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# Fluid Mechanics in France in the First Half of the Twentieth Century

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*Annual Review of Fluid Mechanics*Fluid Mechanics in France  
in the First Half of the  
Twentieth Century

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**Keywords**

fluid mechanics, history, twentieth century, France, aeronautics

**Abstract**

If one opens today a textbook on fluid mechanics, it seems that whereas French scientists of the eighteenth and nineteenth centuries are frequently mentioned, those from more recent times occur rarely; in particular, French contributions to the major breakthroughs of the first half of the twentieth century (boundary layers and turbulence) would appear quite modest. However, study of contemporary documents (PhD theses, journals, correspondence, etc.) reveals remarkable work undertaken by outstanding personalities. A key instigator of these achievements was the French Air Ministry, which, starting in 1929, and with great open-mindedness, created and generously financed four Institutes of Fluid Mechanics and five teaching centers in faculties of science. This reveals the 1930s in their true light as a fruitful decade, with achievements that explain the prominent role played by France in the creation of the International Union of Theoretical and Applied Mechanics (IUTAM) in 1946. This review recounts the story of fluid mechanics in France, with emphasis on the connection between scientific questions and social and cultural issues, in a period marked by two world wars and great strengthening of international relationships.

## 1. INTRODUCTION

The first half of the twentieth century was a very fruitful period for fluid mechanics, bridging the gulf between empirical hydraulics and rational mechanics, with strong motivation coming from developments in aeronautics. It was marked, in particular, by boundary layer theory, by essential steps in the understanding of turbulence, and by decisive answers to the classical problem of hydrodynamic forces on obstacles, including the circulation theory of lift. These advances occurred mostly in two places of outstanding creativity, the Universities of Göttingen and Cambridge, and, starting in 1930, in the United States. French scientists seem to have stayed apart from the movement. In the review by Sydney Goldstein (1969) on fluid mechanics in that period, references to French work are rare: The only contributions cited in any detail are those of the engineer Gustave Eiffel concerning his discovery, in 1912, of the so-called drag crisis on a sphere, and those of Henri Bénard concerning thermoconvective cells and street vortices in wakes. The same scarceness of references appears in the boundary layer history by Hugh Dryden (1955); in *A Voyage Through Turbulence*, edited by Davidson et al. (2011); or in the book by Bloor (2011) on controversies after the First World War concerning the circulation theory of lift.

What happened to French mechanics, which in the previous century, from Navier to Boussinesq, had shone so brightly? In fact, a reexamination of contemporary work (PhD theses, reports, and journals now discontinued) reveals a rich and inventive activity, unfairly forgotten even in France. Before 1930 this activity was due to just a few individuals (Bénard, among others), but it then received a strong impetus from the French Air Ministry, which aimed at a renaissance of French aeronautics. A fruitful decade ensued, with remarkable achievements. Although these were overshadowed by achievements elsewhere, the French prewar dynamism can be seen in the role that France played in the creation, in 1946, of the International Union of Theoretical and Applied Mechanics (IUTAM).

The present review recounts this half-century of fluid mechanics history with attention to the interplay among scientific, industrial, and cultural issues. The next section sketches the aeronautical context and then discusses some salient fluid mechanics achievements before 1930, including the French involvement in the first International Conferences on Applied Mechanics (ICAM). Section 3 tackles the institutionalization of fluid mechanics and, in particular, the creation of four institutes by the Air Ministry. The four subsequent sections are devoted to these institutes—in Paris, Lille, Marseille, and Toulouse. The final section provides a brief summary and analysis. More on this history and complete references are provided in a recent book by the author (Charru 2021).

## 2. FLUID MECHANICS BEFORE 1930

An influential moment of French aeronautics, with consequences on French fluid mechanics, was the first closed-loop flight, in January 1908, by Henry Farman at Issy-les-Moulineaux (near Paris). The demonstration, rewarded with an important prize, was attended by Theodore von Kármán, who saw there his first airplane flight (Dryden 1965, p. 347). Numerous small airplane manufacturers then sprang up, supported by generous sponsors and fervent popular enthusiasm. Attracted by this French dynamism, the Wright brothers visited France in September 1908 with their *Flyer IV* airplane (Anderson 1997). Paul Painlevé (1863–1933), a towering mathematician, witnessed their demonstration in his role as representative for the Academy of Sciences, and was taken for his maiden flight by Wilbur Wright. He then became a passionate advocate of aeronautics in both academic and political circles, from within several ministerial positions.

## 2.1. Aerotechnics Enters the University

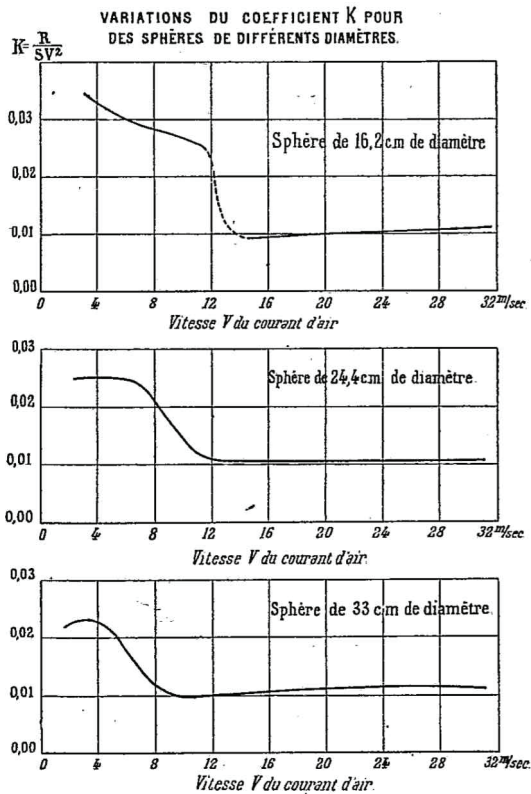
Aeronautics entered the Sorbonne University in Paris when Basil Zaharoff, an international weapons manufacturer, funded in 1909 a Chair of Aviation—he also funded two other chairs in London (at Imperial College) and Moscow. A few months later, the businessman Henry Deutsch de la Meurthe, founder of the *Aéro-Club de France*, offered a generous subvention for the creation of the first French *Institut aérotechnique* (IAT) at Saint-Cyr-l'École near Paris. Leadership of the IAT was entrusted to the physicist Charles Maurain, professor at the Sorbonne, assisted by Albert Toussaint (1885–1956), an engineer. The main facility of the IAT was a railway 1.3 km long, on which a truck, powered by an electrical engine, pulled airfoils and wings. Aerodynamic forces were measured by balances, and the pressure along profiles was measured by ranks of Pitot tubes. Maurain and his wife made the IAT an active intellectual community where influential academic and political personalities liked to gather (e.g., Jean Perrin, Paul Langevin, Marie Curie, Paul Valéry, Léon Blum), as Camille Marbo, novelist and wife of the mathematician Émile Borel, recounted in her memoirs.

## 2.2. Gustave Eiffel and the Drag Crisis

Airplane manufacturers such as Breguet and Blériot preferred the aerodynamic laboratory of Gustave Eiffel to the IAT at Saint-Cyr. After a glorious career devoted to the construction of iron bridges, viaducts, and buildings, Eiffel (1832–1923), then seventy years old, decided to turn to the study of air resistance, to which he devoted the last two decades of his long life. His first laboratory, in 1903, was his own Eiffel Tower on the Champ-de-Mars. Various shaped obstacles were mounted on a device that fell freely along a taut cable between the ground and the first floor of the Tower, 115 m above the ground. The vertical position of the obstacle and the aerodynamic drag (measured with a dynamometer) were recorded on a rotating drum and then retrieved for analysis. The relative windspeed reached 40 m/s, much larger than that provided by contemporary wind tunnels. In 1909, an enclosed laboratory sheltered from the weather was built at the foot of the Tower, where the obstacle, now fixed in a tunnel, was subjected to the air stream created by an extraction fan. Eiffel discussed with Henri Poincaré the conditions to be fulfilled for the two types of experiment (moving body or moving air) to be equivalent in the light of turbulence effects and the finite diameter of the air stream (Eiffel 1914). A novelty introduced by Eiffel was the removal of the lateral walls of the test section, so that the air jet freely crossed a large chamber within which tests could be performed more easily. From 1909 to 1912, four thousand experiments were performed for manufacturers free of charge, subject to the condition that the results might be published freely by Eiffel. A larger wind tunnel was then built at Auteuil, to the west of Paris, this time including a long divergent duct interposed between the test chamber and the fan, which greatly reduced the power required for the fan—a patented invention. The “Man of Iron and Air” (Anderson 1997, pp. 267–82) published his results in several books and coined the terms “wind tunnel” and “polar diagram” for the plot of the lift coefficient versus drag coefficient.

Eiffel's most significant contribution to fluid mechanics was his discovery of the sharp decrease, above a critical velocity, of the drag coefficient on a sphere, as shown in **Figure 1** (Eiffel 1912). To observations of the motion of light woolen threads brought close to the sphere, Eiffel added the commentary:

Below the critical velocity, a cone of low pressure forms at the rear, of length nearly equal to the sphere diameter, similar to that at the rear of plates struck normally by the wind. Above the critical velocity, the new regime exists for which this cone has disappeared and is replaced by a region where air is relatively undisturbed. (Eiffel 1912, p. 1599)



**Figure 1**

Drag coefficient as a function of the wind velocity for three spheres of different diameters. Figure reprinted from Eiffel (1912).

Ludwig Prandtl, intrigued by a phenomenon that had escaped his own investigations, came to visit Eiffel in Paris. Having in mind other observations by Heinrich Blasius about the drag on flat plates aligned with the flow (which did not follow the expected  $U^{3/2}$  resistance law), he soon found the explanation: The drag crisis is due to the transition to turbulence within the boundary layer, which retards its separation (von Kármán 1954; Eckert 2006, section 2.5). As the critical Reynolds number depends on the level of turbulence of the incoming flow, it became, for three decades, a classical method to assess the quality of wind tunnels.

### 2.3. The French Reception of the Circulation Theory of Lift

After the war, Maurain and Toussaint, at the IAT in Saint-Cyr, obtained as spoils of war confidential reports (the *Technische Berichte*) from Prandtl's laboratory at Göttingen. These reports provided numerous tests of formulas for lift and resistance coefficients of wings of finite length, intended to validate the Prandtl theory of the lifting line (Eckert 2006, section 2.6). Toussaint redid these tests for various wings and multiplanes. His results, published in a widely read French scientific journal (Toussaint 1921), confirmed the validity of Prandtl's formulas and their great practical utility.

The circulation theory of lift was therefore rapidly accepted in France. This contrasts with what happened in England, where the Advisory Committee for Aeronautics headed by Rayleigh (and later by Richard Glazebrook) dismissed the theory for a long time and ostracized its first

instigator, the English car manufacturer Frederick Lanchester (Bloor 2011). The main argument of the British scientists was that in inviscid fluid, Kelvin's theorem prevents the generation of circulation around a wing starting from rest, so that any well-based theory should include viscosity (i.e., should be based on "the Stokes equations"). English hostility eventually faded away in the mid-1920s when Hermann Glauert's book, *The Elements of Aerofoil and Airscrew Theory* (Glauert 1926), imposed Prandtl's views.

In France there was no committee for aeronautics where scientists could gather and debate. There was however a journal, *La Technique aéronautique*, similar to the English *Journal of the Royal Aeronautical Society* or the German *Zeitschrift für Flugtechnik und Motorluftschiffahrt*. The French journal, created in 1910 and edited by the Federation of the Aeronautical Industries, introduced itself as "an international journal for sciences applied to aerial locomotion"; it was run by a military officer, a professor at the *École supérieure d'aéronautique*, and its editorial committee included famous French mathematicians and physicists such as Paul Appell, Paul Painlevé, and Henri Poincaré. The first issue included the translation of a paper by Prandtl on the Göttingen laboratories; subsequent issues confirmed an interest in work performed abroad (e.g., in Dimitri Riabouchinsky's Institute of Aerodynamics near Moscow or in the British National Physical Laboratory). The journal showed growing interest in meteorology and also published remarkable studies on propellers by the famous scientist and manufacturer Auguste Rateau.

When, in 1919, the American National Advisory Committee for Aeronautics (NACA) opened an office in Paris for investigations into activities at Göttingen during the war, Toussaint was identified as the best French contact. His (rather technical) *Leçons d'aérodynamique* [Toussaint 1922 (1923)], as well as journal articles, were translated into English. Toussaint then contributed to an encyclopedia on aerodynamics edited by William Durand at Stanford (Toussaint 1935)—the second French contributor was Émile Barrillon, on the hydrodynamics of boats and floats.

With regard to boundary layer theory, it spread slowly outside Germany (Dryden 1955)—Horace Lamb's *Hydrodynamics* devoted a section to the subject only in the sixth edition (Lamb 1932). The first French advocate of the theory may have been Maurice Roy (1899–1985), who visited Prandtl in 1922 and gave an account at the Sorbonne in 1924. The first discussion in a textbook was that of Henri Bouasse (1928), Professor of Physics at the University of Toulouse—a full chapter providing the governing equations and some of their solutions by Blasius and Hiemenz. The first significant account in *La Technique aéronautique* appeared in 1929.

