Application of Computational Fluid Dynamics to optimise module configuration from fibre to module in immersed membrane systems

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INTRODUCTION

- Hollow fibre membranes are widely used in submerged membrane bioreactors (MBRs) for municipal wastewater treatment
- MBRs employ coarse bubble aeration to control fouling and maintain throughput (flux) which results in higher power requirements than conventional processes
- In practice, fouling is unevenly distributed along the fibre increasing problems at the fibre level (micro-scale) with flux distribution and at the module level (meso-scale) with the shear generated by aeration
  - Non-uniform flux distribution → uneven fouling on single fibre (micro-scale)
  - Non-uniform shear stress → uneven fouling on membrane module (meso-scale)

- This project uses Computational Fluid Dynamics (CFD) validated by Particle Image Velocimetry (PIV) to optimise membrane design at both micro-scale and meso-scale

MODEL DEVELOPMENT & VALIDATION

Design variables influencing fouling distribution

- **Micro-scale design variables**
  - Fibre length
  - Fibre diameter
  - Outlet pattern
  - Fibre movement
  - Fibre packing density
- **Meso-scale design variables**
  - Aerators
  - Membrane module
  - Membrane tank

Numerical simulation: ANSYS CFX14.5

- **Membrane filtration tank**
  - Two-phase simulation
  - Porous media model
  - Rheology model
- **Hollow fibre filtration**
  - Axial symmetrical 2D simulation
  - Laminar flow
  - Porous media model
- **Aeration**
  - Euler-Euler Multiphase
  - RNG k-ε Model
- **Fibre movement**
  - Fluid Structure Interaction (FSI)

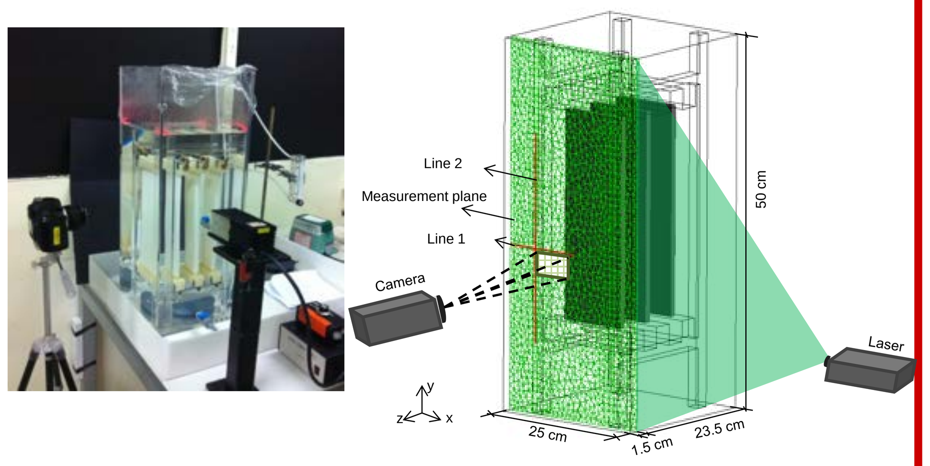
Model validation

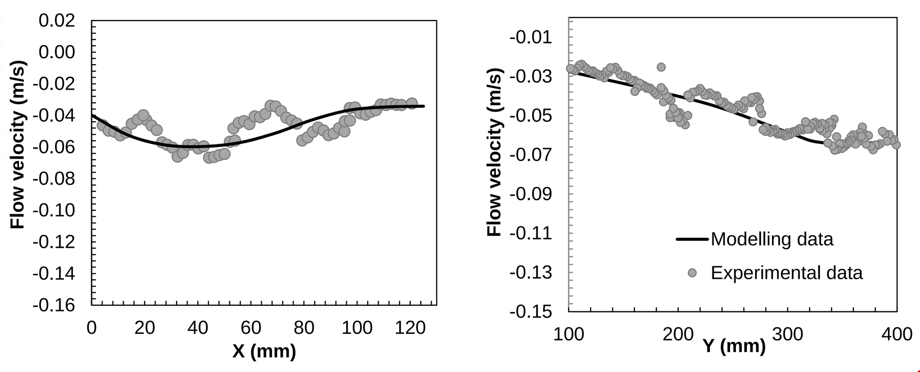
- Validation for micro-scale simulation: filtration experiments
- Validation for meso-scale simulation: Particle Image Velocimetry (PIV)

