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Study of force-dependent and time-dependent transition of secondary flow in a rotating straight channel by the lattice Boltzmann method

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ABSTRACT

A numerical study using the lattice Boltzmann method has been carried out for flow through a rotating straight channel with a rectangular cross section. With different forces applied, the secondary flow exhibits two-cell states, four-cell states or six-cell states at a range of low rotational Reynolds number, however, within which only the two-cell states have been commonly reported. In addition to the force-dependent flow transition, a time-dependent flow transition of the secondary flow among two-cell states, four-cell states and six-cell states is also discovered during flow development. These newly found flow transitions and their regulations by force application have been analyzed. Based on numbers of case studies, it is found that a dimensionless number, the ratio of the driving pressure gradient to the centrifugal force, regulates such flow transitions. This study not only releases new phenomena of flow transition, but also indicates new applications in flow control, particle separation and heat transfer.

1. Introduction

Study of channel flows is still of great importance in mass transport, heat transfer, chemical reaction and blood circulation. Due to the diversity of their practical applications, many types of channel flows have not been fully understood, for instance, channel flow in a rotating system. Flow in a rotating channel can be widely found in various fluid systems. One of the recent applications is so-called "Lab-on-a-CD" [1]. By spinning a compact disk (CD), liquid can flow through microchannel networks placed on the CD from the center of rotation to the edge of the CD. With this simple pumping mechanism, Lab-on-a-CD could be easily adapted to numerous applications in the fields of chemistry, material science and biotechnology [1–12].

In addition to pressure, flow in a rotating channel experiences two more body forces due to system rotation, which are the centrifugal force and Coriolis force. As shown in Fig. 1, the centrifugal force f_ω is along the radial direction and the Coriolis force f_c is perpendicular to the flow direction. Because of existence of these two body forces, flow behaviors in rotating channels become very complex. Flows in rotating channels have been experimentally, theoretically or numerically investigated in the literature [13–20]. Baura [13] and Benton [14] carried out the first theoretical studies on flow through a circular channel by assuming that the channel rotated at a small angular velocity about an axis perpendicular to the channel. Further, Benton and Boyer [15] extended such studies to rotating channels of almost arbitrary cross-section, and to the cases of larger rotation rates. They also verified their theoretical results with experiments by measuring the axial velocity of a rotating cylindrical tube [15].

In the literature, following the velocity field of a rotating channel, subsequent studies focused on flow instability. Lei and Hsu [16] numerically investigated the instability of the axial velocity of a rotating circular tube for a wide range of

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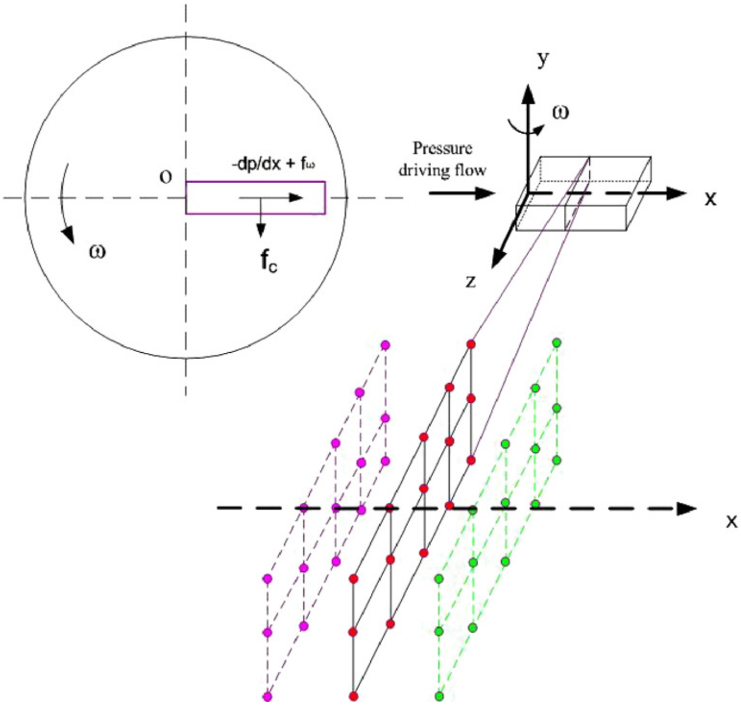

Fig. 1. Flow system on a spinning compact disk (CD).

two dimensionless parameters defined by themselves. They found that there were four types of flow transition regime, depending on the relative magnitudes of the two parameters. Their results are consistent with most of previous asymptotic analyses. Alfredsson and Persson [17] experimentally investigated flow instability of in-plane rotating Poiseuille flow caused by Coroilis effects. Through flow visualization, they found the primary instability in the form of regularly spaced roll cells aligned in the flow direction occurs at Reynolds numbers bigger than 100. At high Reynolds numbers, secondary instability in the form of a twisting of the roll cells occurs. Such experimental results were in good agreement with the later numerical study by Yang and Kim [18]. In-depth experimental studies on the secondary instabilities were further conducted by Marliani, Matzkeit and Ram [19], and Matsubara and Alfredsson [20]. The former work [19] not only restated the experimental outcome of Alfredsson and Persson [17] but also discussed the effects of non-uniform cross sections on the streamwise vortices; the latter work done by Matsubara and Alfredsson [20] focused on the development of a secondary instability consisting of high-frequency traveling waves and their subsequent breakdown. Matsubara and Alfredsson [20] also suggested that the primary instability causing counter-rotating streamwise vortices is induced by Coriolis effects.

One of the main characteristics of flow in a rotating system is the generation of secondary flow caused by the Coriolis force, which remarkably enhances fluid mixing and heat exchange [20]. In addition, vortexes of secondary flows may have more interesting applications in trapping and separating cells or particles [21]. Therefore, study of structure of secondary flow and its flow transition is of practical importance. In the previous studies, two vortexes in the spanwise plane were observed at the range of the rotational Reynolds number $R_\Omega > 1$ ($R_\Omega = \frac{\omega a^2}{\nu}$ where ω is the angular velocity, a is the characteristic dimension of channel and ν is the kinematic viscosity) [16]. However, flow behaviors at lower rotational Reynolds number (e.g. $R_\Omega < 0.1$), which is true for most Lab-on-a-CD applications, have not been fully investigated.

In this work, the lattice Boltzmann method (LBM) is used to numerically investigate flow transition of the secondary flow in the spanwise plane of a rotating rectangular channel. Numerical simulations are mainly conducted in the range of the low rotational Reynolds number $R_\Omega < 0.1$, where most of microfluidic applications are. In addition, this study is also targeted for finding out the underlying regulations of transition of secondary flow.

2. Lattice Boltzmann method

The Lattice Boltzmann method (LBM) is based on the Boltzmann equation for simulating fluids, which differs from the continuum theory based CFD (computing fluid dynamics) due to its representation of underlying physics [21,22]. For example, microscopic interactions can be incorporated by modifying the collision operator in the LBM. The LBM shows many advantages over traditional CFD methods, especially in dealing with multiphase or multicomponent flows [23], complex geometries, microscopic forces, solid–liquid interactions, time evolution analysis and algorithm parallelization [21,22]. The capability of the LBM in recording transients of flow development enables researchers to investigate time-dependent flow transition more conveniently. In recent years, the LBM has been developed as an efficient alternative for simulating flow