity of wastewater is produced. This production can be steady or varied also. Once again, batch systems will take a large amount of space for installation where large waste inputs are there. The quality of the treated material can still change from batch to batch due to fluctuating substrate composition and process variation. Batch operation is much more common in the treatment of solid wastes as typified by composting. This often reflects the small scale of many operations and the general lack of automation. Continuous flow surface aeration systems resemble the real field application as shown in Fig. 1. The geometric parameters, which have been given in the present

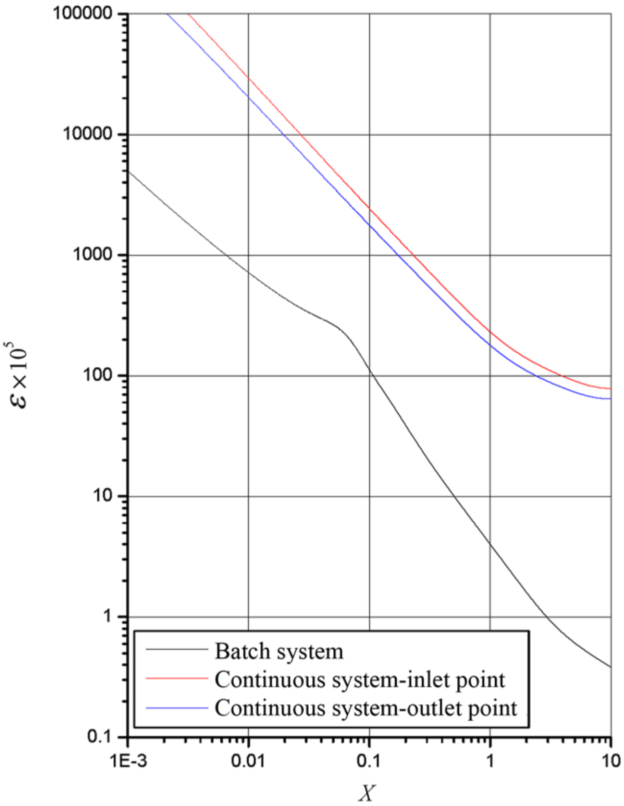

Fig. 8. Comparison of energy consumption in batch and continuous flow surface aeration systems.

work, are for maximum oxygen transfer rates. So these parameters along with simulations equation developed in Eqs. (8) and (9) can be directly applied to the field application. However, where final product quality is important, there is an incentive for a high degree of process intervention and control, which is more readily achieved in a batch system.

CONCLUSION

In reality, the aeration tank employed in the activated sludge plant is of continuous flow type. Present work develops the simulation equations of oxygen transfer rate and power number for the continuous flow surface aeration systems. These simulation equations have been compared with the earlier developed simulation equation for square-shaped batch surface aeration systems. It has been found that batch systems are performing better, but there are certain inherent limitations of using batch systems for a large wastewater plant.

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NOMENCLATURE

B : width of an aeration tank [L]
b : width of the blade [L]
C_0 : initial concentration of dissolved oxygen at time t=0 [mg/*l*]
C_s : saturation value of dissolved oxygen at test conditions [mg/*l*]
C_t : concentration of dissolved oxygen at any time t [mg/*l*]
D : diameter of the rotor [L]
F_r : N^2D/g, froude number
H : depth of water in an aeration tank [L]
h : distance between the top of the blades and the horizontal floor of the tank [L]
I_1, I_2 : input current at no load and loading conditions respectively (amperes)
K_La_T : overall oxygen transfer coefficient at room temperature T °C of water [1/T]
K_La_{20} : overall oxygen transfer coefficient at 20 °C [1/T]
l : length of the blade [L]
L : length of an aeration tank [L]
N : rotational speed of the rotor with blades [1/T]
P : power available to the rotor shaft [ML^2/T^2]
P_0 : ($P/\rho v N^3 D^2$), power number
R_e : ND^2/ν, Reynolds number
R_a : armature resistance of DC motor
V_1, V_2 : input voltage at no load and loading conditions respectively [Volts]
X : $F_r^{4/3}R_e^{1/3}$=theoretical power per unit volume parameter
S : spacing between the rotors [L]
n : kinematic viscosity of water [M^2/T]
ε : energy consumption
α : conversion factor
β : conversion factor
ρ : mass density of water [M/L^3]

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