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CFD modeling of submerged membrane bioreactors (sMBRs): a review

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ABSTRACT

Membrane bioreactor (MBR) systems are an established technology for the domestic and industrial wastewater treatment, but efficient fouling reduction by air sparging remains an operating problem and design rules still are of a purely empirical nature. Therefore, many modeling approaches have been proposed to solve these operating problems and increase the process efficiency. Several experimental and computational studies have been done to access more efficient separation in different membrane application. Recently, computational fluid dynamics (CFD) has been widely used for hydrodynamic simulation of fluid on the membrane surface and pores, modeling mass transfer rate and further predicting the fouling layer. It provides a method for finding the most effective design features at fundamental level. Especially CFD has been preferred to simulate the fouling problem in MBR systems because these systems have highly energy dependent technologies due to air sparging to control fouling. However, designing and optimization of submerged MBRs can be done through CFD simulations and mathematical modeling. This paper aims to summarize both effective design and optimized parameters of submerged MBRs using flat sheet and hollow fiber membranes considering the CFD studies in literature.

Keywords: CFD; Submerged MBR modeling; Air sparging

1. Introduction

Membrane bioreactors (MBRs) have been used for the biological treatment of wastewater and they are becoming an alternative instead of conventional processes. Conventional wastewater treatment systems use solids settling methods for separation which have wide variety of effluent quality and cannot be controlled easily. On the other hand, MBRs have some advantages over conventional processes like, treated water is clear, it can be operated in high mixed liquor suspended solids (MLSS) conditions, reduction in sludge amount produced, and small footprints [1–3]. Besides this, MBRs have some disadvantages such as

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high energy demand generating air sparging or scouring and biofouling problem. Fouling is generally known as the deposition of suspended or dissolved substances on membrane surface (reversible) or in the membrane pores (irreversible) which result in loss of performance [4]. Fouling phenomena within MBR is related to many parameters such as physical and chemical factors [1]. Particle size and shape in solution have important effects on cake layer formation onto membrane surface. Back transport mechanisms of particles greater than 1 μm affected by shear stressed diffusion so they are dependent on shear stress; however the back transport mechanism of particles less than 0.1 μm is molecular diffusion, so they are independent of shear stresses. However the shape of particles in solution can change the packing density of particles onto membrane surface so this phenomenon changes the cake porosity onto membrane surface. This leads to different cake layer resistances. Therefore, the membrane properties also have huge impact on fouling such as pore size, surface charge, porosity, hydrophilicity and roughness etc. Therefore the operating conditions like permeate flux and transmembrane pressure affect hydrodynamic conditions and cake layer formation. There are two types of forces contributing to cake resistance which are the convective drag force and hydrodynamic force. The convective drag forces can cause the accumulation of particles onto the membrane surface. However, when the hydrodynamic forces dominate, the particles into solution cannot reach to the membrane surface. The increasing of hydrodynamic conditions (shear stress and transmembrane pressure [TMP]) resulted from air sparging decrease the cake layer formations on membrane surface by improving hydrodynamic forces.

Air sparging or scouring process is known as an enhancer for permeate flux by back transport of materials such as foulants away from membrane surface for fouling mitigation. Back transport mechanism is affected from membrane module configuration [5–8]. It affects the hydrodynamic conditions within MBR systems to decrease fouling as multiphase cross flow formation occurrence. Also, air sparging improves the flux of hollow fiber (HF) membrane configurations [9]. The intensity, flow rate, and bubble size of air scouring and also the geometry and port size of diffuser are important factors for reducing fouling submerged HF MBRs. Hydrodynamic conditions by itself cannot explain all fouling phenomena. Also, the biological factor should be considered. At first, it was thought that MLSS concentration does not contribute to fouling, however according to the findings; MLSS significantly affects sludge rheology and hydrodynamics. Studies directed researchers' attention to the biological communities within MBR which contain potential foulants. Potential foulants are called extracellular polymeric substances (EPS), soluble microbial products, biopolymers, biopolymeric clusters, and transparent exopolymer particles from biological suspension affect the biofouling mechanism in MBRs [1,9–11]. There are many studies that try to find the relationship between hydrodynamic conditions and biological factors on fouling [4,10,12].

As described above, the fouling is major obstacle for MBR commercialization. Studies showed that membrane fouling is a very complex thing. To understand the mechanisms of membrane fouling, the module characteristic and geometry, feed water characteristic etc. should be considered. Hydrodynamic conditions within submerged MBR systems highly dependent on the module design and geometry. It was seen packing density, location of fibers, fiber length, baffles etc. either enhance or diminish shear stress occurred within membrane which leads to fouling [11].

In MBR systems; designing hydrodynamic modeling is complex because of existence of multiphase flow, unpredictable rheology of activated sludge, unstable transparency of activated sludge, and complex module configurations interacting with the flow [13]. Since MBR is much complex process, the mathematical modeling and computational fluid dynamics (CFD) simulations of MBR system has become an important tool for predicting the conditions, the design of any MBR system.

CFD analyzes systems such as heat transfer in fluids, fluid dynamics in porous media (flow inside a membrane module), chemical reactions (mixing and separation, polymer moulding) etc. by computer-based simulations. In general CFD, predicts performance of any system accurately by using semi emprical formula. CFD simulations are not cost effective due to the usage of work station computers which are also known as super computers. However when they are compared to pilot or industrial scale system installations, they become cost effective and reliable [14]. Usage of CFD become important in membrane applications, since by using basic CFD model, we can be able to predict overall hydrodynamic conditions which includes energy and momentum balances; turbulence models; concentration polarization profile, mass transfers within membranes. Considering MBR sytems, with CFD we can link many submodels such as sludge transport, filtration aspects etc. of MBR systems into what we want to achieve [13]. Another aspect is the effect of CFDs on MBR module design. In a very short period of time, one can achieve and design different modules with the help of CFD for the need of MBR systems.

CFD simulations and also mathematical modeling are used for designing and optimizing the MBR technology and helps the reduce obstacle in front of it [15]. CFD provides methods for prediction of hydrodynamic influences, membrane fouling on MBR processes. In literature, there are many studies concerning CFD of submerged MBR process. This review aims to discuss and summarize these studies in guideline manner.

