Wall Shear Stress in an Orbiting Culture Dish using CFD with PIV Validation

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Abstract

It is well documented that physiological and morphological properties of anchored cells are influenced by fluid shear stress. Common orbital shakers provide a means of mixing the fluid containing nutrients while simultaneously applying shear stress to cells for tens to hundreds of cases by loading the shaker with multiple dishes. However, the complex flow in orbiting dishes is generally not amenable to analytical solution for resolving shear created by the fluid motion. The only existing quantification of shear in this flow is an equation that estimates a constant scalar value of shear for the entire surface of the dish. In practice, wall shear stress (WSS) will be oscillatory rather than steady due to the travelling waveform and will vary across the surface of the dish at any instant in time.

A CFD model is presented that provides complete spatial and temporal resolution of WSS over the bottom surface of a dish throughout the orbital cycle. A Particle Image Velocimetry (PIV) system was developed and used to validate the velocity fields obtained from the CFD model. Velocity fields were obtained for eight cases covering four orbital speeds and two fluids with different viscosities, water and a 5% (v/v) Tween80/water mixture.Qualitatively, the flow patterns obtained from CFD were similar to those obtained from PIV. Quantitatively, mean velocities matched within 20%. The CFD model was also reasonably well validated by the analytical solution with resultant WSS magnitudes that were within ~1 dyne/cm^2. The analytical solution is an extension of Stokes 2nd problem to orbital plate motion for low Froude and high Stokes, and is valid for flow not too close to the vertical walls of the dish.

The discussion will highlight how the traveling waveform in the dish is influenced by dimensionless Froude and Stokes numbers as well as a slope parameter that is defined as the ratio of the steady-state acceleration-induced free surface slope to the static fluid aspect ratio (fluid height to dish radius). Additionally, a directional oscillatory shear index (DOSI) is defined to quantify the bidirectionality of oscillating shear (quantification of tangential vs. radial flow). Examples are presented which show how endothelial cell proliferation and morphology are affected by shear magnitude and the DOSI at different locations within a dish. These results help explain why cellular responses depend on location in the dish.