2 Scientific Biography of Henri Bénard (1874–1939)

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2.1 Biographical Notes

Henri Claude Bénard was born at Lieurey, a small French village in the region of Eure, in Normandy, on October 25^{th}, 1874. He was the only son of Felix A. Bénard (1851-1884) and Hélène M. Mangeant (1837-1901) [1-3]. His father was a small investor, who died very young. H. Bénard finished elementary school in the district of Lisieux and in Caen, nearby his birthplace, and moved to Paris to continue his studies at the Lycée Louis le Grand, one of the best high schools in France. In 1894, he succeeded in the highly competitive entrance examinations to the prestigious Ecole Normale Supérieure in Paris[1]. Indeed, this year, 17 students were selected from 307 candidates in the sciences section and 25 from 205 candidates in the humanities section [4].

H. Bénard studied with some subsequently very well-known companions (the *Normaliens*): he was a classmate of the physicist Paul Langevin and of the mathematician Henri Lebesgue[2]. In humanities studies, the 1894's promotion included Charles Péguy (poet), Albert Mathiez (historian), and Léon Bloch (who started in Literature but worked as a physicist, in collaboration with his brother Eugène). They participated in the activities of the centenary of the ENS and knew the first manifestations of the intelligentsia in favor of the Captain Dreyfus affair initiated by Paul Dupuy and Lucien Herr, the librarian of the ENS.

In 1897, Henri Bénard obtained the degree of *agrégé de physique* and began to work, in the chair of experimental physics at the Collège de France[3], as the

[1] The Ecole Normale Supérieure (also known as "ENS" or Ulm, from the name of the street where it is located) is a French Grande Ecole founded during the French Revolution by a decree of the Convention. Originally meant to train high school teachers, it became an elite institution, training researchers, university professors, and civil servants. It focuses on training through research, with an emphasis on the freedom of curriculum [5].

[2] Paul Dupuy, the main supervisor of the ENS wrote [6]: *"in 1894, I see Paul Langevin getting to the head of a promotion of the Ecole Normale, rich in promises, along with Henri Béghin, Henri Bénard, Noël Bernard, Henri Lebesgue and Paul Montel"*. Indeed, this promotion gave four members to the Institute (the Academy of Sciences of Paris).

[3] The Collège de France is an institution dedicated to knowledge, created in 1529 by the King François I. It has always been independent of any university and free from

assistant of Eleuthère Mascart and Marcel Brillouin[4]. During the first year with Mascart, a specialist in optics, he studied the angle through which polarized light is rotated by sugar in solution. But it was during his second year at the Collège de France that he began to be interested in fluid dynamics. Actually, Marcel Brillouin wanted to repeat Poiseuille's experiments on water-flow-rate laws. He carried out these experiments with mercury, in order to study the influence of viscosity. Great experimental skill was required, especially when measuring the diameter and the cross section of capillary tubes used to study the flux of mercury. Marcel Brillouin wrote, some years later, lectures titled *Lessons about the Viscosity of Liquids and Gases* in which he particularly referred to Bénard's experiments on viscosity in mercury [9]. Under Brillouin's direction, Bénard did the French translation of the second volume of Boltzmann's *Lectures on Gas Theory*, published in 1905. At the same time, Bénard was preparing his Ph.D. thesis. Observing by chance the motion of graphite particles in a molten paraffin bath, he became interested in the organization displayed by particles on the bottom layer of the liquid. Using optical methods, he then studied the movement of the particles in a layer of fluid heated from below, paying special attention to the deformation of the free surface due to convection, using the knowledge and experience he had acquired with Mascart and Brillouin. On March 15, 1901, he defended his thesis before a committee composed of Gabriel Lippmann (1845-1921, Nobel Prize in Physics in 1908), Edmond Bouty (1846-1922) and Emile Duclaux (1840-1904). The second subject of the thesis[5] dealt with the rotation of plane-polarized light by sugar in solutions. The jury did not place enough value on the consequences and meaning of this Ph.D. thesis. In his report on Bénard's thesis, previous to the defense, E. Bouty said that the subject was innovative, and the thesis, a very good one, much beyond the average of the other theses, its main interest lying in the application of a wide range of optical methods, but at the same time he pointed out that Bénard did not make any effort to provide general theoretical explanations to the laws found through experiments. But the

