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Aeration Optimization in an Activated Sludge Wastewater Treatment Plant Based on CFD Method: A Case Study

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***Abstract*—**The extensive aeration process is widely used for wastewater treatment. However, due to the high energy consumption of this process, which is closely related to the issues of environmental sustainability and global climate change, this article presents a simple solution to reduce energy consumption in this process. The amount of required energy is one of the critical considerations for various wastewater treatment techniques. For this purpose, an industrial wastewater treatment plant and all energy-consumer equipment in terms of energy consumption have been analyzed. The investigations and measurements revealed that the aeration unit has the highest energy consumption rate. To address this, an innovative approach is proposed to reduce energy consumption in the identified high-consumer unit. The proposed solution involves introducing baffles to divide the tank into multiple parts and using a tank with a small width and long length to enhance the mixing process. This approach reduces the need for additional equipment and significantly lowers energy consumption. To thoroughly scrutinize the proposed solution and analyze the behavior of the multi-phase fluid inside the tank, the sewage flow has been modeled using the computational fluid dynamics (CFD) method. The study presents an optimal design for the aeration unit based on these findings. The results indicate that implementing the technique suggested in this article can decrease total energy consumption by 33.15% and can be applied to all types of biological treatment plants.

***Keywords*—**Wastewater treatment, aeration, energy consumption, Computational Fluid Dynamics, activated sludge.

I. INTRODUCTION

THE community is currently facing a significant rise in water and air pollution resulting from human activities. In addition to the urgent concern of global warming [1], environmentalists are now focusing on optimizing energy-intensive processes like wastewater treatment. Wastewater treatment plants employ a combination of physical, chemical, and biological processes to treat wastewater and eliminate pollutants [2], [3]. Electricity plays a vital role in these treatment processes, accounting for nearly half of the operational and management costs of wastewater treatment plants [4]. Various processes, including screening and pumping, grit removal, primary and secondary settling, aeration, and sludge treatment, depend on electrical energy. The amount of energy consumed varies depending on the type of treatment plant and available technology, with each unit having its specific energy consumption [2]. Monitoring electricity consumption has long been used as a key indicator for evaluating the performance of aerobic processes [5].

Numerous studies have been conducted on energy consumption in wastewater treatment plants (WWTPs) [6]-[10]. It has been proven that almost 2 to 4% of the total electricity in the community is consumed in WWTPs. Having the environmental requirements and population growth in the coming years been regarded, the essential demands for electrical energy increase and it is necessary to devise a plan for saving energy [11]. The electrical energy consumption in WWTPs depends on the size, treatment technology, influent and effluent quality [12]. One of the most common activated sludge treatment methods is the extensive aeration method. The activated sludge process with extensive aeration has been exploited in the endogenous respiration phase of bacterial growth, which requires a longer aeration time. Due to the long period of aeration compared to other methods of activated sludge process, the electricity consumption increases [13]. Nevertheless, the Integrated Fixed Film Activated Sludge (IFAS) process can produce less sludge and consume less energy [14]. Electric power consumption in WWTPs relies on the level of air consumption [15]. Other studies have demonstrated that 40-60% of the energy used in treatment plants is related to the aeration process identified as the most important energy consumer [16], [17]. Therefore, optimizing the aeration process has been recognized as the necessary step to reduce energy consumption in developed treatment plants.

According to guidelines [18], [19], energy consumption in wastewater treatment utilities can be reduced by optimizing aeration processes through operational modifications. The efficiency of oxygen mass transfer is a critical factor affecting the biological reaction in an aeration tank [20]. Research investigating the thrust required for mixers in the aeration phase showed that the mixing performance does not significantly impact the distribution pattern of dissolved oxygen concentration. Substantial energy savings can be achieved by reducing thrust without compromising treatment efficiency [21].

Hydrodynamic simulation is a key numerical tool for planning and operating wastewater treatment processes [21]-[23]. A CFD simulation conducted on an activated sludge reactor under an intermittent aeration regime demonstrated that on-off aeration improves energy efficiency while facilitating

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anoxic conditions for denitrification [24]. Intermittent aeration, in addition to reducing energy consumption, can suppress nitrite-oxidizing bacteria and decrease N_2O production [25]-[27].

Based on the literature review, the aeration unit is identified as the most energy-consuming component in a treatment plant. Various solutions have been proposed to optimize the aeration unit using CFD, which is considered an efficient tool for designing, operating, and evaluating different scenarios in treatment processes. However, simultaneous investigation of applicability, cost-effectiveness, maintenance of BOD removal efficiency, and the reduction in electric energy consumption resulting from tank modifications has not been fully explored.

This study aims to optimize energy consumption in an industrial WWTP. After identifying the highest energy-consuming unit, CFD is employed to model the sewage flow inside the aeration tank, which is the primary energy consumer. The study presents a cost-effective and efficient solution to reduce energy consumption in this unit.