2. CFD applications in MBR systems

CFD is related to solve equations of continuity, momentum, and energy concerning fluid dynamics by using a computer based simulation. Continuity, momentum, and energy Eqs. ((1)–(3)) are given below. Simulation process of CFD is given in Fig. 1. Shortly, there is a fluid problem. To solve this, physics of a fluid problem should be determined. In CFD, physical properties of the problem can be described by Navier–Stokes equation, to be able to solve Navier–Stokes equation in computer; it should be translated into discretized form. As a discretization method, finite element, finite volume, or finite difference methods can be used. Since discretization is based on many small parts, whole domain should be divided into parts. After that, these small parts can be solved through programs in supercomputers. Simulation results are obtained. These simulation results can be compared and analyzed with experiments or with the real problem. If there is an inconsistency in results, process must be repeated until satisfactory results are obtained [16]. CFD has many applications areas such as aircrafts, biomedical engineering, electronics, and power plants. CFD is also widely used in membrane processes like MBR for mainly investigating flow conditions and fouling mitigation [14,17].

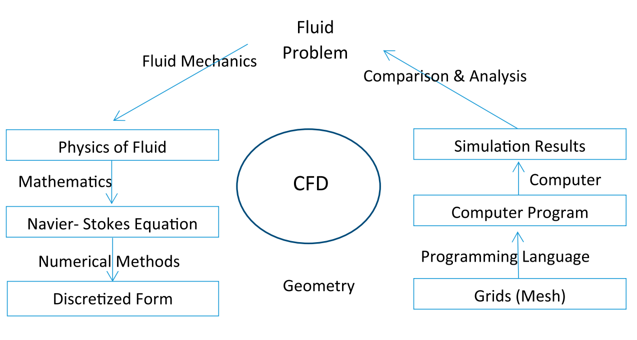

Fig. 1. Schematic of CFD process.

$$\text{Continuity equation} \rightarrow \frac{\partial \rho}{\partial t} + \text{div}\,(\rho u) = 0 \tag{1}$$

Momentum equations for x–y–z directions →

$$x\text{-momentum}\ \frac{\partial(\rho u)}{\partial t} + \text{div}\,(\rho u \mathbf{u}) = -\frac{\partial \rho}{\partial x} + \text{div}\,(\mu\,\text{grad}\,u) + S_{Mx} \tag{2a}$$

$$y\text{-momentum}\ \frac{\partial(\rho v)}{\partial t} + \text{div}\,(\rho v \mathbf{u}) = -\frac{\partial \rho}{\partial y} + \text{div}\,(\mu\,\text{grad}\,v) + S_{My} \tag{2b}$$

$$z\text{-momentum}\ \frac{\partial(\rho w)}{\partial t} + \text{div}\,(\rho w \mathbf{u}) = -\frac{\partial \rho}{\partial z} + \text{div}\,(\mu\,\text{grad}\,w) + S_{Mz} \tag{2c}$$

$$\text{Energy equation} \rightarrow \frac{\partial(\rho i)}{\partial t} + \text{div}\,(\rho i \mathbf{u}) = -\text{p}\,\text{div}\,\mathbf{u} + \text{div}\,(k\,\text{grad}\,T) + \varnothing + S_i \tag{3}$$

where S_m, momentum source, Ø, dissipation function, ρ, density, u, $\text{d}x/\text{d}t$, v, $\text{d}y/\text{d}t$, w, $\text{d}z/\text{d}t$, div (k grad T), rate of heat addition to the fluid particle due to heat conduction, p, pressure

CFD modeling of MBRs consists of several steps. The MBRs do not include the chemical reactions so that the governing equations will be continuity and momentum equations. Generally, the fluid flow equations are non-linear so they must be converted into linearized volumes, and then the analytical solution can be obtained [2]. First of all, the physical boundary conditions of geometry should be defined. Then the geometry should be divided into small discrete cells. The process of discretization of cells is known as meshing. Governing and boundary conditions are applied to the mesh for some algebraic equations [17,18]. Finally, the algebraic equations are solved by either iterative or direct methods. For example, it has a capability of predicting information on flow conditions at any point of membrane structure. However the flow conditions are not disturbed. Modeling by using real experiments are generally time consuming, costly, and there can be some problem related to repeatability of experiments. However the usage of CFD for modeling can decrease these disadvantages. By using current design methods of MBRs, it is hard to predict vessel design, module and membrane arrangement because these parameters will affect hydrodynamics, fouling or overall performance of MBRs.

In submerged MBRs, generally the multiphase flow simulations were applied because the aeration of system is a part of operation. When the multiphase flow is used for CFD simulations, two approaches are used which are Euler–Euler and Euler–Lagrange. In Euler–Euler approach, all phases are treated as interpenetrating continuous cells. Navier–Stokes equations are solved by coupling terms considering the interaction between phases. In Euler–Lagrange method, every single particle, drop or bubble in fluid phase is tracked in a continuous way. More realistic results can be obtained through this approach [2,13].

3. Recent studies related to CFD applications on submerged MBR

Many studies for CFD modeling of submerged MBR were published in literature. Generally, studies focused on HF module configuration rather than flat sheet due to having more design parameters such as fiber packaging and fiber arrangement. In the following chapters, the flat sheet and the HF membrane configurations for submerged MBRs will be summarized.

3.1. Submerged MBRs with HF membrane configuration

CFD simulations done by using HF submerged membranes was summarized in Table 1. HF submerged membranes are used in many areas as well as waste water treatment. Their manufacturing costs are low, they have easy handling and the most important of all and their modules have large surface area to volume ratio. For CFD simulations of HF submerged membranes, investigation of packaging density, air sparging, other parameters such as module and reactor geometry, MLSS concentration, inlet velocity is important. In this section, these parameters and their importance are summarized.