## 2.4. Paul Painlevé and the First Chair of Fluid Mechanics

After the Great War, the numerous airplane manufacturers appeared unable to organize an efficient industry, and French aeronautics declined. At the instigation of Painlevé, in 1923 the Undersecretary for Aeronautics funded at the Sorbonne a Chair of Fluid Mechanics and Applications—the first one in France. Painlevé himself was elected to the Chair. He fully agreed with the orientation requested by the Undersecretary: Theory, experiment, and techniques had to be closely tied, contrary to the French inclination, especially in Paris, to consider mechanics ("rational mechanics") as a branch of mathematics. Painlevé was assisted by Toussaint, the new head of IAT at Saint-Cyr, and by Dimitri Riabouchinsky (1882–1962), a Russian engineer who had emigrated to France in 1917. Riabouchinsky, heir to a large fortune, was well known for having created in 1904 the first Russian Aerodynamic Institute, at Koutchino near Moscow, with the scientific support of Nikolai Joukovsky. Painlevé's teaching, however, remained in line with "rational mechanics" and mainly dealt with inviscid flow; boundary layer theory, which in his view lacked rigor, did not enter his lectures. Very busy with his political and other academic duties (he also held two other chairs at the Sorbonne and at the *École polytechnique*), Painlevé gave up the Chair to Henri Villat in 1927.

## 2.5. Henri Villat and the Beauty of Pure Mathematics

Henri Villat (1879–1972) began his career as a mathematics teacher in a high school in Normandy, where he discovered the fluid mechanics problem of the force exerted by a flow on an obstacle, and the so-called d’Alembert paradox of zero drag in inviscid fluids. He engaged in correspondence with Joseph Boussinesq (still the leader of French fluid mechanics) about the Helmholtz–Kirchhoff flow, where surfaces of discontinuity enclose a wake of quiet fluid and overcome the d’Alembert paradox (Lamb 1932; Darrigol 2005, section 4.3). Villat also got in touch with Marcel Brillouin, who pointed out to him that Levi-Civita’s solution for the flow around curved obstacles, given in 1907, was not fully satisfactory since the shape of the body entered the problem implicitly through some function involved in the conformal transforms; the calculation of the flow around a body of given shape thus required tedious iterations. A more convenient solution would be desirable, Brillouin said (Aubin 2010, Tazzioli 2017). Villat answered the question only partially within his thesis (Villat 1911) and later improved the solution in the form of an integral solution. In the meantime, Brillouin and Villat found the notable result that among the continuous family of solutions (where the separation point may be chosen arbitrarily on the curved obstacle) there exists a unique one for which the singularity at the separation point is removed—the Brillouin–Villat condition, an analog of the Kutta condition at the trailing edge of an airfoil (Charru & Luchini 2019).

After a few years at Montpellier as Assistant Professor, in 1919 Villat was appointed Professor at Strasbourg, in the “recovered provinces” that the French Government intended to promote as a showcase of French excellence in mathematics. Villat’s reputation as a leader was confirmed in 1920 when he chaired the International Congress of Mathematics. Chief Editor of the famous *Journal de mathématiques pures et appliquées* and creator and director of two series of review papers, he was elected correspondent of the Academy of Sciences in 1923, and full member in 1932.

In 1927, Villat succeeded Painlevé to the Chair of Fluid Mechanics. He was ostensibly one of the few mathematicians interested in a problem of major importance for the design of airplanes: fluid resistance to body motion. In fact, Villat had little interest in aerodynamics and engineering problems. His somewhat aesthetic concerns clearly appear in his book *Aperçus théoriques sur la résistance des fluides* (Villat 1920), which deals exclusively with the Helmholtz–Kirchhoff problem. The solid obstacles drawn on the few figures are egg-shaped bodies in various configurations, including nearby walls. No reference is made to any experiment. The few bibliographical references are to the Italian mathematicians Tullio Levi-Civita and Umberto Cisotti, rather than to Kutta or Joukovsky.

## 2.6. Henri Bénard and Vortices

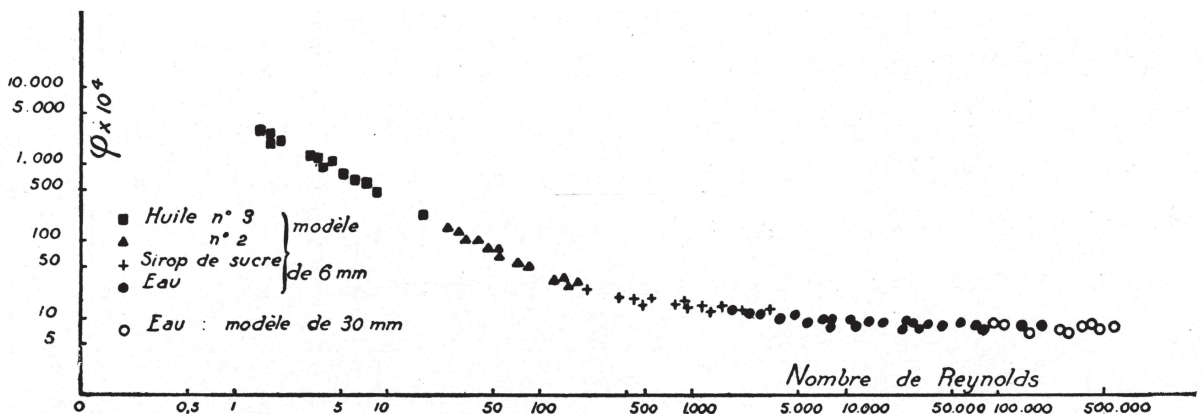
Henri Bénard (1874–1939) is probably the most well-known French fluid dynamicist of the first half of the twentieth century (Wesfreid 2006). He first discovered, in his thesis with Brillouin at the *Collège de France*, the thermoconvective cells that appear in a thin liquid layer heated from below (Bénard 1901). Informed of this discovery, Rayleigh developed a theory for the buoyancy-driven thermal instability of a liquid layer at rest. It was understood later that Bénard cells are in fact created by inhomogeneities of surface tension at the free surface, as fully clarified by J.R.A. Pearson in 1958 (Charru 2011, pp. 75–78). The second famous achievement of Bénard was the detailed study of the alternating vortices that occur in the wake of cylindrical obstacles. Experiments with obstacles of various cross section were first performed by him in Lyon and later in Bordeaux, where he obtained a professorship in the laboratory of Pierre Duhem. An authorship dispute then arose with von Kármán, who provided an inviscid stability theory for the spacing of the vortices, supplemented with some experimental observations.

A great novelty introduced by Bénard, following the pioneering work of the physiologist Étienne-Jules Marey, was the extensive use of photography as a measurement tool, along with the development of high-velocity cinematography (Aubin 2008). Bénard moved to Paris in 1922 and was appointed in 1929 to the new Chair of Experimental Fluid Mechanics funded by the Air Ministry.

## 2.7. Charles Camichel, Similarity, and Flow Visualization

The physicist Charles Camichel (1871–1966), a close colleague of Bénard, played a great role in the development of fluid mechanics in France in the interwar years (Charru 2017). After his PhD thesis with Brillouin on the absorption of light by crystals, he was appointed Assistant Professor at the Faculty of Science of Lille, where he taught industrial electricity. Camichel then moved to Toulouse and created in 1907 an Electrotechnical Institute with the support of the chemist Paul Sabatier, Dean of the Faculty and future Nobel Prize laureate. This creation, funded by the municipality of Toulouse, was in line with the large number of technical institutes founded at around that time in French faculties of science (Paul 1980).

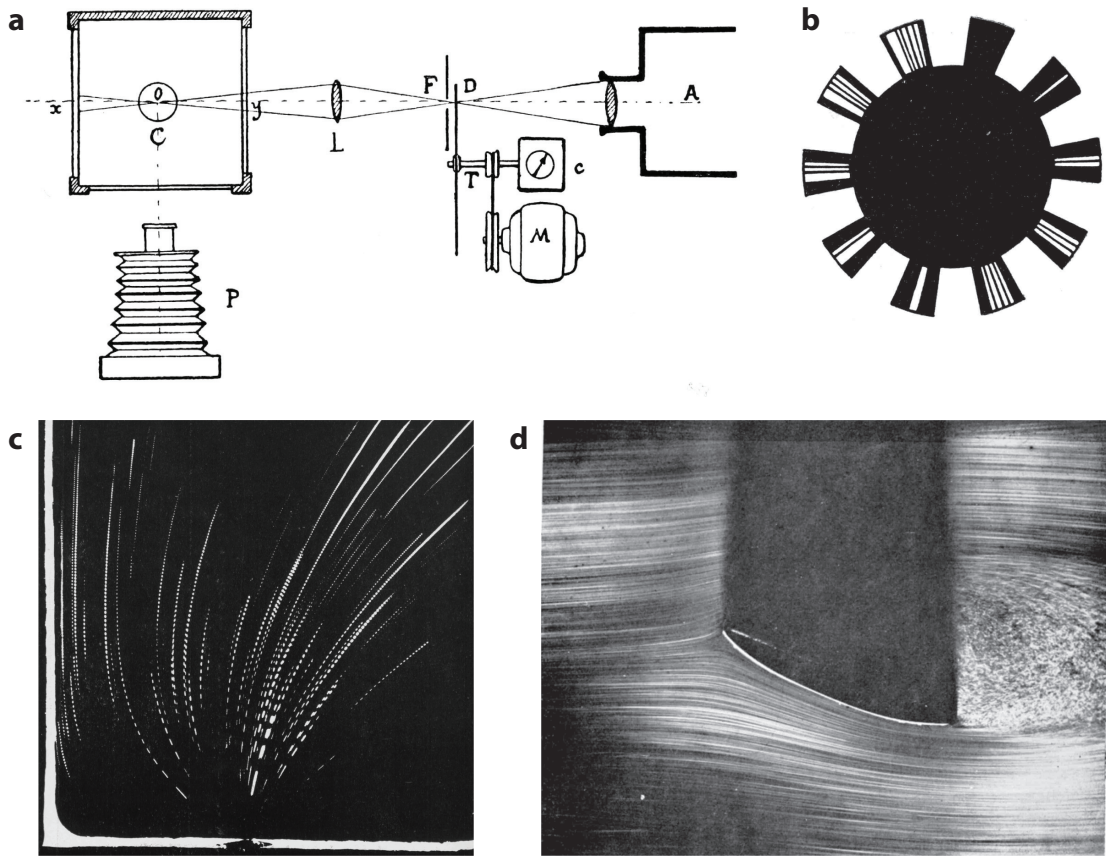
Camichel then engaged with railway companies that had recently converted to electric traction and built hydroelectric plants in the Pyrénées mountains. These companies had to face numerous hydraulic problems, in particular water hammers that occur in long pipelines. Pressed by an increasing number of requests, Camichel created in 1913 a hydraulics laboratory that, with the support of the Ministry of Public Works, soon became famous for both technical studies and fundamental fluid mechanics research. The laboratory investigated flow rate in large ducts, wave propagation along pipelines, the design of water chambers, and fluvial hydraulics (weirs, locks, etc.). Five PhD theses were devoted to these problems between 1919 and 1931, with emphasis on the relevance of similarity laws and studies on small-scale models. **Figure 2** displays, as an example, the normalized pressure drop  $\Delta p/\rho V^2$  in a right-angle bend as a function of the Reynolds number—which spans more than five orders of magnitude. Camichel noticed that the region where the curve reaches a quasi-plateau defines the minimum model size for which, if the flow is sufficiently turbulent and the Reynolds similarity is irrelevant, some other similarity condition may be fulfilled—typically the Froude similarity for free surface flows.



**Figure 2**

Normalized pressure drop  $\varphi = \Delta p/\rho V^2$  in right-angle bends as a function of the Reynolds number; the ratio of the extreme fluid viscosities is 373. Figure reprinted from Camichel et al. (1931).



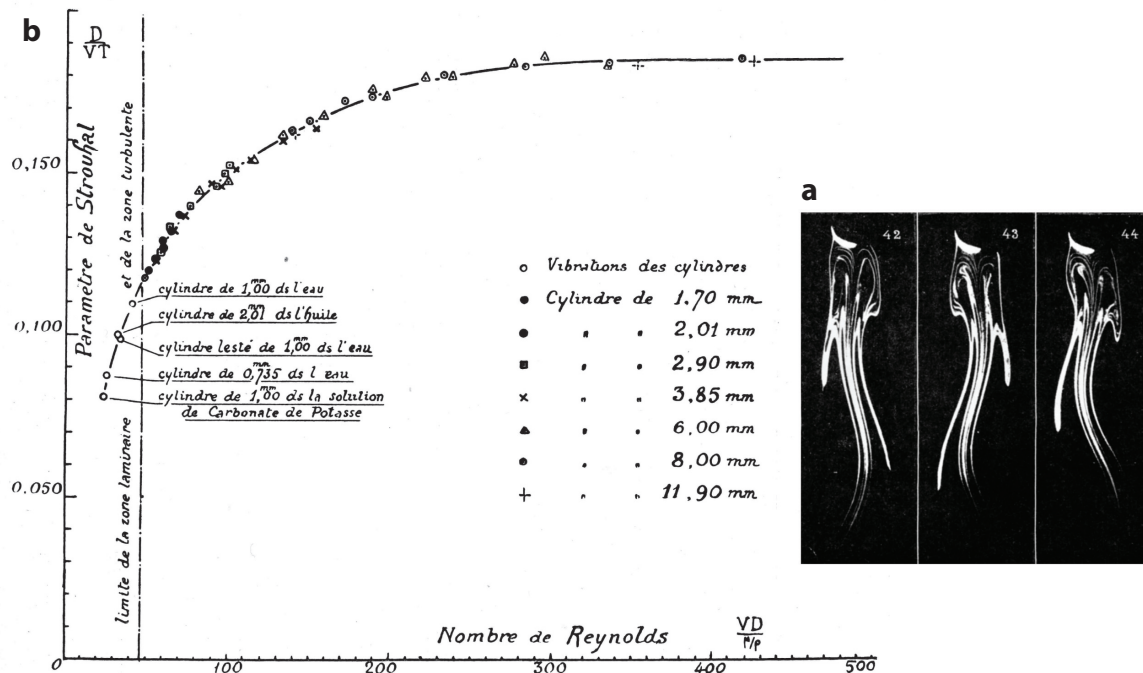


**Figure 3**

(a) Chronophotography setup: The light beam from  $A$  is intercepted by the rotating toothed disk  $D$ ; the intermittent beam emerging from the slit  $F$  lights up the plane  $xOy$  of the flow in the conduit  $C$ , photographed by the camera  $P$ . (b) Toothed disk for the study of unsteady flows. (c) Flow driven by a hole at the bottom of a water tank at a distance of 3 cm from the left wall. Panels  $a$ – $c$  reprinted from Camichel (1920). (d) Streamlines around an inclined blade. Panel reprinted from Camichel et al. (1925).

