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► **To cite this version:**

Y. Couder. Two-dimensional grid turbulence in a thin liquid film. *Journal de Physique Lettres*, 1984, 45 (8), pp.353-360. 10.1051/jphyslet:01984004508035300 . jpa-00232354

**HAL Id: jpa-00232354**

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Submitted on 4 Feb 2008

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# LE JOURNAL DE PHYSIQUE - LETTRES

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*J. Physique Lett.* **45** (1984) L-353 - L-360

15 AVRIL 1984, PAGE L-353

Classification

*Physics Abstracts*

47.25C — 68.15

## Two-dimensional grid turbulence in a thin liquid film

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(Reçu le 2 novembre 1983, révisé le 14 février 1984, accepté le 22 février 1984)

**Résumé.** — Nous observons la turbulence derrière un peigne tiré dans un film liquide mince. L'évolution de la taille des tourbillons, les processus de fusion des tourbillons et l'aspect général du champ de vitesse correspondent qualitativement aux prévisions théoriques et aux simulations récentes concernant la turbulence bidimensionnelle.

**Abstract.** — We present the first observation of grid-generated two-dimensional turbulence in a thin fluid film. The evolution of the vortex sizes, the processes of vortex merging and the general aspect of the velocity field correspond qualitatively to theoretical predictions and to recent numerical simulations.

Two-dimensional turbulence has been widely studied theoretically, but most articles on its observation refer to numerical simulations rather than to laboratory experiments. A general review on the subject was given by Kraichnan and Montgomery [1]. More recent works include articles by Tatsumi and Yanase [2], McWilliams [3], Basdevant and Sadourny [4]... Experimentally, some characteristics of two-dimensional turbulence were observed in bulk fluids when rotation or a magnetic field created a strong anisotropy. Ibbetson and Tritton [5], Hopfinger *et al.* [6, 7] studied turbulence in rotating systems. In M.H.D., the magnetic field has also a two-dimensionalizing effect on turbulent flows as was shown by Sommeria and Moreau [8] and Sommeria [9]. Finally, let us recall that Brown and Roshko [10] have described the persistence of large two-dimensional structures in a turbulent free shear layer.

We have chosen another approach to obtain two-dimensional turbulence by working in a fluid where one of the dimensions is so small that there can be no motion in that direction. This situation has not been studied in the laboratory yet. This is because, a thin layer of fluid must normally be contained, so that friction on the bottom wall creates shear and dissipation that prevent the observation of 2-D turbulence. To avoid this difficulty, we use a self sustaining thin film of the type so easily obtained from soap solutions. These films can be stretched on frames as large as 30 cm square, their thickness then can range from 0.1 to 10  $\mu\text{m}$ . We present here a preliminary report on the decay of grid turbulence in such films. For clarity, it is necessary to first recall a few of their properties.

A soap film is composed of two surface layers having a high concentration of soap molecules separated by an interstitial liquid. In their study of the drainage of soap films, Mysels *et al.* [11] found three different types of soap solution. In their mobile type, two surface layers have a liquid-like behaviour. In all the motions that we will describe, the scale of time being short, the two surfaces move together with the interstitial liquid. The resulting viscosity  $\mu_F$  of the film is (Trapeznikov [12])

$$\mu_F = \mu_b + 2 \frac{\mu_s^s}{e}$$

where  $\mu_b$  is the bulk viscosity of the fluid,  $\mu_s^s$  the surface viscosity of the superficial layers and  $e$  the thickness of the films.

In a previous series of experiments related to the present one (Y. Couder and H. Thomé [13]), we studied the two-dimensional instability of a wake. Figure 1 shows the Von Karman street behind a 0.2 cm cylinder towed in a film. The film is slightly inclined at an angle  $\alpha$  with horizontal, and its thickness varies slowly with height. The interference fringes obtained by the reflexion of monochromatic light are used for visualization.



Fig. 1. — Wake of a cylinder  $d = 0.2$  cm.

The following conclusions can be drawn :

— A vortex street appears in the film for velocities at which the wake of the cylinder in the surrounding air is still linear. The vortices are thus located in the film and their appearance provides an order-of-magnitude estimate of  $\mu_F$ . We find  $3 \times 10^{-2}$  poises for a film 10  $\mu\text{m}$  thick. It corresponds to  $\mu_s^s \sim 10^{-5}$  surface poises.

— The vortices are damped downstream by the friction on the neighbouring air. This damping becomes very important in thin films as their inertia is small.

— Any inclination of the film creates a gradient of thickness and thus a gradient of the surface density. Buoyancy forces result from this gradient. A thin zone displaced in a thicker lower region is subjected to a return force. This effect becomes quite significant if the inclination is large.