3.1.1. Packaging density of HF submerged MBRs

In submerged MBR process, it is important to have voids within HF bundles. Unless, there are no voids between HF bundles, not only mass transfer through fibers occurs but also fouling is favored due to unfavorable hydrodynamic conditions. Since packaging density of HF affects hydrodynamic conditions and thought as an important parameter [19–21]. Günther et al. [22] investigated the influence of HF module packing density on flow distribution. In the study, they used single phase fluid without particles and large packing densities. To obtain an analytical solution, Navier–Stokes and Darcy equations were solved for large packaging densities in outside/in and inside/out configurations. They assumed that HF bundle as perfectly regular cylinders (Fig. 2); the fluid flow was measured from unit cells of this model. They used 0.4, 0.6, and 0.8 packaging densities. For outside/in configuration, for packaging density of 0.4, 0.6, and 0.8, the pressure drops in the retentate side at the top of the fiber were 0.04, 1.5, and 0.63 bar whereas values for permeate side were 0.1, 0.12, and 0.17 bar, respectively. TMP between top and the bottom of the fiber reaches 80% for high packaging values. For in/outside configuration, for packaging density of 0.4, 0.6, and 0.8, pressure drop in the retentate side became 0.04, 0.09, and 1.5 bar whereas at the permeate side, pressure drop was 0.56, 0.13, and 0.01 bar, respectively. TMP difference is lower for lower packaging density. CFD based results of their model showed that the package density especially affected filtration velocity and spatial distribution of permeate velocity. They also found that the filtration flux decreased at very high packaging densities, the filtration tended to happen at the bottom of fiber and an increase in packaging densities may lead to non-uniform permeate flux along the fiber.

3.1.2. Air sparging

Air sparging of submerged MBRs is one of major studied subject. It is highest energy consuming part of the process and it can be optimized through improving hydrodynamic conditions of modules. In submerged MBRs, the air sparging not only supplies oxygen to biomass but also keeps solids in suspension and used for fouling mitigation by producing shear stress [4]. An effective air distribution contributes membrane permeability, sustainable applied flux, and decrease in fouling. In one of the studies related to the effect of aeration efficiency of submerged HF MBR, Buetehorn et al. [23], made CFD simulations of single and multi-phase flows through submerged membrane units having irregular fiber arrangement. They took X-ray computer scans from irregularly arranged fibers and they were processed to write CFD codes based on porosity and friction factor matrices. The results of single phase flow showed that fiber arrangement, MLSS concentration and superficial inlet velocity (Fig. 3) affected the cross-flow velocity and turbulent viscosity. Multiphase flow simulations showed that higher mixture velocities can be obtained at cross sectional regions without fibers. Occurrence of bypass jets and fluid channels which lead to enhanced cake layer removal and high transient shear patterns was affected by fluid–structure interactions.

Table 1
Some studies related to HF submerged MBR CFD simulation

Membrane geometry	Brief objective	Fluids	CFD code/ models	Varied parameters	Brief results	References
Hollow fiber	Determining the effect of module design, packing density and filtration mode	Single phase	COMSOL	Packing density, filtration mode, module design	Packing density affected spatial distribution of permeate velocity, decreased filtration flux, high packaging densities led to non-uniform permeate profile	[22]
Hollow fiber	Determining the impact of irregular fiber arrangement on aeration efficiency	Single and multiphase	ANSYS, VOF, RNG k-ε model	Inlet velocity, MLSS concentration,	Fiber arrangements, inlet velocity and MLSS concentration affect cross flow velocity and turbulent viscosity	[23]
Hollow fiber	The effect of aeration on fouling of tight HF membrane	Multiphase	VOF, Euler–Euler	Aeration type	There was no influence of wall shear due to its low levels and matter deposit induced by liquid flow rate towards fibers	[24]
Hollow fiber	Understanding and diagnosing the two phase flow inside a submerged MBR	Multiphase system	Euler–Euler, k-ε model	Module and reactor geometry, aerator design, operation condition	Uniform distribution of air affect membrane filtration behavior, bubble frequency, wall shear stress are linked to void fraction	[27,28]
Hollow fiber	Aeration rate and operational parameters on filtration performance were examined	Multiphase	Not specified	Geometry, pore blocking, concentration polarization, scaling, biofouling and hydrodynamics of feed and permeate side	High concentrations of EPS led to biofouling, high concentration of solid enhance cake layer formation and pore blocking, aeration rate can both decrease and increase cake layer formation	[29]
Hollow fiber	A model is depicted to filtrate yeast suspensions by developing bubbling enhanced microfiltration	Multiphase	Mathematical model	Nozzle type, gas flowrate, nozzle size, suspension concentration, cleaning efficiency	Gas bubbling efficiency parameter was dependent on gas flow rate, nozzle size and suspension concentration	[25]
Hollow fiber	Comparing maximum initial flux and critical flux parameters to	Not specified	Mathematical model	Fiber characteristic	Model can be used for determining optimal fiber length and radius of	[31]

(*Continued*)

Table 1 (*Continued*)

Membrane geometry	Brief objective	Fluids	CFD code/ models	Varied parameters	Brief results	References
	obtain filtration behavior of submerged HF MBRs				submerged HF module	
Hollow fiber	Simulation of hydrodynamics of membrane bioreactor as a whole	Multiphase	Euler–Euler approach and κ-ε turbulence model	Flow direction, flow viscosities, porous zone, geometry, MLSS concentration	Flow regime was affected by sludge viscosity and inertial losses resulted from hollow fiber membrane module	[30]
Hollow fiber	Dependency of wall shear stress on vibration and geometrical parameters	Not specified	FLUENT	Frequency of vibration, distance between two fiber	Maximum shear stress can be obtained by optimizing distance between fibers; wall shear stress depends much more on fiber distance	[32]
Tubular	Effects of aeration and membrane configuration on overall membrane performance	Multiphase flow	Euler–Euler approach and κ-ε turbulence model	Inside and outside submerged membrane configuration and aeration	Aeration is dominant factor for membrane performance. When aeration was low, plug flow conditions dominated	[26]

Chan et al. [5], investigated the surface shear forces in air sparged submerged HF MBRs. They found that, the shear force profile of surface affected by gas sparging rate, fiber packaging density, diffuser nozzle size, bubble size, shape, flow path, and module configuration. Martinelli et al. [24], investigated the effect of aeration on tight HF membrane. They used spherical cap and fine bubble as an aeration method (Fig. 4). For spherical type of bubbles intermittent flow occurred and CFD solution was given by using volume of fluid method. For fine bubbles, it was assumed that continuous flow of bubbles occurred and numerical simulations were done using Euler–Euler approach. The results of hydrodynamic analyses showed that wall shear stress had no effect on fouling because of low wall shear stress and matter deposit induced by liquid flow rate towards fibers.

