Oxygen and Carbon Dioxide Transport Modeling in Extracorporeal Membrane Oxygenators with Sinusoidal Fiber Morphology

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Introduction and Study Purpose

Respiratory diseases affect large numbers of patients worldwide, representing one of the main causes of death in the EU [1]. Currently available therapies are associated with high morbidity and mortality. In **BioMembrOS**, we follow a groundbreaking new biomimetic approach and replicate main characteristics of the most effective respiration found in vertebrates, mainly birds and fish, in order to develop membrane structures that will serve as key elements for a novel generation of artificial respiration devices. We will optimize the geometry of the to-date available membrane structures by increasing the outer surface per membrane area and by applying μ-PIV experimental flow investigations as well as CFD assisted design optimization.

Materials and Methods

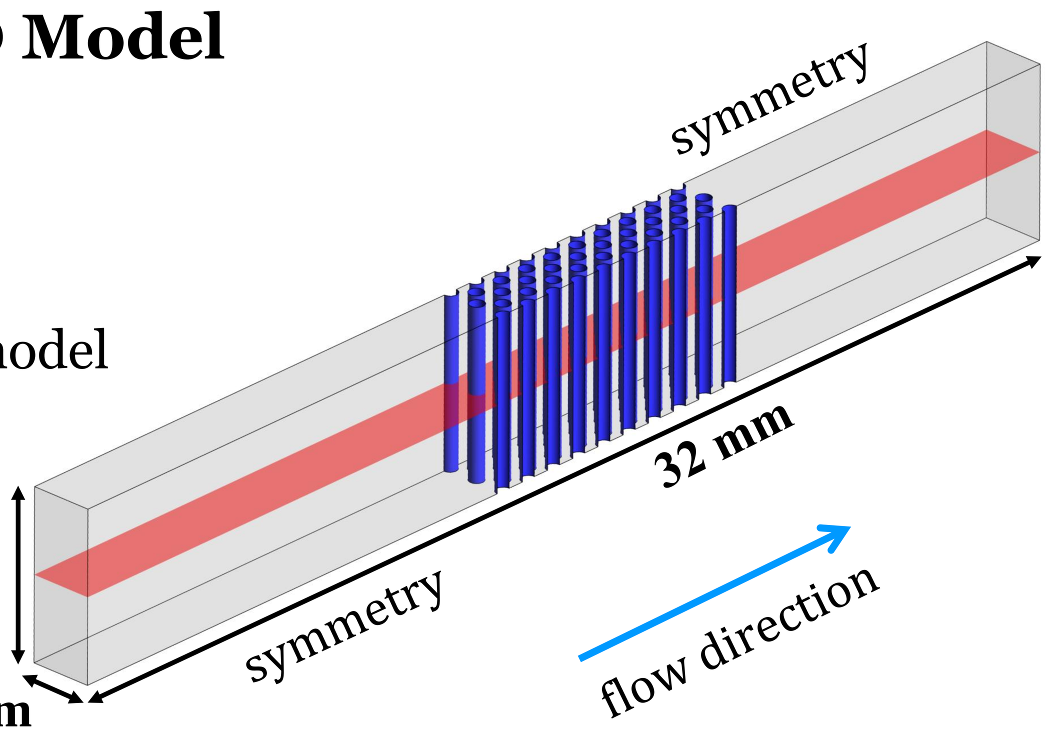
CFD Model

- Micro-oxygenator with 38 fibers
- Laminar flow
- Non-Newtonian modified Casson model
- Boundary Conditions:

$\dot{V} = 160\ ml/h$

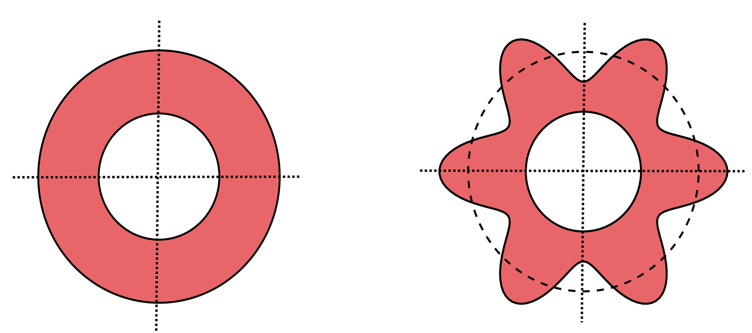
$P_{O_2} = 56\ mmHg$

$P_{CO_2} = 45\ mmHg$



P_{O_2} = Partial pressure of oxygen in blood
P_{CO_2} = Partial pressure of carbon dioxide in blood

- Cylindrical and sinusoidal fibers:



- Governing equations for mass transfer:

$$\mathbf{V}.\nabla P_{O_2} = D_{eff_{O_2}}.\nabla^2(P_{O_2})$$
$$\mathbf{V}.\nabla P_{CO_2} = D_{eff_{CO_2}}.\nabla^2(P_{CO_2})$$

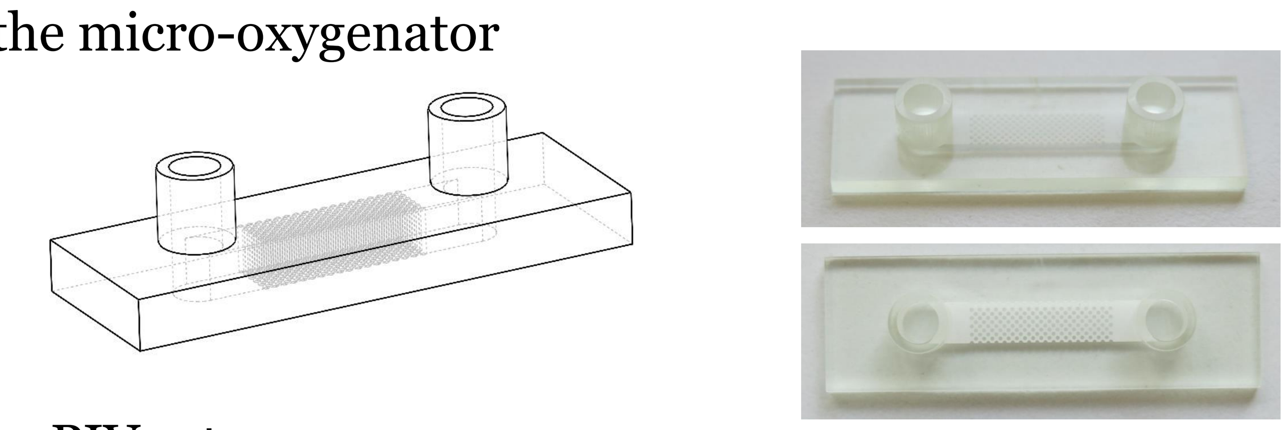
- Hemolysis formulation: $HI(\%) = C\,\sigma^{\beta}\,\tau^{\alpha}$, $HI = HI'^{\alpha}$

$$\frac{\partial (HI')}{\partial t} = (D\nabla - \mathbf{V}.\nabla)\,HI' + \left(C\,\sigma^{\beta}\right)^{1/\alpha}$$

