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Numerical modelling of non-Newtonian fluid in a rotational cross-flow MBR

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Introduction & Objectives

- Fouling is the main bottleneck of the widespread of MBR systems.
- Process hydrodynamics can decrease and/or control fouling.
  - by increasing liquid cross-flow velocity.
- Rotational cross-flow (RCF) MBR (Grundfos BioBooster®) (Fig. 1)
  - Rotating impellers between filtration and aeration membrane discs prevent fouling.
  - It operates up to 5 times higher sludge concentration than in conventional MBR systems (TSS up to 50 g·l^{-1}).
  - Impellers ensures low viscosity in the reactor biomass due to the non-Newtonian behaviour of activated sludge.
  - ↓ energy consumption and ↑ flux.

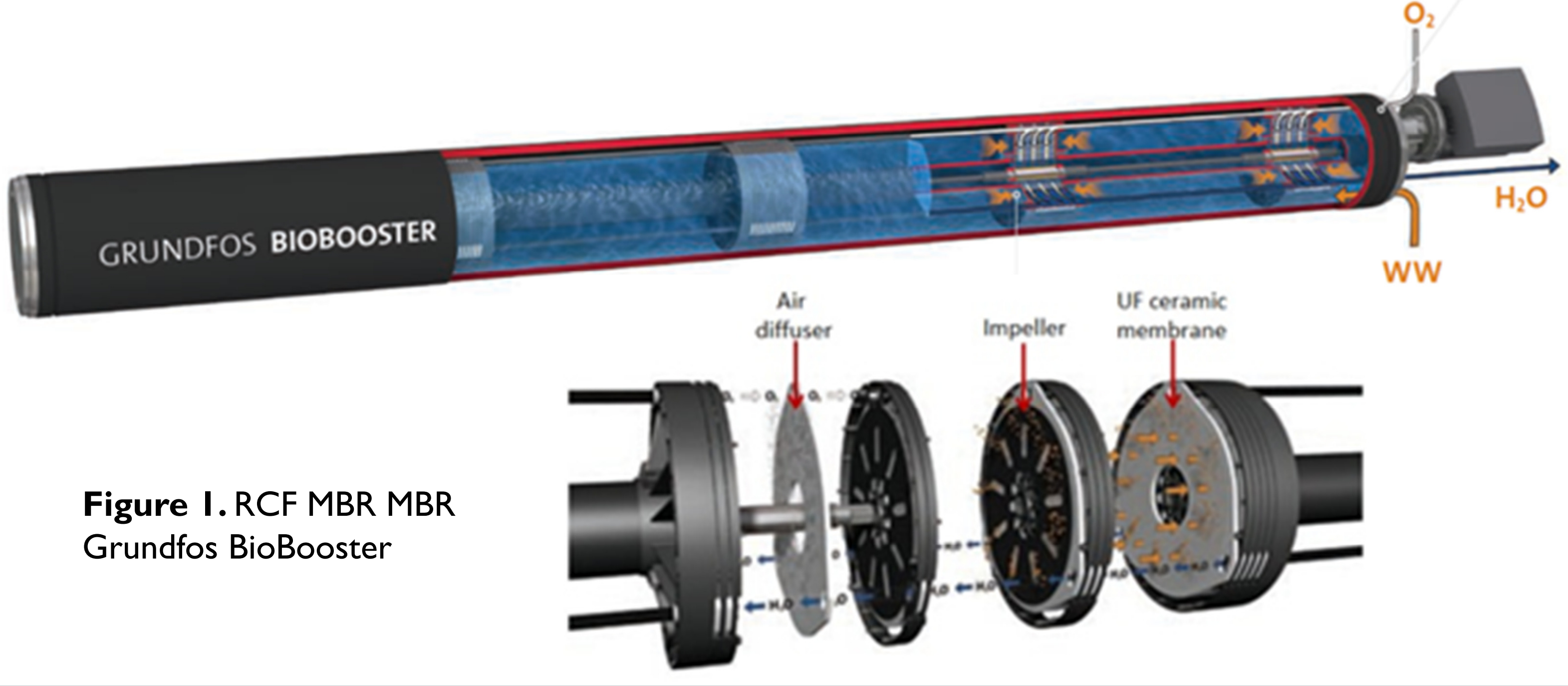

Figure 1. RCF MBR MBR Grundfos BioBooster

Background

Viscosity of non-Newtonian (NN) liquids

- Shear stress (τ) can be related to shear rate ($\dot{\gamma}$) according to a power-law relationship.

$$\tau = m\,\dot{\gamma}^{n} \qquad m = 0.001\exp(2\,TSS^{0.41})$$

$$n = 1 - 0.23\,TSS^{0.37}$$

- where m is the flow consistency index (Pa·s^n) and n is the flow behaviour index (-).