The experimental disposition that we are going to describe is designed to observe two-dimensional grid turbulence in these films. We will minimize the effect of air friction by working with thick films which also have minimum viscosity  $\mu_F$ . They will be placed horizontally so as to avoid buoyancy effects.

### 1. Experimental apparatus.

All the experiments were performed with a 0.3 % solution of a commercial liquid soap composed of a mixture of sodium lauryl sulfate and sodium benzene sulfate. An addition of 10 % of glycerol increased the stability of the films.

We used two rectangular frames of length 33 cm and width respectively 10.6 and 15.8 cm. In order to stretch the film, they were dipped in the solution, then, after a very short drainage, set in a horizontal position. Monochromatic observation of the equilibrium state showed the effect of the curvature of the film under its own weight. There was a strong thickness gradient near the frame (from 1  $\mu\text{m}$  to 10  $\mu\text{m}$  in the two centimeters nearest the border) then a slowly varying thickness (from 10  $\mu\text{m}$  to 12  $\mu\text{m}$ ) in the central area 12 cm wide. We performed most experiments in such films. However a few were done in a film whose thickness has a random distribution. This was done by towing the grid a second time while the disorder created by the first passage had not yet relaxed to equilibrium. The results in both cases were very similar.

The grid was in the form of a comb of length 10.4 or 15.6 cm and made of parallel cylinders of diameter  $d = 0.2$  cm. Different combs were used with the spacing between cylinders  $M_d = 0.1$  or 0.2 cm.

The comb was placed through the film across its width and could be towed from one end of the frame to the other with a constant velocity  $V$  ranging 5 cm/s to 60 cm/s.

The evolution of the turbulence was observed with a motorized photographic camera taking 3 images per second. We took a first photograph of the comb being towed through the film with the vortices behind it and then repeated photographs to observe the time evolution of the vortex field.

Two visualization techniques were used. In the first, we dropped dispersed resin particles onto the surface of the film and lit them with an intense tangent white light. Photographs taken with a time exposure of 0.033 s showed traces of the particles giving the velocity field (the motion being in the plane of the film). In the second, we observed the monochromatic light of a sodium source reflected by the film. All the patches of different thickness present in the film get elongated along the flow lines and so do the corresponding interference fringes.

## 2. Experimental results.

Figure 2 (a to e) shows a series of seven photographs taken 0.36 s apart. In the first one, the grid ( $d = 0.2$  cm,  $M_d = 0.1$  cm) is seen passing from left to right across the frame with a velocity 55 cm/s. The corresponding Reynolds number based on the cylinder diameter is of the order of 400. In the following, the grid has reached the extremity of the frame and stands still. A scale has been added below each photograph showing for each zone of the film the time  $t$  elapsed since the passage of the grid.

All theoretical predictions on two-dimensional turbulence describe the increase of length scale which is evident on these photographs. The process of this increase through merging of vortices can be clearly observed. In a velocity field, such as the one shown on figure 2c, the vortices are randomly distributed. As the grid has generated a zero total vorticity, an equal quantity of vortices of both directions are observed. The absolute direction of the rotation of a vortex can be found by careful observation of the photographs. The dust particles scattered on the film are of unequal size, the larger ones are more sensitive to centrifugal forces and the slight tilt of their traces reveal the direction of rotation. Furthermore, two neighbouring vortices, when rotating in opposite directions add their velocities and create an intense stream between them, while when rotating in the same direction, they are separated by a saddle point with zero velocity.

Each image can thus be analysed and shows that the field of randomly distributed vortices form domains of vortices of the same sign. With time each domain merges into a large vortex. In the particular case where the domain is only composed of two eddies of similar sizes, they coalesce through a classical vortex-pairing process after rotating around each other. An event of this type involving two counter-clockwise rotating vortices is seen in the upper left part of figure 2 (c-g).

