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CFD simulations of membrane filtration zone in a submerged hollow fibre membrane bioreactor using a porous media approach

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ABSTRACT

The current membrane bioreactor (MBR) design methods and the popular bio-kinetic models rely on the assumption that membrane bioreactor is completely mixed, neglecting the real hydrodynamic condition within the reactor. MBRs differ from conventional reactors in so far as the spatial distribution of reactor discharge points is very broad for an MBR compared with a conventional bioreactor. Computational Fluid Dynamics (CFD) provides a possibility to investigate the hydrodynamic behaviour of large scale MBRs. The CFD modelling of whole MBR plant requires a macro-scale approximation which can keep the mesh size and computation effort within the reasonable limit. However, the simulation of the flow behaviour surrounding the membranes requires high mesh resolutions and hence large element numbers. Therefore, it is impossible to model each individual hollow fibre using the Navier–Stokes equations as it is too computationally costly. In this paper, the effects of Siemens Memcor Memjet® hollow fibre membrane bundle on flow field were transferred to a porous media model. This porous media model was coupled with a three-dimensional multiphase model to account for the hydrodynamic behaviour of a full-scale submerged MBR. An experimental approach was developed to calibrate the inertial loss caused by the hollow fibre bundle against various liquid velocities at different flow direction and fluid viscosity. The experimentally determined inertial losses were compared against those estimated from the empirical correlations for tube banks. These experimental calibrations were then applied to the porous media model. Significant improvement on the hydrodynamic descriptions was observed by coupling the porous media model compared with the previous developed MBR CFD model.

1. Introduction

For a given wastewater, the parameters affecting the MBR design can be categorized into three groups, (i) biological factors, (ii) membrane factors, and (iii) hydrodynamic factors [1]. The hydrodynamic conditions of a reactor can be characterised by the degree of mixing [2]. Current MBR design tools such as BioWin® or WEST® [3] utilise variants of the Activated Sludge Model (ASM) [4–7] and therefore usually assume that the mixing characteristics confirm with either complete mixing (CSTR) for aeration tanks, or plug flow (PFR) for some anoxic channels. Unlike conventional wastewater treatment process that have a single discharge point, MBR may have multiple discharge points resulting from its variable positions along the reactor length [8]. Therefore, non-ideal mixing (e.g. the existing of dead zones) would lead to non-uniform nutrient conversion.

Research has been carried out on the characterisation of mixing regimes of the whole full-scale MBR plants by acquiring residence time distribution profiles through tracer studies [9] and computational fluid dynamics (CFD) modelling [10]. Results from these studies suggested that the full-scale MBRs being examined were close to CSTR conditions but not 100% completely mixed and therefore the ideal flow models cannot be used to predict the flow regimes within the reactor. Another study [11] tried to couple the ASM No. 1 with the CFD model to predict the biological treatment performance and compared various biological process variables against COST benchmark [3]. Minor difference on nutrient conversion was observed due to the deviation from CSTR condition. These were the first efforts ever to investigate the mixing behaviour and its impact on nutrient removal of the entire full-scale MBR.

The mixing of entire MBR plant is affected by the power inputs required by the aeration for biological reactions, pump required for returned activated sludge and aeration for membrane scouring [9]. By contrast, the mixing behaviour of membrane filtration zone itself is only affected by the aeration energy for membrane scouring. To achieve the uniform conversion from various membrane elements in the tank, it is essential for the membrane filtration vessels to be completely mixed. However, although attempts have been made to acquire residence time distribution profiles from various pipelines (e.g. the common filtrate vs. returned activated sludge stream) in

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the MBRs [9], it is hard to measure residence time distribution profiles from the lead and tail element separately in large-scale MBRs. The CFD modelling of whole MBR plants requires a macro-scale approximation which can keep the mesh size and computation effort within the reasonable limit. However, the simulation of mixing behaviour of membrane filtration vessels or the flow behaviour surrounding the membranes requires high mesh resolutions and hence large element numbers [12]. Therefore, it is impossible to model each individual hollow fibre using the Navier–Stokes equations as it is too computationally costly. Since we are interested in the flow resistance induced by the hollow fibre array and its impact on mixing profile, the whole membrane module can therefore be modelled as a porous media with macroscopical characteristics. Effects on the flow field caused by the membrane module can be transferred to the porous zone [12,13]. The porous media model has been used for modelling the pressure drop across tube banks and its impact on heat transfer [14–16]. The tube banks have geometry similarity as the hollow fibre array. Therefore, there was attempt [13] to apply the empirical correlations of tube banks to model the flow resistance induced by hollow fibre. The challenge is that the flow resistance induced by different membrane modules is different, leading to different inertial loss coefficients required in the porous media model. There is no information available in the literature on how to characterise the flow resistance caused by the hollow fibre bundle.