II. MATERIALS AND METHODS

A. Process Setup

The WWTP being investigated, located in Iran, has an average capacity of 300 m^3/d. It utilizes a combined biological process called UABR + IFAS (Upflow Anaerobic Sludge Blanket Reactor + Integrated Fixed-Film Activated Sludge) to efficiently treat real industrial wastewater. The UABR acts as a pretreatment and an improved septic tank, featuring a series of baffles that force the wastewater to flow upward through the sludge bed reactors. It offers operational advantages such as a simple design, low hydraulic retention time, continuous operation, long solids retention time, phase separation possibilities, and zero energy consumption [28]. The IFAS method combines two processes, activated sludge and Moving Bed Biofilm Reactor (MBBR), providing the benefits of both fixed bed and activated sludge methods. It offers advantages over conventional activated sludge processes, including increased nutrient removal, improved sludge volume index, complete nitrification, extended solids retention time, and increased mixed liquor suspended solids. This combination of activated sludge's flexibility and fixed bed's resistance to organic and biological shock ensures high efficiency for the system [14].

The WWTP has been designed to include physical, biological, final treatment, and sludge management phases. Fig. 1 schematically illustrates the process diagram of the investigated industrial WWTP.

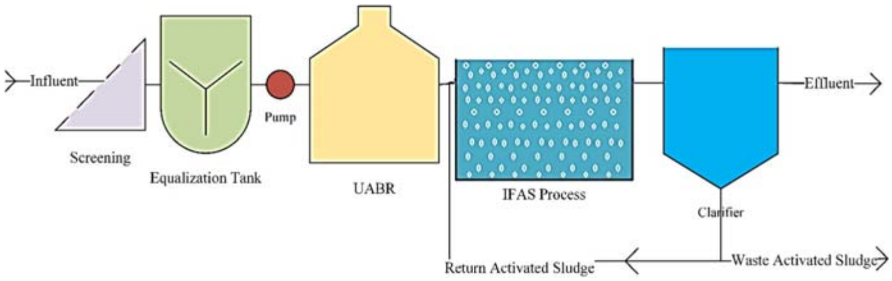

Fig. 1 Schematic process diagram of the investigated industrial WWTP

B. Equipment and Installations Utilized in WWTP

Table I indicates various units of the treatment plant, equipment used, power rating, and operation time.

TABLE I
SPECIFICATIONS OF THE EQUIPMENT USED IN THE WASTEWATER TREATMENT PLANT

Number	Unit	Description	Power	Operation time
1	Pump station	Pump 1	1kW	24 hours
		Pump 2	1 kW	
		Pump 3	1 kW	
2	Balancing tank	Mixer 1	1.5 kW	16 hours
3	Aeration	Blower 1	25 kW – 12 m^3/min	24 hours
		Blower 2	25 kW – 12 m^3/min	
4	Return Sludge	Sub. pump 1	2 kW	24 hours
		Sub. pump 2	2 kW	
		Compressor	1 kW	
5	Effluent	Pump 1	5.5 kW	24 hours
		Pump 2	5.5 kW	

Table II indicates the energy consumption of each unit based on device nominal power and operating time, and the energy consumption chart in varied units of the treatment plant is presented in Fig. 2.

TABLE II
ENERGY CONSUMPTION IN VARIOUS UNITS OF THE WWTP

Number	Unit	Energy consumption [kWh]	Ratio [%]
1	Pump station	48	4.5
2	Balancing tank	24	2.3
3	Aeration	600	56.8
4	Return Sludge	120	11.4
5	Effluent	264	25.0
	Total	1056	100

As perceived in Fig. 2, the highest energy consumption occurs in aeration. This unit consumes approximately 56% of the total energy of the WWTP which occurs by blower devices that provide air or oxygen. In biological process, air blowers are applied for two purposes; aeration and mixing in which the fluid undergoes irregular fluctuations, in contrast to laminar flow in which the fluid moves in smooth paths or layers. The mixing in the aeration tank is required to prevent solids from settling on the bottom of the tank as well as create a uniform mixture for

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the optimal activity of microorganisms and last but not least, the possibility of appropriate aeration of the entire mixture. In order to provide desired mixing within the aeration tank, air blowers should remain active permanently and continuously, since switching off the blowers results in an out-of-schedule deposition and inappropriate oxygen transfer to the entire mixture which all of these items reduce the efficiency.