Great progress was also made in flow visualization techniques in order to determine velocity fields. **Figure 3a,b** displays the setup used in 1920 and the special toothed disk designed to remove indeterminacy in the direction of unsteady flows. **Figure 3c** shows a chronophotography of the flow driven by a hole at the bottom of a water tank. The fluid acceleration as it approaches the hole is clearly visible; the potential nature of the flow was then assessed using Stokes' theorem. **Figure 3d** displays streamlines around an inclined blade and the sharp boundary between the laminar (potential) flow and the turbulent wake. Other pictures can be seen in Camichel (1932), including the velocity profile of a flowing non-Newtonian gelatin solution.

Wake vortices were the subject of three PhD theses of Dupin, Teissié-Solier, and Castagnetto, respectively defended in 1930, 1931, and 1939. Regular oscillations of the vortices as well as transients were visualized using a chemical precipitate diffused from the surface of the obstacle and entrained in the wake (**Figure 4a**), filmed with a high-speed camera (200 frames per second). The films are lost but sequences of pictures are visible in Camichel et al. (1927) and in the thesis of



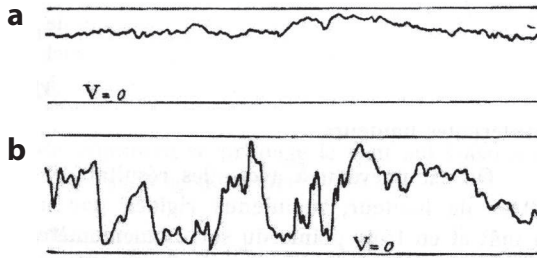
**Figure 4**

(a) Oscillating wake of a circular cylinder visualized with a chemical precipitate. (b) Dimensionless frequency (Strouhal number) of the vortices as a function of the Reynolds number; the points below the critical Reynolds number  $Re_c \approx 48$  correspond to transient oscillations triggered by a localized perturbation in the vicinity of the cylinder. Panels reprinted from Camichel et al. (1927).

Pierre Dupin. The period of the vortices (as small as 0.02 s) was measured by stroboscopy or by hot wires—a technique used in Toulouse from 1928. **Figure 4b** displays the plot of the dimensionless frequency of the vortices (Strouhal number) versus Reynolds number for different fluid viscosities and cylinder diameters. The critical Reynolds number, below which the wake remains steady, was found to be  $Re_c \approx 48$  (the value accepted today). It was noted that when a perturbation is created in the vicinity of the cylinder below  $Re_c$  (by the injection of a small amount of fluid or by a slight shock on the cylinder), transient (damped) oscillations appear whose frequency falls on the extrapolation below  $Re_c$  of the Reynolds–Strouhal curve. The plot shown in **Figure 4b** is certainly the first providing so much insight into the cylinder wake. Vortices in turbulent flow were also studied. Other experiments tackled the flow around cylindrical rods with one tip free, where vortex shedding interacts with flexional vibrations of the rod, giving rise, as the fluid velocity is varied, to beating and frequency-locking phenomena.

## 2.8. Antoine Magnan, Animal Locomotion, and Atmospheric Turbulence

Independent of the faculties of science, the doctor and physiologist Antoine Magnan (1881–1938), at the *École des hautes études* in Paris, made unexpected contributions to fluid mechanics and atmospheric turbulence. Magnan was interested in animal locomotion and particularly in bird flight and the swimming of fish. He also built his own gliders and participated in international aeronautics conferences. To achieve detailed observations worthy of Étienne-Jules Marey, he improved



**Figure 5**

Magnan’s 1925 hot-wire measurements of wind velocity at *Île de Ré*: (a) a marine west-southwest wind 2 m above the ground, and (b) a land northeast wind 10 m above the ground. The duration of the records is 20 s, and the vertical scale between the strokes is (a) 12 m/s and (b) 15 m/s. Panels reprinted from Magnan [1929 (1932)].

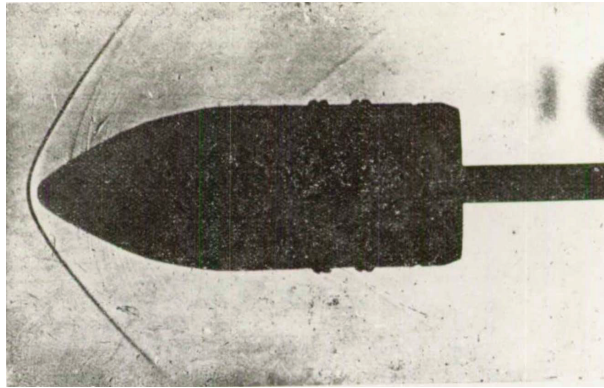
high-speed cinematography techniques and devised many measurement devices such as small acceleration recorders to be fastened onto the backs of birds. In order to learn about wind dynamics, Magnan and his colleagues Eugène Huguenard and André Planiol developed, starting in 1923, hot-wire anemometry (Huguenard et al. 1923). From measurements transmitted to the ground by radio waves, Magnan determined vertical profiles of the mean velocity and turbulent intensity of the wind, as well as the effect of ground roughness (vegetation, buildings, etc.). Searching for “turbulent waves” reminiscent of the billows of clouds in the sky, he determined their “wavelength” at different heights above the ground. **Figure 5** displays two time series of the wind velocity on a beach of the *Île de Ré* (an island off the French Atlantic coast) recorded in September 1925. The upper plot corresponds to a weakly turbulent marine wind; the lower one to a much more turbulent land wind. The hot wire allowed recording of rapid variations (e.g., from 12 to 21 m/s in a time of 0.3 s). Although Magnan provided few bibliographical references in his publications, he nevertheless quoted similar measurements by G.I. Taylor in Scotland. In addition to measurements at several places in France, Magnan also investigated thermal winds in desert regions of Tunisia. In 1926, the Air Ministry funded for him a Chair of Animal Mechanics Applied to Aviation at the *Collège de France*.

Some of Magnan’s publications and the course he taught in 1929 at the *Collège de France* were translated by NACA [Huguenard et al. 1924; Magnan 1929 (1932), 1931 (1980)] and cited by, for example, Dryden & Kuethe (1929). Thus, compensated hot-wire anemometry appeared in France in the same years as it did in Delft (Johannes Burgers and his student) and Aachen (Ludwig Hopf), and somewhat earlier than it did in other places (Dryden & Kuethe 1929, Bodenschatz & Eckert 2011).

Huguenard, Magnan’s colleague and author of one hundred patents in acoustics and optics, had a marked interest in ballistics. He studied in the 1920s the resistance to motion of high-velocity projectiles and fast-rotating propeller blades in compressible fluid, and provided impressive photographs (**Figure 6**).

### 2.9. The French Participation at the First International Conferences on Applied Mechanics

In the years following the Great War, scientific relations between the former belligerents remained tense, especially between France and Germany. In December 1919, Prandtl attempted to get back in touch with Eiffel, who responded with a flat refusal:



**Figure 6**

Shadowgraph of a stationary shock wave in front of a 37-mm projectile. Figure reprinted from Huguenard [1924 (1925)].

I consider it unquestionable that, following the unanimous opinion of French scientists and notably of the Academy of Sciences, it is impossible to contemplate personal relationships with German scientists for a long time. So, whatever the very high esteem in which I hold the work of so eminent a man as Mr Prandtl, I shall try to obtain whatever he publishes by buying it and thereby profit from it as best I can. (Eckert 2006, p. 87; cited in French)

At the institutional level, the International Research Council, dominated by representatives of the Allies, ostracized Germany. In this context, the initiative of von Kármán in organizing an ICAM appears remarkable (Battimelli 2016). The conference, held in 1922 at Innsbruck, was organized with Levi-Civita, who was known for his internationalist and pacifist views. The invitation letter, in French, was signed by von Kármán, Levi-Civita, Prandtl, and Oseen. French scientists stayed away, arguing that they could not shake German hands before the Germans had paid for the destruction they had caused. Two years later, von Kármán, strengthened by the success of the Innsbruck conference and now associated with Burgers, proposed another conference in Delft—which announced itself as the first ICAM. But both French and Germans still refused to meet. The atmosphere then relaxed. For the second ICAM, in 1926 in Zurich, the scientific committee included four Frenchmen: Ernest-Paul Hahn, Émile Jouguet, Gabriel Koenigs, and Henri Villat. Of the 251 participants, 22 were French, of whom two gave invited talks: Camichel on the theory of water hammer, and Jouguet on the thermodynamic theory of the propagation of explosions (Pöschl 1926). From then on, the French regularly participated in the ICAM (henceforth quadrennial), although Bénard, who was the official representative of the French ministry, complained in his reports of the low number of his compatriots.

### 3. THE INSTITUTIONALIZATION OF FLUID MECHANICS

When the Air Ministry was created in 1928, its technical direction was entrusted to a powerful personality, Albert Caquot (1881–1976). After studying at the *École polytechnique*, Caquot distinguished himself during the Great War with the design of a new type of aerostat, adopted by the British and French armies. Returning to civil engineering after the war, he acquired an international reputation in the domain of reinforced concrete. At the Air Ministry, Caquot immediately launched an ambitious plan to restructure the airplane industry. In particular, he decided on the construction of a giant wind tunnel—with an elliptic test section of 8 m × 16 m, allowing full-scale

aircraft to be tested. This came into service in 1935 (as did the similar wind tunnel at Langley Field in Virginia).

Convinced that aeronautics needed open-minded academic research, Caquot persuaded the faculties of sciences to create four Institutes of Fluid Mechanics in Paris, Lille, Marseille and Toulouse and five smaller teaching centers in Strasbourg, Poitiers, Nantes, Lyon, and Caen. In Paris, two new Chairs were created, of theoretical and experimental fluid mechanics, together with Assistant Professor positions and PhD grants for scientific collaborators. Various awards were to be given for the best work. Invited conferences were also encouraged and funded—the model was the seminars organized by Felix Klein at Göttingen (Bodenschatz & Eckert 2011). In each of the three other Institutes, one new chair (or its equivalent) was created with the same accompanying system of grants, and subventions were given for the construction of large wind tunnels. Manufacturers were invited to contract with the Institutes for tests and research. In the secondary teaching centers, subventions were given for new courses and PhD theses. The policy of the Air Ministry was maintained until the Second World War, in spite of the worldwide economic crisis that hit France from 1932 onward.

On the teaching side, each faculty had to create a new certificate of fluid mechanics (the bachelor's degree corresponded at that time to the acquisition of three certificates). The program, imposed at the national level, comprised three parts, each of 25 teaching hours: theory (to be taught by a mathematician), experiments (by a physicist), and aeronautical techniques. It included classical topics, as well as the aerodynamics of finite wings and notions on the modern theory of boundary layers; the experimental part included hot-wire anemometry and flow visualization techniques. An important issue, often stressed by Caquot, was that theory and experiments should be connected, unlike the traditional partitioning between theoretical rational mechanics and empirical hydraulics. In order to favor emulation between faculties, a national examination was organized each year and all students were invited to compete. In view of its magnitude, this national policy for fluid mechanics can be considered as the first national French program for scientific research.

#### 4. THE INSTITUTE OF PARIS

The Institute of Fluid Mechanics of Paris was created in the autumn of 1929, less than one year after Caquot got in touch with the university. Meanwhile, the faculty nominated Villat and Bénard to the new Chairs of Theoretical and Experimental Fluid Mechanics, as well as the mathematician Henri Beghin (1876–1969) and the physicist Adrien Foch (1887–1980) as Assistant Professors. The Chair of Aeronautical Techniques, held by the physicist Lucien Marchis (1863–1941) since its creation in 1909, was attached to the Institute, with Toussaint as Assistant Professor. IAT in Saint-Cyr (still headed by Toussaint) became the aerodynamic laboratory of the new Institute. Villat was appointed Director, with Riabouchinsky as Assistant Manager. (Being of Russian citizenship, Riabouchinsky could not be appointed to an academic position in France.)

Two years later, in 1932, the Laboratory of Mechanical Engineering was absorbed by the Institute, whose title shortened to “Institute for Mechanics.” With about 20 people, including 12 scientific collaborators preparing PhD theses and supported by the Air Ministry, this Institute was one of the largest institutions for academic research in Paris. At the same time, the assistant of Villat was appointed to the Chair of Mechanical Engineering and replaced by Joseph Pérès, previously professor and head of the Institute of Fluid Mechanics of Marseille. (As with Bénard, Beghin, and Foch before him, Pérès gave up a professorship for an inferior but more promising position in Paris.)