Wall shear stress in rotating systems

- Impellers generate scouring effect.
- ↑ in shear stress prevent particles to attach to membrane surface due to larger tangential velocities.

	Newtonian	Non-Newtonian
Reynolds number	$Re_r = \dfrac{\rho\,\omega\,r^2}{\mu}$	$Re_r = \dfrac{\rho\,(\omega\,r)^{2-n} r^n}{m}$
Shear stress		
• Laminar ($Re_r \leq 2\cdot10^5$)	$\tau_{m\_lam} = 0.77\,\rho\,\nu^{1/2}\,(k\,\omega)^{3/2}\,r$	$\tau_{m\_lam\_NN} = G'(0)\,m\,\propto^{\frac{n-1}{2}}\,(k\,\omega)^n\,r^n\left(\dfrac{(k\,\omega)^{2-n}\,r^{1-n}\,\rho}{m}\right)^{\frac{n}{n+1}}$
• Turbulent ($Re_r > 2\cdot10^5$)	$\tau_{m\_tur} = 0.0296\,\rho\,\nu^{1/5}\,(k\,\omega)^{9/5}\,r^{8/5}$	-
Area-weighted average shear stress		
• Laminar ($Re_r \leq 2\cdot10^5$)	$\overline{\tau_{m\_lam}} = 0.5133\,\rho\,\nu^{1/2}\,(k\,\omega)^{3/2}\,\dfrac{R_m^3 - R_{in}^3}{R_m^2 - R_{in}^2}$	$\overline{\tau_{m\_lam\_NN}} = \dfrac{G'(0)\,(1+n)\,\propto^{\frac{n-1}{2}}\,(k\,\omega)^{\frac{3n}{1+n}}\,\rho^{\frac{n}{1+n}}\,m^{\frac{1}{1+n}}}{(2n+1)\left(R_{in}^2 - R_m^2\right)}\left[R_{in}^{\frac{2\,(2n+1)}{1+n}} - R_m^{\frac{2\,(2n+1)}{1+n}}\right]$
• Turbulent ($Re_r > 2\cdot10^5$)	$\overline{\tau_{m\_tur}} = 0.0164\,\rho\,\nu^{1/5}\,(k\,\omega)^{9/5}\,\dfrac{R_m^{18/5} - R_{in}^{18/5}}{R_m^2 - R_{in}^2}$	-

* where ν is kinematic viscosity ($\nu = \mu/\rho$), k is velocity factor and $G'(0)$ and α are dimensionless velocities in the tangential direction.

Methodology

Tangential velocity measurements

- RCF MBR operates between 50 to 350 rpm (Fig. 2).
- Experimental tangential velocity measured at 59, 119 and 177 rpm with water
- Measured with Laser Doppler Anemometry (LDA) (Fig. 3)
- LDA is an optical technique to measure velocity field in transparent media and cannot be used with activated sludge.

CFD model (Fig. 4)

- Star CCM+ V6.02
- Single phase and rigid body motion
- Laminar and k-ϖ SST

Figure 2. Experimental RCF

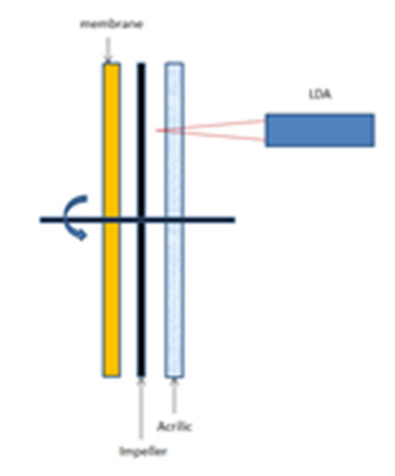

Figure 3. LDA

Figure 4. Real and virtual representation of impeller and membrane.

Results and discussion

Tangential velocity measurements

- A good agreement between the experimental measurements and the CFD simulation results, with an error up to 8 % (Fig. 5).

