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Hydrodynamics and gas transfer performance of confined hollow fibre membrane modules with the aid of computational fluid dynamics

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ABSTRACT

The use of gas permeable membranes for bubbleless aeration is of increasing interest due to the energy savings it affords in wastewater treatment applications. However, flow maldistributions are a major factor in the impedance of mass transfer efficiency. In this study, the effect of module configuration on the hydrodynamic conditions and gas transfer properties of various submerged hollow fibre bundles was investigated. Flow patterns and velocity profiles within fibre bundles were predicted numerically using computational fluid dynamics (CFD) and the model was validated by tracer-response experiments. In addition, the effect of fibre spacing and bundle size on the aeration rate of various modules was evaluated experimentally. Previous studies typically base performance evaluations on the liquid inlet velocity or an average velocity, an approach which neglects the effect of geometric features within modules. The use of validated CFD simulations provides more detailed information for performance assessment. It was shown that specific oxygen transfer rates declines significantly with increasing numbers of fibres in a bundle. However, the same trend was not observed when the fibre spacing is increased. A correlation was proposed for the prediction of the overall mass transfer coefficient utilizing the local velocity values obtained from the validated CFD model.

1. Introduction

Hollow fibre gas-liquid contact membranes are of increasing interest in a wide variety of applications including wastewater treatment, medical devices, and de-gassing of process industry liquid streams. The use of such contactors as bubble-less aeration devices in water/wastewater treatment has been under investigation for several years [1–10]. Enhancing the oxygen transfer rate to the liquid is of critical importance in these processes. High rates of mass transfer, close to 100% transfer efficiency [4], good process control and ability to operate at flow rates and pressure independent of the bulk fluid phase are some of the reasons for their superiority over energy intensive bubble aeration systems [8]. A commonly used membrane material in these applications is Polydimethylsiloxane (PDMS), due to its high oxygen permeability and robustness in the wastewater milieu. The dense or non-porous nature of PDMS eliminates the possibility of bubble formation above moderate pressures and additionally prevents intra-pore fouling and wetting, which are disadvantages of porous membranes in these applications.

The rate of aeration is largely dependent on the effective surface area of the membrane and the driving force for permeation (the concentration gradient across the membrane wall) [2,3]. The total resistance to gas transfer consists of three terms, gas side resistance, liquid side resistance, and membrane resistance [2,9–11]. The gas side resistance is typically significantly smaller than that of the liquid side resistance. Furthermore, the mass transfer coefficient is independent of gas partial pressure, for partial pressures below 3 bar [1]. Thus with the membrane side resistance of a module being constant, the efficiency of the aeration process is most dependent on the liquid side resistance in submerged membrane bundles [1].

Previous research has highlighted the importance of module configuration and hollow fibre layout on the performance of various heat and mass transfer processes utilizing membrane modules [7,12–23]. Hollow fibre systems with parallel flow are often prone to flow mal-distribution with reduced flow through the centre of the fibre bundle. The water velocity increases radially culminating in preferential flow or channelling around the outside of the membrane bundle. This flow mal-distribution is influenced by the module design (membrane diameter, length, packing

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density or inter-fibre spacing, bundle diameter, Reynolds number, bundle spacing, shell diameter, and possible dead zones caused flow around the potted ends of the module etc.) in a complex way that is poorly understood. Since the local velocity and shear flow determine the local mass transfer coefficient, the occurrence of such radial flow variation across the bundle results in lower overall rates of mass transfer and reduced reactor performance [17,24–26].

Many studies have been undertaken to understand and engineer the liquid flow field in membrane modules to enhance mass transfer [16,20,27–33]. Among applied methods, computational fluid dynamic (CFD) tools provide detailed analysis of the flow fields and the macro-scale diffusion of the species within the system, allowing for confident design and characterization of mass transfer within membrane bundles. Typically to reduce computational costs and time, single fibres or a section of the module geometry is modelled and simplifying assumption are applied [17,28,31,34–36]. Previous studies have utilized CFD modelling to, for example, predict the effects of operating parameters on the performance of various hollow fibre membrane processes [17,18,30,37]. The impact of module packing density on filtration efficiency, as well as fouling and cake growth, have been assessed using a finite element approach [38,39]. The results showed the significance of packing density on the flow distribution and filtration rate, with a 30% increase in membrane packing density leading to a 50% reduction in filtration flux.

In this paper we extend this approach to develop a validated CFD model of flow distribution in the modules followed by experimental gas transfer performance studies in order to better inform the analysis and design of hollow fibre modules. Flow distributions in different hollow-fibre modules, having different numbers of fibres and fibre spacings, were characterised experimentally using a tracer-response approach, and the residence time distribution (RTD) curves obtained were compared with those predicted by a CFD model; allowing validation of the CFD model. To evaluate the significance of the hydrodynamic conditions on the overall mass transfer performance, specific oxygen transfer rate (OTR) tests were performed with the same modules. The novelty of this research is the robust experimental validation of the CFD model, thus allowing for more confident assessment of the effect of localised flow patterns in the module and subsequent analysis of the impact of these patters on gas-transfer performance.

