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Research Article

Effect of Temperature Fluctuations on Biological Activity and Membrane Performance in Anaerobic Membrane Reactors

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Abstract

Anaerobic membrane bioreactors (anMBR) are increasingly used in wastewater treatment processes. These reactors aim to increase treatment efficiency by combining membrane filtration with biological treatment. In this context, many factors need to be taken into consideration in order to effectively maintain the biological processes taking place in reactors. Water temperature is one of these factors and can significantly affect treatment performance by directly affecting the metabolism of microorganisms. It is known that an increase in water temperature improves the performance of bacteria used in the treatment process. In the current study, it was observed that physical properties changing with temperature slightly reduced treatment performance and it was concluded that the appropriate treatment temperature value is 35 °C, which is still valid in practice. This result provides critical information for optimizing anMBR systems and opens the door to new research on how certain temperature ranges can increase the effectiveness of treatment processes.

Keywords: anMBR, temperature, permeate, water treatment

1. Introduction

Anaerobic membrane reactors (anMBR) are increasingly becoming a preferred technology in wastewater treatment processes. These systems allow microorganisms to break down organic matter without oxygen and produce methane gas. Temperature plays a critical role in anMBR processes; it can increase treatment efficiency by directly affecting the activity of microorganisms and biogas production. Temperature changes can lead to unexpected results by affecting the fluid properties and heat transfer within the reactor. In addition, the integration of membrane technologies increases the effect of temperature management on the performance of membranes. In this context, this thesis aims to investigate the effects of temperature differences on mass transfer and treatment efficiency in anMBR applications. The results of the research will contribute to the development of more sustainable and effective water treatment methods. In wastewater treatment technologies, anaerobic membrane reactors (anMBR) have developed remarkably in recent years. There are many studies showing that increasing wastewater temperature in these reactors positively affects treatment performance. In particular, it has been observed that increasing temperature increases bacterial productivity and thus improves membrane performance (Ding et al., 2014; Özgün et al., 2015). The effects of temperature difference on mass transfer stand out as an important mechanism in terms of membrane treatment efficiency (Qtaishat et al., 2008; Glavatskiy et al., 2012). Some studies in the literature examine the interaction between temperature and mass and heat transfer in detail. For example, Gryta et al. (1997) and Charfi et al. (2010) analyzed the mechanisms of temperature effects on membranes and revealed the effects of heat transfer on mass transfer. In this context, Phattaranawik et al. (2003) and Alkhudhiri et al. (2012) investigated the effects of temperature and pressure difference on membrane processes and emphasized the potential of high temperatures to increase overall efficiency. Another study examining the effects of temperature on treatment performance was conducted by Gao et al. (2014). This study revealed that decreasing the temperature during the treatment of domestic wastewater with fluidized bed anMBR negatively affected COD removal and methane production. Another study conducted by Özgün et al. (2015) evaluated the effects of temperature change on membrane fouling and treatment performance in UASB anMBR systems. As a result, better understanding the effects of temperature change on the membrane is an important step to increase the efficiency of anMBR systems. In this context, studies in the existing literature focusing on the effects of temperature on membrane performance in anMBR systems are of great importance for optimizing treatment processes and increasing efficiency. Temperature stands out as an important parameter to be taken into consideration in anMBR processes and it is concluded that further research is required on this subject.