Validation results: micro-scale simulation

Design Flux (L/m^2.h)	Measured flowrate (ml/s)	Simulated flowrate (ml/s)	Difference
16.7	3.393 ± 0.001	3.500	3.15%
20.0	4.064 ± 0.001	4.451	9.52%

Validation results: meso-scale simulation





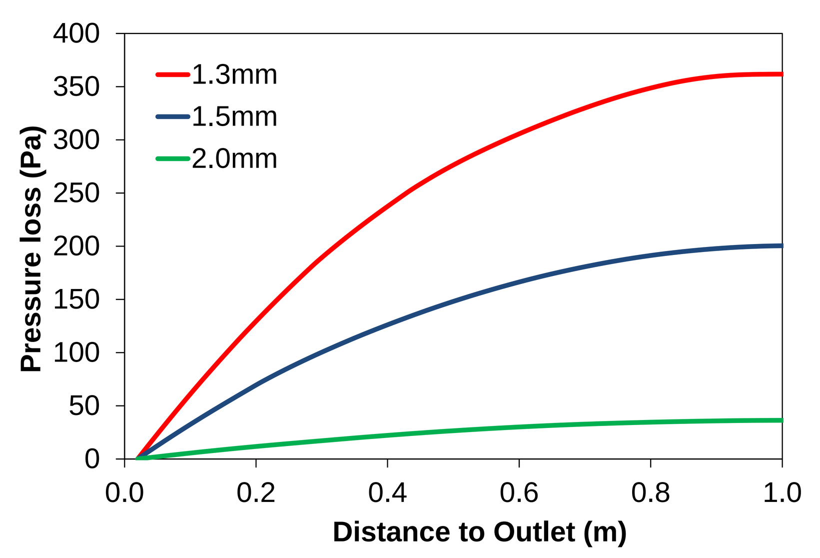
MICRO-SCALE SIMILATIONS

Fibre length: Decrease in flux along fibre

Length (m)	Outer Diameter 1.3mm	Outer Diameter 1.5mm
0.3	1.86%	0.77%
1.0	16.90%	9.38%
2.0	43.82%	21.62%

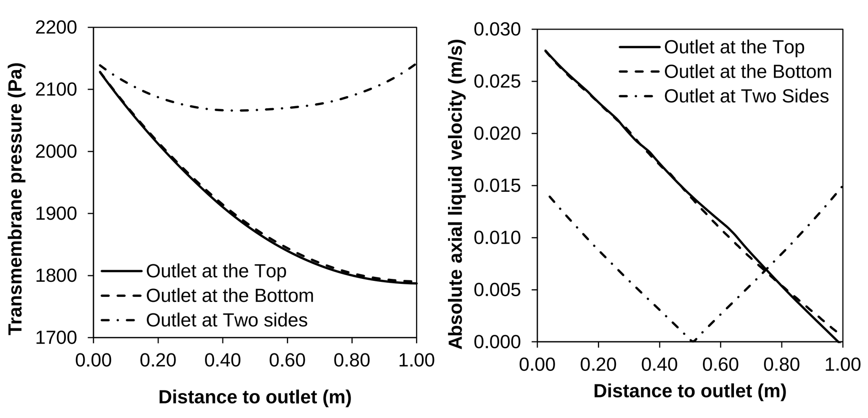
- Longer fibre length caused a larger flux decline flux along the axial direction regardless of fibre diameter.

Fibre diameter: Pressure loss along fibre



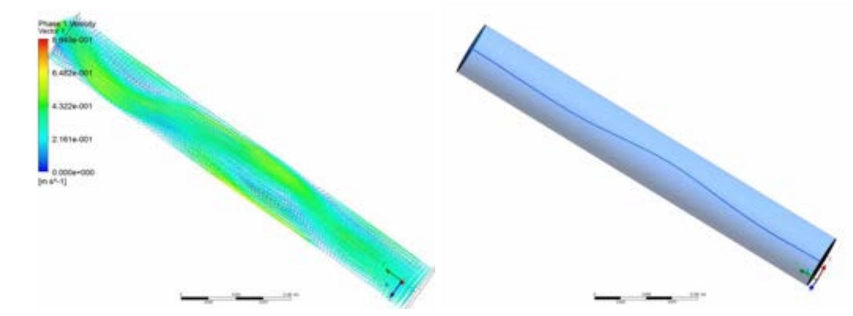
- Increase of fibre diameter results in a decrease in local pressure loss and subsequent increase in local flux.

