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The Impact of Climatic Parameters on the Performance of Wastewater Treatment Facilities: Aeration Tank Flow Modeling

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Abstract

The escalating temperatures linked to global warming are having a direct effect on the efficiency of aeration tanks, which play a crucial role in the biological processes of wastewater treatment systems. In particular, rising temperatures can modify the physical characteristics of water, resulting in notable changes in flow patterns and the distribution of dissolved oxygen. This research included field measurements taken in a full-scale aeration tank at the Bursa Eastern Wastewater Treatment Plant, where the current flow dynamics of the system were analyzed. Velocity measurements were recorded at eight distinct locations around the baffle walls, and the outputs from the numerical model were compared with these measurements to evaluate the model's accuracy through relative error analysis. After validation, a scenario reflecting the maximum operating temperature set by the facility was developed, adjusting only the viscosity and density parameters while maintaining all other boundary conditions constant for the CFD analysis. Visual assessments conducted through streamline analysis indicated that the rise in temperature modifies the flow pattern and induces changes in the configuration of low-velocity areas.

Keywords: Aeration tank, climate change, CFD, wastewater treatment

1. Introduction

One of the main issues caused by the rapidly increasing demand for consumption is the diminishing access to clean water. The growth in residential areas and industrial facilities naturally leads to an increase in wastewater production, which intensifies the pressure of human activities on ecosystems [1]. Climate change significantly intensifies the pressure on water systems by reducing available water resources, deteriorating water quality, and increasing both hydraulic and environmental loads on treatment facilities. Elevated temperatures accelerate evaporation rates, while altered precipitation patterns challenge the reliability of existing design assumptions for treatment plants, potentially leading to operational inefficiencies and unforeseen performance issues. In this framework, the effectiveness and longevity of systems designed for wastewater treatment that do not adversely impact the environment are fundamental to sustainable water management. Aeration tanks, which are among the most vital elements of these systems, play a crucial role in determining the efficacy of biological treatment processes. Within these tanks, organic matter is broken down by microorganisms, and the overall treatment efficiency is significantly influenced by hydrodynamic factors such as flow rate, turbulence patterns, and the distribution of dissolved oxygen. Consequently, the design of aeration tanks has a direct impact on

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the sustainability of microbiological processes, as well as on energy efficiency and sludge management. However, in recent years, rising water temperatures attributed to climate change have had a direct impact on the functioning of these systems. Particularly during the summer months, elevated temperatures can cause the water temperature in aeration tanks to exceed the design limits of the facility. This situation leads to alterations in the physical properties of the fluid, directly affecting the flow regime within the tank, particularly in fundamental parameters such as dynamic viscosity and density. A decrease in viscosity may influence the formation of low-velocity regions; furthermore, as temperature increases, the solubility of dissolved oxygen in water decreases, potentially resulting in a decline in the efficiency of biological treatment.

The mixed liquor in aeration tanks consists of a complex structure that includes water, dissolved organic matter, suspended solids, microorganisms, and biological flocs [2]. The active sludge present in this environment contains microorganisms that break down organic nutrients, serving both as a nutrient medium and a treatment agent. Therefore, the rheological properties of this biological environment—particularly its viscosity, which varies with temperature—are among the engineering parameters that directly influence system performance. In this context, the flow rate and the turbulence structure within the tank not only influence physical transport but also directly affect the efficacy of microorganisms and the stability of flocs. Insufficient mixing or regions of low velocity can lead to floc sedimentation, uneven distribution of dissolved oxygen, and disruption of the aerobic environment. Conversely, excessively high velocities may result in the disintegration of floc structures and the removal of biomass from the system. Therefore, it is crucial that the flow in aeration tanks is neither too low nor excessively high to ensure optimal biological activity and system equilibrium.

One significant study that illustrates this relationship is by [3], which demonstrated through rheological experiments conducted at various temperatures that the viscosity of the sludge significantly decreases as temperature increases. This phenomenon can be attributed to the weakening of the bond forces between flocs and the enhancement of molecular mobility; consequently, it is stated that the carrying capacity of the sludge phase diminishes. These findings are particularly crucial for accurately modeling and assessing in-tank flow performance in scenarios where temperature fluctuations are frequent.

Similarly, the study by [4] thoroughly examines the impact of temperature fluctuations in aeration tanks on dissolved oxygen distribution and system efficiency. It highlights that sudden variations in temperature and flow rates observed in cold climate regions lead to irregularities in dissolved oxygen profiles, consequently reducing the energy efficiency of the system. With climate change, it is evident that the frequency and intensity of such hydraulic and thermal fluctuations will increase. Therefore, it has become a critical engineering necessity to reassess and optimize existing treatment systems in accordance with these conditions to meet future sustainability goals.