Liu et al. [25], developed a mathematical model for bubbling enhanced microfiltration for submerged HF MBRs. They introduced a gas bubbling cleaning efficiency parameter to predict the effect of different bubbling conditions. In Fig. 5 the bubbling conditions can be seen. According to their results, introducing a gas bubbling cleaning efficiency parameter in the model, was able to define the effect of gas bubbling on the enhancement of fouling. Gas bubbling efficiency parameter was dependent on gas flow rate, nozzle size, and suspension concentration; module performance was affected from gas bubbling cleaning efficiency parameter due to the changes in local flux distribution and suction pressure at the outlet of the module.

Brannock et al. [26] investigated the effects of aeration and membrane configuration such as size and position of inlets, baffles, or membrane orientation on the overall membrane performance. For that purpose they used inside submerged and outside submerged membrane modules. It was assumed that each bioreactor had a volume of 1.4 m^3 and an influent rate of 0.15 m^3/h. Tubular membranes were used. In Fig. 6, it can be seen that internal recirculation of flow in outside configuration was higher than inside configuration which was encouraged from baffles and recycled flow, however, main parameter was aeration rate. Also it was found that inlet position affects plug-flow conditions which are short circuiting and dead zones. If aeration rate is low, plug-flow conditions dominates. They concluded that for fouling prevention, there is a

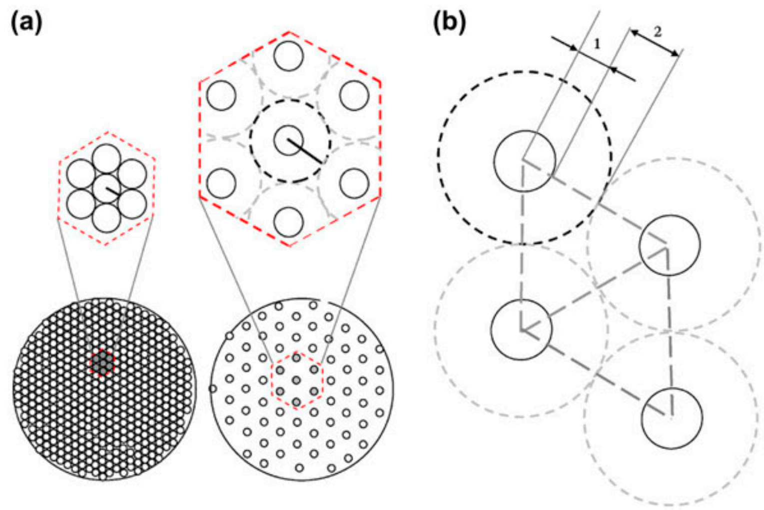

Fig. 2. (a) Schematic representation of high and low packing density in hexagonal stacking and (b) basic mesh used in the study (Rhombus) with Rext ≥ 1 and $D \geq 2$, vertices are the four neighboring discs [21].

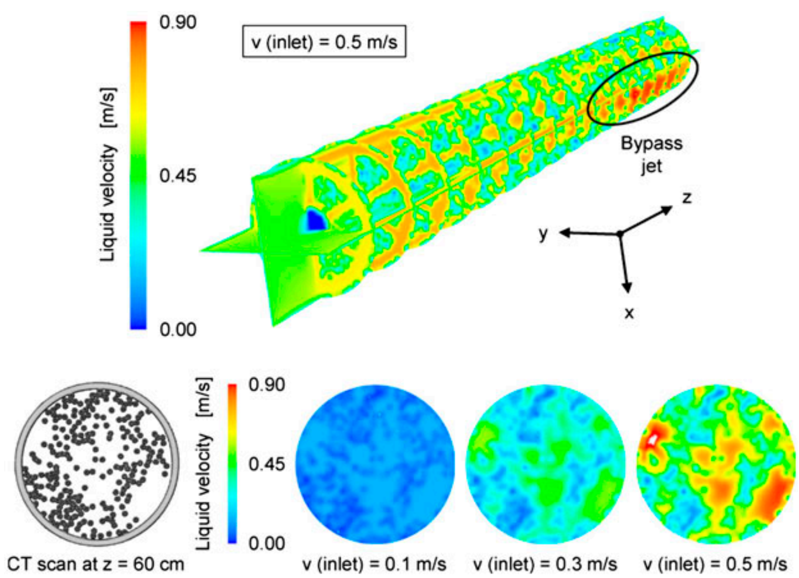

Fig. 3. Single-phase CFD results; velocity contours in the heterogeneous porous medium for a superficial inlet velocity of 0 5 m/s (top) and in a cross-section at $z = 60$ cm for three different superficial inlet velocities (bottom) with MLSS = 10 g/L [22].

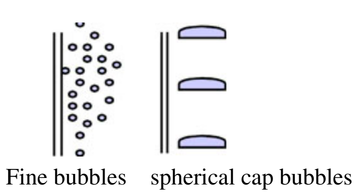

Fig. 4. Fine bubble and spherical cap bubble configurations [23].

minimum level of oxygen supply required. When this level is found, optimal performance within reactor can be obtained.

3.1.3. Other parameters

Other than air sparging and packaging density of fibers, the effect of parameters such as MLSS concentration, reactor geometry, operating conditions, HF

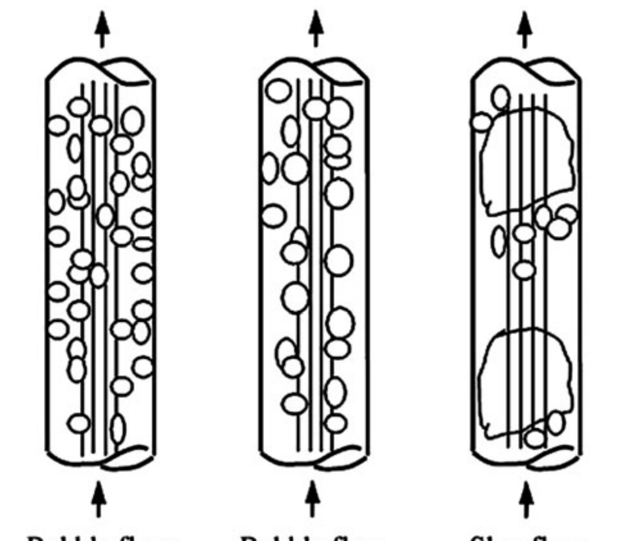

Fig. 5. Bubbling conditions of submerged HF MBRs [25].

vibration on submerged HF MBRs are investigated. Nguyen Cong Duc et al. [27,28], applied CFD on submerged HF MBR system to optimize the module and reactor geometry, aerator design, and operating conditions. In Fig. 7, experimental setup was given. They used Euler–Euler approach for multiphase flow and as a turbulence model κ-ε model were used. It was found that the wall shear stress and bubble frequency (Fig. 8) was linked to void fraction within HF modules; non-uniform distribution of air affected membrane filtration behavior. The local maximal values of the void fraction were 0.10, 0.20, and 0.27 for 20, 50, and 90 Nm^3/h, respectively. Busch et al. [29], developed a model which considers the geometry of system, the hydrodynamics of feed and permeate flow and the filtration resistance (membrane resistance, pore blocking, cake layer formation, polydispersed particles, biofilm formation, and concentration polarization included). According to the results of study, several comments can be given that high concentrations of EPS led to biofouling, high concentration of solid enhance cake layer formation and pore blocking, the aeration rate can both decrease and increase cake layer formation. This model can be able to explain the role of particle size distribution on cake layer formation for the time.

