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RESEARCH PAPER

Mapping low-Reynolds-number microcavity flows using microfluidic screening devices

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Abstract Low-Reynolds-number flows in cavities, characterized by separating and recirculating flows are increasingly used in microfluidic applications such as mixing and sorting of fluids, cells, or particles. However, there is still a lack of guidelines available for selecting the appropriate or optimized microcavity configuration according to the specific task at hand. In an effort to provide accurate design guidelines, we investigate quantitatively low-Reynolds-number cavity flow phenomena using a microfluidic screening platform featuring rectangular channels lined with cylindrical cavities. Using particle image velocimetry (PIV), supported by computational fluid dynamics (CFD) simulations, we map the entire spectrum of flows that exist in microcavities over a wide range of low-Reynolds numbers ($Re = 0.1$, 1, and 10) and dimensionless geometric parameters. Comprehensive phase diagrams of the corresponding microcavity flow regimes are summarized, capturing the gradual transition from attached flow to a single vortex and crossing through two- and three-vortex recirculating systems featuring saddle-points. Finally, we provide design insights into maximizing the rotational frequencies of recirculating single-vortex microcavity systems. Overall, our results provide a complete and quantitative framework for selecting cavities in microfluidic-based microcentrifuges and vortex mixers.

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1 Introduction

Flow separation and internal recirculation at low Reynolds numbers are well-known properties of cavity flows (Shankar and Deshpande 2000). In classic examples at the creeping flow regime where the Reynolds number is much smaller than unity ($Re \ll 1$), slow internal recirculation is driven by the translation of one or more of the containing walls for closed cavities (Leong and Ottino 1989; Shankar 1993, 1997; Patil et al. 2006) or by a shear flow over the cavity's mouth for open configurations (O'Brien 1972; Higdon 1985; Shen and Floryan 1985). Other mechanisms leading to recirculation include rotating a cylinder inside a cavity (Hellou and Coutanceau 1992), as well as the action of surface tension gradients (Rashidnia and Balasubramaniam 1991; Sznitman and Rösgen 2010) and acoustic streaming (Sznitman and Rösgen 2008).

Historically, cavity flows have been extensively characterized using analytic and numerical methods. In a seminal work, Moffatt (1964) predicted analytically a series of 2D counter-rotating eddies for Stokes flow in sharp corners. The study of separated flows was later expanded to a variety of 2D and 3D geometries. For example, O'Neill (1977) studied numerically flows in a cylindrical cavity or protrusion in a plane, and O'Brien (1972) investigated recirculating 2D flows in a rectangular cavity. For 3D flows in spherical cavities, Pozrikidis (1994) showed numerically the existence of recirculation with open streamlines that spiral into singular points. More recently, Heaton provided a detailed quantification in 2D rectangular-driven cavities for the number of eddies and the shape of the corresponding streamlines as a function of the rectangle's aspect ratio (Heaton 2008). In all the aforementioned theoretical and numeric studies, the topologies of separated recirculating cavity flows were shown to be determined by details of the geometry.