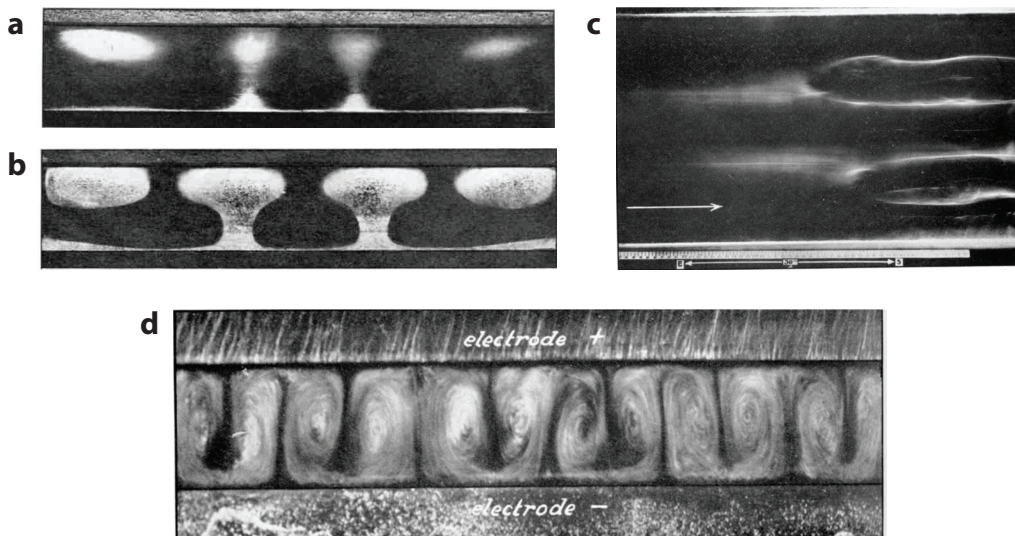
## 4.1. Henri Bénard's Laboratory of Experimental Fluid Mechanics

Once elected to his new Chair, Bénard first worried about a location for his laboratory. After several ups and downs, the solution was finally provided by Caquot, who offered a small building adjacent to the Air Ministry on rue de la Porte d'Issy, 6 km from the Sorbonne. With numerous scientific collaborators appointed by the Air Ministry, Bénard then pursued research in several directions on cellular patterns.

**4.1.1. Thermoconvection.** One challenge was to extend the observation of steady thermoconvective patterns to fluid layers of large thickness, beyond the few millimeters that had been previously considered. Steady rolls were successfully established in boxes of thickness up to 10 cm. **Figure 7a,b** shows photographs of thermoconvection in air, in which the rolls are visualized by the condensation of water vapor in the upper (colder) part of the box.

Bénard also explored the effect on thermoconvection of a transverse flow [thesis of Avsec (1939)]. It was shown that Poiseuille or Couette–Poiseuille flow promoted longitudinal rolls. It was then understood that the transverse wavelength is selected from the growth of “initial disturbances, due to chance,” and that this wavelength may be controlled by imposing some well-defined perturbations. **Figure 7c** shows a situation with three pairs of rolls being imposed at the entrance of the duct; accidental perturbations then create two new pairs downstream—a phenomenon now understood as the result of the Eckhaus instability. These observations were supplemented with measurements of vertical temperature profiles, using small thermoelectric probes. Convection in stratified flows was also studied (e.g., pure air over dense smoke). Travelling transverse waves were then observed, similar “to the waves of H. von Helmholtz which occur at the interface between two air layers moving with different velocity” (Avsec 1939, p. 5).

As a member of the Commission for Atmospheric Turbulence created by the Air Ministry in 1935, Bénard was involved in research activities conducted by Joseph Kampé de Fériet at Lille



**Figure 7**

Thermoconvection in air visualized by the condensation of water vapor in the upper (colder) part of the box: (a) immediately after the start-up of the experiment, and (b) one hour later. (c) Cellular thermoconvection with transverse flow (channel width = 335 mm); the wavelength imposed at the entrance (on the left,  $\lambda/H \approx 2.8$ ) relaxes to a smaller one ( $\lambda/H \approx 1.7$ ) as the geometrical forcing disappears. (d) Electroconvection in a layer of oil (of thickness 28 mm). Panels reprinted from Avsec (1939).

(see below). In line with his general interest in periodic patterns, he was intrigued by the strips of clouds visible in the sky, and in particular the question of whether these strips corresponded to thermoconvective or shear instabilities (the name “Kelvin–Helmholtz instability” appeared much later in the 1950s). Some other observations were carried out on the formation of thermals above hot spots created by electric arcs in relation to turbulent plumes. The possible involvement of electrical effects in cloud motion also inspired studies on convection triggered by electric fields, as illustrated in **Figure 7c**. Also worth mentioning are studies on thermoconvection in viscous liquids and dense suspensions in relation to certain geological formations, observations of solidification patterns in wax reminiscent of basalt columns, and thoughts about solar granulations.

**4.1.2. Wake vortices.** The second major concern of Bénard’s research was wake vortices. The setup he installed, which was 13 m high and extended from the basement to the third floor, allowed a large field of view of 24 cm and was first presented at the third ICAM in 1930 in Stockholm. The lateral confinement of the street of vortices was then investigated, as well as the shifting of the obstacle off the vertical symmetry plane. A theoretical study of such configurations was also undertaken, extending results by Louis Rosenhead in Cambridge.

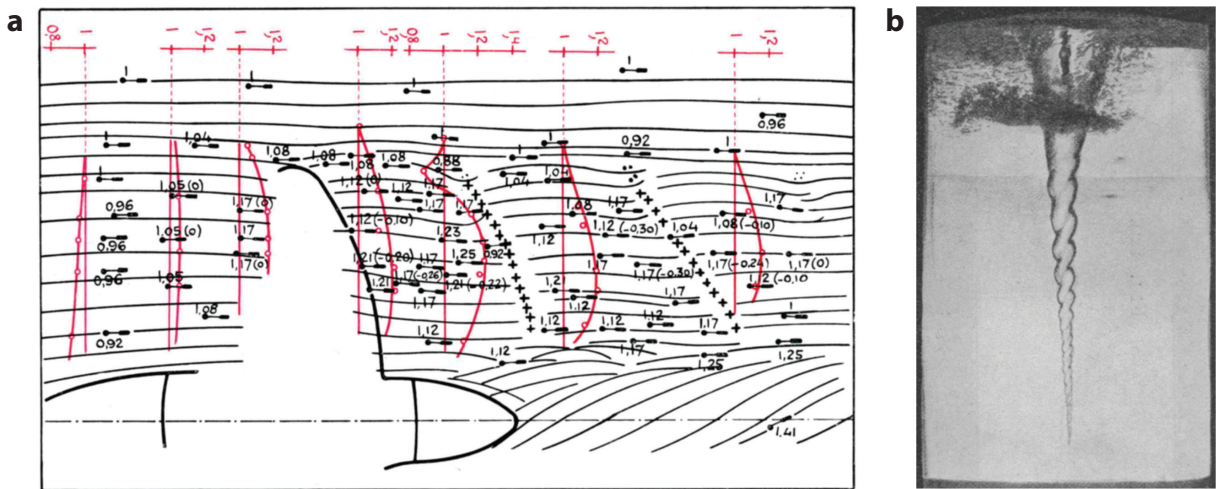
In relation to questions of flow resistance, the effect of a large air bubble attached to the obstacle was investigated by M. Luntz. Cosupervised by Pérès, Luntz also studied inviscid flows around rotating obstacles, fixed or free. Another situation studied by Luntz, in collaboration with his friend P. Schwartz, was the flow created by a rotating vertical cylinder plunging into a thin layer of liquid with a free surface. Spiraling vortices around the cylinder were observed, as well as circular rings of Bénard–Kármán vortices.

Bénard also had interests in self-sustained oscillations, such as those that appear at the end of an elastic tube from which a liquid jet emerges (thesis of F.-J. Bourrières). The study appealed to the theory of nonlinear oscillators, developed in Russia by A. Andronov, and to the van der Pol equation that appeared in 1927. On the same topic, work was conducted on the acoustics of free-reed instruments (the thesis of L. Auger).

**4.1.3. Compressible flows and shock waves.** A growing interest in compressible flows and shock waves arose in the early 1930s, due to the increasing velocity of airscrews and airplanes (along with older topics of ballistics and flows in steam turbines). The Volta Conference organized in Rome by Arturo Crocco in 1935, which brought together gas dynamics specialists (e.g., Jacob Ackeret from Zurich and Adolf Busemann from Dresden), showed the importance of the subject (Goldstein 1969; Eckert 2006, section 10.3). In France, the leader in these questions was Émile Jouguet, Professor of Mechanics at the *École polytechnique* in the interwar years, who developed the thermodynamic theory of the propagation of explosions (the Chapman–Jouguet condition).

As for experiments, in 1931 Bénard’s assistant Adrien Foch installed the first supersonic wind tunnel of the Institute, followed by a second more efficient one—with a test section 58 mm wide and Mach number up to 2.3, with characteristics similar to those found abroad at that time. Visualization techniques based on interferometry were developed by his students R. Tremblot, L. Santon, and J. Dupuy in collaboration with the optics laboratory of Charles Fabry at the *École polytechnique*. Observations allowed for, in particular, the assessment of the compressible Saint–Venant equations and shock calculations.

**4.1.4. Unsteady flows and the physics of fluids.** Another topic developed by Foch was the visualization of unsteady flows, such as wakes behind vehicles and buildings, and flows around propellers (**Figure 8a**). With his student Charles Chartier, he developed a stereoscopic method reproducing three-dimensional flows (Chartier later founded, in 1942 with Henri Poncin, the Fluid Mechanics Laboratory of Poitiers). Most flow visualizations performed in French



**Figure 8**

(a) Flow around a marine three-blade propeller, for a propeller rotating velocity corresponding to maximum efficiency. Panel reprinted from Chartier (1937). (b) A twisted bathtub vortex. Panel reprinted from Riabouchinsky (1935a) with permission; copyright 1935 Royal Aeronautical Society.

laboratories at that time involved a device called the stroborama, designed by engineers Louis and Augustin Seguin at the *Service technique de l'aéronautique*. The stroborama was based on the electric discharge of a large capacitor in a neon (or krypton) tube, triggered by low-current impulses. Very short flashes at frequencies up to  $10^4$  Hz, associated with high-speed cinematography, allowed researchers to obtain detailed images of fast phenomena. The society founded by the Seguin brothers sold more than 250 of these devices to academic and industrial laboratories.

Other studies investigated the physics of fluids: the size of molecules from viscosity measurements (A. Fortier), the breakup of liquid jets (G. Littaye), and the mean free path of molecules from sonic flows through nozzles (L. Agostini). Agostini then shifted to the theory of turbulence, on which he published a book with J. Bass, subsequently translated by NACA [Agostini & Bass 1950 (1955)].

**4.1.5. Dimitri Riabouchinsky.** Assistant Manager of the Institute, Riabouchinsky was an experimentalist with a pronounced taste for theory. He initiated research in several directions: flows around rotary wings, flows of thin liquid layers, natural and forced convection, shock waves and their analogy with hydraulics, and cavitation. Related to the question of the formation of cyclones, **Figure 8b** shows a beautiful conical-helicoidal air column formed on the axis of a closed cylinder, nearly filled with water entrained in rotation by a small propeller. Strongly attached to Russian culture (he always refused French nationality), Riabouchinsky attracted several Russian students. An elected Foreign Correspondent of the Academy of Sciences in 1935, a member of several scientific societies abroad, and author of more than 200 scientific papers, Riabouchinsky published a summary of his work from 1904 to 1962 in three papers in the *Journal of the Royal Aeronautical Society* (Riabouchinsky 1935a, 1935b, 1962).

**4.1.6. Yves Rocard and the fluttering instability.** A prominent figure of French physics, Yves Rocard (1903–1992) stayed for a short while at the Institute of Paris. A double doctorate in mathematics (1927) and physics (1928), Rocard began his career as an engineer. Consulted by the Air Ministry about the fluttering of wings (responsible for dramatic accidents), he realized that the



phenomenon corresponded to a fluid–structure instability: the merging of the flexion and torsion eigenfrequencies of the wing as velocity increases (Rocard 1988). He then computed the critical velocities of many French fighters and proposed improvements in their design (typically, the shifting of mass toward the leading edge of the wing).

When B nard died in 1939, his assistant Foch succeeded him as the Chair of Experimental Fluid Mechanics and Rocard became the assistant of Foch. Occupied with many tasks (he quickly entered the *R sistance* against the Germans), Rocard made little impact on the Institute of Fluid Mechanics, which he left in 1941 for a position at the * cole normale sup rieure* in Paris. After the war Rocard played a major role in the French nuclear program.

**4.1.7. The war and the disappearance of B nard’s laboratory.** When the German *Wehrmacht* entered Paris in May 1940, the Air Ministry was requisitioned, as were the adjacent laboratories of Foch and P r s. Scientific equipment was destroyed or sent to Germany. In particular, B nard’s films were lost. After the Armistice, some clandestine research continued at the * cole normale sup rieure*, where the physicist Georges Bruhat, head of the physics laboratory, provided a room. (Bruhat was later arrested by the Gestapo for refusing to betray Jewish students, and died in a concentration camp.)

## 4.2. Henri Villat’s Theoretical Fluid Mechanics

At the Institute of Paris, Villat still worked on his favorite problem, the Helmholtz–Kirchhoff flow around obstacles, and on related inviscid problems. He agreed that viscosity may be important (he conceded that Helmholtz–Kirchhoff wakes strongly underestimate drag), but thought little of boundary layer theory, which was not “rational mechanics” and which he never taught. Following Oseen’s investigations on flows with small viscosity, he sought for an integral solution of the full viscous problem, in which viscosity might then be put to zero. However, he never made any progress in this direction. In the 1930s, Villat supervised six PhD theses: on flows around air bubbles (by H. Poncin), rotating flows (M. S dille), finite-amplitude waves (M.-C. Dubreil-Jacotin), and general hydrodynamics (A. Gay, C. Jacob, and J. Leray). In the following decade he supervised three theses on the Helmholtz–Kirchhoff problem (by J. Kravtchenko, A. Oudart, and R. Huron), and one on vortices (I. Carstoiu). His most famous student was Jean Leray, who demonstrated a theorem of existence of “turbulent solutions” of the Navier–Stokes equations (Leray 1933). Leray then authored reference works on hyperbolic equations, on the Cauchy problem, and on asymptotic expansions, and was elected professor at the *Coll ge de France*.