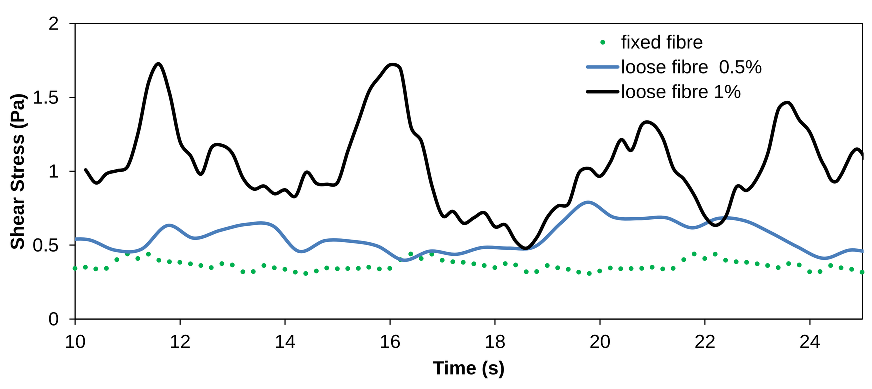
Location of permeate header



- Suction from both ends has an equivalent effect as reducing the fibre length by 50%, therefore decreasing the degree of uneven flux distribution along the fibre.

Fibre movement



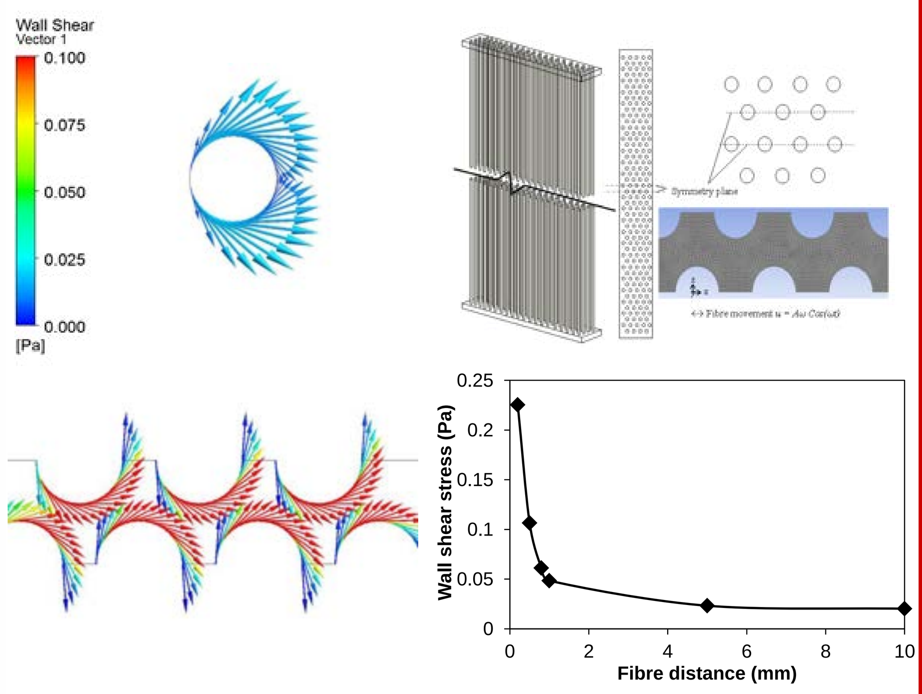


- Shear stress on fibre surface can be improved by fibre movement.
- Increasing fibre looseness leads to an increase in average membrane shear stress

Packing density

Simplifications:

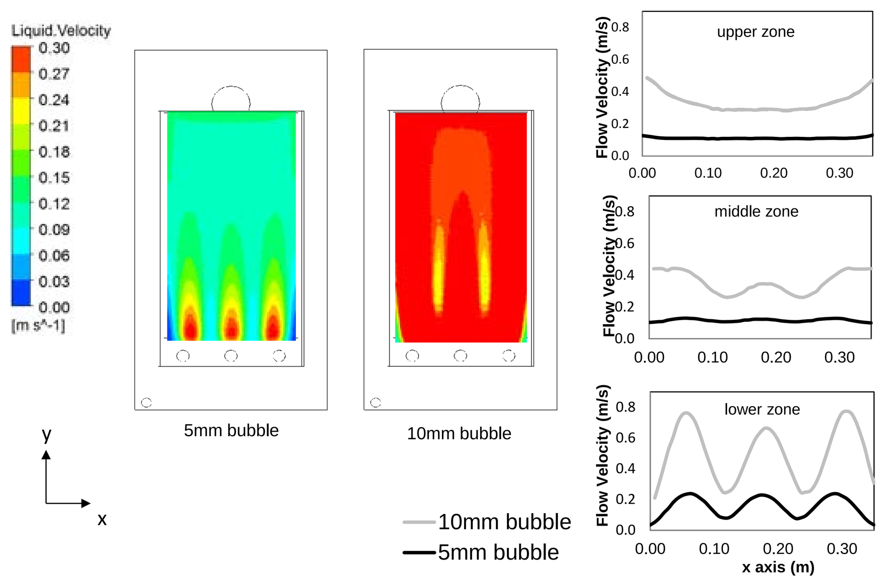
- Moving in one direction
- Cosine fibre movement
- Symmetry boundary conditions



- Lower packing density (larger distance between fibres) reduces the interactions between adjacent fibres and decreases the membrane shear stress.

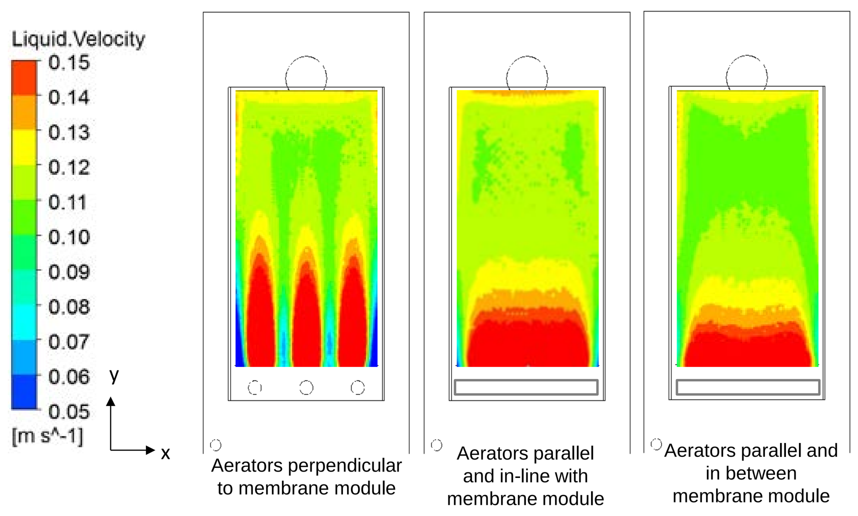
MESO-SCALE SIMULATIONS

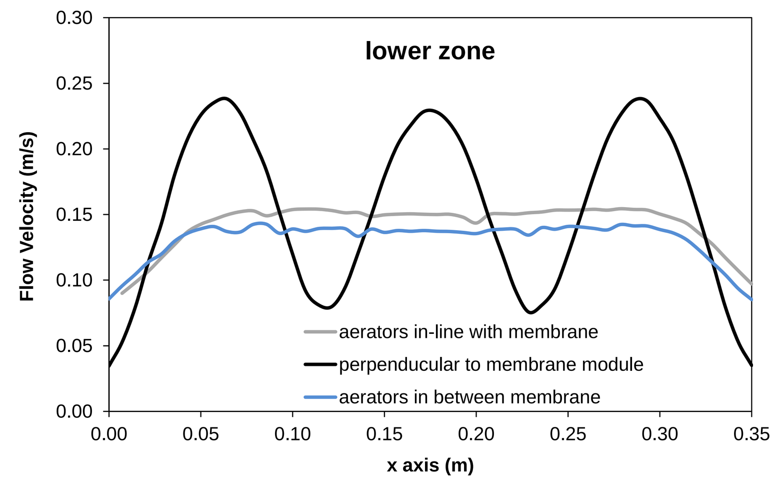
Aerators: bubble size



- The average near membrane flow velocity increased 3 fold by increasing bubble size from 5mm to 10mm.

