Summary

Water scarcity is one of the biggest challenges our world is facing today. It is critical to utilize natural resources in a sustainable manner, which includes reusing and recycling the treated water. Membrane bioreactor (MBR) technology is proving to be a treatment technology having the potential to offer the previous demands. An MBR treatment plant is an activated sludge plant where the separation of the activated sludge and the treated effluent is accomplished through a membrane filter instead of a sedimentation tank as is the case in Conventional Activated Sludge (CAS) treatment plants. An MBR plant is characterised by an extremely low content of suspended solids in the effluent, as the membrane acts as an efficient barrier to particles larger than the membrane pore size including pathogens. This opens perspectives for water reuse and recycling.

However, the MBR technology is facing some challenges: membrane fouling and lower cost-effectiveness compared to CAS. For the former, the hydrodynamics are of great importance for reducing sludge deposition on the membrane surface and prolonging the operating period below the critical transmembrane pressure (TMP). Membrane performance measured in terms of membrane fouling has been observed to be enhanced by gas sparging. Several mechanisms were identified (i.e. bubble-induced secondary flow, physical displacement of the mass transfer boundary layer, pressure pulsing caused by bubbles). The purpose of this study was to develop tools to analyse and better understand the hydrodynamic conditions in MBR systems. This analysis consisted of both experimental investigation as well as a model-based approach to translate the observations into mechanistic models.

An experimental setup was developed to investigate the shear stress imposed on the surface of a tubular membrane under different two-phase flow conditions (gas and liquid), by varying the flow of each phase. The slug flow pattern behaviour of three different compounds (water, carboxymethyl cellulose and activated sludge) in two vertical tubes with different diameters was investigated using a high speed camera (HSC). The behaviour in terms of gas slug rising velocity was compared to theoretical equations from literature. Although these expressions seem valid, the tube diameter has and the fluid viscosity is likely to have an influence. Furthermore, it was observed that the degree of coalescence of gas slugs is lower and delayed for non-Newtonian liquids as successions of slugs without actual coalescence into a single larger gas slug were observed.

Due to the similar, though non-uniform, behaviour of shear profiles (long and short duration of shear events) caused by the difference in length of the gas slugs (due to the coalescing of gas slugs as they traversed up the tube), time series as such could not be used for analysis. Instead, for ease of interpretion and comparison of these shear profiles, Shear Stress Histograms (SSH) were introduced. For all cases, bimodal SSHs were observed, having one peak corresponding to the shear induced by the liquid flow, and a second one induced by the gas flow. This distribution was modelled using a simple empirical relationship based on an overlapping combination of two normal distributions. As literature suggests that fouling control is expected to be optimal when the frequency of shear stress induced by the liquid flow is approximately equal to that induced by the gas flow, the simple empirical relationship could be used to identify those two-phase flow conditions that balance the peaks and, hence, optimize fouling control. It was concluded that for a combination of low liquid flow rates and relatively high gas flow rates, the peaks in the SSH are balanced and the energy consumption is minimized. However, the empirical model has its limitations that it cannot be extrapolated and that it does not learn us anything on the mechanisms that are occurring.

To overcome the limitations of the empirical model, a CFD model was developed to study the effect of slug flow on the surface shear stress in a vertical tubular membrane in more detail. The model was validated using: (1) surface shear stresses, measured using an electrochemical shear probe and (2) gas slug rising velocities, measured using a HSC. All simulated conditions resulted in bi-modal SSH (recovered from the simulation output), similar to the experimental measurements. It was found that the positive peak (liquid slug) was well described by the CFD model. However, the negative peak (gas slug) was shifted to the left due to the selection of the turbulence model for the entire flow. In reality, a slug flow changes flow pattern continuously when gas slugs are passing.

Next to this CFD model at micro-scale, a macro-scale CFD model was developed for an entire airlift membrane module present in full-scale MBRs. Due to computational limitations, a stepwise approach was followed to set up a more conceptual model. Moreover, filtration was included, which was not the case in the micro-scale model. First, a one-phase model including filtration (through a resistance representing the opposition to filtration) was developed and validated. This was then extrapolated to a bundle of tubes by defining a second resistance representing the resistance of the bundle to flow. Second, the air diffusion system was modelled for two types: ring aerator and disc aerator. The latter proved to give rise to a better air distribution. To account for influences of the membrane module on the behaviour of the air diffuser, both models were coupled and yielded comparable results. However, this verification was needed to check the values of the resistances.

Viscosity plays an important role in many aspects of activated sludge. Also here, it was found that the slug flow behaviour and, hence, the shear stress pattern that governs fouling control is affected by viscosity. An alternative, on site method is proposed. This viscosity was studied for 10 different pilot- and full-scale plants using the Delft Filtration Characterisation method (DFCm). The apparent viscosities determined were found having values twice as high as conventional rheological measurements performed with activated sludge. This can be caused by the difference in measurement technique. Here, both techniques exhibit flaws. The tube diameter of the presented method is significantly larger than that for which the rheological derivation is propsed. On the other hand, ex-site techniques suffer from floc breakage which is likely to influence the remainder of the measurement. A general rheological model for the viscosity of activated sludge was developed as a function of Total Suspended Solids (TSS). First, it was observed that there is a large variation remaining in the data, suggesting that an important factor is missing in the model. Moreover, the model structure is overparameterised and needs further investigation as parameter estimations performed with it are highly unreliable.

The mass transfer coefficient plays an important role in predicting shear stresses in tubular systems. However, it is a quantity that is difficult to measure. Using similarities between heat-and-mass transfer mechanisms, an empirical model was proposed to predict heat and mass transfer coefficients for two-phase slug flow in vertical pipes. By using the same setup with shear probes and an electrolytic solution, it was possible to measure the mass transfer coefficient. An empirical model was developed as a function of the Nusselt number based on a robust two-phase heat transfer correlation.

Finally, to extend the study to a different type of MBR system, a CFD model of a submerged hollow fiber MBR was developed and validated using data obtained from 60 shear probes located in different sections of the MBR tank. It was found that the CFD model is under-predictive in terms of shear, caused by some assumptions made in the model to allow computation. One of those assumptions was to approximate the hollow fiber module as a flat sheet module. It is likely that a great fraction of the shear force comes from the movement and collision of fibers and only a small portion comes directly from the liquid-gas movement that can be obtained from the CFD simulation. Which effect has most impact on fouling control (shear magnitude or shear direction change) is to be further investigated. Although further improvements are needed to use the CFD model to accurately simulate shear stress distributions, the results from the present study look promising and suggest that CFD modelling could be used to effectively optimize the air sparging and membrane module configuration to minimize the use of energy for fouling control.