The aura of Villat among his French colleagues and his strong academic power contrasted with his scant regard for new ideas. He employed his formidable calculation skills in the search for elegant solutions to well-posed problems rather than in the understanding of new problems. Experiments were excluded from his courses and books “for conciseness,” as he put it. An anonymous review in *Nature* of his *Le ons sur la th orie des tourbillons* (Villat 1930) reported:

Prof. Villat’s treatment of vortex motion has both the virtues and defects which are usually found in French treatises on mathematical physics. The mathematical treatment is clear and logical, and presented in an attractive style. On the other hand, although the lectures on which the book is based were delivered at an Institute founded by the Ministry of Air, we have scarcely any reference to experimental data. There is one oasis in the desert of mathematical symbols (p. 80), where we read that a cylinder moving in liquid is really found, in certain circumstances, to set up two series of vortices closely conforming to those calculated by B nard. With this exception, the book suggests that the author cares much for mathematical analysis and little, if at all, for real fluids. However, if we accept his point of view, there can be no question as to the quality of the work. After an exposition of the classical results, we have a good account of more recent work, in particular that of B nard, Syng , Rosenhead, Caldonazzo,

Riabouchinsky, and Lichtenstein. The last chapter uses Oseen's integral equation to discuss vortices in a viscous fluid. (P. 1930)

In a letter to Jerome Hunsaker, the organizer of the fifth ICAM in 1938 at Cambridge, Massachusetts, von Kármán gave a similar opinion of Villat, offering praise instead for Kampé de Fériet:

Concerning Levi-Civita's recommendation of French representatives of Applied Mechanics, I agree that Villat and Pérès are excellent men; however, Villat is far beyond the line of what we would call the frontier of useful or applied mechanics. I really believe that the man we could use best for a general lecture is Kampé de Fériet, director of the Institute of fluid mechanics, in Lille. In the last years, he published two reviews on recent progress concerning waves and turbulence. Both reports were excellent and just on the limit between the practical and theoretical viewpoint as we like it. Besides that, he follows the experimental research, whereas Villat, in spite of the fact that he is director of an experimental institution, has no idea of experimental questions. (Tazzioli 2016, p. 33)

Villat also ignored turbulence and sometimes hindered work on the topic, as the physicist Charles Sadron experienced. A scientific collaborator of the Air Ministry in Strasbourg, Sadron obtained a grant from the Rockefeller Foundation in 1932 for a stay at Caltech. There he developed a technique to measure fluid velocity in turbulent boundary layers, using the optical birefringence of liquids. (He observed that the use of polymer solutions enhanced the effect, and then turned to the physics of colloids and macromolecules, in which he became a prominent figure.) Back in France, Sadron attempted to publish a book on turbulent boundary layers (the first in France), but he came up against Villat, who "torpedoed" his project, as he wrote to von Kármán (Wesfreid 2017, p. 463). The book was published, in the end, by the Air Ministry. In 1949, in the preface to a memoir on jets, Villat still denounced the "precariousness of some of the hypotheses made [about turbulence], often for practical convenience, far from any solid foundations: thus the definitions they introduce, of transfer coefficients or the mixing length, can hardly satisfy the pure logician" (Villat 1949, p. i).

### 4.3. Joseph Pérès and Lucien Malavard

In 1932, Joseph Pérès (1890–1962), Director of the Institute of Fluid Mechanics in Marseille, was appointed Assistant Professor attached to Villat's Chair. Pérès and his student Lucien Malavard were welcomed "very warmly" in Bénard's laboratory. They pursued their investigation of the rheoelectrical analogy, tackling a wide variety of problems governed by Laplace-like equations, with plane or axial symmetry (lift forces on airfoils, effect of ailerons, and water waves on jetties), and finite-length wings (induced drag, shape of wing tips, and finite-size corrections of wind tunnels). Starting in 1937, their "*calculateur d'ailes*" attracted airplane manufacturers, who saw its advantages compared to long and expensive tests in wind tunnels. Beyond aerodynamics, Pérès and Malavard also tackled problems arising from elasticity (torsion of beams) and electrostatics or magnetism (electric machines), with the support of the Air Ministry and, starting in 1938, of the *Centre national de la recherche scientifique appliquée* (CNRSA). Yves Rocard, consultant for the CNRSA, provided very favorable reports on their grant applications: "The hard problem of the liaison with industry seems to have been solved quite well. [...] The situation of Malavard, one of the most brilliant scientists in Aeronautics, must be made secure" (Rocard 1939). Pérès' team then counted about fifteen people. During the war, Pérès was made welcome with Foch at the *École normale supérieure*, where some clandestine activity was pursued.

Pérès supervised two PhD theses before the war (by L. Malavard and M.-A. Modjtahédi), and four between 1945 and 1950: J. Legras on the lifting line theory, P. Germain on supersonic aerodynamics, R. Siestrunk on the aerodynamics of propellers and flow in turbomachines, and H. Cabannes on transonic flows and shock waves.

#### 4.4. Aerotechnics at Saint-Cyr

Lucien Marchis, holder of the Chair of Aviation since 1909, had close ties with airplane manufacturers but held back from research; he retired in 1934 and his chair was then abolished. Toussaint, his assistant and Director of the aerodynamics laboratory at Saint-Cyr (IAT), was then appointed to the Chair of Aerial Navigation at the *Conservatoire national des arts et métiers* (CNAM)—a teaching institution training technicians and engineers. This appointment confirmed a decision of Painlevé, Air Minister in 1933, to withdraw the IAT from the Institute of Paris (where Villat had no interest in practical questions) and to attach it to the CNAM.

Toussaint directed five theses in the 1930s: on the aerodynamics of biplanes, the interaction of propellers and wings, and the sensitivity of airplanes to turbulent bursts. An active researcher there was Élie Carafoli, future member of the Romanian Academy of Sciences. Throughout the 1940s, only one PhD thesis was defended, on diffusers in wind tunnels.

#### 4.5. Postwar Reorganization

After the war and the recovery by the Air Ministry of the building previously lent to Bénard, Foch was made welcome at the laboratory of mechanical engineering at Saint-Cyr. In 1947 he moved to the Chair of Mechanical Engineering, and his former student André Fortier succeeded him in the Chair of Experimental Fluid Mechanics. Ten years later, Fortier and his student Raymond Comolet moved to Orsay where the University of Paris, at the instigation of the Dean Joseph Pérès, had created a new campus. The laboratory of Fortier and Comolet at Orsay then became the FAST laboratory, which still exists to this day.

Pérès and Malavard left the Institute of Mechanics in 1946 and created a center for applied mathematics, the *Institut Blaise Pascal*, set up near Paris with the new *Office national d'études et recherches aéronautiques* (ONERA)—of which Malavard became an active scientific director. Pérès and Malavard then engaged in the development of scientific computing in fluid mechanics (analog computing). In 1948 they organized an international conference on this topic, with the support of the Rockefeller Foundation. In 1972, Malavard moved his laboratory to Orsay where it became the *Laboratoire d'informatique pour la mécanique et les sciences de l'ingénieur*, which he directed until his retirement.

As for Villat, he found himself at the head of a deserted institute. He remained involved in the *Académie des sciences* until his death in 1972 at the age of 93.

### 5. THE INSTITUTE OF LILLE

At the beginning of the twentieth century, Lille, close to the border with Belgium, was a dynamic city with thriving industry (mines, textiles, and chemicals) and a reputable airplane manufacturer founded by Henry Potez. It had long possessed powerful catholic schools and faculties that had prompted, by reaction, the development of public academic institutions where famous scientists had taught, such as Pasteur, Boussinesq, Painlevé, and Duhem. The teaching of applied sciences was particularly active. The soundness of the project submitted by the rector of the university convinced Caquot to establish an Institute of Fluid Mechanics, despite the drawback of its closeness to the border with Germany. The Institute of Lille opened in November 1929, as did the Institute of Paris (Demuro 2018).

#### 5.1. The Golden First Decade

At Villat's suggestion, the new Chair of Fluid Mechanics was entrusted to the mathematician Joseph Kampé de Fériet (1893–1982), with André Martinot-Lagarde (1903–1986) as Assistant

Professor—a physicist preparing a PhD thesis in the technical services of the Air Ministry. Kampé de Fériet then obtained financing for a new building from a large national investment program, on land offered by the municipality. The construction included, in particular, a large wind tunnel of 2.2 m in diameter and a speed of 55 m/s. A vertical wind tunnel was added in 1938 for the study of spiral dives of airplanes. When it moved into its new building in 1934, the Institute numbered 12 people. Five years later, it had grown to 38, most of them paid by the Air Ministry.

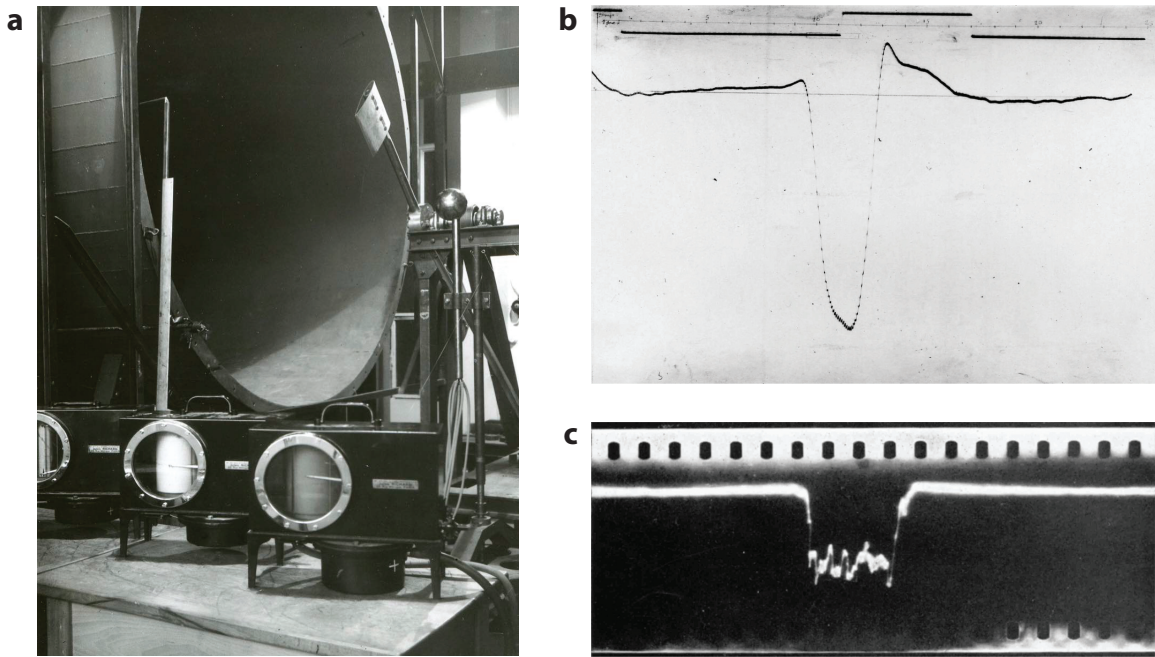
**5.1.1. Research.** Two of the scientific collaborators supported by the Air Ministry defended their PhD theses before the war: on the accelerated motion of solid bodies in liquids (J.-D. Vagner) and on boundary layers in slowly diverging channels (J. Demontis). A theoretical study of viscous flow around a cylinder was achieved by a Turkish student funded by his government (A.R. Berker)—Berker later became Dean of the Faculty of Sciences of Istanbul and in 1952 organized the eighth ICTAM. Martinot-Lagarde, greatly involved in the installation of the new building and the wind tunnel, had little time for his own research (on visualization techniques) and defended his thesis much later, in 1958.

Applied studies for the Air Ministry and aircraft manufacturers included classical measurements and tests. Specific experiments were designed to assess the effect of turbulence carried by the airstream, which was controlled with grids. Other studies were about ventilation problems and the aerodynamic design of cars and railway vehicles—in the wind tunnel, these involved a running belt mimicking the moving ground under the fixed model.

**5.1.2. Teaching and public awareness.** The Certificate of Fluid Mechanics of the bachelor's degree attracted about ten students per year beginning in 1930, together with students from engineering schools. Kampé de Fériet initiated the following year a new master's-level Certificate of Advanced Aerodynamics and Hydrodynamics, whose program changed every year and related to innovative topics such as boundary layers, the mechanics and thermodynamics of the atmosphere, statistical mechanics, and turbulence. Kampé de Fériet, who had a passion for gliding, created a university sailplane club at the local aeronautic association, to which he took his students every week. More generally, the Institute was thoroughly committed to promoting public awareness of fluid mechanics. It participated in commercial fairs and aeronautic exhibitions, where small-scale models were shown together with photographs and films of fluid flows. Pedagogical devices were also created, mass produced by the Air Ministry and distributed to technical high schools.

**5.1.3. Meteorology and turbulence.** Meteorology and atmospheric turbulence were noteworthy concerns of the Institute of Lille. From its creation, the Institute was approved by the *Office national météorologique* (ONM) as a Center of Meteorological Information for Aeronautics, operated by military staff. Measurements of the state of the atmosphere in the area were taken several times a day and transmitted to other centers in France and abroad—in London, Brussels, and Cologne. Conferences for pilots, technicians, and the general public were also given. Motivated by meteorological questions, Kampé de Fériet's own scientific interests turned to turbulence starting in 1933. In 1935, the Institute joined the new Commission for Atmospheric Turbulence created by the Air Ministry. This Commission, headed by the director of the ONM, Philippe Wehrlé, aimed to bring together meteorologists and physicists and to encourage the application of turbulence studies to aeronautics, with Bénard's participation (Wehrlé 1940).