2. Anaerobic Membrane Reactors

Anaerobic treatment technology has a wide range of applications in the effective treatment of industrial wastewater. The main advantage of this technology is the economic benefits it provides in the treatment of wastewater containing high organic pollution. When compared to aerobic treatment processes, anaerobic treatment processes are considered to be more cost-effective. Especially in recent years, anaerobic treatment methods have also started to be used in domestic wastewater treatment. Anaerobic membrane bioreactor (anMBR) is formed by the integration of existing anaerobic treatment technologies (such as UASB, EGSB) with membrane technology. In these systems, wastewater is treated by means of reactors containing anaerobic bacteria. The reactor structure can be designed in different ways, such as upflow or holding, depending on the characteristics of the facility. Methane bacteria in the reactor decompose pollutants called chemical oxygen demand (COD) into chemical building blocks and convert them into methane gas, thus providing wastewater treatment. In anaerobic treatment processes, the decomposition of organic substances occurs in two main stages. During the first stage, hydrolysis and acid fermentation, organic substances are converted into organic acids, alcohols and carbon dioxide by acid bacteria. In the second stage, the metabolic products of acid bacteria are converted into methane, carbon dioxide and water by methanogens. The efficiency between these stages depends on the appropriate time for wastewater and methane bacteria to come together and for the bacteria to complete their growth phase (Anonymous, 2021a). Membrane technology allows the wastewater separated into building blocks from the anaerobic treatment pool to be subjected to a second treatment process. The membrane acts as a transition barrier between anaerobic bacteria and treated water. The transition mechanism in membranes is carried out by the osmotic pressure created due to the hydraulic pressure or density difference depending on the system used. Treated water is called “filtrate” and can be used in secondary works such as garden irrigation, fire extinguishing or discharged directly to the receiving environment, depending on the condition of the facility. Thanks to the physical separation ability of the membranes, the retention of small bacteria that have not yet completed their growth phase within the system provides a significant advantage over traditional treatment systems. In anaerobic membrane applications, the drift of bacteria that have a sandy structure and have not yet completed their growth phase with the wastewater poses a major problem, while these problems are minimized with the use of membranes.

The advantages of using membranes after anaerobic treatment can be summarized as follows:

The COD values of the outlet water are quite low. There is no bacteria in the outlet water of the systems. Water that does not contain bacteria and has low pollution values increases the reusability of water. There is no need for a biological treatment stage in anMBR systems, which means less space is needed for businesses. The absence of an airless stage prevents the formation of waste sludge and eliminates the need for a sedimentation tank. In anaerobic treatment plants, more economical and easy-to-manage facilities can be created by replacing the airy stage, which is difficult to operate and manage, with a membrane. The solid model and working principle of such an anaerobic reactor is given in Figure 1.

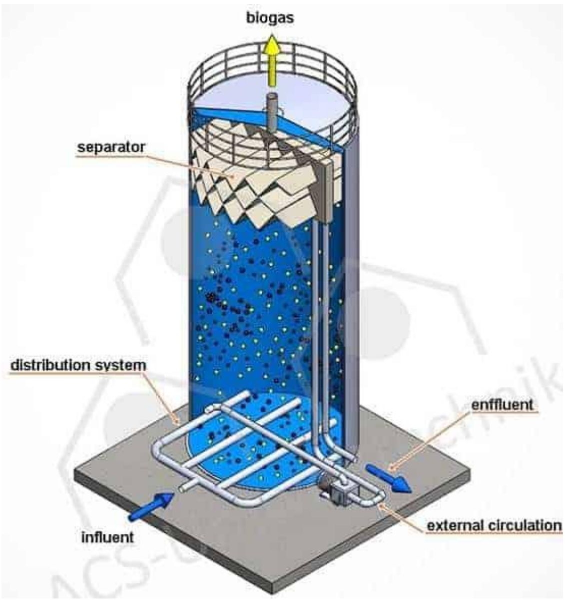


Figure 1. Anaerobic membrane reactor (Anonymous, 2021b)

3. Membrane Technologies and Integration

3.1. Membrane technologies

Membranes are permeable layers with fine pores and are manufactured from various materials. Membrane types used to obtain clean water are classified as microporous (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). Ultrafiltration membranes are the most commonly used in wastewater treatment. The efficiency of membranes is measured by two main parameters, selectivity and continuity. There are four main membrane types: flat plate, hollow fiber, tubular and multi-hole membranes. Figure 2 shows the internal structure of the membrane.