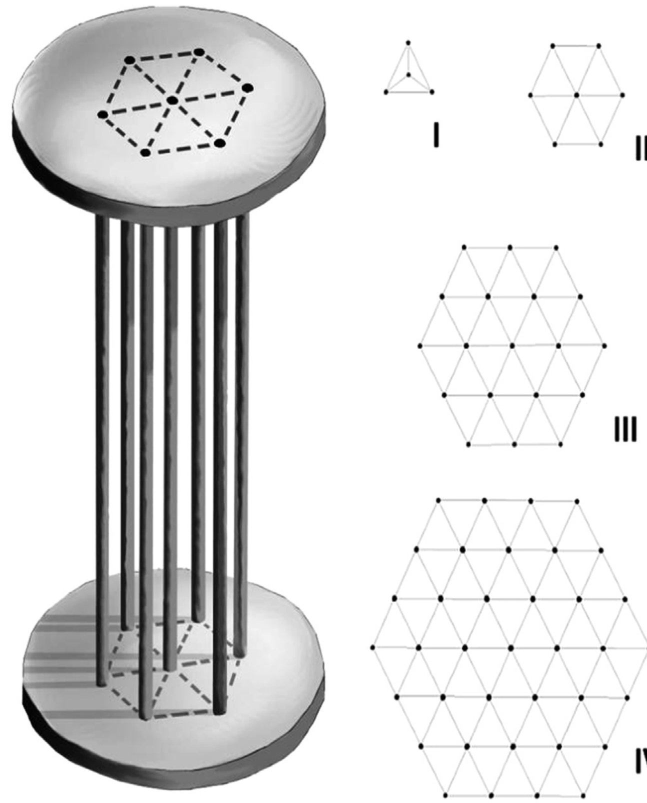

Fig. 1. Left – Schematic of a sample fibre bundle, Right – The hexagonal fibre orientation with (I) 4, (II) 7, (II) 19 and (IV) 37 fibres.

Table 1
Details of the Membrane Module Design.

Membrane material	PDMS
Membrane oxygen permeability, Barrer	600
Membrane fibre ID, μm	300
Membrane fibre OD, μm	500
Effective fibre length, cm	42
End Spacer Diameter, mm	17.8
Oxygen supply tubing/bundle holder OD, mm	6
Glass column ID, mm	25
Glass column effective length, mm	800
Distance from the inlet to the bundle lower spacer, mm	115

2. Materials and methods

2.1. Membrane bundle fabrication

Hollow fibre membrane modules typically consist of parallel fibres packed in an external shell. This provides a very large specific surface area for transfer. It has been shown that structured fibre configurations cause less flow mal-distribution and enhance mass transfer efficiencies [36,40,41]. In this study, homogeneous dense PDMS hollow fibre membranes were used. Fibre bundles were assembled using a predetermined hexagonal spacing, held in place by two plastic disk spacers on each end of the bundle. Details of the module designs are summarized in Fig. 1 and Table 1.

Modules were fabricated with 4, 7, 19 and 37 fibres of the same length and assembled in 2 mm, 4 mm, and 6 mm spacing configurations (due to design restrictions and the small column diameter, bundles of 19 fibres with 6 mm spacing, and 37 fibres with 4 and 6 mm spacings, could not be tested). In all, nine fabricated bundles were used to study effects of geometry on hydrodynamics of the shell side flow and mass transfer efficiency.

The membrane bundles were potted into 6 mm OD (4 mm ID) polyethylene tubing at each end, using polyurethane potting agent (RS Components, Dublin Ireland). This potting material reduces the risks of gas or liquid leaks and can endure high pressures of up to 3 bar gauge. Spacers were placed at the ends of the bundle, keeping the effective fibre length of all fibres 42 cm, from spacer to spacer. Each potted bundle was inserted in an 80 cm vertical glass tube with an inner diameter of 25 mm. Two stainless steel 6 mm OD pipes held the bundle at a fixed vertical position (Fig. 3) and provided the air flow to the membranes.

2.2. Computational fluid dynamics

The flow characteristics controlling the performance of hollow fibre membrane bundles were investigated numerically with a finite volume CFD method. The membrane bundle in the glass column was chosen as the computing domain. The three dimensional geometric structures of the computational domain were generated using Gambit 2.4 software which was then divided into smaller sub-domains. Hydrodynamic studies were carried out by developing a double precision model using the commercial