Advanced CFD Simulations for Optimizing Fluid Transfer in Centrifugal Microfluidic Chips for In-Situ Pollutant Detection

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Centrifugal Microfluidic Chips (CMCs) offer a transformative solution for water quality monitoring by integrating multiple functions into a miniaturised platform, enabling fast, accurate, and low-cost detection with minimal reagent use and simplified operation. To further enhance their performance, Computational Fluid Dynamics (CFD) is employed to optimise CMC design and fluid behavior. CFD-based optimisation turns a basic design into a high-performance chip by revealing fluid behavior, minimising design flaws, and maximising function all before fabrication. In our study, simulations were conducted using COMSOL Multiphysics® software, focusing on the optimisation of the inclination angle and angular acceleration of the syphon valve to ensure a stable liquid transfer. Assuming both water and air are incompressible, the CFD module was developed with supplementary physics, including laminar flow with two-phase flow and phase field, whilst the phase field system was used to trace the behaviour of the two immiscible fluids (water & air) over time. A rotating machinery was equipped to define the simulation's motion. Three different angular accelerations (250 rad/s², 500 rad/s², and 750 rad/s²) and four inclination angles (33°, 43°, 53°, and 63°) were tested to optimise the system's performance. The fluidic motion varied significantly with each combination of angular acceleration and inclination angle. At 250 rad/s², the liquid filling process in the syphon valve took the longest due to weaker forces, resulting in slower movement and laminar flow dominated by surface tension and viscosity. In contrast, at 750 rad/s², the higher acceleration increased fluid velocity, leading to instabilities and a transition to turbulent flow. The 500 rad/s² acceleration with a 33° inclination angle was identified as the optimal choice, balancing efficient filling and controlled flow behaviour. It is necessary to widen the simulation to encompass the whole device to achieve a better comprehension of various in-situ tests.

Keywords: Centrifugal microfluidic chip, Computational Fluid Dynamics, syphon value, angular acceleration