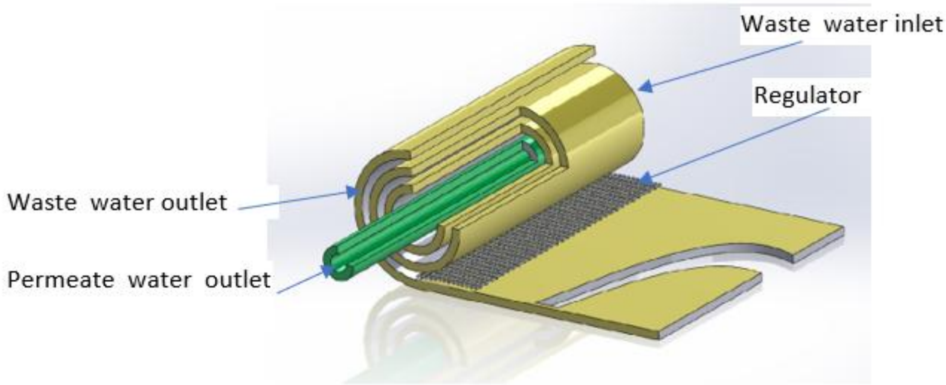


Figure 2. Structural representation of the membrane (Anonymous, 2021c)

3.2. Integration of membrane systems into wastewater treatment plants

Anaerobic membrane reactors (anMBR) perform second-stage treatment using ultrafiltration or microfiltration membranes instead of aeration tanks. These systems overcome the disadvantages of traditional methods, provide high COD removal efficiency and take up less space. anMBRs are effective in treating wastes with low biodegradability and provide energy savings. The membrane filter fabric retains solids as small as 0.2 microns and is cleaned by periodic backwashing with purified water.

4. Traditional Waste Water Treatment System

Classical treatment systems perform pre-treatment with coarse and fine screens to prevent unwanted substances from entering the facility. In facilities with large flow rates of wastewater, pre-sedimentation tanks are used to reduce the load on the anaerobic reactor. Unwanted physical structures such as coarse particles, foam and oil are cleaned in these tanks. Water is brought to a neutral pH value for suitable bacterial growth in the anaerobic reactor; sodium hydroxide (caustic) is used for this purpose. After the balancing tank, the wastewater is fed to the anaerobic reactor with centrifugal pumps. In this process, methane bacteria break down the wastewater and produce CO_2, CH_4 and H_2S gases. The amount of methane shows the efficiency of the treatment process and an average of 0.35 liters of CH_4 is produced for 1 gram of COD removal. The bacteria used in the anaerobic reactor vary according to temperature and climate conditions; the most common type is mesophilic bacteria. The methane gas formed is 5 times more polluting than CO_2 and can be purified and used as fuel. However, since purification is costly, some companies prefer to burn methane gas and release it into the atmosphere. The pH value can affect the bacterial balance in the reactor; inappropriate pH values can cause the bacteria to die. While the operation of anaerobic membranes is easy with the control of a few parameters, the operation of the air stage is more difficult and costly. Figure 3 shows traditional treatment plant.