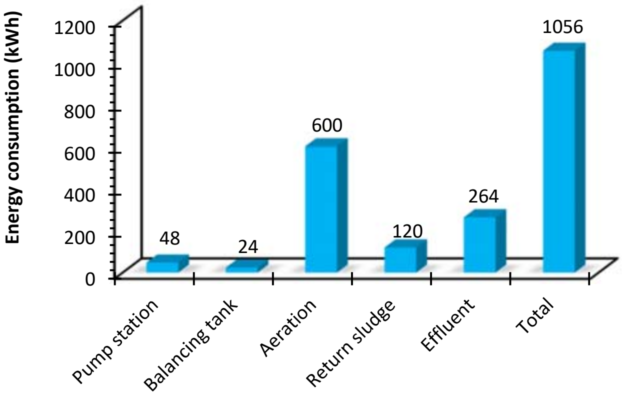


Fig. 2 Energy consumption of different of the WWTP

Normally, the amount of dissolved oxygen in an aeration tank to provide the required oxygen for the growth of microorganisms should be about 1-3 mg/L. DO concentration higher than 3 mg/L can result in an over-aerated mode of operation, therefore increasing the energy consumption and aeration cost significantly [29]. DO concentration should be controlled by an operator according to the nominal capacity of air blowers. Hence, it could be pointed out that a 24-hour continuous operation of air blowers to provide oxygen is not required except in particular emergency conditions.

The dissolved oxygen (DO) concentration in the aeration tank should typically be maintained at 1-3 mg/L to support the growth of microorganisms. Higher DO concentrations exceeding 3 mg/L can result in excessive aeration, leading to increased energy consumption and aeration costs. The operator should control the DO concentration based on the nominal capacity of the air blowers. Therefore, continuous operation of air blowers for 24 hours is not necessary, except in specific emergency situations [29].

The chosen blower is a three-phase type with an aeration rate of 12 m^3/min and device performance has been assessed with respect to the nominal capacity of the air blower. A huge part of energy is consumed for creation of mixing inside the aeration tanks. On the other hand, the long-lasting operation of the blowers ascends the essential periodic repair which causes wasting time and cost. The aim of this study was to survey the aeration tanks' conditions for rising the mixing rate thus a tank in which the blower is not used for the mixing is investigated.

C. Analytical Methods and Oxygen Requirement Calculations

Biochemical oxygen demand (BOD) refers to the quantity of DO required by aerobic microorganisms to decompose organic substances present in wastewater within a defined timeframe and at a specific temperature [30]. Effluent BOD concentration was measured according to EN standards (EN 1899-2, 1998) [31], [32] by using the respirometric BOD System (BOD OxiTop C110, WTW: Weilheim, Germany) [33]. Although the equations must be based on the ultimate BOD load (BODL) [34].

The oxygen requirement for BOD removal by considering 300 m^3/d wastewater flow rate, 100 mg/L effluent BOD, 60% biodegradability, 9277.25 mg/L influent substrate concentration, 42.06 mg/L effluent substrate concentration, 0.68 conversion factor for BOD5 – BODL, 70% sludge recycle ratio, and 831.17 kg/d net waste-activated sludge, was determined 2894.09 kg/d (1):

$$O_2 = \left(\frac{Q(S_0\text{-}S)}{f} \times 10^{-3}\left(\frac{kg}{g}\right)\right) - 1.42\, P_x \tag{1}$$

where Q is wastewater flow rate (m^3/d), S0 and S are respectively influent and effluent substrate concentration (g/m^3), f shows conversion factor for BOD5 – BODL, and P_x represents net waste-activated sludge (kg/d).

Hence by considering 5% efficiency of aeration devices and an air volume safety factor of 2, and 21% oxygen-to-air ratio, the necessary amount of air was determined 242.48 m^3/min. Moreover, operation time could be calculated by using the nominal capacity of the blowers.

D. Aeration Tank Optimization

The aeration unit is the main energy consumer in biological treatment. The 24-hour operation time of air blowers is absolutely non-engineered and simply a waste of energy and cost. A huge amount of this energy consumes due to mixing creation in the aeration tanks. One of the most recent and effective strategies of optimization is employing smart controlling systems which require installing sensors that process intended data parameters [35]. In this study, in order to understand the role of baffles in changing the flow pattern in the aeration tank, a simple strategy has been used which is only based on supplying oxygen requirement for BOD removal and feedback signals have been ignored. Therefore, the following describes a tank that does not have a blower for creating mixing but provides conditions for increased mixing.

1) Optimal Hydraulic Design of the Aeration Tank

To reduce power consumption primarily attributed to mixing creation in aeration tanks, it is advisable to explore alternative solutions. One highly cost-effective approach for achieving mixing within aeration tanks is the incorporation of partition walls, commonly known as baffles. By strategically placing an appropriate number of baffles, the extent of liquid mixing in the tank can be significantly improved, consequently enhancing process performance [36]. In the case of the intended aeration tank design, it is rectangular with a single input and output, where sewage flows in a straight line towards the output. By introducing baffles along the path of sewage flow, the straight and uniform flow can be transformed into a spiral and non-uniform flow, effectively promoting the desired mixing effect.

This modification offers an efficient means of achieving the desired mixing outcome while reducing the blowers' energy consumption.

2) Computational Fluid Dynamics Analysis

By leveraging insights gained from previous studies [37] on sedimentary modeling of granular materials, an investigation was conducted to understand and diagnose the flow pattern inside the tank. This analysis utilized CFD to examine path lines, vectors, and contours of velocity and turbulent intensity. To accurately capture the behavior of the flow, a suitable multi-phase model, specifically the Eulerian model, was employed.

