Stereoscopic-PIV study of a dipole in a shallow fluid layer

Citation for published version (APA):

Akkermans, R. A. D., Cieslik, A. R., Kamp, L. P. J., Clercx, H. J. H., & Heijst, van, G. J. F. (2007). Stereoscopic-PIV study of a dipole in a shallow fluid layer. In J. M. L. M. Palma, & A. Silva Lopes (Eds.), *Proceedings of the 11th EUROMECH European Turbulence Conference, Porto, Portugal, 25-28 June, 2007* (pp. 265-267). (Springer Proceedings in Physics; Vol. 117). Springer. https://doi.org/10.1007/978-3-540-72604-3_83

DOI:

[10.1007/978-3-540-72604-3_83](https://doi.org/10.1007/978-3-540-72604-3_83)

Document status and date:

Published: 01/01/2007

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Stereoscopic-PIV study of a dipole in a shallow fluid layer

R.A.D. Akkermans¹, A.R. Cieslik¹, L.P.J. Kamp¹, H.J.H. Clercx^{1,2}, and G.J.F. van Heijst¹

¹ Dept. of Applied Physics & J.M. Burgerscentrum, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands,
e-mail: R.A.D.Akkermans@tue.nl

² Dept. of Applied Mathematics & J.M. Burgerscentrum, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

The large-scale dynamics of the Earth's atmosphere and oceans can be considered as quasi-two-dimensional (Q2D). This motivates laboratory experiments in shallow fluid layers aimed at studying the dynamics of vortices and 2D turbulence. The geometrical confinement, when the vertical dimension $\mathcal{H}$ is significantly smaller than the horizontal length scale $\mathcal{L}$, is then a commonly used argument for the flow to behave in a Q2D fashion. When these experiments are performed, a no-slip boundary condition applies to the bottom of the tank and a stress-free condition at the free surface. The resulting shear in the vertical direction leads to a 3D structure of the velocity field and will set up a secondary circulation in the case of a monopolar vortex [1]. Beside this secondary circulation, the emergence of the so-called frontal circulation is seen in the dipolar vortex case [2].

In this contribution, we demonstrate that in general the assumption of Q2D flow in a shallow fluid layer is questionable. For this purpose, we study one of the elementary vortex structures of 2D turbulence, the dipolar vortex, in a shallow fluid layer. In this investigation both experimental and numerical techniques are used. Stereoscopic-PIV is used to measure instantaneous (three-component) velocity fields at several heights inside the fluid layer. Beside this, 3D numerical simulations are performed which provide the full 3D velocity and vorticity field. The flow is characterized by the horizontal Re -number ($=\mathcal{U}\mathcal{L}/\nu$) and vertical Reynolds number Re_α ($=\mathcal{U}/\alpha\mathcal{L}$). The latter is based on the bottom friction coefficient α , defined as $\nu(\pi/2\mathcal{H})^2$. The characteristic velocity $\mathcal{U}$ is defined as the maximum horizontal velocity of the dipole.

The experimental setup consists of a 52×52 cm² square tank with a magnet below the bottom and two electrodes on opposite sides of the tank. A salt solution serves as the conducting fluid enabling electromagnetic forcing. The forcing protocol constitutes of a 1 s pulse of constant current. The fluid layer is thin (up to 12 mm), thus 3D motions are assumed to be suppressed

by the shallowness. The settings of the numerical simulations are identical to the experimental ones. Results of the forcing and free evolution phase are presented.

We start with the flow field during the forcing period. An instantaneous velocity field is shown in Fig. 1(a) at time $t = 0.96$ s, for total fluid height of 9.3 mm (measurement plane 5 mm above the bottom). As the total forcing

Fig. 1. Instantaneous velocity field of dipolar vortex during the forcing phase ($t = 0.96$ s). Vectors represent in-plane velocities and colors the out-of-plane velocity. (a) Experimental result. (b) Numerical result.

time is 1 s and time equals zero at the onset of forcing, this is at the late stage of the forcing period. As can be seen in Fig. 1(a), two well-defined regions of negative velocities are present inside the vortices and upward motion at the tail of the dipole. During the entire forcing phase, a buildup of downward motion is seen inside the vortices. As a comparison, we show in Fig. 1(b) a numerical result for the same time as the experimental result. A striking quantitative resemblance is seen with the experimental result, although the upward motion at the frontal side is not clearly visible in the experimental result of Fig. 1(a). The origin of the negative velocities inside the vortex cores cannot be explained solely by the acting Lorentz force in the vertical direction since this is directed oppositely with respect to the plane $X = 0$.

In Fig. 2 we see an experimental (a) and numerical result (b) of the dipole during the free-evolution, 1 s after the forcing stopped. A good qualitative resemblance is seen. In front of the dipole we see a recirculation zone, the frontal circulation, upward motion close to the dipole and downward further away. The maximum vertical velocity is 25% of the horizontal velocity. This makes the assumption of 2D behavior of shallow fluid layers indeed questionable. Inside the vortex cores upward motion is seen similar to the secondary circulation in the monopolar vortex [1], although the driving mechanism is quite different. During the forcing phase there is a partial magneto-hydrostatic bal-

Fig. 2. Instantaneous velocity field of dipolar vortex during the evolution phase ($t = 2.00$ s). (a) Experimental result. (b) Numerical result.

ance between the vertical pressure gradient and the vertical component of the Lorentz force. Departure from this equilibrium (viz. after the forcing stopped) leads to a vertical motion observed which cannot be explained solely by the effect of the no-slip boundary condition. This was confirmed by numerical simulations with both stress-free surface and bottom boundary conditions, which even questions quasi-two-dimensionality of flows in some stratified two-layer fluids. As time progresses we see an oscillating motion of the vertical velocity component inside the two vortex cores, which we identify as inertial oscillations. Initially two well-defined vorticity patches are seen, at later time instances this vertical component of the vorticity becomes more fragmented.

Our findings question the assumption of two-dimensionality in laboratory experiments based on geometric confinement, for decaying as well as forced Q2D turbulence. For this purpose, we have identified regions of significant vertical motion during the forcing and evolution phase. We show a good qualitative agreement between experiments and numerical simulations. A regime diagram is constructed which enables to identify regions in the (Re, Re_α) parameter space where the flow might be considered as Q2D.

The authors wish to thank the Foundation for Fundamental Research on Matter (Stichting voor Fundamenteel Onderzoek der Materie, FOM) for financial support.

References

1. M.P. Satijn, A.W. Cense, R. Verzicco, H.J.H. Clercx, G.J.F. van Heijst: *Phys. Fluids*.**13**, 1932 (2001)
2. D. Sous, N. Bonneton, J. Sommeria: *Phys. Fluids*.**16**, 2886 (2004)