Wall shear stress (Fig. 6)

- It was inferred from CFD simulation that values of the shear stress were accurate (Fig. 7).
- The velocity factor (k) for the RCF MBR was found to be 0.795 ± 0.002 (R^2 = 0.957), which is within the limits of k for impeller with vanes (0.35 to 0.85).
- CFD model was modified to account for NN behaviour for 3 different TSS concentrations (30, 40 and 50 g·l^{-1}) and 4 rotational speeds (50, 150, 250 and 350 rpm).
- α was found to be 0.525 ± 0.008 (R^2 = 0.946), that can be used for the different angular velocities and TSS concentrations.

Area-weighted average shear stress (Fig. 8)

- An empirical relationship, to determine the area-weighted average shear stress in function of angular velocity (in rpm) and TSS was developed:

$$\bar{\tau} = 0.369\,\frac{\Omega}{ln\,\Omega} + 0.013\,TSS^2 - 2.873$$

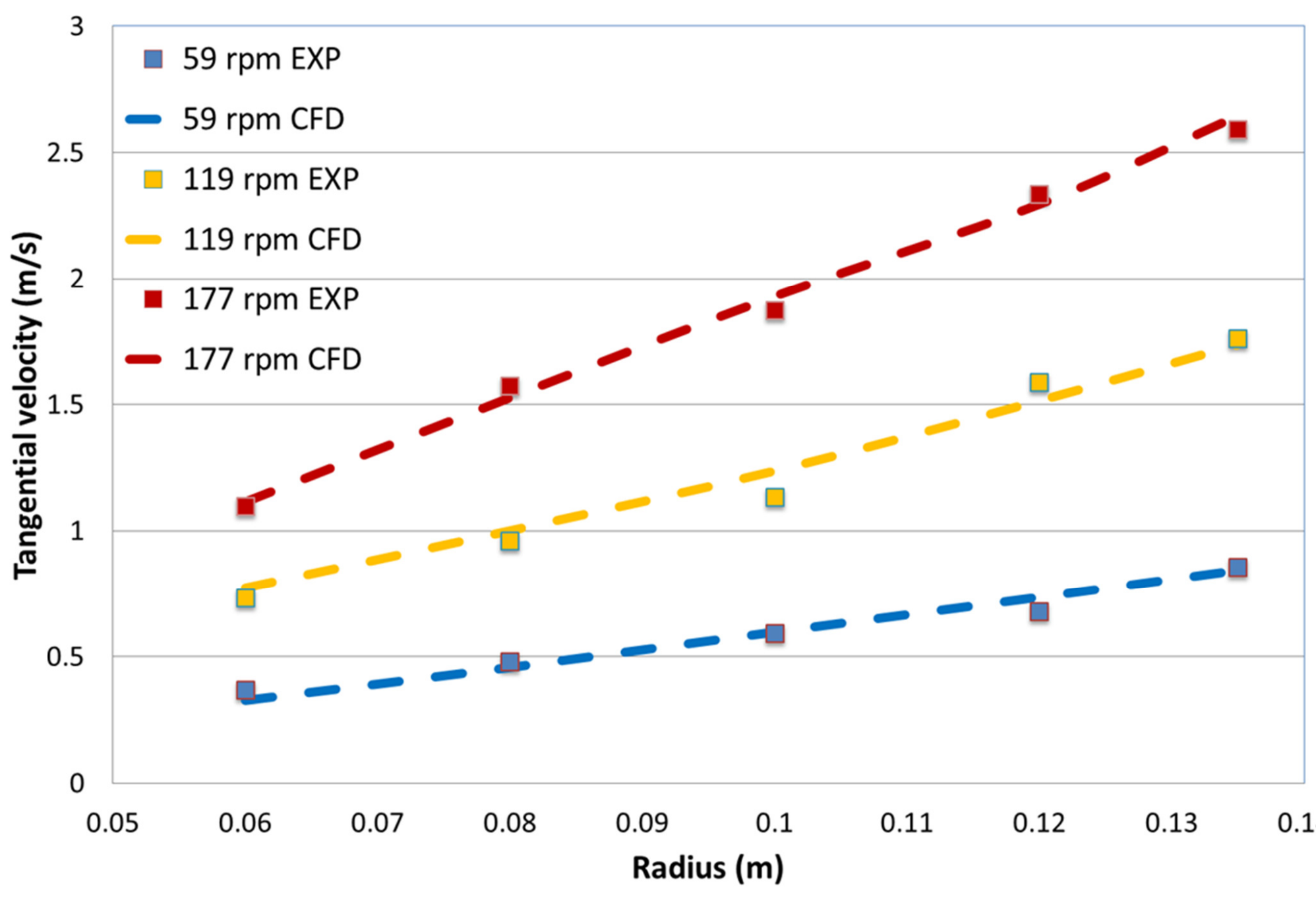

Figure 5. Tangential velocity vs. radius for 3 impeller velocities (59, 119 and 177 rpm).