This study evaluates the hydrodynamic performance of an existing system based on field measurements conducted in a full-scale aeration tank. Point velocity measurements were taken at eight selected locations, corresponding to areas with baffle walls, under field conditions. The data obtained were analyzed to assess the flow field. Through this analysis, the velocity distribution within the tank and the locations of dead zones were identified, prompting a review of the efficiency of the current design. Furthermore, considering the potential impacts of climate change, the study examined how changes in the physical properties of the sludge under increasing temperature conditions could affect the flow pattern within the tank, with the system's response to these conditions evaluated through numerical modeling.

2. Materials and Method

2.1. Problem description

This study was conducted at the full-scale aeration tank of the Eastern Wastewater Treatment Plant located in Bursa, Turkey. The aeration tank examined in this research has a water depth of 5.55 meters and a calculated volume of 24.041 m^3. The channel lengths are 140 m, 32 m, and 6.7 m, respectively. The tank features two inlet and two outlet structures. The inlet structures are designed as two window forms of varying sizes. Inlet-1 measures 2.5 m in width and 0.75 m in depth, while Inlet-2 is positioned 1.4 meters to the left of Inlet-1, also measuring 2.5 m in width but only 0.3 m in depth. The outlet area consists of two windows, each 2.5 m wide and 2.35 m deep.

2.2. Field Measurements

Field measurements conducted on the guiding walls were performed using the Hach FH950 model flow velocity meter. This portable and lightweight device, powered by batteries, is designed to deliver high-accuracy velocity measurements even under challenging field conditions. Obtaining accurate and reliable velocity data is particularly crucial in environments such as aeration tanks, where complex flow patterns are present. The device features an extendable cable that can reach up to 10 meters, allowing access to various areas of the tank and facilitating measurements in restricted access zones like guiding walls [5].

In the context of the measurement study, access to the outer side of the guiding walls was achieved using a basket crane, and point velocity measurements were conducted at eight predetermined locations (Figure 1). These measurements were undertaken to assess the hydrodynamic effectiveness of the guiding walls and to analyze their impact on the flow regime within the tank. The measurement points were strategically selected to represent areas where the flow enters and exits the guiding walls. This approach allowed for a detailed examination of how the direction, velocity, and distribution of the flow interact with these structures.

2.3. Numerical Study

In the context of numerical analysis, the geometry of the aeration tank was initially modeled in SpaceClaim to align with the architectural designs of the facility. During the geometric modeling process, the inlet and outlet structures, guiding walls, and water level were defined. To enhance the accurate representation of the flow field and improve the precision of the numerical solution, local mesh refinement was specifically applied in the inlet and outlet regions. This approach resulted in improved mesh quality in areas with high gradients within the tank, thereby strengthening solution stability. For the flow solution, a single-phase and steady-state approach was adopted, utilizing the

Realizable k-ε turbulence model. The rationale for selecting this model lies in its ability to more accurately represent complex flow structures characterized by jet flows, recirculation zones, and high shear gradients [6]. Boundary conditions were established based on field data and the existing operational parameters of the facility. The inlet flow rate was set at 1.64 m^3/s, with 'pressure outlet' conditions applied at the outlet regions and 'symmetry' conditions at the water surface. The fluid used in the numerical model was defined to represent the properties of activated sludge; however, it was modeled as a single-phase water-sludge mixture without phase separation. The standard density and dynamic viscosity of clean water are recognized to be 998.2 kg/m^3 and 0.001003 Pa·s, respectively. However, due to the presence of suspended solids (SS) and biological flocs in the process water of wastewater treatment facilities, the density is typically approximated to be around 1050 kg/m^3 [7]. The experimental data utilized in this study is based on field measurements taken at a temperature of 20 °C. At this specified temperature, the viscosity value was calculated using the formulation proposed by [7], taking into account the determined MLSS (mixed liquor suspended solids) concentration of the facility.