For times  $t > 1$  s, the increase of the vortex size begins to saturate (Fig. 3d) as the size of the vortex field is no longer large enough to feed the evolution. On the last image (2g), the size of the

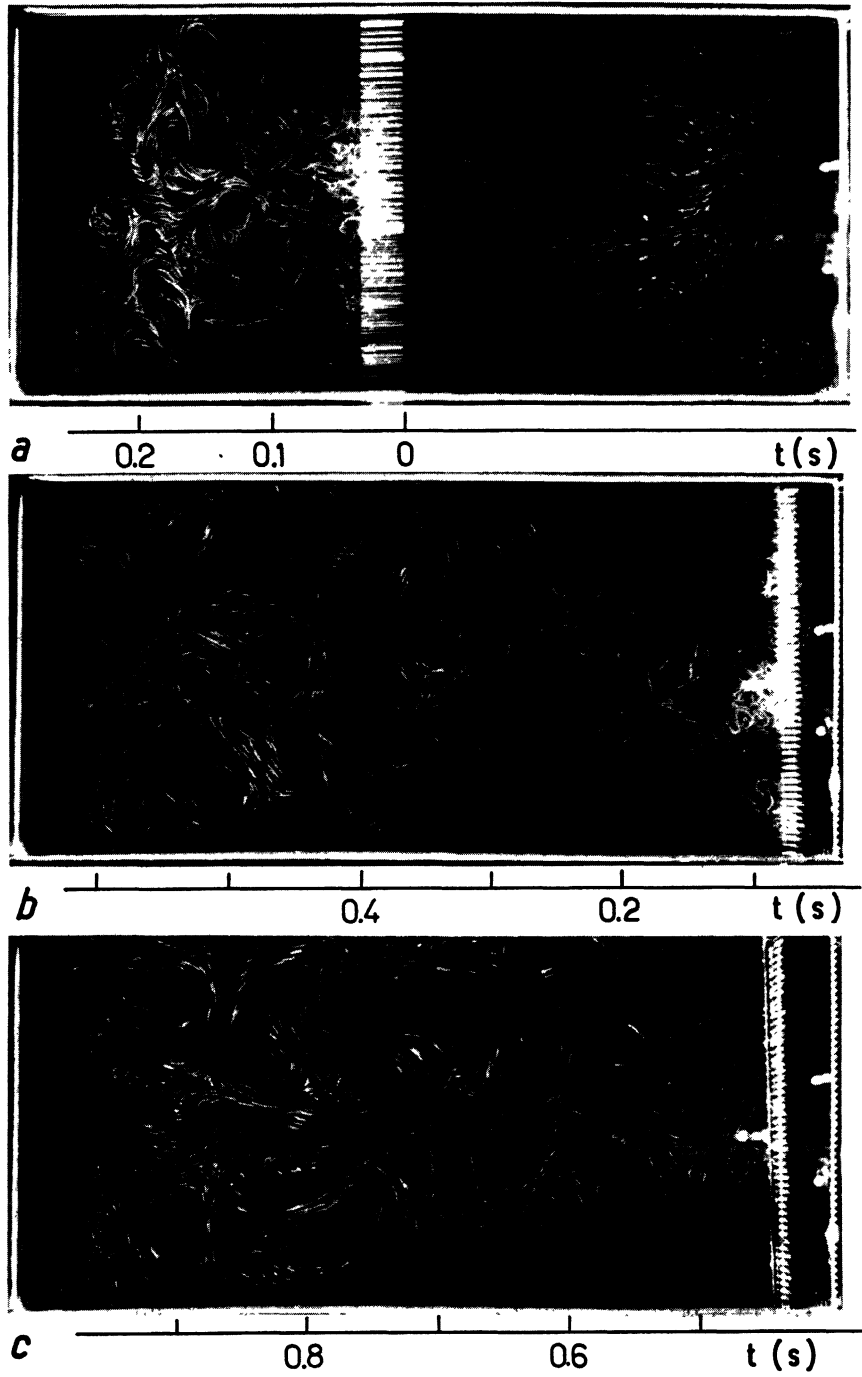


Fig. 2. — See caption of figure 3.