Given the presence of baffles that affect the boundaries of fluid movement, turbulence models based on wall boundaries were utilized. In this case, the k-ε model and the realizable sub-model were selected in the presence of baffles. These models help capture the turbulence characteristics and provide insights into the flow dynamics.

Following the hydrodynamic modeling and analysis of flow patterns in the tank, optimal operating conditions were investigated. Considering both quantitative and qualitative characteristics of the influent and effluent, as well as relevant standards, a new hydraulic design was developed for the aeration tank. The flow patterns in the new design were thoroughly examined, and a comparison was made with the previous design. The primary objective of this design is to reduce energy consumption while maintaining or potentially enhancing treatment efficiency.

3) Mathematical Modeling

Mathematical modeling is an applied method of design as well as the operation of WWTPs, which enables the examination of multiplex technological solutions in a short time and low cost [38]. The flow was simulated by a 3D two-phase CFD model which was developed by using the 13.0 version of FLUENT.

Navier-Stokes equations rule the velocity and pressure of a fluid flow. The mixture velocity vector is defined as the mass averaged velocity of the liquid and dispersed phases [39].

The number of factors that are modeled in momentum equations in multiphase flows is more, this makes the modeling of the multiphase turbulent flows extremely difficult. The turbulence equations for the turbulence model are written as (2):

$$\frac{\partial}{\partial t}\left(\alpha_f \rho_f k_f\right) + \nabla.\left(\alpha_f \rho_f v_f k_f\right) = \nabla.\ \left(\alpha_f \frac{\mu_{t\,f}}{\sigma_k} \nabla k_f\right) \alpha_f G_{kf} - \alpha_f \rho_f \varepsilon_f + \alpha_f \rho_f \Pi_{kf} \tag{2}$$

where α_f and ρ_f are volume fraction and density of fluid phase respectively, k is kinetic energy of turbulence, μ viscosity of the fluid, σ is surface tension coefficient, G_{kf} represents turbulence kinetic energy generation term, ε indicates turbulence kinetic energy loss rate, and Π is effect of dispersed phase turbulence on continuous phase.

In the boundary regions besides the wall, due to the existence of the pressure and velocity gradients, turbulence modeling needs a specific accuracy. The regions on the wall are divided into three following parts:

- Viscous under layer which has a perfectly laminar flow.
- Middle layer which the viscosity and turbulence influence is very important.
- The outer layer which has a turbulence flow.

The three *wall* treatments which have been investigated are the *standard wall functions* [40], the non-equilibrium *wall functions* [41] and the enhanced *wall functions*.

The standard *wall functions* are used for high Re numbers, non-equilibrium wall functions can solve pressure gradients and finally, the enhanced wall treatments can solve turbulence in both the middle and out layer with perfect precision. Due to the simulation of the two middle and outer layers, an enhanced wall function model is used, for reviewing turbulence on the wall.