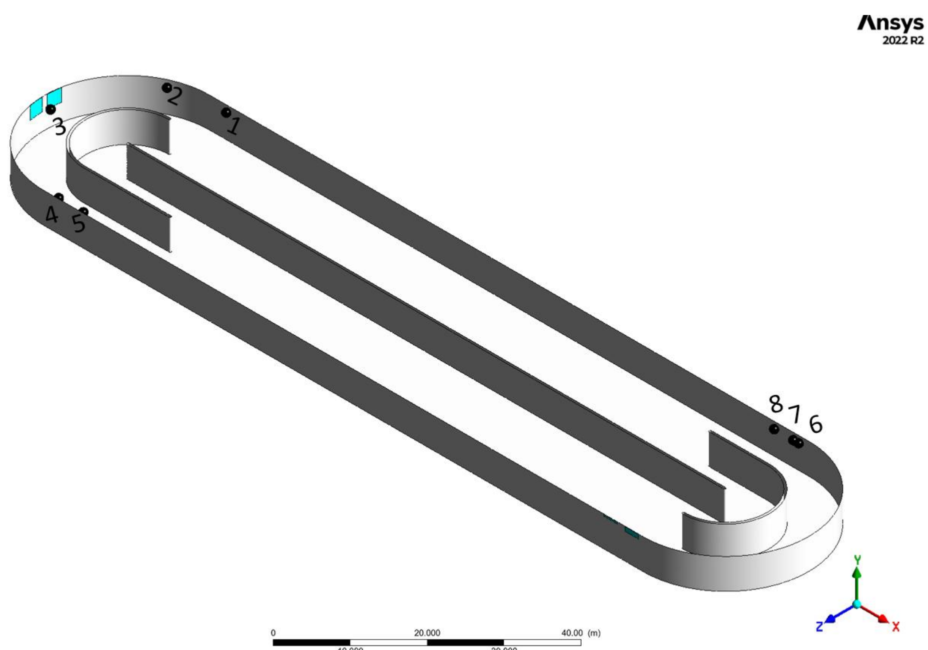

Figure 1. Measurement points

3. Results

The numerical analysis results conducted in accordance with the defined boundary conditions were evaluated for accuracy by comparing them with field measurement data (Figure 2). In this context, experimental velocity measurements were performed at eight distinct points in areas where guiding walls were present in the aeration tank, and the obtained field data were compared with the results of the numerical model. This comparison was assessed based on the relative error values calculated at each point. Figure 2 illustrates the validation outcomes derived from eight surface velocity measurements performed along the guiding wall using a portable velocity meter. The calculated average relative error (RE) was 2.9%. In computational fluid dynamics (CFD) studies, RE values below 10% are typically interpreted as a sign of high accuracy, while values up to 20% are generally deemed acceptable for practical engineering use [8]. The results of the current evaluation confirm that the relative errors fall well within these established thresholds, thereby indicating a satisfactory level of agreement between the model predictions and experimental observations.

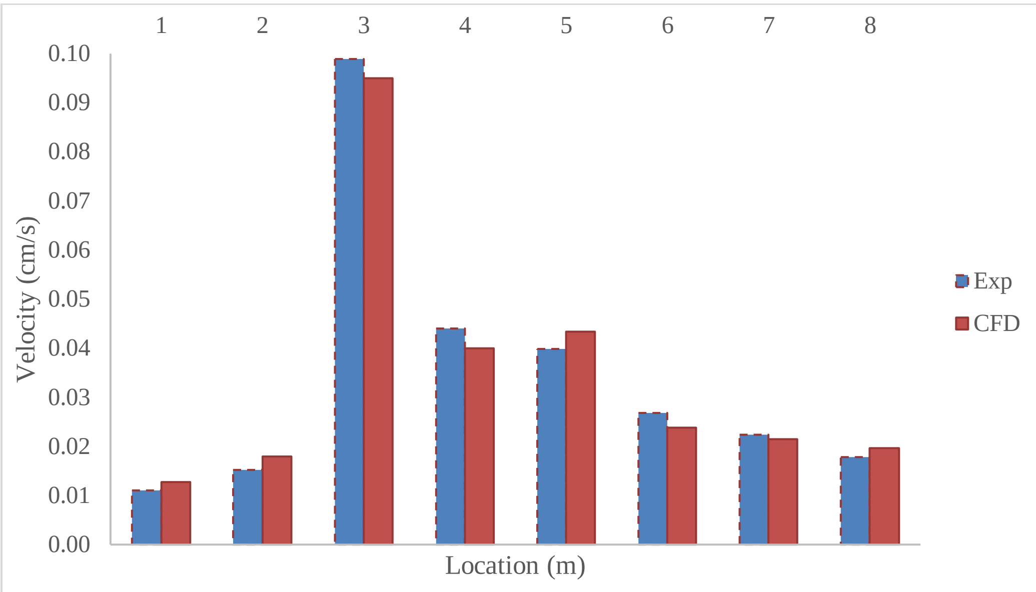

Figure 2. Validaiton of CFD and Field Study

To evaluate the hydrodynamic behavior of the system under extreme temperature conditions associated with climate change, a supplementary analysis was carried out. In this scenario, all boundary conditions—such as inlet flow rate, outlet configuration, turbulence model, and mesh structure—were preserved as per the original setup. However, the fluid's physical properties, namely density and viscosity, were adjusted to reflect the maximum temperature projected by the facility. This analysis specifically aimed to investigate how temperature-induced variations in these properties influence the internal flow dynamics within the tank.