Wang et al. [30], made CFD simulations of membrane filtration zone in a submerged HF MBR using a porous media approach. In simulations, the flow field of Siemens Memcor Memjet HF bundle transferred to porous media model. Multiphase model with Euler–Euler approach and κ-ε turbulence model were used to explain the hydrodynamic behavior of full-scale submerged MBR system and the solution obtained by FLUENT. Different flow direction and viscosities were used to calibrate inertial losses. In Fig. 9, the computational geometry of HF MBR system was given. According to results, the hydrodynamic descriptions of porous model approach were good. Flow regime was affected by sludge viscosity and inertial losses resulted from HF membrane module. Aeration requirement and mixing zone of membrane filtration predictions were more accurate.

In an another study done by Chang et al. [31], the filtration behavior of two different conditions which related to constant permeate-flow operational mode of submerged HF was investigated. The conditions were explained that the maximum initial flux along the fiber is smaller than the critical flux (Jimax < Jcr) and the maximum initial flux along the fiber is greater than the critical flux, but the averaged imposed flux is smaller than the critical flux (Jimax > Jcr but Jmi < Jcr). At first condition, no deposition occurs and the filtration resistance stays at constant during filtration period and it can be used to predict the initial flux distribution along the fiber. However at second condition, a deposition occurs and steady state conditions can be achieved and it can be seen that filtration resistance increases if fiber diameter decreases. This initial deposition was affected from average imposed flux based on inner fiber area/critical flux (Jmi/Jcr) and fiber characteristics such fiber length, fiber inner radius, and membrane resistance. It is especially important for narrow and long fibers. Obtained simulation results showed that the optimum fiber length and radius should be 0.5–3 m and 0.2–0.35 mm, respectively.

Zamani et al. [32] investigated the effect of vibrating HF membranes to reduce concentration polarization and membrane fouling in high solid content suspensions. In this study, the effects of vibration parameters such as amplitude, frequency and geometrical parameters such as fiber radius, distance between fibers within the same fiber bundle on the wall shear stress were investigated. 3D CFD simulations were done by FLUENT. For finer meshing GAMBIT software was used. Flow regime was considered as laminar and segregated solver was chosen for discretization of the governing equation. Results of CFD simulations showed that the wall shear rate was dependent on the distance between the fibers, very high density packaging was not recommended.