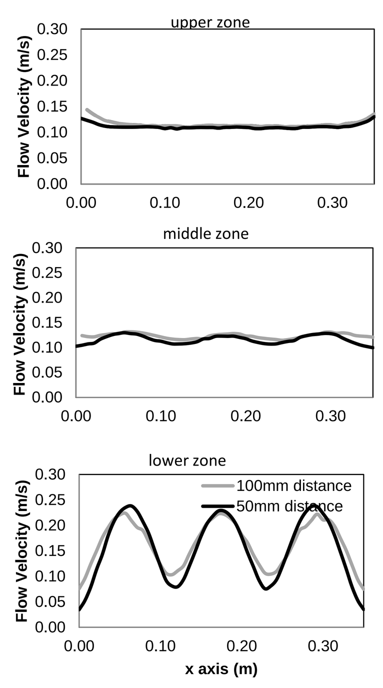
Aerators: layout





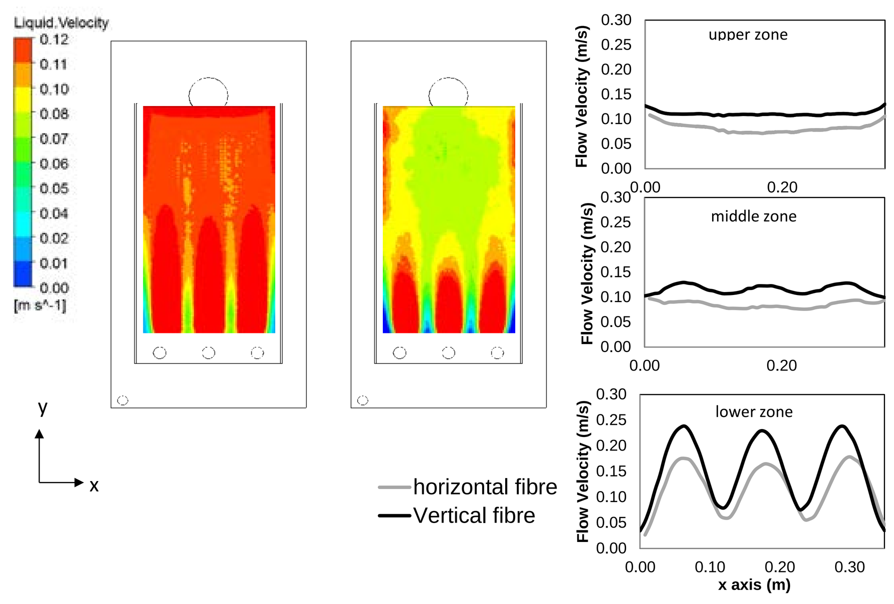
- Locating aeration pipes parallel to membrane module improved the near membrane flow velocity distribution at the lower zone.

Membrane module: Distance of aerator to membrane module



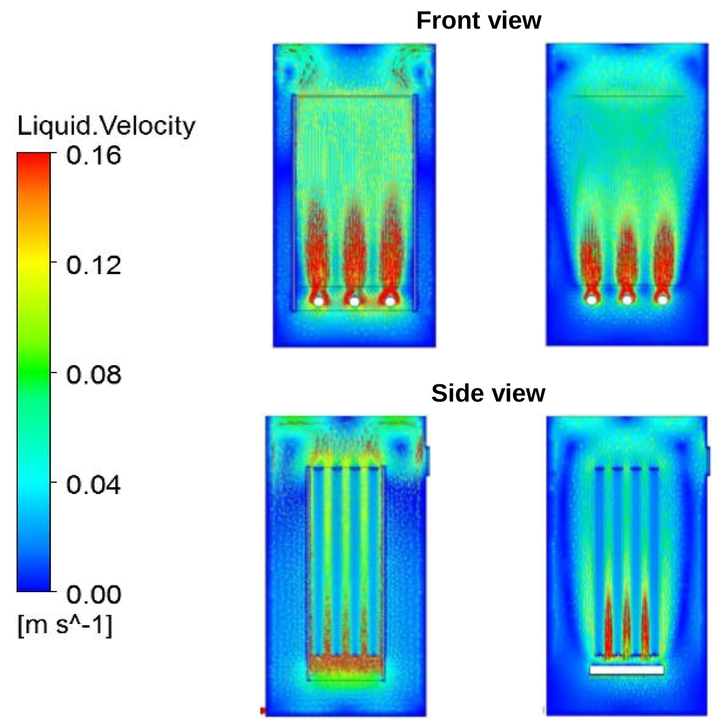
- Increasing the distance of aerator to membrane module
  - Reduced the variations of near membrane flow velocity at the lower zone
  - Increased the average near membrane flow velocity at the middle zone and upper zone

