EXPERIMENTAL INVESTIGATION OF LARGE SCALE CIRCULATION GENERATED OVER A 2D TURBULENT FLOW

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Abstract One of the striking features of two dimensional turbulence is the presence of large coherent structures, formed by the inverse cascade of energy. In 2D turbulent flows, the energy cascades from the energy injection scale to the large scales and if the injected power ϵ is sufficiently large, a large scale flow can be generated at the scale of the domain. We report the experimental study of the emergence of this large scale circulation (LSC) for an electromagnetically forced flow in a liquid metal (GalInStan). We demonstrate that this bifurcation can be described in the same framework as equilibrium phase transitions. Finally, we analyze the structure of the chaotic attractor that governs the LSC dynamics.

PHYSICAL CONTEXT

The inverse energy cascade is one of the most striking properties of 2D turbulent flows. The energy is transfered from the energy injection scale to the large scales, until the energy flux is balanced by the dissipation rate in the largest scale. When the injected power, ϵ is sufficiently large, the inverse cascade is bounded by the size of the domain L, and energy accumulates at this scale. This phenomena is called "condensation" and a large scale circulation (LSC) appears [2] [1]. The emergence of this LSC is continuous when ϵ is increased for a constant dissipation and few studies deals with the properties of the transition from the 2D turbulence to the condensate regime [3]. Is it possible to quantify this transition? What is the structure of this LSC? These are the questions, that we will address in our presentation.

THE SET UP

A liquid metal (Galinstan) layer of thickness $h = 2cm$ is contained in a square cell $L \times L$ with $L = 12cm$. The flow is driven by Lorentz forces, generated by a vertical magnetic field ($B \in [0.08 - 0.1]T$) and a DC current provided by an array of eight electrodes ($I \in [1 - 180]A$) at the bottom of the cell. The laminar flow is made of 8 counter-rotating vortices (figure 1).

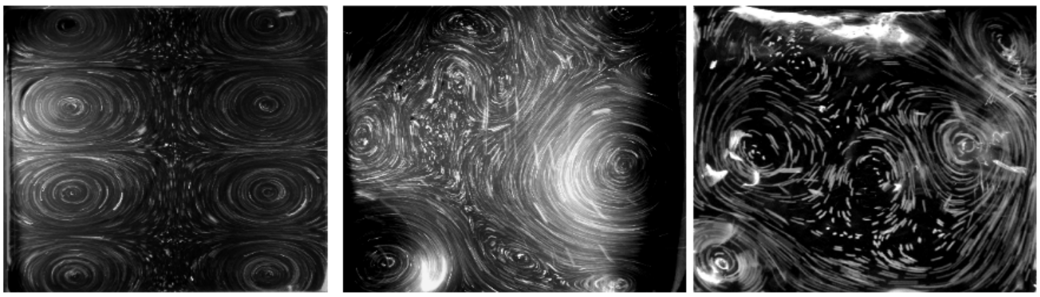

Figure 1. Photographs of the three different regimes, from left to right: laminar regime (with the 8 counter-rotating vortices), turbulent regime and condensate state.

We use a set of Vives probes (in the center of the cell and close to the walls) to measure the dynamics of the LSC. We also have developed a technique to follow particles on a reflecting metallic surface with a high speed camera.
The different regimes are determined by two dimensionless parameters Re, the usual Reynolds numbers and Rh, the ratio of the inertial term (increasing with ϵ) over the friction. In our study Re is larger than 100 Rh, such that Rh is the only control parameter in the experiment.

RESULTS

Bifurcation of the LSC

We observed that the probability density function of the LSC amplitude (fig 2, left) changes shapeat $Rh > Rh_c$ with $Rh_c = 12$. When the flow is turbulent, the PDF (fig 2, middle) is gaussian for $Rh < Rh_c$ (in red). For $Rh > Rh_c$, it

becomes a bi-gaussian distribution with two maxima (in blue). Both maxima, $\pm U_m$, increase like $|U_m| \sim \sqrt{Rh - Rh_c}$. This scenario displays similarities with what is observed in equilibrium phase transitions. More precisely, if we define an energy by $p(x) \propto \exp(-H(x))$, the form of the energy functional $H(x)$ changes from having one minimum to having two minima and one maxima. This explains that the value of the most probable state (Um) scales with the departure from the bifurcation (like $\sqrt{Rh - Rhc}$) in the same way as the order parameter calculated from a Landau free-energy.
We can describe this transition, such that both attractors corresponding to the opposite sens of rotation, are embedded for $Rh < Rh_c$ and for $Rh > Rh_c$, start to separate. The turbulent fluctuations drive reversals between both attractors.

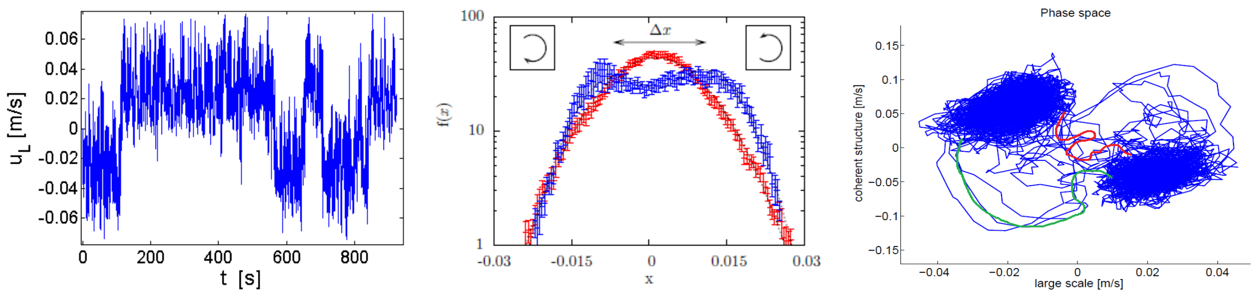

Figure 2. Left : amplitude of the LSC for $Rh = 15$. Middle: in red: PDF of the LSC amplitude for $Rh < Rh_c$ and in blue PDF of the LSC amplitude for $Rh > Rh_c$. Right: phase space.

Structure of the chaotic attractors

For $Rh > 30$, a new behavior is observed. The phase space (fig 2, right) clearly shows two symmetric chaotic attractors, connected by paths corresponding to reversals of the LSC. These paths connect both attractors either by random walk in the phase space (in red) or by two symmetric trajectories (in green). These trajectories that avoid the origin are likely to be related to an underlying deterministic behavior.
Indeed, we demonstrate that for large Rh, the chaotic attractor is made of few coherent recurrent structures. For $Rh > 40$, the attractor corresponds mainly to one coherent state, which minimizes the amplitude of the LSC and the injected power.

CONCLUSION

Our experimental study shows an original behavior in which increasing Rh (i.e. increasing the inertial term with respect to the dissipation term) simplifies the structure of the attractors and the reversal dynamics. Indeed at low Rh, both chaotic attractors are connected by reversals driven by turbulent fluctuations. For $Rh > 30$, the system seems to be ruled by low dimensional dynamics, where the system reverses between two symmetric structures through trajectories, avoiding the origin in the phase space.
To explain this transition between this two behaviors, we need an alternative approach, that should fill the gap between classical theories of non-linear systems and statistical theories of turbulent flows.

References

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