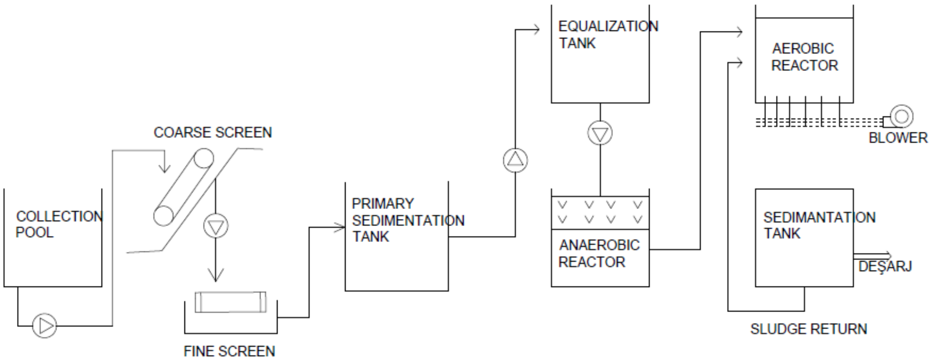


Figure 3. Schematic view of a traditional treatment plant

4.1. Anaerobic reactor and methane bacteria

Methane bacteria in anaerobic reactors exhibit different characteristics depending on operating temperatures and climate conditions. While the temperature range in which they operate most efficiently varies, the most commonly used type is mesophilic bacteria, and their efficiency increases up to 35 °C. The pollutant nature of the produced methane gas is 5 times higher than CO_2, which means that methane gas can be used as fuel after undergoing the necessary purification processes. Businesses that avoid high investment costs can burn the formed methane gas and release it into the atmosphere. Other gases are directed to the air purification stage and are expected to have a catalyst effect; in facilities without air purification, purification processes are required for the disposal of gases. When the pH value of the water fed to the reactor is acidic or basic, the bacterial balance may be disrupted, which leads to a decrease in purification quality and the death of bacteria. Bacteria in the death stage can be easily observed with water. While anaerobic membranes are simpler to operate with control of a few key parameters, controlling large numbers of bacteria in aerobic stages is more complex and costly.

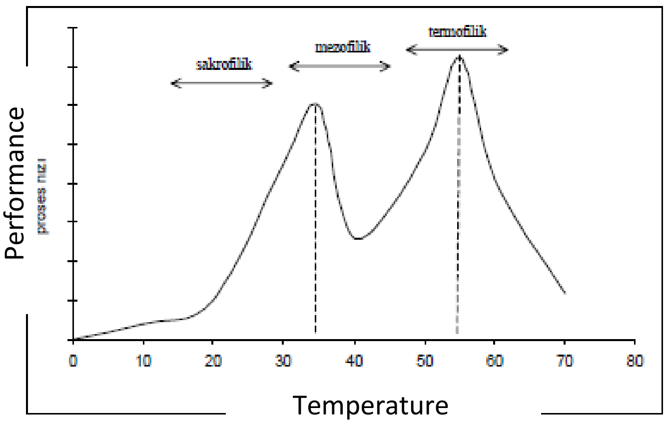


Figure 4. Relationship between temperature and performance of anaerobic bacteria (Joseph, 2019)

4.2. Anaerobic membrane bioreactors (anMBR)

Anaerobic membrane biorectifiers (anMBR) include the pretreatment and balancing processes in conventional treatment systems. These processes are similar to activated sludge systems. It is useful to have a second fine screen in the system to ensure that anaerobic bacteria crawl on the membrane and to remove large particles that may cause damage.

There are two main approaches to the application of membrane modules in wastewater treatment plants:

Direct Immersion: Placing membrane modules directly into the anaerobic reactor.

External Integration: Integrating the membrane system with an external tank.

Both of these methods increase the functionality of the membrane application in the system. Figure 5 shows the place of the membrane application in a conventional treatment system.