4) Geometry

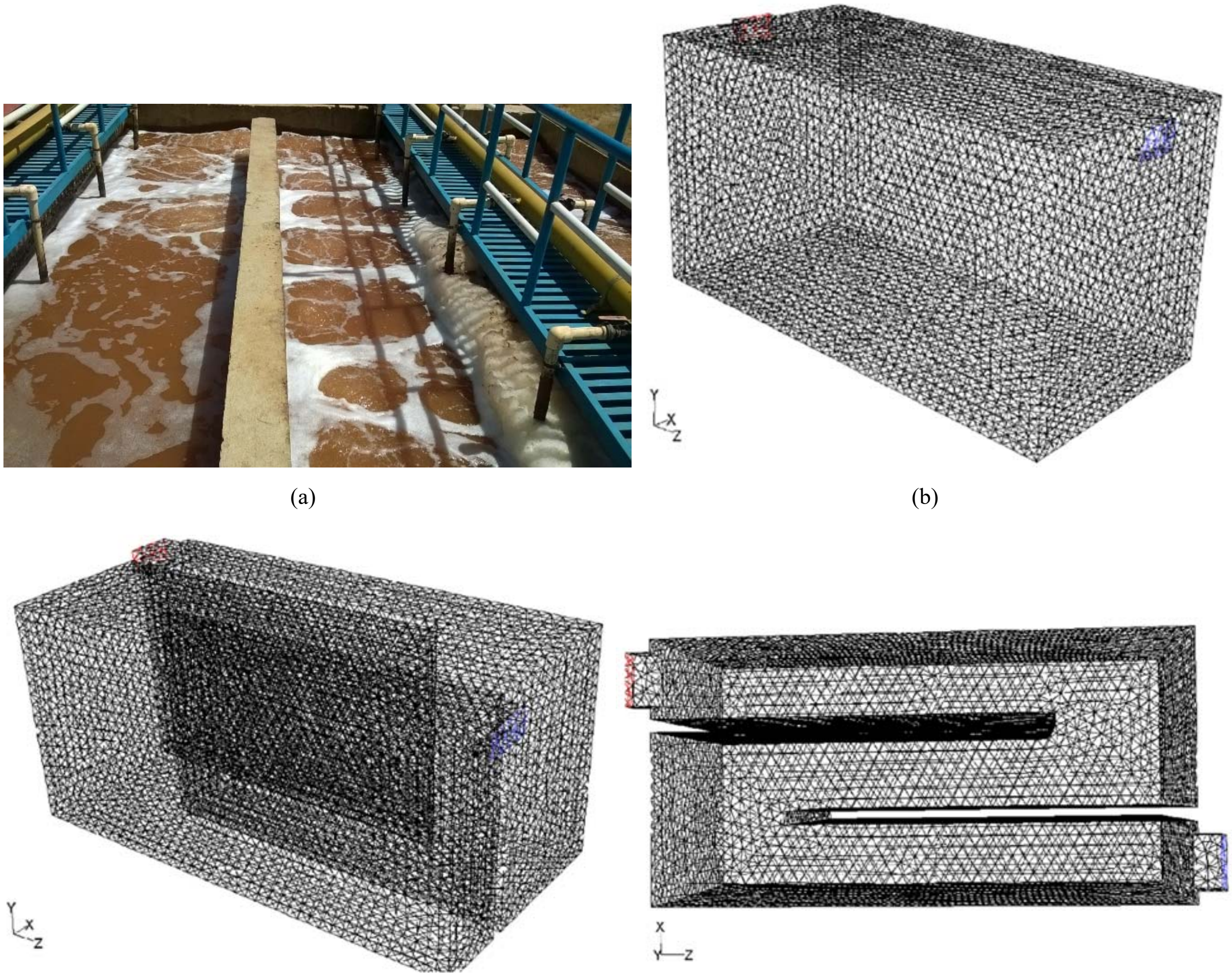
The CFD analysis began with a thorough examination of the geometry. The intended tanks were designed based on the precise measurements of the treatment plant's existing tanks. Solid Works and Gambit software (Gambit 2.4.6, Exceed 13) were utilized for the design process. To establish the actual boundary conditions, networking was carried out on the geometry. This involved creating computational nodes on the geometry to define the conditions. The choice of element types for networking plays a crucial role in the accuracy of results and computation time. Tetrahedron elements were selected for enhanced precision, although they require more computation time compared to triangular elements.

For the hydrodynamics simulations, a geometric network was constructed using a grid comprising 200,000 cells. This grid, along with the utilization of Tetrahedron elements, ensured accurate results in the simulations. Fig. 3 illustrates the aeration tank (a), the tank's geometry without baffles (b), and the tank with baffles (c), (d). This visualization aids in understanding the different tank configurations.

III. RESULTS AND DISCUSSION

In Fig. 4, the diagram depicts path lines, vectors, and velocity contours in different sections of a simple tank. The observations indicate that when the flow enters the tank, it creates a trap, forming an eddy current that follows a horizontal path before directly exiting the tank. This vortex generates resistance, leading to a phenomenon called a flow trap in tanks. Flow traps in simple tanks give rise to two types of issues.

The first issue is the reduction in the effective volume of the tank. A vortex forms at the bottom of the tank, causing resistance against the flow of lower layers. This decreases the retention time inside the tank and increases the velocity of surface flow. This has a significant negative impact on biological treatment as it requires sufficient time for the influent to undergo biological treatment and combine with oxygen, which cannot be achieved.



(a) (b)

(c) (d)

Fig. 3 Aeration tank (a), geometry of the tank without baffles (b) and geometry of the baffled tank (c), (d)

Moreover, the vortex at the bottom of the tank creates a dead zone that prevents fresh sewage from entering, leaving a portion of the tank unused. This results in decreased DO in that specific section of the tank, eliminating the ideal conditions for biodegradation. Mixing and proper retention time are vital for biodegradation, and this situation hampers the creation of ideal conditions, preventing sewage decomposition

Fig. 5 displays the path lines, vectors, and velocity contours in a baffled tank, in three horizontal cross-sectional areas: from the bottom, middle, and top of the tank.