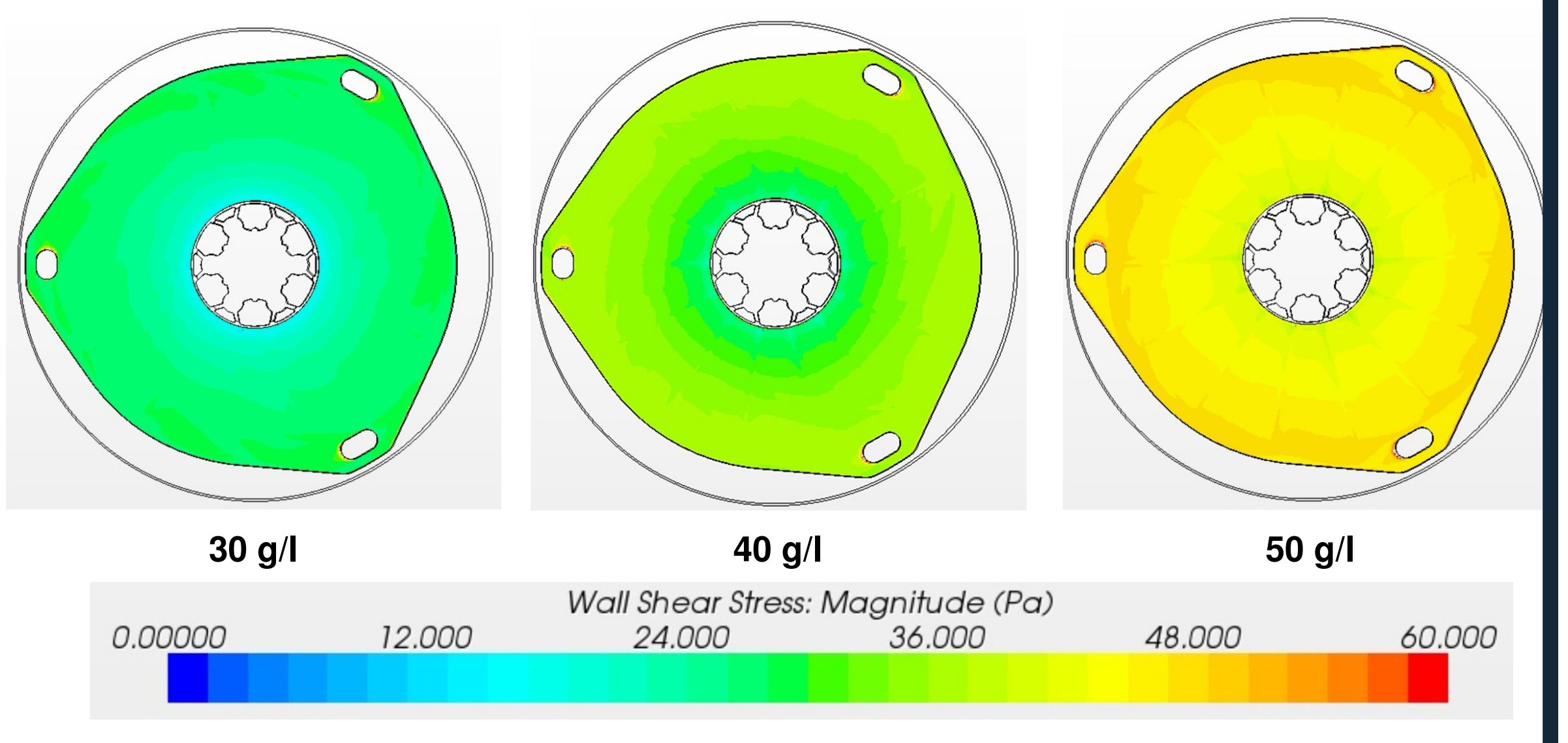

Figure 6. Wall shear stress contours for 250 rpm

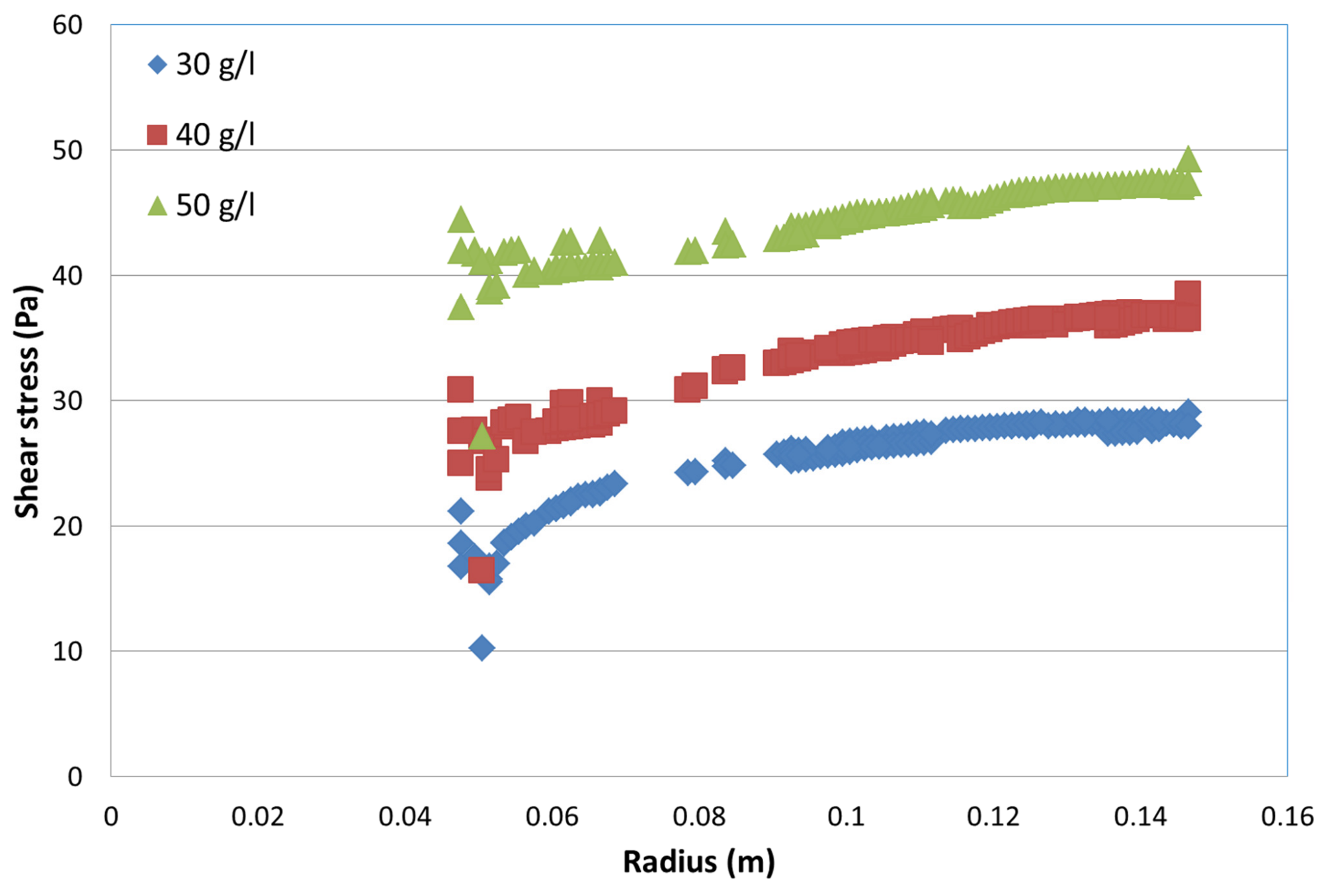

Figure 7. Shear stress vs. radius for three different TSS concentrations (30, 40 and 50 g·l^{-1}) at an angular velocity of 250 rpm.