This paper demonstrates an experimental approach to measure the flow resistance of the hollow fibre membrane bundles. The correlations obtained from measurements were applied to the porous media model which was used to simulate the flow behaviour of the membrane filtration zone of a 2.2 MLD MBR located in Sydney. The porous media model was coupled with the CFD model developed by Brannock et al. [10] to show the improvement on the hydrodynamic description by using porous media model.

The packing density of the membrane bundle used in the experiments was as same as the hollow fibre membrane module used for Sydney Water's North Head MBR plant [9]. The porous media model was then applied to the hollow fibre membrane module of this full scale submerged MBR using the lab calibration data.

2. Theory

2.1. Porous media model

The porous media model is widely used for determining the pressure loss in the flows through packed beds, filter papers, perforated plates, flow distributors, and tube banks [16]. A momentum source term is added to the governing momentum equations which creates a pressure drop that is proportional to the fluid velocity:

$$S_i = -\left(\underbrace{\sum_{j=1}^{3} D_{ij}\mu v_j}_{\text{viscous loss term}} + \underbrace{\sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho v_{mag} v_j}_{\text{inertial loss term}} \right) \quad (1)$$

where S_i is the source term for the ith (x, y, or z) momentum equation, and D and C are prescribed matrices.

In laminar flows through porous media, the pressure drop is typically proportional to velocity. Ignoring convective acceleration and diffusion, the porous media model then reduces to Darcy's law:

$$\nabla p = -\frac{\mu}{\alpha}\vec{v} \quad (2)$$

where α is the permeability.

At high flow velocities, the inertial resistance factor, C_{2ij}, can be viewed as a loss per unit length along the flow direction, thereby allowing the pressure drop to be specified as a function of dynamic head.

The aim of current work is to model the effects of pressure drop caused by membrane bundles, which is similar to the situation of modelling a perforated plate or tube bank, in which cases the viscous term can be eliminated, yielding the simplified form of the porous media equation [16]:

$$\nabla p = -\sum_{j=1}^{3} C_{2ij}\left(\frac{1}{2}\rho v_j v_{mag}\right) \quad (3)$$

where C_2 is the inertial resistance factor.

Eq. (3) can be written in terms of the x, y, z directions:

$$\begin{aligned} \Delta p_x &= \sum_{j=1}^{3} C_{2xj}\Delta n_x \frac{1}{2}\rho v_j v_{mag} \\ \Delta p_y &= \sum_{j=1}^{3} C_{2yj}\Delta n_y \frac{1}{2}\rho v_j v_{mag} \\ \Delta p_z &= \sum_{j=1}^{3} C_{2zj}\Delta n_z \frac{1}{2}\rho v_j v_{mag} \end{aligned} \quad (4)$$

where Δn_x, Δn_y, and Δn_z is the actual thickness of the porous region.

2.2. Empirical correlations for tube banks

The challenge of using porous media model is that the flow resistance/pressure drop induced by different membrane module is different and therefore the inertial resistance factor C_2 is hard to determine. One way to determine the pressure drop across the hollow fibre membrane bundle is using the empirical correlations which are used to estimate pressure drop across tube banks as the configuration of tube banks is similar to that of hollow fibres.

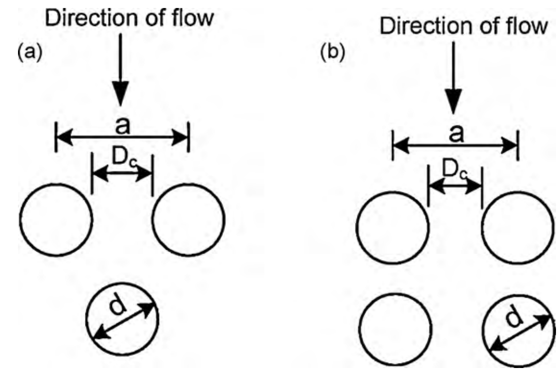

Fig. 1. Tube layout and dimensions; (A) staggered arrangement; (B) in-line arrangement.

Pressure drop for tube banks can be presented in the form of a friction factor vs. Reynolds number and affected by the arbitrary characteristic of the tube bank such as tube spacing and configuration (i.e. staggered arrangement or in-line arrangement, Fig. 1) [17,18].

For the turbulent flow with the flow direction perpendicular to tube banks:

$$\Delta p = 4fN_t \frac{\rho u_{\max}{}^2}{2} \quad (5)$$

where N_t is the number of tube rows in the direction of fluid travel, f is friction factor. The configuration of the hollow fibre membrane bundle has the similarity with the configuration of tube banks with