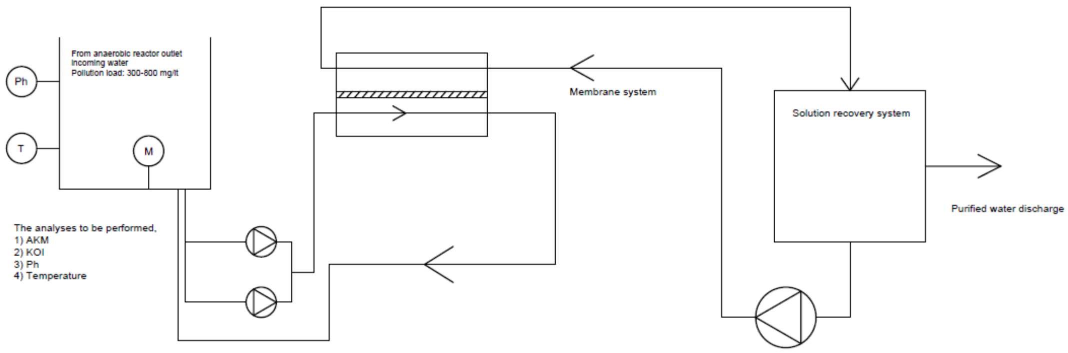


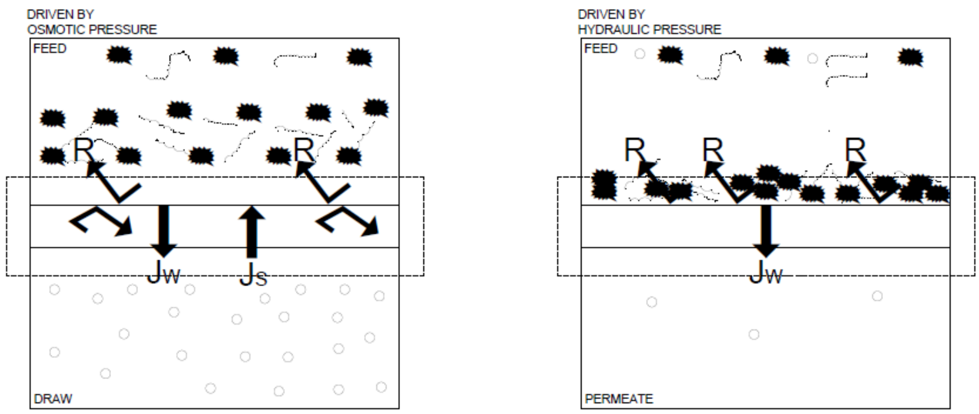
Figure 5. The position of membrane application in anaerobic treatment systems

5. Materials and Methods

An important problem in industrial wastewater treatment is the amount of waste sludge formed during the treatment process. After anaerobic reactors, the required pollution values can be achieved by using aerobic reactors. However, anaerobic membrane bioreactor (anMBR) applications are becoming increasingly widespread in order to reduce sludge formation and increase reactor efficiency. There are two basic membrane approaches in main wastewater treatment systems:

Forward Osmosis: In this method, osmotic pressure is created by the density difference between wastewater and solution water, and the contaminants are retained by the membrane.

Reverse Osmosis: Here, the wastewater is pressurized with a pump and passed over the membrane, and the contaminants are again retained. These applications are designed to increase the treatment performance of wastewater.



a) b)

Figure 6. Membran systems a) Forward osmosis b) Reverse osmosis

5.1. Numerical studies

In this study, Forward Osmosis system in wastewater treatment is modeled using OpenFOAM open source code.

5.1.1. Membrane model in OpenFOAM in forward osmosis application

OpenFOAM® program is an open source toolkit used in solutions. This software, which is a registered trademark of OpenCFD Limited, develops CFD packages and has expanded significantly in the last decade. Schematic representation for Forward Osmosis application is given in Figure 7. The function of the membrane is to separate the desired phase from the undesired phase. In this context, the part of the water passing through the membrane is called "feed" and the part where the particles added with the starting solution are located is called "draw". If the driving force is due to the pressure based on the chemical potential difference, this system is called FO (Forward Osmosis).

5.1.2. Modeling with forward osmosis approach

The schematic representation in Figure 7 shows a membrane where the feed side is separated by the suction. As the wastewater flows from the feed side, the unwanted fractions are retained by the membrane and only Jw (relatively clean water) passes to the suction side.

The analytical model is based on the balancing of the chemical potentials of the feed and suction at the membrane interface. In this model, the transport equation for each component includes the Fick diffusion expression. The membrane allows water to pass through and rejects the contaminants. A schematic representation of this mechanism is also provided. The transport and mass transfer equations expressed by Gruber et al. are defined in terms of the mass fraction of the solvent mA (Gruber et al., 2011).