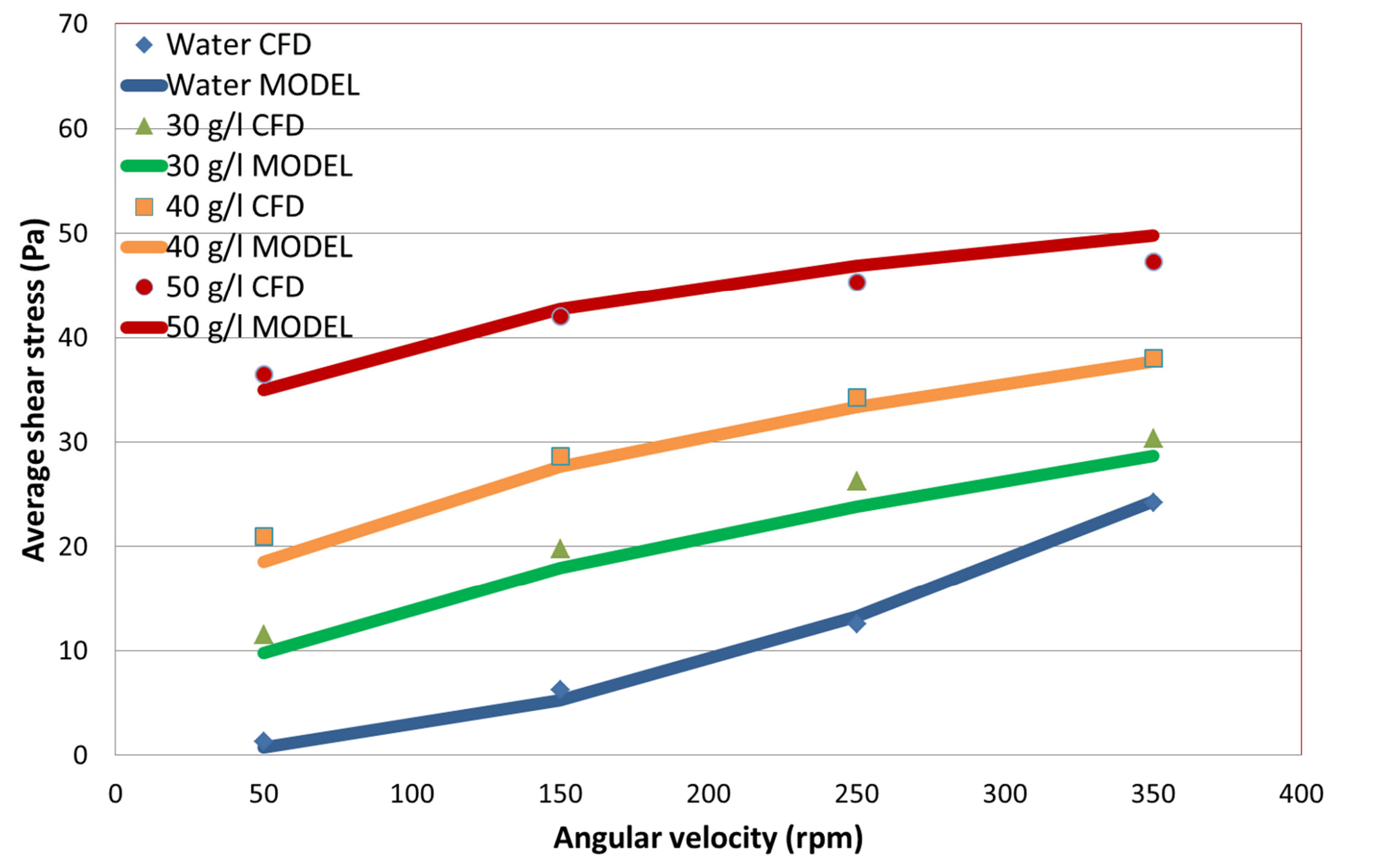

Figure 8. Area-weighted average shear stress vs. radius for three different TSS concentrations (30, 40 and 50 g·l^{-1}) at an angular velocity of 250 rpm.

Conclusions

- A proper validation of the CFD model was made in terms of tangential velocity measurements using a LDA system with water.
- RCF MBR operates with AS and LDA measurements cannot be made.
- CFD model was modified to account for the viscosity of AS.
- Local shear stress at any place of the membrane surface and area-weighted average shear stress was determined.
- An empirical relationship was made, to determine the area-weighted average shear stress in function of the angular velocity (in rpm) and the TSS.

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