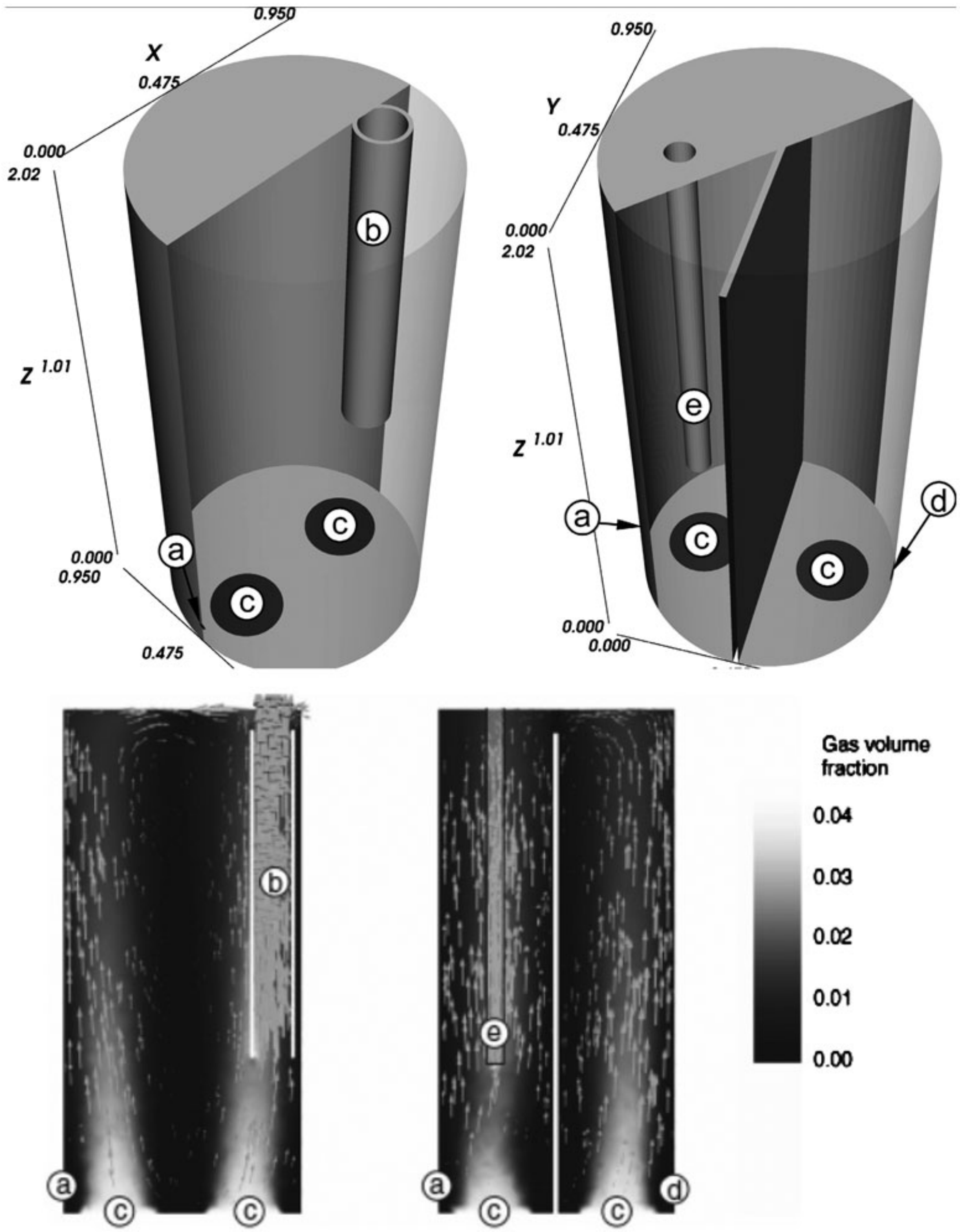

Fig. 6. Computational representation of the inside (upper left) and outside (upper right) configurations. Volume fraction and velocities for inside (lower left) and outside (lower right) configurations with an aeration rate of 12.5% of the maximum, where (a) inlet, (b) inside membrane module, (c) aerators, (d) outlet to the external membrane module, and (e) membrane recycle [26].

3.2. *Submerged MBRs with flat sheet membrane configuration*

Flat sheet configurations have also used for submerged MBRs [7,33,34]. Process is affected from fouling like the same as HF configuration. All parameters affecting the efficiency of submerged HF MBRs also affect flat sheet configuration except packaging density of fiber. In flat sheet configuration, the use of membrane baffles is important. Gas sparging applied generally for decreasing fouling of submerged flat sheet membranes too. In Table 2, CFD simulations done by using flat sheet submerged MBR systems were summarized. Ndinisa et al. [9] investigated the use of two

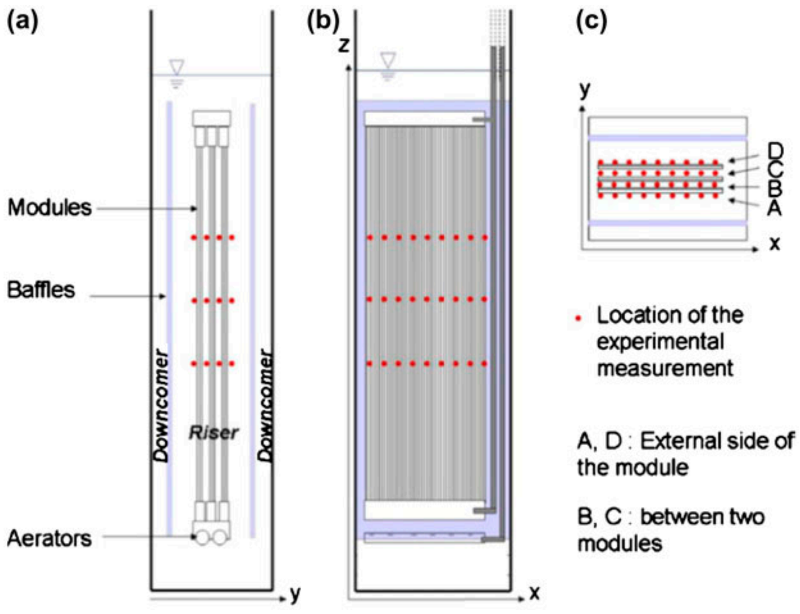

Fig. 7. HF submerged MBR experimental setup [27,28].

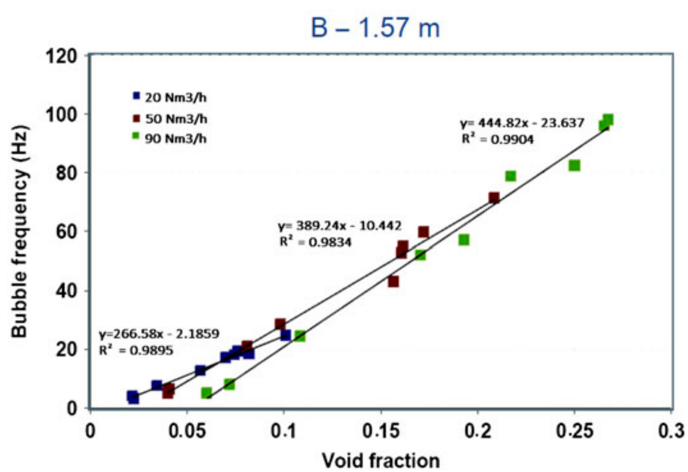

Fig. 8. Bubble frequency (Hz) vs. void fraction comparison of HF submerged MBR system [28].

phase flow as fouling control mechanism, the effects of hydrodynamic factors (air flow rate, nozzle size, channel gap width etc.) and the use of membrane baffles. As a consequence, they found that there are links between air flow rate and fouling were inversely proportional, the nozzle size and effect of bubbling were proportional, the gap between flat sheets and fouling were proportional, and the usage of intermittent filtration and energy requirements were inversely proportional to each other. Also the usage of baffles can be able to decrease fouling up to a point and to increase critical flux. Ndinisa et al. [3] carried their study one step further and made multiphase CFD simulations of submerged flat sheet MBRs. Their experimental results concluded that if bubble size increased, the cleaning effect increased. However the cleaning effect was stable when bubbles were larger than the channel gap. CFD results brought out that when overall shear stress increase, flux enhancement is obtained and the introduction of gas phase into the system resulted in high turbulence. Wei et al. [35] developed a CFD model to control fouling which investigates the hydrodynamic characteristic of slug bubble flow in submerged flat sheet membranes. Volume of fluid method which is good for modeling motions of large bubbles in liquids was implemented by using spherical cap shape

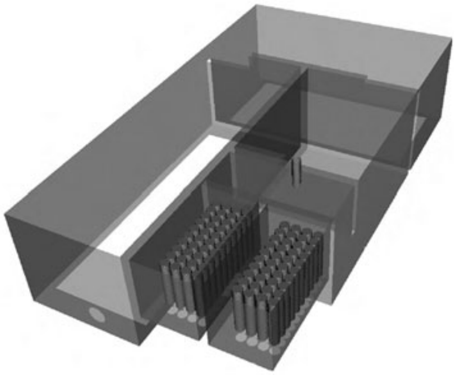

Fig. 9. Computational geometry of HF MBR system [30].