4. Discussion

The analysis shows that the temperature increase has a significant effect on the flow pattern in the aeration tank. Under the current temperature condition, the energy dissipation of the jet stream exiting the inlet zone is weakened at a shorter distance and shows a more limited flow through the tank (Figure 3a). In particular, the circulation cells formed after the baffles are prominent but narrower, and the direction of the flow changes some parts of the tank. This indicates a more limited movement of the flow lines due to the internal resistance caused by the high viscosity.

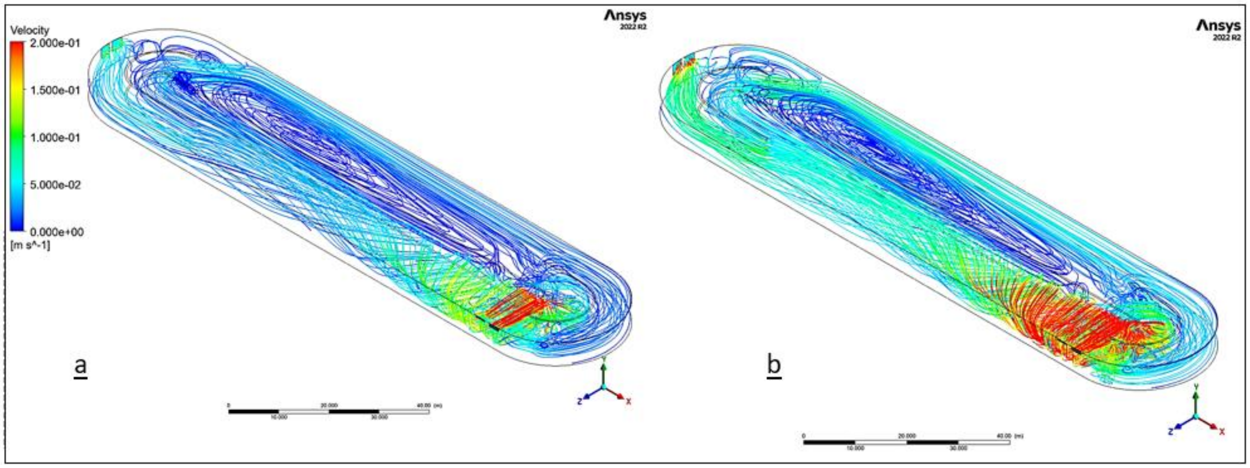

Figure 3. Streamline patterns under: a) Current operating temperature conditions, b) Elevated temperature scenario

In contrast, in the temperature scenario corresponding to the 30 °C condition, the internal friction of the flow decreased with the decrease in fluid viscosity, resulting in a wider spread of streamlines (Figure 3b). The jet flow was carried further, with increased circulation cells, especially around the outlet zone. It is also observed that the streamlines are more continuous throughout the tank and the formation of dead volume is reduced in the low velocity regions. High temperature can limit dead volume formation in the short term by reducing the transport resistance of the fluid, but it can also trigger critical processes such as decreased dissolved oxygen solubility, disruption of microbiological balance and the risk of biomass migration out of the system.

As a result, the jet propagation distance increased with increasing temperature due to lower viscosity and the streamlines were found to be more effective and evenly distributed throughout the tank. However, this should be considered together with other parameters that may limit biological processes, such as decreased dissolved oxygen solubility.

Conclusions

In this study, CFD simulations performed on a full-scale aeration tank were compared with field measurements and the accuracy of the model was evaluated by RE. As a result of the validation process, the reliability of the model was demonstrated and the flow patterns obtained were shown to be consistent with field conditions. Then, an analysis was performed under the maximum temperature scenario defined by the plant in the context of climate change and the effect of temperature increase on the flow regime was studied by varying only the physical properties of the fluid (viscosity and density). The results obtained show that with increasing temperature, the viscosity of the fluid decreases, resulting in the flow lines traveling over longer distances inside the tank. In addition, the shape and distribution of the circulation cells changed and low velocity areas were observed to decrease in some regions.

As temperature rises, the flow tends to become more diffuse and uniform; however, the implications for system performance must not be assessed solely from a hydrodynamic perspective.

Elevated temperatures diminish the solubility of dissolved oxygen, disturb the metabolic equilibrium of microorganisms, and excessive flow rates may jeopardize the structural integrity of biomass. Consequently, evaluations of these situations should consider not only the organization of flow but also the viability of biological processes.

These findings provide a significant perspective for understanding the behavior of aeration tanks under climate change conditions and for making design improvements. Future studies should model parameters such as flow rate, dissolved oxygen, and microbiological activity in conjunction with temperature, which will contribute to a holistic assessment of the system.

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