A crucial experimental issue for the study of turbulence was the development of fast anemometers and the characterization of their response time. **Figure 9a** shows the rig within which various anemometers were submitted to sudden variations of wind speed, induced by the passage of a rotating paddle or by the rapid translation of the anemometer across the test section. The response



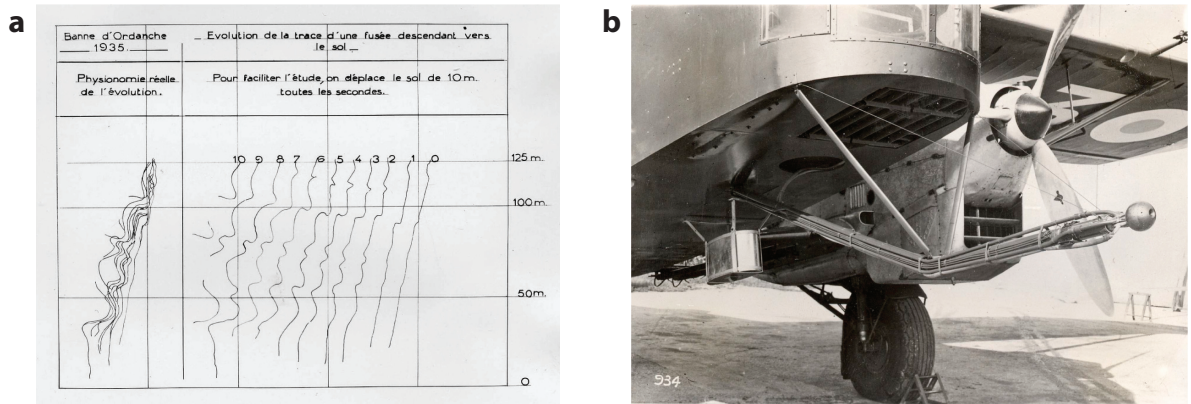
**Figure 9**

(a) Break-wind paddle for the study of the time response of anemometers; on the table are three rotating-drum recorders. (b) Response of an “*anémomètre Papillon*”; the break duration is 2.2 s. Panels *a* and *b* reprinted with permission from Kampé de Fériet (1937). (c) Response of a hot-wire anemometer. Panel *c* reprinted from Kampé de Fériet et al. (1938); copyright 1938 *Académie des sciences*.

of the anemometer was registered mechanically on rotating drums (**Figure 9b**) or by filming the screen of an oscilloscope (**Figure 9c**). A novel anemometer called the anemoclinometer was developed and patented, allowing all three velocity components to be measured; based on the Pitot tube, it consisted of several pressure gauges gathered on a small sphere, with their holes appropriately arranged on the surface. Time series were recorded on photographic paper through an optical system. Anemoclinometers were particularly used for the assessment of the Taylor hypothesis of so-called frozen turbulence—using, in the wind, three devices arranged in a triangle. It was observed that the advection velocity of vortices is generally different from the mean wind. The anemoclinometer was improved and miniaturized over the years (with a cutoff frequency as high as 10 Hz) and exported to laboratories abroad.

The dynamics of the lower layers of the atmosphere (over flat ground or reliefs such as cliffs) was studied by means of cinematography of kites and strings or windsocks, or the drift of wisps of smoke emitted by rockets (**Figure 10a**). For investigations at higher altitudes, a laboratory airplane was equipped with the anemoclinometer (**Figure 10b**). Campaigns conducted at the National Aerological Center at La Banne d’Oranche (in Massif Central) investigated turbulence in convective clouds.

At larger scale, the dynamics of the atmosphere was studied from low-speed cinematography of cloud motion—with positions determined from triangulation using distant cameras triggered electrically. Campaigns of observation of “cloud seas” were carried out in the mountains of the Massif Central and the Alps, with the cameras placed up to an altitude of 4,105 m—the summit of the Mönch mountain in Switzerland. Comparing the motions at noon and at sunset showed the importance of thermal effects.



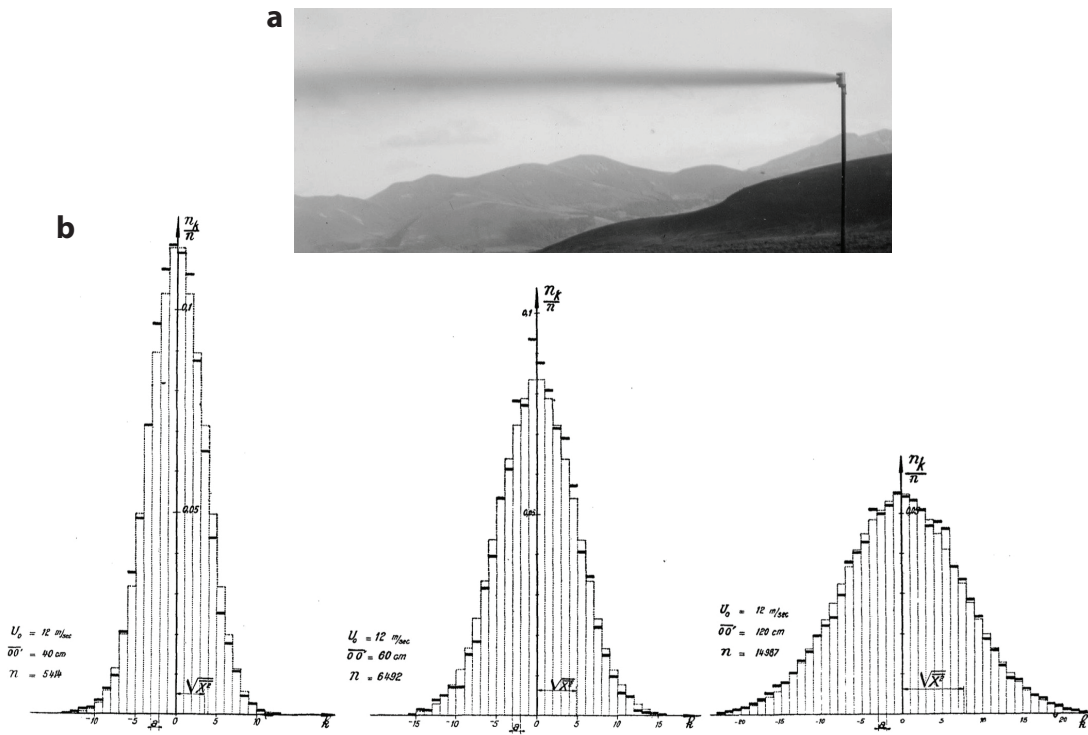
**Figure 10**

(a) Drift of a wisp of smoke emitted by a rocket, shown at time intervals of one second; a discontinuity of the wind velocity, at height of about 100 m, is clearly visible (1935). (b) The anemometer mounted ahead of the fuselage of the laboratory airplane (Potez 54) of the Commission for Atmospheric Turbulence. Panels reprinted from Kampé de Fériet (1937).

In the winter of 1940, Kampé de Fériet and his assistant Henri Guillemet stayed two months on a desert plateau of the Sahara, where they assessed the logarithmic profile of the wind velocity. They also recorded temperature profiles (with resolution of  $0.1^{\circ}\text{C}$ ) and assessed the phenomenon of nocturnal inversion, due to thermal radiation (positive gradient upward) and the warming up from the ground in the morning (negative gradient).

An important concern of Kampé de Fériet was turbulent diffusion. A great admirer of G.I. Taylor and “his marvelous physical intuition,” Kampé de Fériet managed to integrate Taylor’s famous equation (1921) relating the mean-square displacement of fluid particles to the Lagrangian correlation function of the velocity component in the same direction (Batchelor 1996, pp. 162–64). Experiments on smoke plumes showed that, as predicted by Taylor, the shape of the plume is conical near the point of emission and paraboloidal further downstream (**Figure 11a**). Wind tunnel experiments on the diffusion of small soap bubbles allowed for a more quantitative assessment of the radial dispersion (**Figure 11b**)—the results were presented at the fifth ICAM in 1938 (Kampé de Fériet 1940). The statistical analysis of turbulence was pursued in several directions, aiming at, in particular, the improvement of definitions of turbulent statistics, in collaboration with Wehrlé (Kampé de Fériet 1939a,b). These works gave rise to, starting in 1933, considerable correspondence with scientists abroad, especially with von Kármán.

**5.1.4. The Fluid Mechanics Conference of 1934.** On the occasion of the inauguration of the new building of the Institute, a fluid mechanics conference was held in April 1934 under the patronage of the Air Ministry and the Ministry of Public Education. This conference, organized by Kampé de Fériet, was the first of its kind in France—the meetings organized since 1902 by the *Société hydrotechnique de France* were specialized in technical hydraulics. The conference gathered about sixty participants, mostly French academics and engineers (notably Louis Breguet). The presentations were grouped into seven topics based on applications, from aerofoils to air conditioning. Experimental works dominated, with prominence given to flow visualization, meteorology, and the assessment of the circulation theory of lift. Boundary layers appeared twice: in experiments on rotating cylinders by two students of Bénard, and in a calculation of the flow near a stagnation point by Georges Darrieus, known as the inventor of wind turbines with vertical axis and theoretician of the Darrieus–Landau instability of combustion fronts. Turbulence was discussed in a single paper about the effect of turbulence on lift. A talk given by von Kármán



**Figure 11**

(a) Diffusion of smoke in the wind at La Banne d'Ordanche. Panel reprinted from Kampé de Fériet (1937). (b) Radial distribution of small soap bubbles at three distances downstream of the point of emission (wind tunnel experiments) (1938). Panels reprinted from Kampé de Fériet (1940) with permission; copyright 1940 American Institute of Aeronautics and Astronautics.

in Paris in 1932, which had made a big impression on the attendees, was often cited. Although the conference brought modest results, it showed that the policy of the Air Ministry had already borne fruit: Fluid mechanics could gather dozens of academics and engineers with a wide range of interests.

**5.1.5. Loss of scientific independence.** In 1938 an important change occurred in the administrative situation of the Institute of Lille. In the context of persistent weaknesses of French aeronautics and the threat of an imminent war, the Air Ministry and aircraft manufacturers (nationalized in 1936) created a foundation aimed at the coordination of aeronautical research: the French Grouping for the Development of Aerodynamical Research (GRA). The Lille Institute, most of whose staff (nearly forty) were paid by the Air Ministry, was placed under the supervision of this grouping, and henceforth had to execute work ordered from above. Kampé de Fériet was thus released from thankless administrative tasks and the search for funding, but he and Martinot-Lagarde found themselves de facto pushed aside at the Institute they had successfully built with great personal involvement. Harmful consequences for the scientific quality of the Institute would later become apparent.

## 5.2. Withdrawal to Toulouse During the War

When the Germans invaded France in May 1940, the GRA ordered the staff of the Institute to leave Lille hastily. A few documents and instruments were taken in suitcases, while the rest

were destroyed. After three weeks in a hotel south of Paris (where a dancing hall was converted into offices), the personnel moved with their families to a castle in the surroundings of Toulouse. Some scientific life started again, such as courses on fluid mechanics and meteorology in the park and measurements on airfoils mounted over the roof of a car. Supported by Charles Camichel, the Director of the Toulouse Institute of Fluid Mechanics, Kampé de Fériet obtained from the municipality a disused church adjoining the Electrotechnical Institute. There, three wind tunnels were reconstructed under the supervision of the GRA. The largest wind tunnel was equipped with an aerodynamic balance that Martinot-Lagarde succeeded in transporting, despite wartime conditions, from Issy-les-Moulineaux near Paris to Toulouse. Scientific flight campaigns were also conducted in the area.

After the invasion of the southern part of France (the “free zone”) in November 1942, activities continued but in a semiclandestine manner—Kampé de Fériet, foreign member of the *Lilienthal-Gesellschaft für Luftfahrtforschung* before the war, was sought after by the German Air Ministry. Closely linked to the Vichy Government that signed the armistice, the GRA claimed that the studies they ordered the Lille Institute to perform benefited French aviation; in fact, the GRA also collaborated with Germans, as became clear after the war. In November 1942, Kampé de Fériet, troubled by the bureaucratic management that was imposed on him, announced in a long letter to the president of the GRA that he had “the very painful duty” to ask for the cessation of their collaboration: “Scientific research no longer exists for me,” he explained. Nothing occurred at that time, but when the Institute returned to Lille in August 1945, Kampé de Fériet resigned and left the Institute, succeeded by Martinot-Lagarde.

Kampé de Fériet pursued his own research on the statistical theory of turbulence, with frequent stays in American universities and participation in conferences. He then moved his research toward the development of a general theory of time-dependent random systems. His work is cited in books on turbulence by Batchelor (1953) and Monin & Yaglom [1965 (1971)], and in his own review on turbulent diffusion (Kampé de Fériet 1975).

### 5.3. François Naftali Frenkiel

In June 1939, a Polish engineer, F.N. Frenkiel, began a PhD thesis on turbulent diffusion under the supervision of Kampé de Fériet. Displaced from Lille, he pursued his experiments in the wind tunnel of the Institute of Fluid Mechanics in Toulouse, while being harassed by the French administration because he was Jewish. When the *Wehrmacht* entered Toulouse in November 1942, Frenkiel fled to Italy with his pregnant wife. They were arrested at the border by the Gestapo and sent to concentration camps. Frenkiel survived, but his wife did not. He defended his PhD thesis in Lille in July 1946 and received not a State *doctorat ès sciences* but a “university doctorate” because he did not have the required French bachelor’s degree (**Figure 12**). His work appeared in five *Comptes rendus* (Frenkiel 1946a–e) and in a report for the GRA [Frenkiel 1948 (1958)] that was later translated by NACA. Two years later, he emigrated to California at von Kármán’s invitation. The continuation of the story is well known: Frenkiel became a major figure of fluid mechanics and founded the journal *The Physics of Fluids* (Emrich et al. 1987).