bubbles (Fig. 10). Modeling was done by FLUENT applying finite volume method. The effect of bubble size on wall shear stress was investigated. According to the results, for 25 mL bubble size, shear stress covered half width of the membrane, whereas for 60 mL bubble size, shear stress covered whole membrane width. If 200 mL bubble size was used, intense shear stress was obtained and shear stress covered 65% of the whole domain (Fig. 11). Given results were up to a bubble size, shear stress increased; gap size affected the wall shear stress and optimum gap size was settled as 8 mm; if liquid viscosity increase, a slight increase on shear stress occurred. In another study Li et al. [36] investigated the fluid flow through spacer-filled disk type membrane module. According to their findings, properties of fluid flow depend on membrane module geometry, collection tube size and the spacer thickness. Also in the study, changes in volumetric flow rate permeate flux and distribution of permeation rates due to geometry was investigated. Six different collection tube thicknesses (5, 10, 15, 20, 25, and 30 mm) and 4 different spacer thicknesses (0.5, 0.75, 1, and 1.5 mm) were chosen. Results showed that when structural configurations affected inherent changes occurred on hydrodynamic behavior. In Fig. 12, the effect of collection tube sizes on permeation rates of membrane having 0.50 mm spacer size can be seen. Permeation rates ranged between 3.70×10^{-3} and 5.00×10^{-3} m/s. The widest range was obtained when collection tube size was 5 mm (3.70×10^{-3} to 5.00×10^{-3} m/s). The narrowest range was obtained at collection tube size of 30 mm

Table 2
Some studies related to flat sheet submerged MBR CFD simulation

Membrane geometry	Brief objective	Fluids	CFD code/ models	Varied parameters	Brief results	References
Flat sheet	The effect of bubbling and hydrodynamics for fouling mitigation in submerged flat sheet MBRs	Multiphase	Not specified	Air flow rate, nozzle size, baffles, imposed flux, channel gap width, intermittent filtration	Fouling reduction could be obtained if air flow rate, nozzle size increased. Better distribution of bubbles which promote slug flow and shear stress can be obtained by baffles	[9]
Flat sheet	Identifying effective flow profiles for fouling mitigation in submerged flat sheet MBRs	Multiphase	κ-ε turbulence model, ANSYS	Nozzle parameters, gas inlet velocity, bubble size, baffles	Overall shear stress increase results in flux enhancement. Gas phase introduction results in high turbulence	[3]
Flat sheet	Modeling of intermittent bubbling for fouling mitigation	Multiphase	VOF, ANSYS, finite volume method	Bubble size, gap between membrane, viscosity	Optimal gap width was found as 8 mm to obtain maximum wall shear stress. Wall shear stress depends slightly on viscosity	[35]
Flat sheet	The effects of spacer thickness and collection tube sizes on fluid flow in membrane modules	Single phase	SIMPLEC and QUICK	Spacer thickness, collection tube size and transmembrane pressure	Structural changes affected hydrodynamic behavior. Properties of fluid flow depended on membrane module geometry	[36]

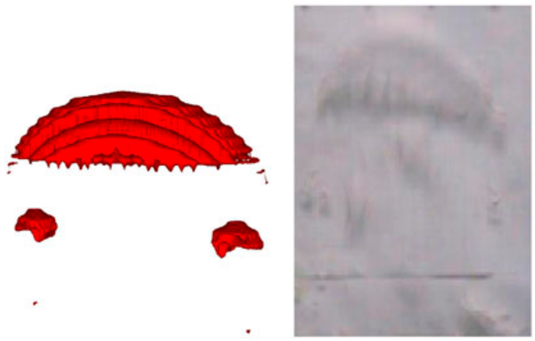

Fig. 10. Comparison of the simulated bubble shape with an experimental bubble [35].

(4.87×10^{-3} to 5.00×10^{-3} m/s). It can be concluded that permeation rate distribution on the membrane was non-uniform and can be improved by increasing the collection tube size. Optimum condition was obtained, when collection-tube size of 15–20 mm and a spacer thickness of 0.75–1.0 mm were chosen.

4. Future trends

Many steps have been done towards submerged MBRs in recent years both considering operational and structural parameters. Up to now, filtration flux, aeration parameters are widely investigated. For further studies, strategies should be formed to decrease energy consumption by air sparging. It is important to generate or find some global trends which can be applied to all MBR systems. Primarily, hydrodynamics, and aeration homogeneity should be settled for fouling mitigation. For these purposes, CFD should be taken into account because it is a powerful and useful tool for optimizing/designing MBR systems. However, modeling difficulties must be considered. A good knowledge of both local mechanisms effects and