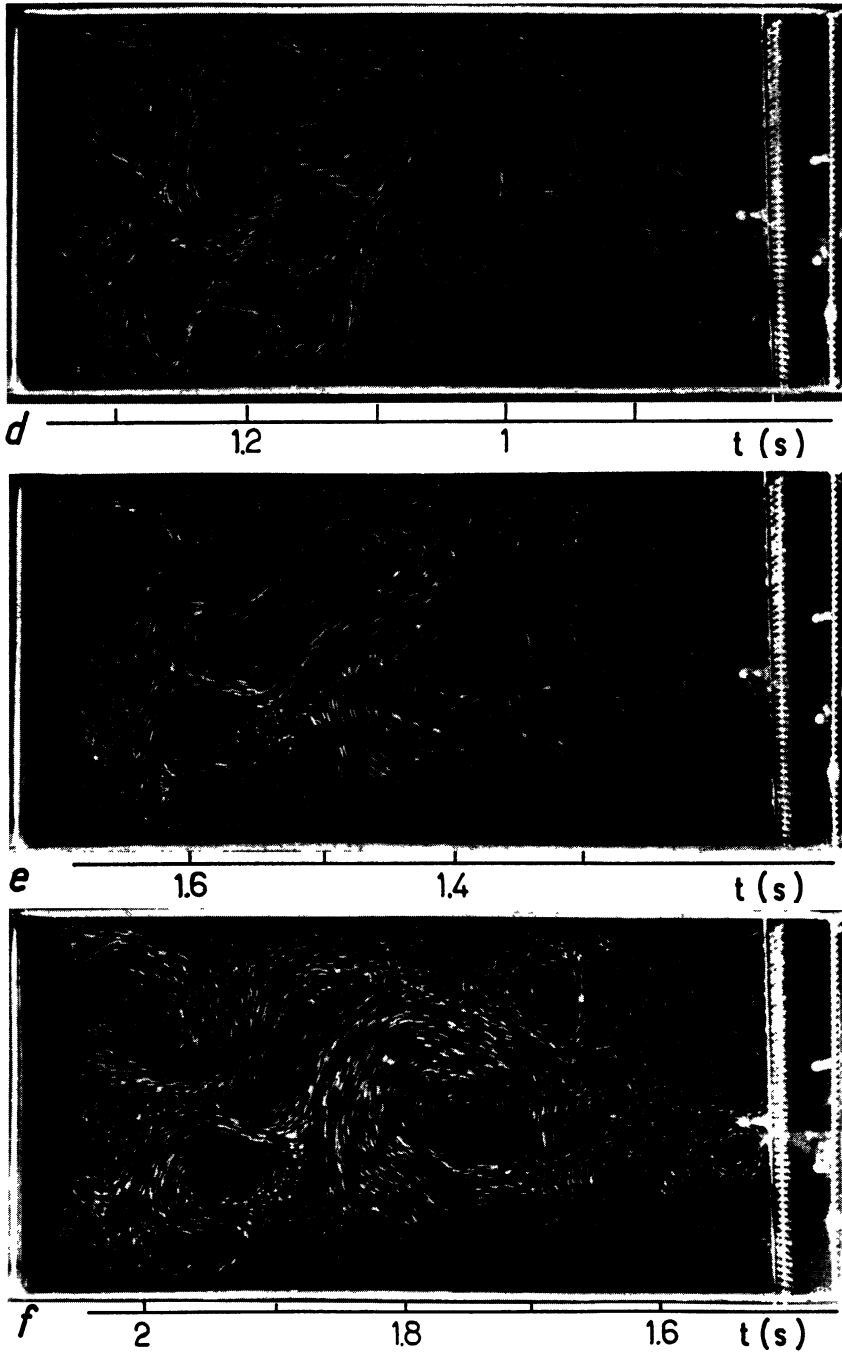


Fig. 3. — The preceding figure and this one show six photographs taken 0.36 s apart showing the evolution of the flow. The size of the frame (15.8 × 33 cm) gives the scale.

vortices have become comparable to the width of the frame and a quasi-organized system of alternate vortices is observed in the length of the frame.

The visualization provided by the interference fringes shows a different type of image of the same phenomenon. The general aspect can be compared to the patterns produced by the simulations of McWilliams [3] or Basdevant and Sadourny [4]. Some characteristics are similar. In particular, the relative stability and strong activity of pairs of opposite vortices is evident, smaller structures located on their axis are seen drawn-in and then engulfed.

### 3. Discussion

We measured on several similar sets of photographs the diameter  $D$  of all the vortices in a given zone corresponding to a range of values  $t \pm \Delta t$ . Figure 4 (a, b, c) represents the probabilities of the various values of the wavevector  $2\pi/D$  at three different times  $t_1 = (0.1 \pm 0.05)$  s,  $t_2 = (0.42 \pm 0.07)$  s and  $t_3 = (0.67 \pm 0.07)$  s. Each statistic corresponds to the measurements of only about 100 vortices and this explains the coarse aspect of these histograms. However, the displacement of the spectrum towards smaller  $k$  and its narrowing corresponds to an inverse energy transfer of the type described by Tatsumi [2] in the case where the initial energy spectrum density is zero at zero wave number.

Figure 3d shows the time evolution of the mean value  $\bar{D}$  corresponding to these statistics. The evolution is a fast linear increase of  $\bar{D}$ . It extrapolates at  $t = 0$  to a finite value that corresponds to the size of the vortices directly shed behind a cylinder of diameter  $d = 0.2$  mm.

This evolution (completely different from the three-dimensional case where  $\bar{D} = \sqrt{10 \nu t}$ ) is similar to that predicted by Batchelor [14] for an energy-preserving two-dimensional system where the spectrum should have a self similar form, the length scale being proportional to time.