Membrane module: Fibre orientation



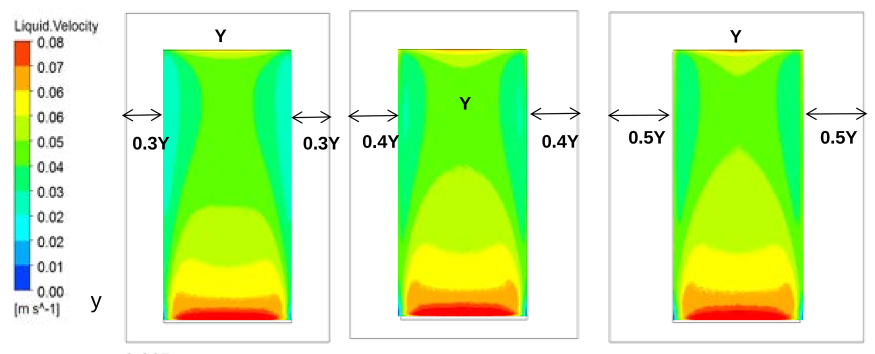
- Relocating the fibre orientation form vertical to horizontal increases near membrane flow velocity.

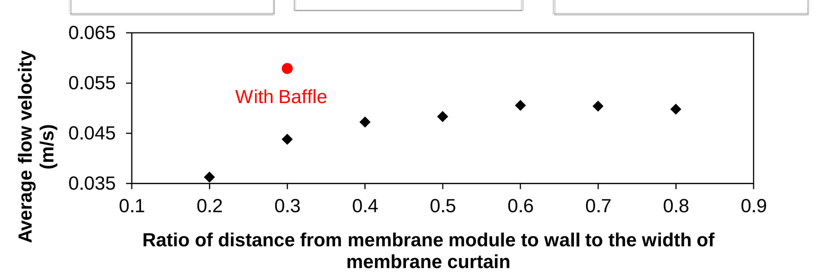
Membrane tank: effects of baffle



- Baffle constrained the uprising flow and divided the flow field into two regions: uprising flow region inside baffle and downward flow region outside baffle.
- Removal of baffle resulted in a decrease of average near membrane flow velocity.

Membrane tank: Distance of membrane to wall





- Increasing the distance of membrane to wall resulted in an increase in near membrane flow velocity.
- The optimum distance is 0.6 times module width.

CONCLUSIONS

- **Micro-scale Design**
  - **Fibre length:** The closer to the permeate collection header, the hgiher the local flux. This phenomenon exacerbates with longer fibres, resulting in more severe uneven distribution of flux.
  - **Fibre diameter:** Increase of fibre diameter results in a decrease in local pressure loss and increase in local flux.
  - **Filtration mode:** Suction from both ends of the module reduces pressure loss along the fibre.
  - **Fibre movement:** Aeration induced fibre movement increases average membrane shear stress and subsequently improves aeration efficiency.
  - **Fibre packing density**: Increase of fibre distance decreases membrane shear stress induced by fibre movement
- **Meso-scale Design**
  - **Aerator**:
    - Coarse bubbles can produce larger near membrane velocity comparing to fine bubbles
    - Aerator located below and in-line with the membrane module resulted in higher shear stress.
    - Increasing the distance between the air diffusers and the membrane module increased the turbulence near membrane.
  - **Module:**
    - Hollow fibre located vertically to fluid flow (parallel to air diffusers) resulted in higher shear than horizontally oriented membranes.
    - Membrane shear increased with the presence of baffles.
  - **Tank Design:**
    - Sufficient space between membrane module and tank wall facilitated the circulation of liquid flow, and therefore increased the shear stress near the top of membrane module. The optimum distance was found to be 0.6 times of the width of the membrane module.
- **Features of a module having an efficient aeration system**
  - ✓ Hollow fibres with diameter larger than 1.5mm for membrane module higher than 1 meter
  - ✓ Suction from both ends
  - ✓ 1% of Looseness
  - ✓ Coarser bubbles with aerators located below and in-line with membrane module.
  - ✓ Baffles

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