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho U) = 0 \tag{1}$$

$$\frac{\partial \rho U}{\delta t} + \nabla.(\rho U U) = \nabla.[\mu(\nabla U + \nabla U^T)] - \nabla p + \rho g \tag{2}$$

$$\frac{\partial \rho m_A}{\delta t} + \nabla.(\rho U m_A) - \nabla.\left[\rho D_{AB} \nabla_{m_A}\right] = 0 \tag{3}$$

Figure 7 shows the flux vectors in the numerical solution region. The membrane separates the feed and suction regions; where Jw represents the clean water passing to the suction side and Js represents the solution flux forced to the feed side.

ΔP = 0 is assumed across the membrane, so the transport equations are obtained. The flux is calculated by balancing the convection-diffusion terms due to zero pressure drop. The membrane is assumed to have homogeneous mechanical properties. The water flux is calculated with the following equations (Koch, 2015)

Here Jw_is the clean water passing to the suction side and Js is the blocked solution flux; A and B coefficients are determined experimentally.

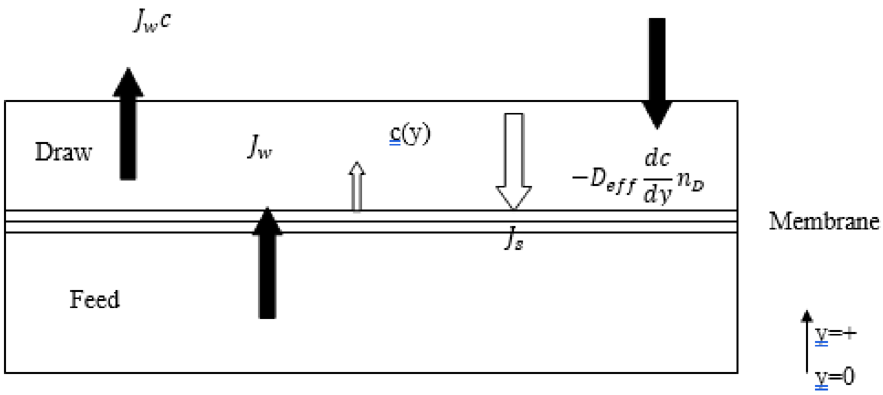


Figure 7. Representation of flux vector directions

$$J_w = A(\pi_I - \pi_{F,m})n_D \quad (4)$$

$$J_s = -B(c_I - c_{F,m})n_D \quad (5)$$

In previous studies, density, viscosity, mass diffusion coefficient and osmotic pressure have been shown to depend on the solute mass fraction (Gruber et al., 2011). The following empirical equations were used to show the dependence of these variables on the solute mass fraction (Geraldes et al., 2001). The assumptions are as follows:

The main force acting on the liquid is only the gravitational force.

The pressure gradient across the membrane is zero.

The amount of solution remains constant.

Density, viscosity and diffusion coefficient vary depending on the solute mass fraction.

The following equations express these variables:

$$\rho = 997.1 + (694)m_A \quad (6)$$

$$\mu = 0{,}89.10^{-3} + (1{,}45.10^{-3})m_A \quad (7)$$

$$D_{AB} = \max\,(1{,}61.10^{-9}(1 - 14m_A), 1{,}45.10^{-9}) \quad (8)$$

$$\pi = (805{,}1.10^{5})m_A \quad (9)$$

5.1.3. Velocity boundary conditions

In the current model, the membrane is not considered as a separate flow area. The velocity and solute concentration boundary conditions for the membrane surface are solved using empirical equations. In the case of OpenFOAM, the H and C files are compiled into a user-defined library and then imported into the OpenFOAM file system.

The water flux through the membrane is modeled using the linear relationship between solute concentration and osmotic pressure. The water flux equation is given below:

$$J_w = \frac{1}{K}\ln\left[\frac{B + A\pi_{d,m}}{B + |J_w| + A\pi_{f,m}}\right]n_d \quad (10)$$

Here,

A: Pure water permeability coefficient.