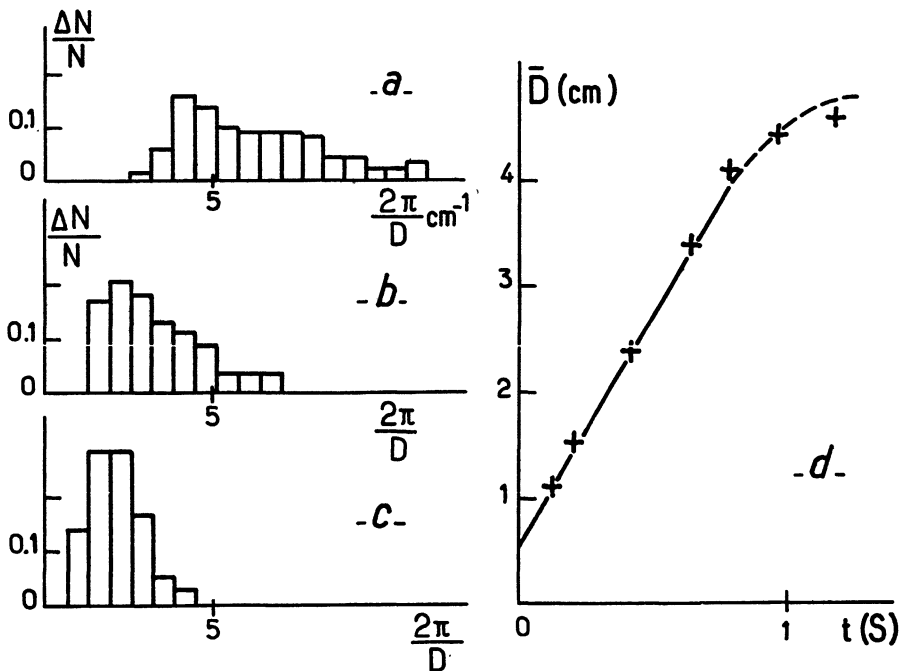


Fig. 4. — (a, b, c) Histograms of the wavevectors  $k = 2\pi/D$  corresponding to times : a)  $t = (0.12 \pm 0.05)$  s, b)  $t = (0.42 \pm 0.07)$  s, c)  $t = (0.67 \pm 0.07)$  s; d) Evolution of the average vortex diameter with time.

Rhines [15] investigated this evolution which he described by

$$\frac{dk_1^{-1}}{dt} = Tu$$

where  $k_1$  is the mean wavenumber and  $u$  the rms speed. In a numerical simulation of unforced inviscid flow, he found  $T \sim 3 \times 10^{-2}$ . Hopfinger *et al.* [7] interpret their results of a rotating tank experiment with a similar value. Though the numerical value of  $T$  is subject to the choice of definitions of  $D$  and  $k_1$ , our results clearly correspond to larger values of  $T$  ( $T \sim 1$ ). This result is surprising in view of the fact that dissipation of energy through viscous friction with the surrounding air should rather tend to slow down the evolution of  $D$ . The explanation probably lies in the inhomogeneities of the film thickness. These inhomogeneities are not due to a compressibility of the film but exist already in the static state because of the slight curvature of the film under its weight and because of the addition of solid particles for visualization. Around each vortex, centrifugal forces will tend to displace the thicker zones (and the added visualization particles) towards the outer regions. The surface density of the film thus increases from the centre to the outer limit of each vortex. The region between neighbouring vortices is thickened so that their interaction is strongly enhanced. Furthermore, the inhomogeneities can play the rôle of a sort of « spatial noise » favouring the pairings.

#### 4. Conclusion.

Various experiments that we performed with soap films show that they behave as two-dimensional fluids. However, they present several difficulties that appear in the present experiment. It is difficult to obtain a homogeneous thickness, so that the density of the film per unit surface is not constant. The friction of the ambient air is not negligible and damps the motion. Finally, it is difficult to obtain very large films which would permit the energy cascade to be observed on a larger range of scales.

We do believe, however, that our results show clearly the two-dimensional turbulent evolution of the structure towards large scales as well as its mechanisms. Further experiments and comparison to numerical models should provide a better understanding of the processes involved in the enstrophy evolution.

#### Acknowledgments.

For the undertaking of this type of experiments, I am very grateful to A. Libchaber's backing and stimulation through many discussions. I am also indebted to H. Thomé, J. Brochard, G. Post, S. Portier, L. Taylor and M. Douchez for their help at different stages of this work.

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