# Transient behavior between multi-cell flow states in ferrofluidic Taylor-Couette flow

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We investigate transient behaviors induced by magnetic fields on the dynamics of the flow of a ferrofluid [1] in the gap between two concentric, independently rotating cylinders. Without applying any magnetic fields, we uncover emergence of flow states constituted by a combination of a localized spiral state in the top and bottom of the annulus and different multi-cell flow states with toroidally closed vortices in the interior of the bulk. However, when a magnetic field is presented, we observe the transient behaviors between multi-cell states passing through two critical thresholds in a strength of an axial (transverse) magnetic field [2]. Numerical simulations are carried out by solving the ferrohydrodynamical equation of motion using the Niklas approximation [3]. Before the first critical threshold of a magnetic field strength, multi-stable states with different number of cells can be observed. After the first critical threshold, we find the transient behavior between the three- and two-cell flow states. For stronger magnetic fields or after the second critical threshold, we discover that multi-cell states to disappear and a localized spiral state remains stimulated in the system.

Without applying any magnetic fields, we found the emergence of two flow states constituted by a combination of a localized spiral state ($\mathrm{SPI}_l$) in the top and bottom of the annulus and different multi-cell flow states ($\mathrm{SPI}_{l+2v}$, $\mathrm{SPI}_{l+3v}$) with toroidally closed vortices in the interior of the bulk ($\mathrm{SPI}_{l+2v}= \mathrm{SPI}_l + \mathrm{SPI}_{2v}$ and $\mathrm{SPI}_{l+3v}= \mathrm{SPI}_l + \mathrm{SPI}_{3v}$). The appearing of these multi-stable states is based on the initial conditions.

Applying any magnetic field and changing it's strength can trigger transitions among various flow states, for example, the two-cell and three-cell flow states. The emergence of the flow states, dynamical evolution, and transitions among the various flow states can be summarized in detail, as follows. By increasing the axial [transverse] magnetic field strength, we first identify a transition from $\mathrm{SPI}_{l+3v}$ [($\mathrm{SPI}_{l+2v}$] to $\mathrm{SPI}_{l+2v}$ [$\mathrm{SPI}_{l+3v}$], respectively. However, for strong enough magnetic fields, we discover the second transition only leaving a $\mathrm{SPI}_l$ state behind.

Although the flow states under fairly large magnetic fields ($s_x$ or $s_z$) are $\mathrm{SPI}_l$, there is a significant difference between two final $\mathrm{SPI}_l$ states. For applying the strong transverse magnetic field ($s_x$), $\mathrm{SPI}_l$ is orientated close to top and bottom lid located in the Ekman vortex regime. But $\mathrm{SPI}_l$ under the strong axial magnetic field ($s_z$) is orientated more towards the center of the bulk. According to the different type of magnetic fields, $\mathrm{SPI}_l$ state can move to or away from the Ekman region.

As to expect, the transitions between the multi-cell flow states are always accompanied by a change in the wavelength and wavenumber, respectively. However, in the present study the symmetry breaking effect (a stimulated two-cell mode [4, 5]) of the transverse magnetic field is obviously present, but plays a significant minor role than in other studies. It becomes more and more pronounced for the larger magnetic field strength $s_x$ and $s_z$.

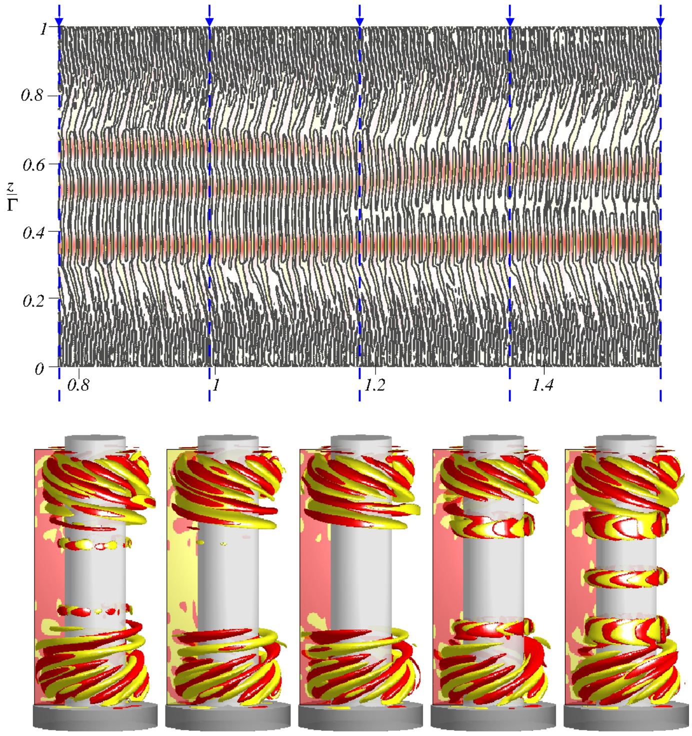


Figure 1: Transitions from $\text{SPII}_{l+3V}$ to $\text{SPI}_{l+2V}$. *Top:* Space-time plot of the azimuthal vorticity $\eta$ during the transition at $r = r_1 + 0.1d$. Red (dark gray) and yellow (light gray) correspond to positive and negative values, with $\eta \in [-440, 440]$. *Bottom:* Snapshots of corresponding vortex structures during the transition.

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**References**


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