B: Solution permeability coefficient.
K: Membrane interface diffusion resistance coefficient.
$\pi_{d,m}$: Osmotic pressure between the porous surface and the active layer of the membrane.
$\pi_{f,m}$: Osmotic pressure across the feed side membrane.
$n_{d,}$: Unit normal vector at the porous boundary.
For these coefficients, the numerical values given in Gruber et al. 2011 were used.

$$A = 1.10^{-12}\left[\frac{m}{s.Pa}\right] \tag{11}$$

$$B = 1.10^{-12}\left[\frac{m}{s}\right] \tag{12}$$

$$K = 0.5\left[\frac{s}{\mu m}\right] \tag{13}$$

5.1.4. Solution boundary conditions

If the water flux in the membrane is expressed in this way, the solution flux for FOmembrane application can be written as a function of the water flux. (Koch, 2015).

$$J_s = -\left[\frac{B}{\varphi.A}\right]J_w \tag{14}$$

$$\varphi = \frac{\pi}{c} = 805.10^2 \tag{15}$$

Here ϕ represents the linear proportionality between the osmotic pressure and the solution concentration within the membrane structure. In this case, mixed boundary conditions ("Robin BC") can be written for the solution mass fraction (Lee et al., 1981).

Also, to maintain mass balance, the convective flux and diffusive solution flux must be kept in balance. Therefore, it is more convenient to use the following equation for the solution boundary condition in the membrane:

$$\rho_m\left(-D_{AB}\frac{\partial m_A}{\partial n_D}n_D + m_{A,m}J_w\right) = J_s \tag{16}$$

6. Finding and Discusion

In wastewater treatment processes, the efficiency and performance of bacteria are affected by many factors such as operating temperatures. The temperature at which mesophilic bacteria, especially used in anaerobic reactors, operate at their highest efficiency is generally determined as 35 °C. This temperature range is of critical importance in terms of increasing bacterial activity and increasing the efficiency of the wastewater treatment process. This study aims to examine the effects of temperature changes on the overall efficiency of membranes and treatment systems due to the changes in the physical properties of water.

6.1. Effect of temperature on water flux

The operating temperatures of bacteria used in anaerobic reactors vary according to their species. The temperature at which mesophilic bacteria, which are widely used in our country, operate with the highest efficiency is 35 °C.

According to the literature, each 1 °C increase in temperature increases the treatment performance of bacteria by 5%. The change in temperature also affects the physical properties of water. It has been shown that the pump power required for wastewater treatment increases inversely proportional to the temperature difference between the inlet and outlet of the reactor (Ugrozov and Kataeva 2004). In addition, it is stated that the heat transfer caused by the temperature difference positively affects mass transfer (Glavatskiy et al., 2013). It has been shown that in permeable pipe or plate flows, heat transfer and therefore mass transfer increase with the increase in the temperature difference between the two surfaces of the membrane (Gryta et al., 1997; Phattaranawik et al., 2003; Qtaishat et al., 2008; Buia et al., 2010). Heating wastewater increases the performance of bacteria and reduces treatment costs (Ferrer et al., 2015). In membrane systems and membraneless anaerobic reactors, heating wastewater increases membrane performance and treatment capacity. In systems where FO is applied, it is clear that the feed and suction sides will reach thermal equilibrium after a certain period of time and the temperatures will be equal as long as heat is not drawn from the solution recovery tank. In this study, temperature values of 10°C, 20°C, 30°C and 35°C were taken into account for both sides of the membrane, respectively, and the energy equation solution was carried out with the physical properties of the water at these temperatures. The physical properties at these temperatures are given in Table 1. The thermal boundary condition on the membrane was evaluated as a zero temperature gradient in the direction perpendicular to the axis.