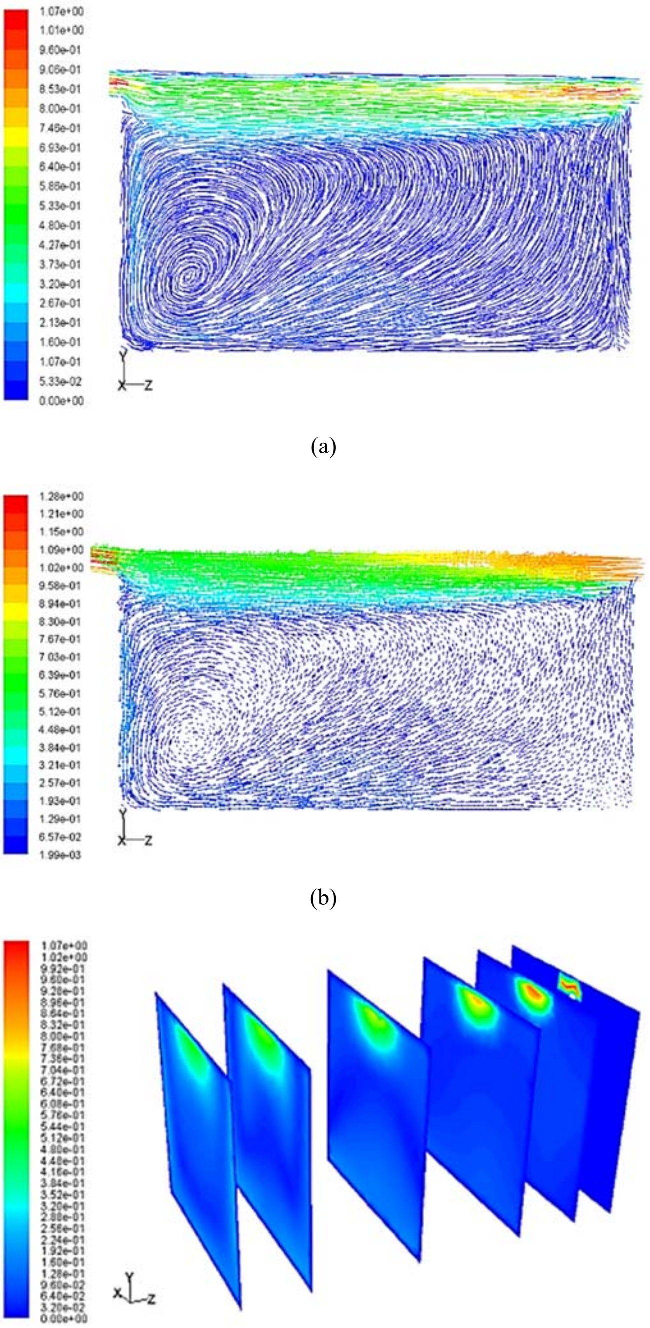
The flow initially enters the tank and follows a straight path. It then enters the second path, where it undergoes a 180-degree rotation. During this rotation, the different layers of the incoming flow blend together, resulting in one-dimensional mixing. One part of the fluid moves downward while the other part rises upward. This mixing along the flow path is evident in the subsequent FIGURES. At the end of this path, the flow undergoes another 180 degrees of rotation, leading to a second round of mixing.

Fig. 7 demonstrates the turbulent intensity along the flow path, specifically in horizontal layers from the bottom, middle, and top of the baffled tank. The highest rate of mixing is observed in the middle and output sections. This characteristic of mixing can be advantageous as it reduces the number of diffusers required in the flow path. Conversely, additional diffusers can be installed in sections where the flow is less turbulent.

Based on the findings, it can be concluded that the addition of only two walls to induce turbulence has a significant impact on the mixing process. This approach eliminates the need for an aeration blower to create mixing and also prevents permanent sedimentation. This indicates that the tank can achieve efficient mixing without the need for additional equipment or the risk of sedimentation buildup.

A. The Efficacy of the Baffled Tank on the Energy Consumption

The inclusion of baffles in an aeration tank enables mixing without the reliance on air blowers. Based on the calculated oxygen (O_2) requirement for proper aeration in the baffled tank, the air blowers should remain active for approximately 10 hours per day or as needed. In contrast, for a simple tank to achieve mixing, the air blowers must operate continuously.