## 6. THE INSTITUTE OF MARSEILLE

When the Air Ministry chose Marseille for the creation of an Institute of Fluid Mechanics in 1930, the city already had a long aeronautical history. After the pioneering flight of Henri Fabre in his seaplane over the lagoon *Étang de Berre* in 1910, bases for naval aviation and aircraft manufacturers were established in the area. Marseille thus possessed in the 1930s one of the main aerodromes in Europe, with links to the Far East.





**Figure 12**

The staff of the Institute of Fluid Mechanics of Lille on July 3, 1946, the day of F.N. Frenkiel's PhD defense. Under the arrows are (left to right) F.N. Frenkiel, J. Kampé de Fériet, and A. Martinot-Lagarde. Photo courtesy of M. Dubois; reprinted with permission of the *Institut de mécanique des fluides de Lille*.

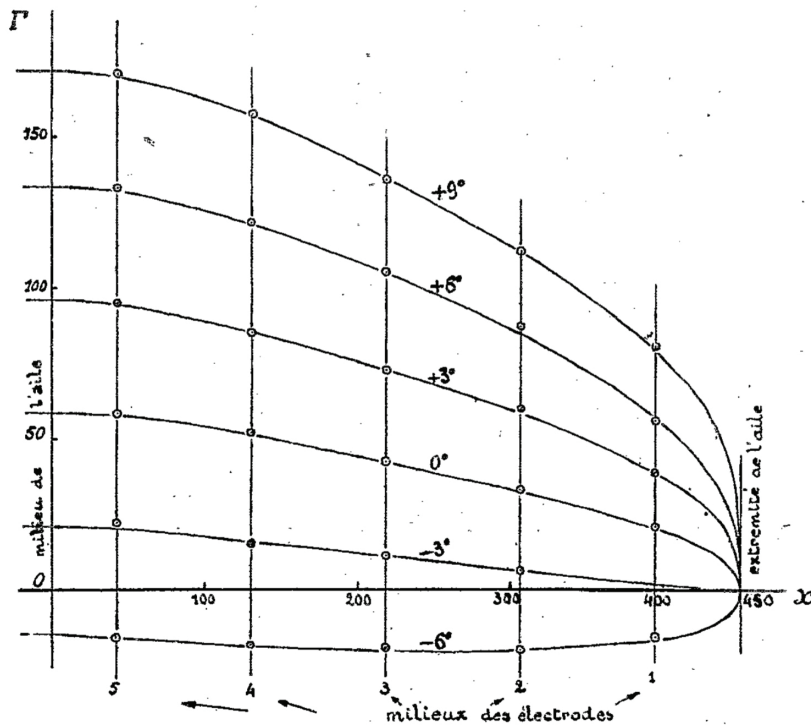
Joseph Pérès, Professor of Rational Mechanics at the Faculty of Sciences, was appointed Director of the Institute. A mathematician, Pérès had prepared his PhD thesis in Rome with Vito Volterra (1915). For the teaching of experimental fluid mechanics, he was assisted by Jacques Valensi (1903–1992), an engineer who had worked on the aerodynamics of propellers at the *Service technique de l'aéronautique*. A student of Pérès, Lucien Malavard, was appointed as scientific collaborator by the Air Ministry.

### 6.1. The Electric Analogy of Potential Flows

The first achievement of Pérès and Malavard was the development of the “rheoelectric analogy” between two-dimensional potential flows around an obstacle and the electric current in a tank filled with saltwater around the same obstacle. Once the streamlines had been determined electrically, the pressure distribution along the obstacle could be quickly obtained from the Bernoulli theorem. Beyond this basic problem, Pérès and Malavard studied various situations, including controlled circulation, discontinuity surfaces, airfoils with flaps, and axisymmetric flows. In particular, they determined the secondary flow around wings of finite length (i.e., in the plane normal to the wind direction) controlled by the variation of the circulation along the wing, which itself obeys an integro-differential equation established by Prandtl (Malavard 1932, Pérès & Malavard 1932). As illustrated in **Figure 13**, the electrical translation of this equation provided the distribution of lift for any geometry of the wing more rapidly than any other method.

### 6.2. Aerodynamics of Wings

In 1932, Pérès moved to Paris and took Malavard with him. Pérès' successor André Marchaud put all his effort into obtaining a plot of land for the Institute and the construction of a building and a wind tunnel. He was still assisted by Valensi and by Alexandre Favre (1911–2005), who succeeded Malavard. Valensi specialized in the aerodynamics of propellers and wings: flow visualization using



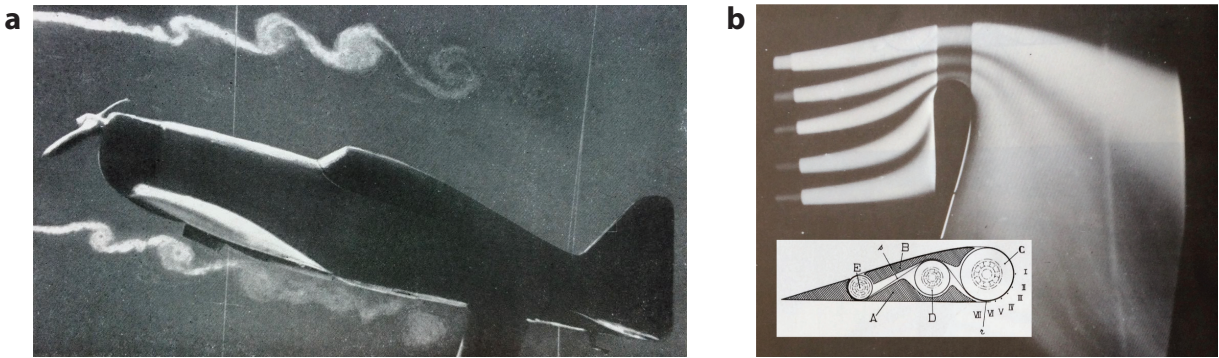
**Figure 13**

Distribution of the circulation along a wing, for six incidences, from Pérès and Malavard's rheoelectric analogy. Figure reprinted from Malavard (1932).

the stroborama described above (**Figure 14a**), assessment of the circulation theory (from pressure and velocity measurements along the wing and in the near wake), and the structure of the wingtip vortices.

Favre first studied two-dimensional flows around obstacles using a Toussaint–Carafoli flume (a water flume with large aspect ratio designed at Saint-Cyr that achieved potential flow in its upstream part). Using velocity fields deduced from the pattern of wave-like streak lines of dye emitted by an oscillating ramp, Favre quantified each term of the Navier–Stokes equations, as well as the vorticity and viscous dissipation—over 580 points for one particular flow! He then invented a “hypersustentation” technique that prevented flow separation on airfoils at large incidence, based on the motion, on the extrados of the airfoil, of a belt running at the speed of the outer flow (**Figure 14b**). The flow thus remained attached at an incidence as high as  $115^\circ$ , providing quite large lift. The running belt was then replaced by a rotating drum that was much easier to design. The technique, applied to flaps, was tested during the war in the wind tunnel of Toulouse—the only working wind tunnel in the free zone of France—and was rediscovered in the 1960s by NASA, which built an aircraft that flew with such flaps.

After his thesis (1938), Favre was appointed to an engine factory near Paris where he designed a new centrifugal compressor, solving an intake problem encountered in the first turbopropellers—separate diffusers arranged at the periphery of the rotor minimized flow detachment and the formation of shock waves. With the outbreak of war, the invention was communicated to French expatriates in Great Britain, where it probably leaked out of French circles, as suggested by the similar design of British compressors.



**Figure 14**

(a) Marginal vortices generated at the tip of the propeller of a Morane 406 (a famous French fighter). Panel reprinted from Valensi (1938). (b) Attached flow around an airfoil at an incidence of  $90^\circ$  with extrados formed by a belt running with the wind speed. (Inset) A sketch of the airfoil design. Images reprinted from Favre (1938).

### 6.3. The War Period

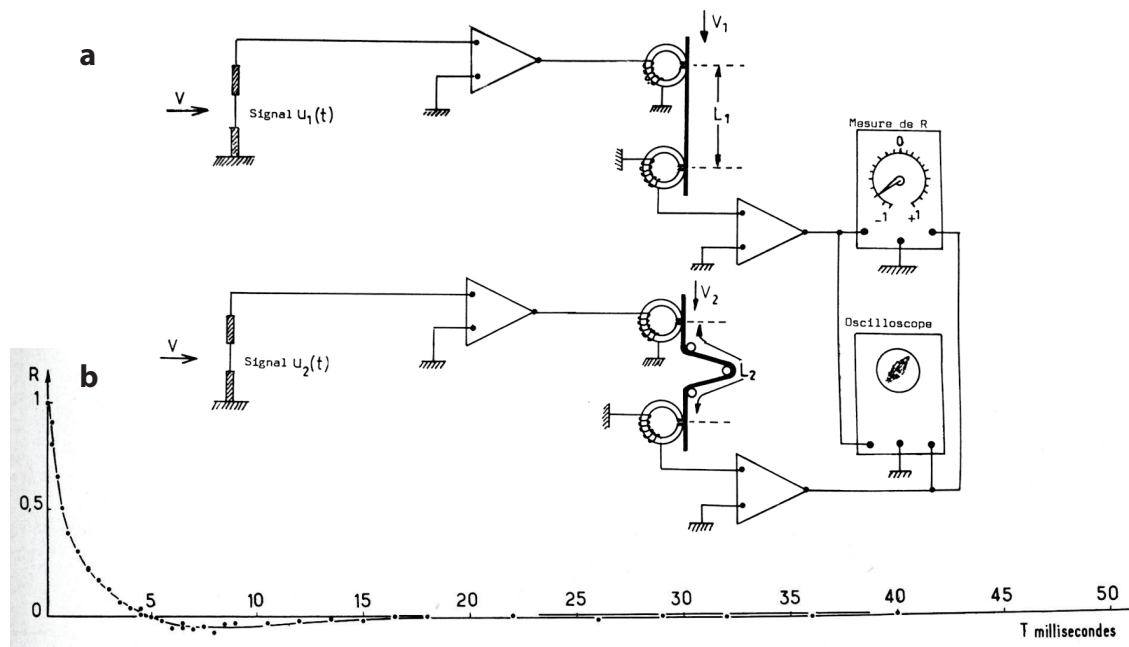
From 1938, the Institute of Marseille was headed by René Thiry (1886–1968), a mathematician who had created in Strasbourg a fluid mechanics laboratory supported by the Air Ministry. Interested in applied mechanics and clever with his hands, Thiry spared no effort to complete, with Valensi, the installation of the Institute of Marseille. The new building was finished at the end of 1940, but the construction of the wind tunnel practically stopped—it was operational only in 1948.

In December 1940, Valensi, who was Jewish, was dismissed by the Vichy Government from his position as Assistant Professor, as all Jews were then excluded from the French administration. However, he continued working in the Institute, unpaid, for one year. Wanted by the Gestapo, he eventually fled to Spain and then to Great Britain where he joined the *Résistance*. Favre, back in Marseille in September 1940, now showed increasing interest in the fluid mechanics of the atmosphere and in turbulence. With the support of ONM, in 1941 he inaugurated a new course in meteorology and mechanics of the atmosphere, which attracted numerous students (universities in the south of France welcomed a great number of refugees after the armistice).

### 6.4. Turbulence and International Openings

Valensi, back in Marseille in 1946, was rehabilitated and appointed as professor in a new Chair of Experimental Fluid Mechanics—still funded by the Air Ministry. Two years later, he succeeded Thiry as Director of the Institute. The main wind tunnel (with an elliptic section  $3.3 \times 2.2 \text{ m}^2$ ), inaugurated in 1948, was immediately active for both industry and the national defense. Studies included airplane stability, aerodynamics of parachutes, dispersion of smoke emitted by ship funnels, transonic flows in compressors, and lubrication of bearings. Electric computers for flow calculations entered the Institute. A high-velocity wind tunnel came into service in 1952, with Mach number up to five. The Institute became very open to foreign scientists, such as Goldstein, von Kármán (who received a *Doctor Honoris Causa* from the University in 1949), and Leslie Kovasznay, who established close relations with Favre.

Favre resolutely turned toward turbulence. In 1947 he created, in a disused chapel, a new laboratory of mechanics of the atmosphere and meteorology, equipped with a low-turbulence wind tunnel (0.038%). In 1951 he was appointed to a new Chair of Mechanics of the Atmosphere and Meteorology, financed by the Air Ministry. With scientists and engineers of the CNRS (*Centre national de la recherche scientifique*) and the ONERA (in particular, Jean Gaviglio), Favre developed



**Figure 15**

(a) Favre's correlation device: Two electric signals from hot-wire anemometers (at the same point or two different points) were recorded on magnetic tapes and then read with time lags  $L_1/V_1$  and  $L_2/V_2$ , where  $V_1$  and  $V_2$  are the tape velocities and  $L_1$  and  $L_2$  are the tape lengths between the writing and reading magnetic heads, respectively. The signals were then multiplied and time-integrated electronically. Variation of the time lag was achieved by displacing the roller between the magnetic heads. (b) Correlation coefficient of the longitudinal velocity fluctuations in a boundary layer. Panels reprinted from Favre et al. (1955).

devices for space and time correlation. Two electric signals from hot-wire anemometers (at the same point or two different points) were recorded on magnetic tapes (**Figure 15a**) and then read with time lags  $L_1/V_1$  and  $L_2/V_2$ , where  $V_1$  and  $V_2$  are the tape velocities and  $L_1$  and  $L_2$  are the tape lengths between the writing and reading magnetic heads, respectively. The signals were then multiplied and time-integrated electronically. Variation of the time lag was achieved by displacing the roller between the magnetic heads. As an illustration, **Figure 15b** shows the time-correlation coefficient of longitudinal fluctuations in a boundary layer.