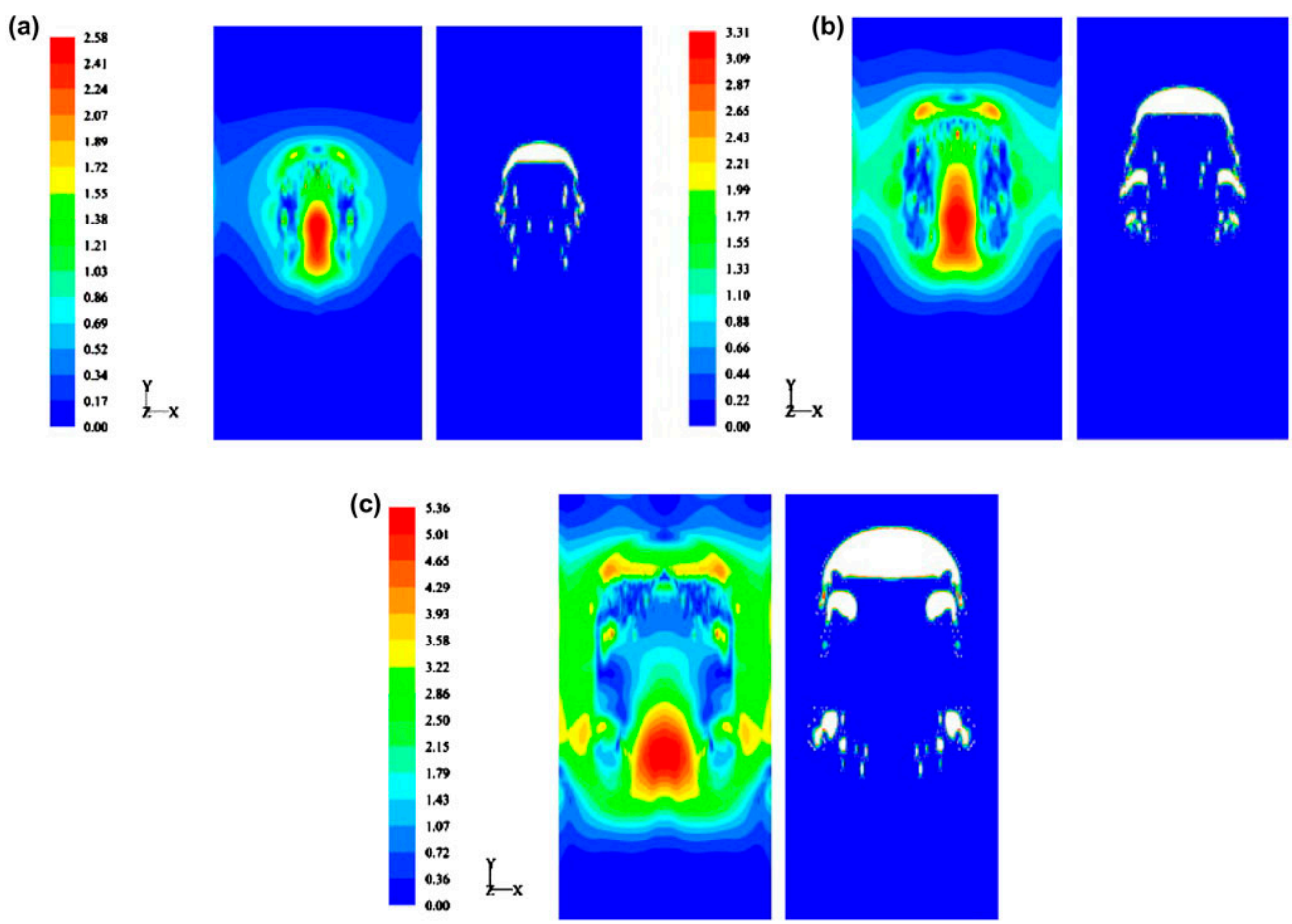

Fig. 11. The calculated distribution of shear stress (Pa) on the whole membrane surface. (a) 25 mL, (b) 60 mL, and (c) 200 mL. (Left: map of shear stress, right: bubble shape and position) [35].

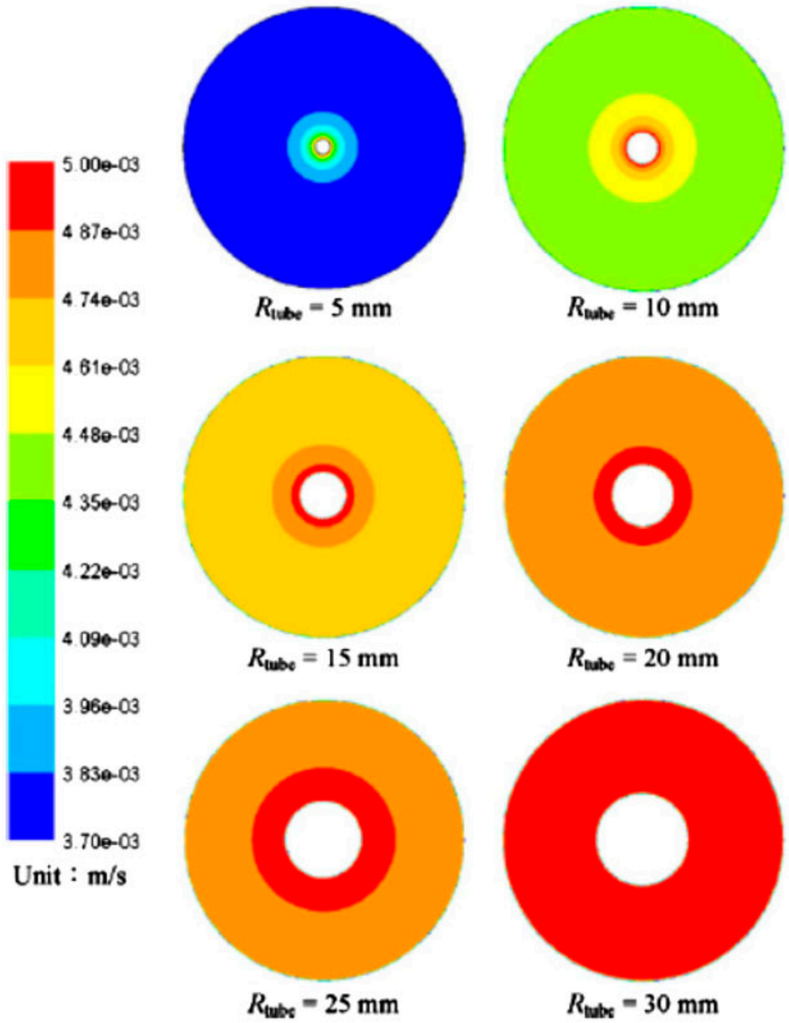

Fig. 12. The effect of collection-tube sizes on the permeation rate at the h_{sp} of 0.50 mm and a TMP of 1.0 bar [36].

biological media behavior is the key to achieve accurate models which lower energy consumption, fouling and has better hydrodynamic conditions ultimately.

5. Conclusion

Submerged MBR systems are widely used technology within MBR technologies. The process of submerged MBR is optimized a little bit further after each year to decrease problems that occur in submerged MBRs. Since experimental optimization is time consuming and hard to repeat, CFD simulations are important. In this review, we try to summarize the CFD studies done with flat sheet and HF submerged MBR combinations.

Fouling is the main energy consuming thing in submerged MBRs. Throughout the studies, the causes of fouling phenomena and other parameters was investigated. It can be concluded that, when submerged MBR is designed, the effects of flux heterogeneity, packing density, air scouring (diffuser size, gas flow rate, nozzle type, frequency, bubble size, channel gap between flat sheets etc.), shear stress and its effect on EPS, sludge, and membrane surface should be considered. Also, there are some other parameters (sequencing of aeration, and of filtration; backwashing etc.) affecting the operation of submerged MBRs however these parameters are not simulated through CFD simulations.

In conclusion, it is important to improve submerged MBR systems to avoid energy losses. Researches should concentrate CFD simulations which is a powerful tool for solving problems associated with submerged MBRs. Besides, since the design of SMBRs is affected by combination of both hydrodynamic and biological conditions, CFD models and simulations should be done considering both of these phenomena.

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