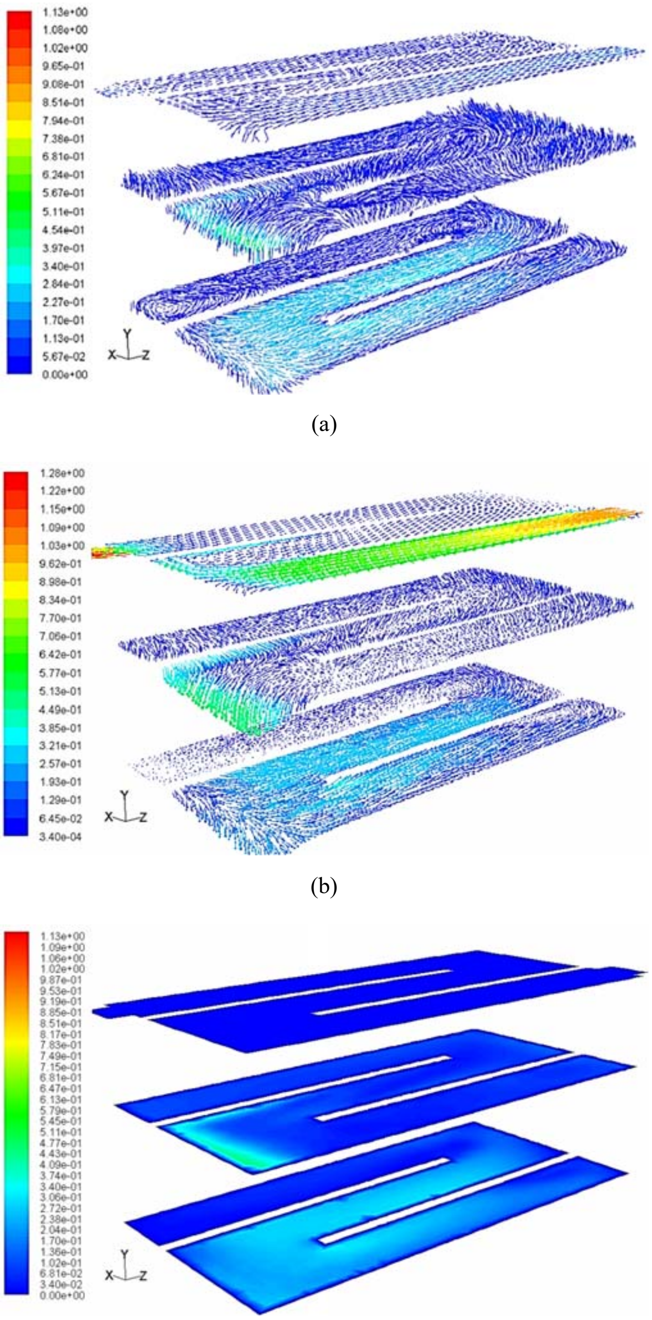
(a)

(b)

(c)

Fig. 4 Pathlines (a), velocity vectors (b) and, contours of velocity magnitude in simple tank (c)

To control the aeration rate, which includes the amount of air intake and the duration of aeration, continuous online monitoring of DO concentration is necessary. Tables III and IV provide information on the reduced energy consumption resulting from the creation of turbulent flow using embedded baffles.



(a)

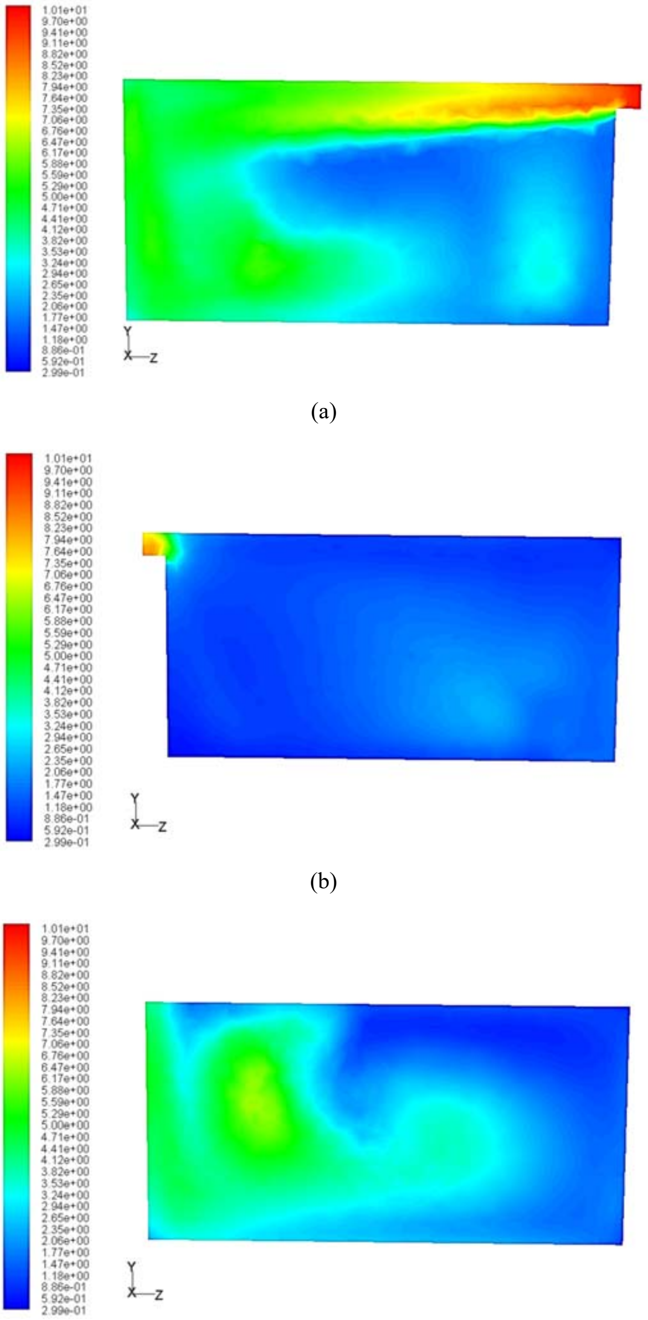
(b)

(c)

Fig. 5 Path lines (a), velocity vectors (b) and contours of velocity magnitude in baffled tank (c)