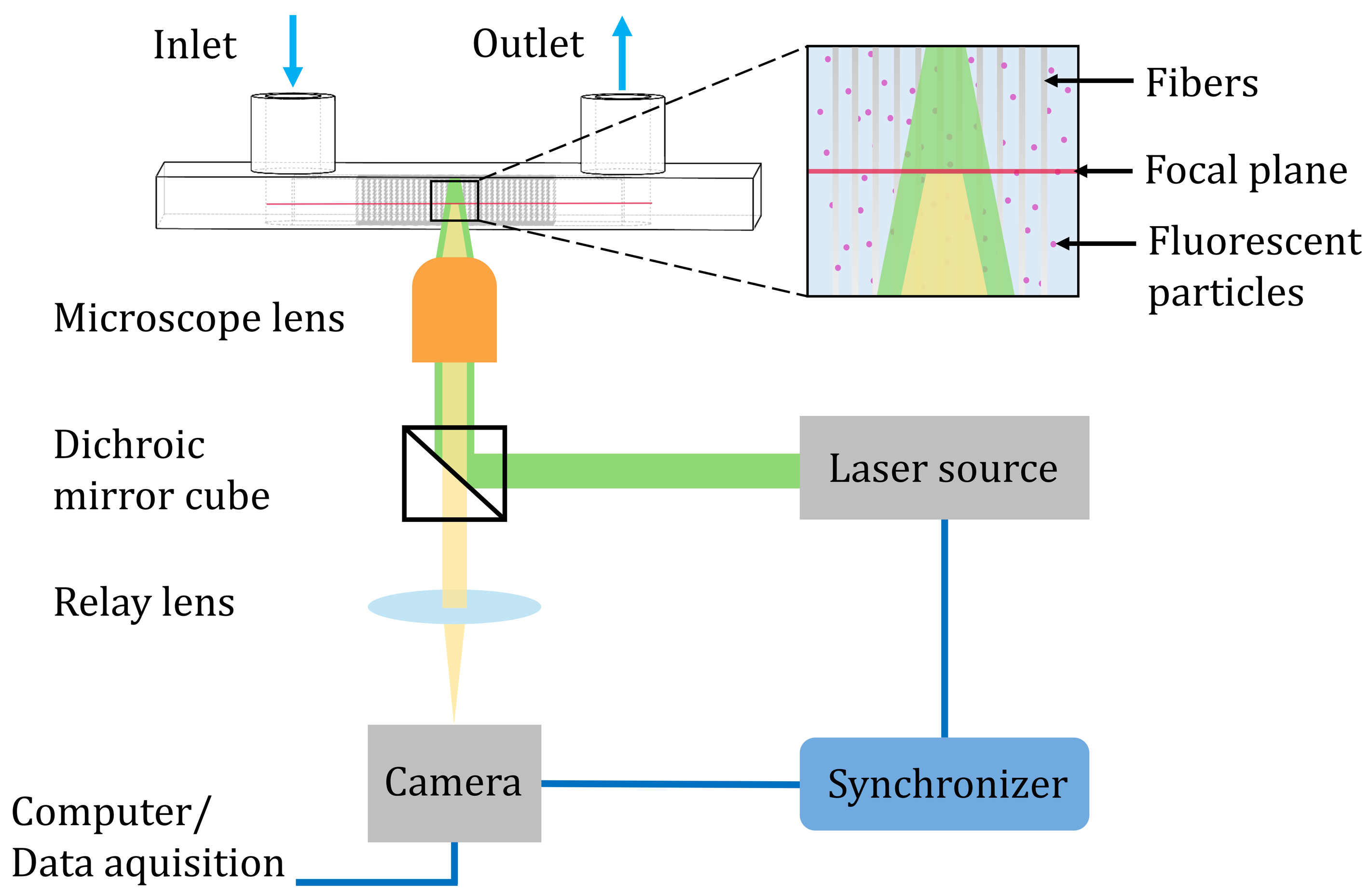
Where: $$\sigma = \left[\frac{1}{6}\sum_{i\neq j}\left(\tau_{ii}-\tau_{jj}\right)^2 + \sum_{i\neq j}\tau_{ij}^2\right]^{0.5}$$