Table 1. Physical properties of water at different temperatures

Physical properties Temperature	Density (ρ) (kg m^{-3})	Dynamic viscocity(μ) (kg ms^{-1})	Kinematic viscocity(φ) ($m^2 s^{-1}$)	Thermal diffusion coefficient (α) ($m^2 s^{-1}$)
10 ^{0} C	999.65	0.0013076	0.0000013081	$1.38.10^{-7}$
20 ^{0} C	998.19	0.001005	0.0000010023	$1.43.10^{-7}$
30 ^{0} C	995.67	0.000797	$8.005.10^{-7}$	$1.47.10^{-7}$
35 ^{0} C	994.06	0.0007198	$7.24.10^{-7}$	$1.49.10^{-7}$

As a result of applying the boundary condition on the membrane to the energy equation, which is Equation (29), it was observed that after a certain period of time, the supply and suction sides reached thermal equilibrium and the temperatures were equalized. It was observed that the supply and suction sides reached thermal equilibrium in the steady state and the momentum equation was solved by examining the effect of temperature on the physical properties of water. The effect of temperature on water flow is given in Figure 8.

$$\frac{\partial \rho T}{\partial t} + \nabla(\rho U T) = \nabla(\rho \alpha \nabla T) \quad (17)$$

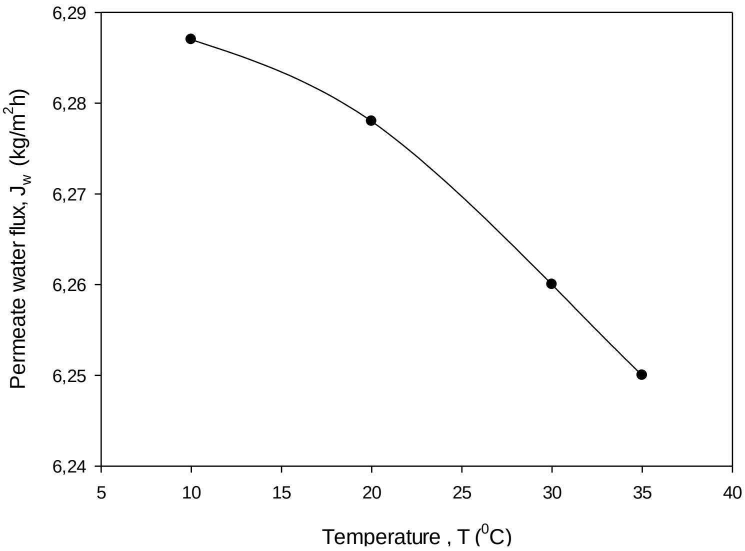


Figure 8. Variation of water flux with temperature

Studies have shown that bacteria used in anMBRs improve their treatment performance with increasing temperature (Özgün et al., 2005). In the literature, it is stated that a 1°C increase in water temperature increases bacterial treatment performance by 5%. The numerical results in the current study show that a 10°C temperature increase reduces water flux by 0.15%. This situation reveals that the positive effect of increasing temperature on the performance of bacteria is more important than the decrease in water flux resulting from the effect of temperature on physical properties. As a result, it is evaluated that it is appropriate to carry out the treatment process at 35°C as recommended in the literature.

7. Conclusion

This study investigated the effects of temperature on water flux in anaerobic membrane bioreactors (anMBR). It is stated in the literature that the optimum temperature for bacterial activity is 35 °C and every 1 °C increase increases the treatment efficiency by 5%. However, in the present study, it was observed that the increase in temperature caused a decrease in water flux by 0.15%. However, it was concluded that the increase in bacterial performance was more important than the decrease in water flux due to changes in physical properties. In this context, it is suggested that the temperature should be optimized to increase the treatment efficiency in anMBRs.

Declaration of Author Contributions

The authors declare that they have contributed equally to the article. All authors declare that they have seen/read and approved the final version of the article ready for publication.

Declaration of Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

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