In 1960, the laboratory created by Favre separated from the Institute of Fluid Mechanics and became the *Institut de mécanique statistique de la turbulence*. The following year, at the occasion of its inauguration, a colloquium on turbulence was organized that gathered together the most famous fluid dynamicists of the time, including Kolmogorov. (The proceedings are still available online.) The colloquium was followed by a symposium on geophysical turbulence, organized under the aegis of IUTAM and the International Union of Geodesy and Geophysics. Favre then turned his interests to compressible turbulence—he established the mass-weighted mean equations that now bear his name.

## 7. THE INSTITUTE OF TOULOUSE

When the Air Ministry proposed the creation of an Institute of Fluid Mechanics in Toulouse, the town was already famous for its aircraft factories founded during the Great War by Pierre-Georges Latécoère and later by Émile Dewoitine. It was also famous for the legendary airline

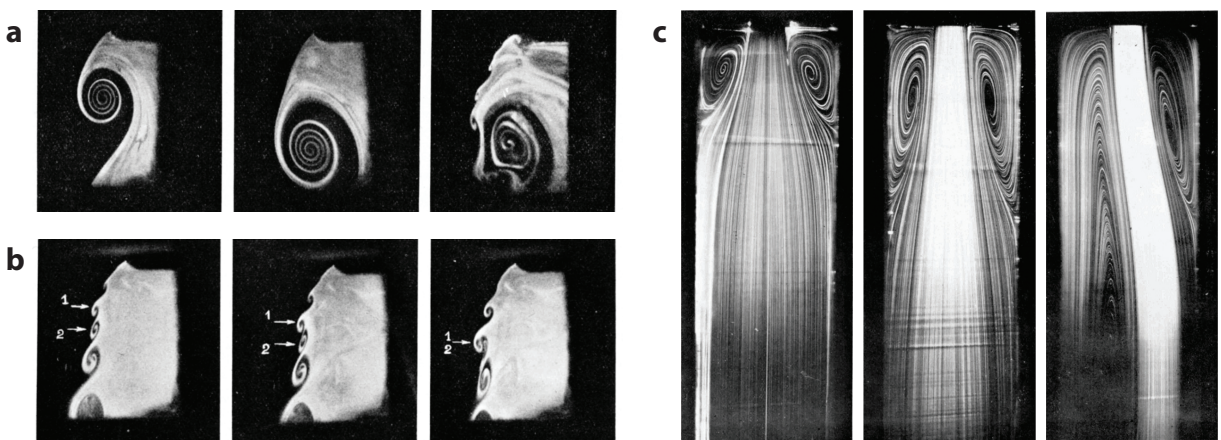
*L'Aéropostale*, which had inaugurated the first commercial flights with South America and employed the French heroes Jean Mermoz and Antoine de Saint-Exupéry. Regular flights had been opened by Latécoère using giant seaplanes from the Biscarosse Lake in the southwest of France to New York. Dewoitine designed efficient fighters—his D.520 was the best French fighter aircraft of the Second World War.

The Institute was created in 1930 with the particular mandate to study seaplanes, and included the hydraulics laboratory established in 1913 by Charles Camichel (see Section 2). Camichel became head of the new Institute, with his student Léopold Escande (1902–1980) as Assistant Professor—a new post funded by the Air Ministry. Following on from the work of the previous decade, the Institute experienced a period of great creativity in the 1930s. Funding and new plots of land were obtained for the construction of a large channel (100 m long, with a traction truck for the study of seaplanes) and a wind tunnel (with a diameter of 2.4 m and velocity of 40 m/s) that was in service in 1938.

### 7.1. Vortices, Forces on Unsteady Flows, and Transition to Turbulence

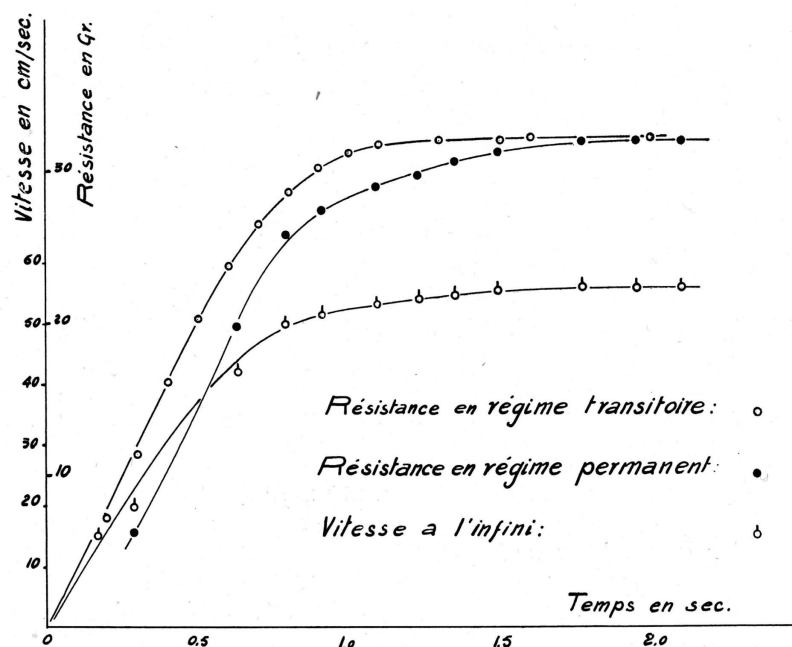
In addition to studies for the hydraulics industry and aircraft manufacturers, research was pursued in several other directions. Experimental techniques reached spatial resolutions less than one millimeter and temporal resolutions of the order of one millisecond.

Étienne Crausse, appointed by the National Fund for Scientific Research (predating the CNRS), studied in particular the vortices downstream of a plate normal to the flow. **Figure 16a** shows the large vortex that first develops as the flow is started, and the small “secondary vortices” that then grow in the sheared region (Kelvin–Helmholtz vortices). Crausse clearly highlighted the phenomenon of vortex pairing (**Figure 16b**). Varying the fluid velocity and viscosity, a viscous scaling law was derived for the frequency of the vortices (measured from stroboscopy and hot wire). **Figure 16c** illustrates another study, on the flow patterns that appear downstream of a sudden enlargement. As the velocity is increased, the steady vortices first stretch, and then the symmetry breaks. It was shown that the orientation of the jet (right or left) may be controlled by a small perturbation (e.g., a thin wire) placed just at the exit of the enlargement. Similar observations were made on turbulent flow in relation to questions of fluvial hydraulics.



**Figure 16**

(a) Development of the starting vortex in the wake of a plate and the appearance of the “secondary vortices.” (b) The pairing of the secondary vortices. (c) Flow in a sudden enlargement at three velocities, with symmetry-breaking at the larger velocity (*right*). Panels reprinted from (a) Crausse & Baubiach (1931), (b) Crausse (1936), and (c) Camichel (1935).



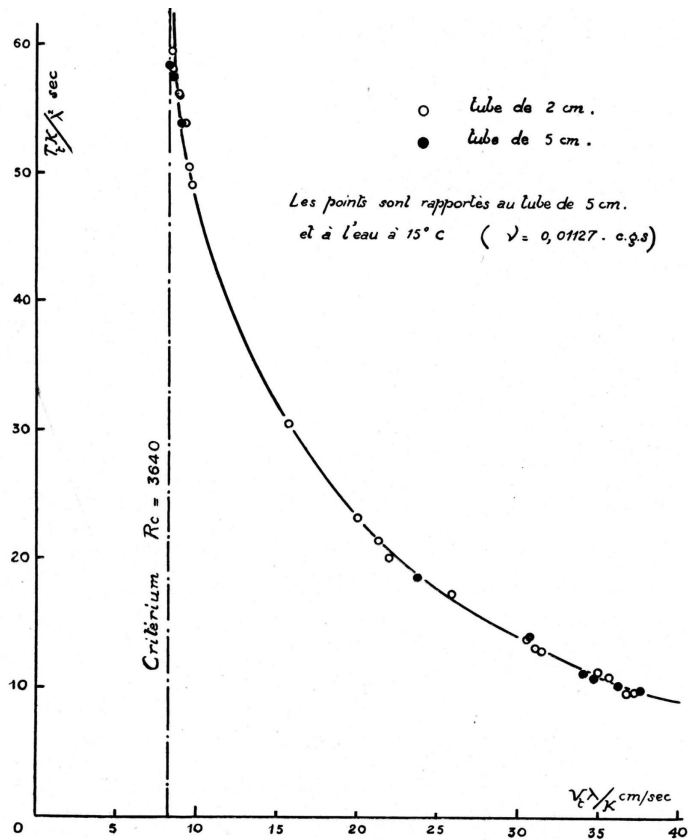
**Figure 17**

Dynamics of a body accelerated by gravity in water: time variation of body velocity (*open circles with tick marks*), actual drag (*open circles*), and drag in steady motion at the same velocity (*filled circles*). Figure reprinted from Baubiac (1936).

Jean Baubiac, appointed by the Air Ministry, studied the hydrodynamic forces on accelerated bodies, which he released in a large tank or in a lake in the Pyrénées—where the motion could be recorded over large depths, up to 80 m. As shown in **Figure 17**, added-mass effects were clearly highlighted by the difference between the actual (measured) force and the force that the body experienced in steady motion at the same velocity (as obtained with an Atwood machine). Baubiac also studied the transition to turbulence in pipes. By suddenly increasing the flow rate from subcritical to supercritical, he observed “a slow dislocation of the non turbulent regime,” with relaxation time (of the mean velocity on the tube axis) growing larger as the Reynolds number (of the final steady flow) approaches the critical value  $Re_c$  (**Figure 18**). He concluded that the most relevant and confident definition of  $Re_c$  is the divergence to infinity of the relaxation time—a quite modern view at the time. The transition from steady to oscillating wakes downstream of obstacles was analyzed similarly, within the frame of the nonlinear van der Pol equation. Finally, among the variety of other problems he studied were the vortex-induced vibrations of beams and wires (leading to phenomena of quasi-periodicity or frequency-locking) and the assessment of the logarithmic velocity profile of free-surface flows up to  $Re \approx 10^7$ .

## 7.2. The War Period and After

The war led to the transfer to Toulouse, in May 1940, of several scientific institutions, including the Institute of Lille, the services of the Air Ministry, the IAT of Saint-Cyr, and the Institute of Mechanics of Paris, along with many major researchers at those institutions (Villat, Pérès, and Foch, among others). The wind tunnel of the Institute of Toulouse then saw considerable activity, mainly for airplane manufacturers.



**Figure 18**

Transition to turbulence in pipes: the divergence of the relaxation time of the mean velocity at the center of the pipe as a function of the mean velocity. Results for the 2-cm pipe are rescaled to those of the 5-cm pipe using the Reynolds similitude ( $\lambda$  and  $\nu$  are the diameter and kinematic viscosity ratios, respectively). Figure reprinted from Baubiac (1936).

The team gathered by Camichel was dispersed, and Camichel retired in 1941. Escande, the new head of the Institute, devoted himself to hydraulics studies for the hydroelectrical industry and to the development of the Electrotechnical Institute. The exceptional know-how in fluid mechanics built up during two decades seemed to be lost. A scientific rebound occurred in the 1960s with the emergence of new fields of research, such as porous media, environmental fluid dynamics, and two-phase flows.

## 8. CONCLUSION

The above panorama (to which should be added, for completeness, works of the centers of Poitiers, Strasbourg, Nantes, and Caen) shows that French fluid mechanics in the first half of the twentieth century achieved important results. Until 1930 these were the work of individuals, notably Bénard and Camichel (on thermoconvection, wake vortices, and similitude laws) and Magnan (on hot-wire measurements and dynamics of the atmosphere). The ambitious program for fluid mechanics set up by the Air Ministry, with the creation of four Institutes and five teaching centers, then gave strong impetus to the discipline. Municipalities, concerned about economic and

social development, favorably welcomed the new Institutes. Remarkable personalities emerged, in particular Kampé de Fériet and Pérès, who, in addition to their scientific contributions to turbulence or scientific computing, played a large part in the organization of teaching and research in faculties.

Strongly encouraged by the Air Ministry, teaching developed considerably. The Certificate of Fluid Mechanics, with a national program at the bachelor's level and equal importance given to theory, experiments, and techniques, as well as advanced courses on more specialized topics, formed the core of university mechanics departments, which trained both engineers and future researchers, among them Leray, Malavard, and Favre.

The international recognition of French fluid mechanics grew from 1926 (once the animosity toward Germans abated) and throughout the fruitful decade of the 1930s, with increasing French participation in ICAM. French mechanicians then played an important role in the creation, in 1946 at Paris, of IUTAM, of which Pérès became the first president. Pérès then created in 1962, with Malavard and their former students Paul Germain and Raymond Sierstrunck, the *Journal de mécanique*, which later merged with other journals to give birth to the *European Journal of Mechanics*.

However, the post–World War II period was a troubled one, with, on the one hand, the disappearance of a generation of scientific leaders (Bénard's death, Camichel's retirement, and Kampé de Fériet's resignation) and, on the other hand, an unfavorable government policy toward funding research. The 1960s then saw an upturn, particularly in Marseille and Grenoble (the latter had been absent from the program of the Air Ministry for geographical reasons), and later in Toulouse.

## DISCLOSURE STATEMENT

The author is not aware of any biases that might be perceived as affecting the objectivity of this review.

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## Errata

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