μ-PIV Experiment

- 3D printed microfluidics with embedded fibers recreating the micro-oxygenator

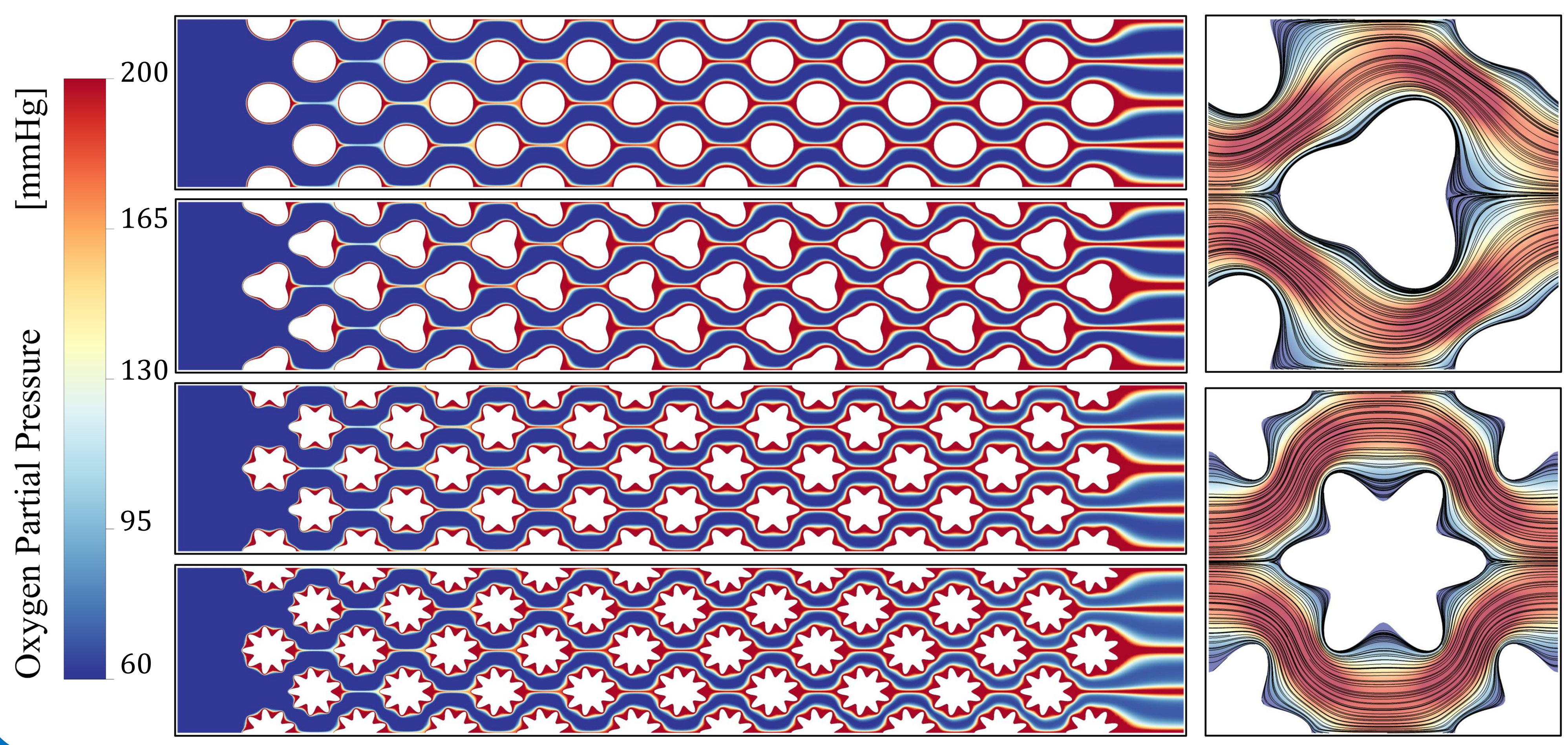


- μ-PIV setup



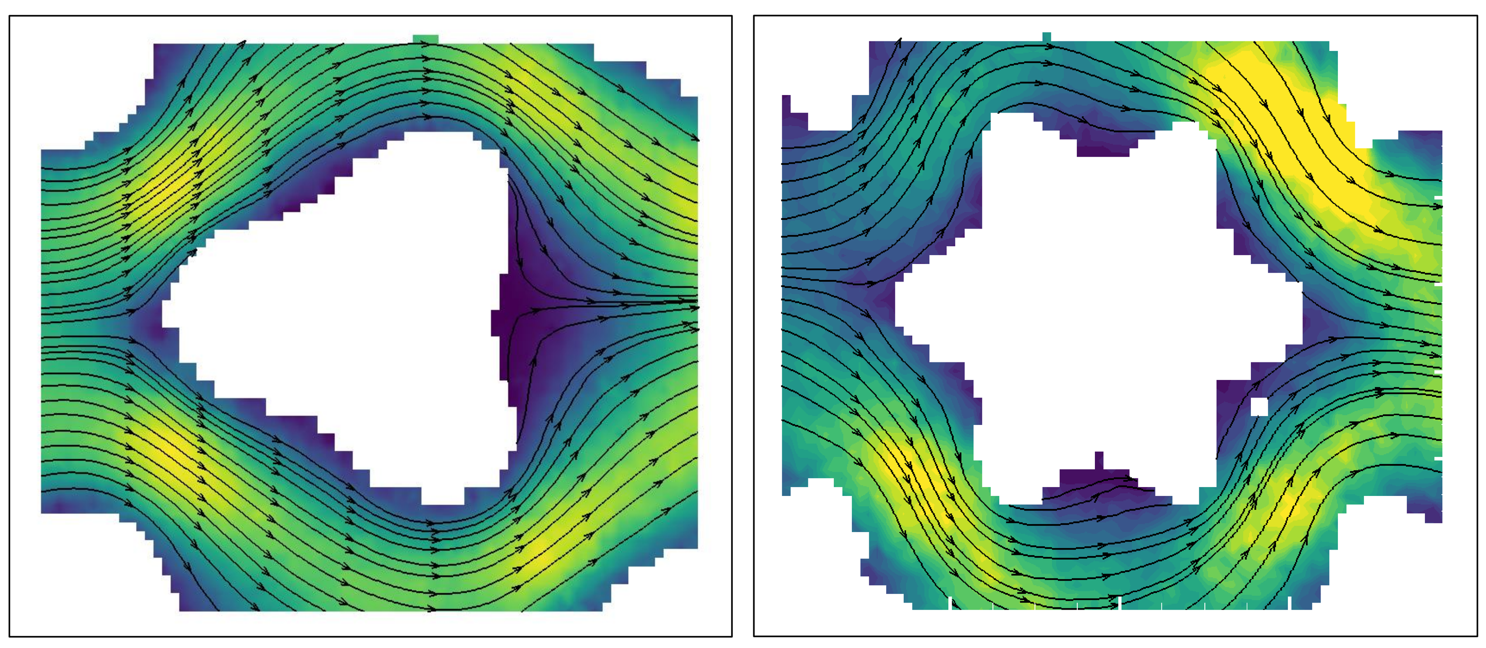
Results

CFD



μ-PIV Experiment

Velocity streamlines:



The presence of air bubbles upstream of the considered fibers results in asymmetry in the velocity profiles.

Conclusions

Summary table:

	Area Increase [%]	O_2 transfer increase [%]	CO_2 transfer decrease [%]
Sinusoidal 3	13	4.8	0.2
Sinusoidal 6	43	11	**0.7**
Sinusoidal 9	**81**	**12.1**	0.3

- **Decrease** in hemolysis index by 35% (sinusoidal 9)
- **Increase** in dead zone volume - region with chance of thrombosis - by at least 350%
- Using sinusoidal fibers will increase the gas transfer but the side effects should be considered as well

References: [1] *Respiratory diseases statistics*, Eurostat, data extracted in October 2023.
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