TABLE III
COMPARISON OF ENERGY CONSUMPTION IN THE BAFFLED AND SIMPLE TANK

Tank	Power of blowers	Operation time	Energy consumption
Simple tank	25 kW	24 hours	600 kWh
Baffled tank	25 kW	10 hours	250 kWh



(a)

(b)

(c)

Fig. 6 Contours of turbulent intensity (%) in the right section (a), in the left section (b) and the in middle section of baffled tank (c)

TABLE IV
ENERGY CONSUMPTION RATIO IN DIFFERENT UNITS OF THE WWTP WITH BAFFLED AERATION TANK

Number	Unit	Energy consumption (kWh)	Ratio (%)
1	Pump station	48	6.8
2	Balancing tank	24	3.4
3	Aeration	250	35.4
4	Return Sludge	120	17.0
5	Effluent	264	37.4
	Total	706	100

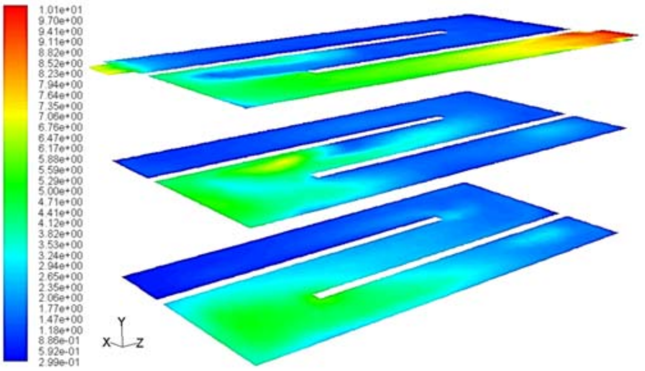


Fig. 7 Contours of turbulent intensity (%) in the horizontal cross-sectional areas of the baffled tank

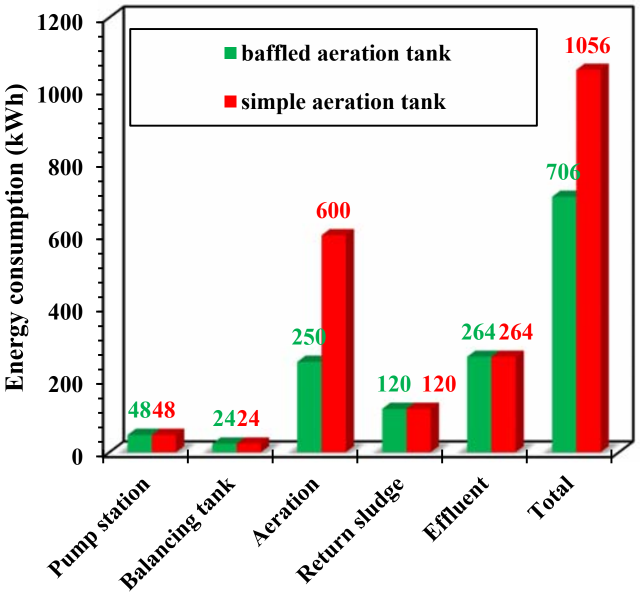


Fig. 8 Comparison of energy consumption different units of the WWTP with baffled and simple aeration tank

By eliminating aeration for the purpose of mixing, a substantial 33.15% reduction in total energy consumption during the treatment process can be achieved. Furthermore, the use of baffles and intermittent aeration can enhance the phosphorus removal capabilities of denitrification by promoting the formation of granular sludge. Implementing an aeration cycle of 7 minutes followed by a 3-minute pause not only decreases energy consumption but also increases nutrient removal efficiency by an additional approximate 8% compared to continuous aeration. These improvements in energy efficiency and nutrient removal demonstrate the benefits of employing baffles and optimizing aeration strategies in wastewater treatment systems [42].

IV. CONCLUSION

Advanced wastewater treatment technologies aim to minimize energy consumption during the treatment process. Urban communities with growing populations and increased wastewater production have experienced a rise in energy consumption dedicated to treatment plants. Additionally, continuous and long-term operation of equipment and installations in WWTPs leads to depreciation and reduced efficiency, resulting in increased energy consumption and maintenance costs.

To address these challenges, simple adjustments can be made to the treatment plant's structures, which can be cost-effective and help reduce energy consumption. CFD modeling is an applied method that aids in the design and operation of WWTPs, allowing for the examination of various technological solutions.

The presented solution in this article offers a way to significantly decrease energy consumption at a very low operational cost. By optimizing the aeration tank through a combination of a baffled tank and intermittent aeration, the total energy consumption of the treatment process can be reduced by 33.15%. This effective solution not only lowers operating costs but also does not negatively impact the efficiency of biological treatment.

Implementing a combination of baffled tanks and intermittent aeration in all treatment plants can be advantageous as it extends the life of electromechanical equipment and installations. This approach contributes to energy savings and maintenance cost reduction while maintaining the effectiveness of the biological treatment process.

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