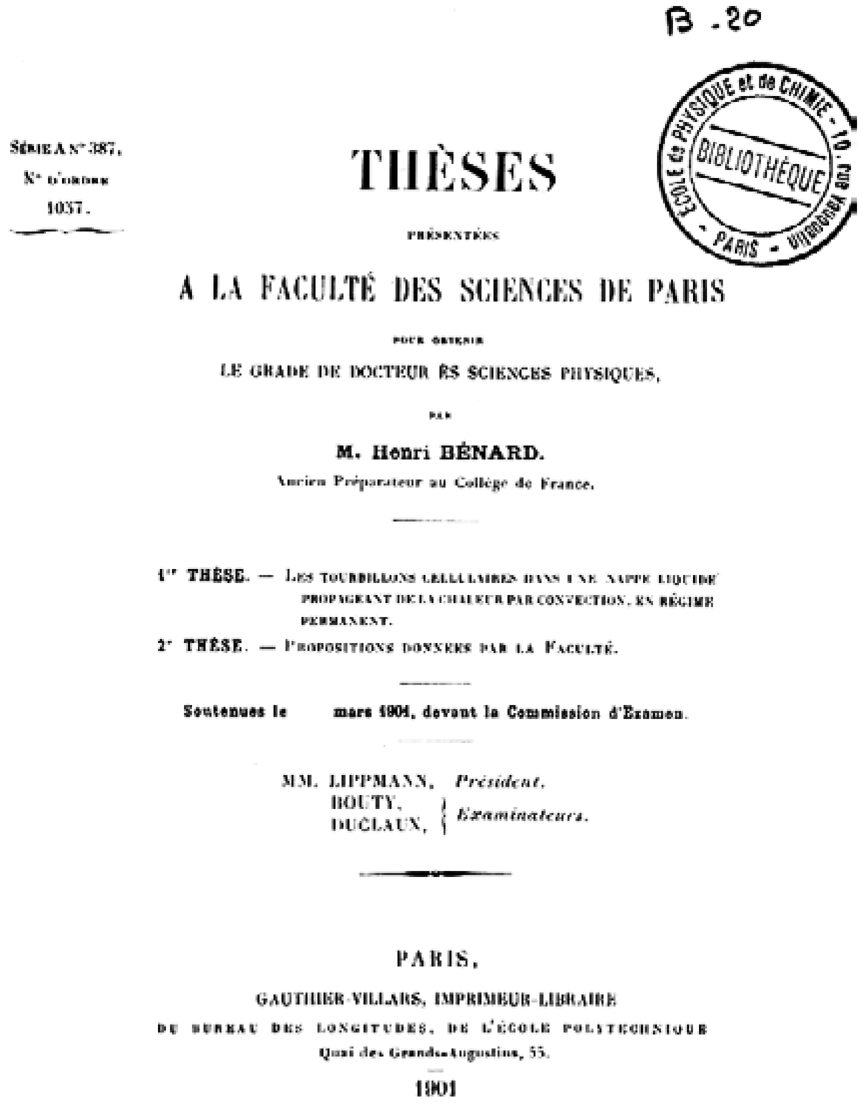
supervision. The lectures are open to the public without registration. The Collège de France does not deliver any certificate or degree. Nowadays, its range of studies includes humanistic and scientific fields. Its faculty staff includes many distinguished scholars.

4 E. Mascart (1837-1908), Professor of Experimental Physics at the Collège de France from 1872 to 1908, was one of the first to study the influence of the earth on optic phenomena. He introduced Maxwell's electromagnetism in France and became very well known for his work on electricity [7]. M. Brillouin (1854-1948) was Professor of Mathematical Physics at the Collège de France from 1900 to 1931. He wrote over 200 experimental and theoretical papers on topics including the kinetic theory of gases, viscosity, thermodynamics, electricity, and physics of condensed matter. Precursor of wave mechanics, and an open-minded scientist, he extended his work from the history of science to the physics of the earth and of the atom. Both, Mascart and Brillouin, were respectively, grand-father and father of another professor of the Collège de France, the physicist Leon Brillouin (1889-1969) [8].

5 A second subject, mostly bibliographical, was at that time, required by the jury at the final stage of doctoral studies.

Fig. 2.1. The 1894 sciences promotion at the Ecole Normale Supérieure, in 1896. Seated, from left to right: Renaud, Massoulier, Béghin, Langevin, **Bénard** and Montel. Standing, from left to right: Lebesgue, Bernard, Foulon, Angelloz-Pessey, Patte, Cambefort, Meynier and Dubreuil (*Centre de Ressources Historiques de l'ESPCI*).

The members of the 1894 sciences promotion were: Joseph Angelloz-Pessey (Professor of Mathematics at the Lycée Buffon, ? -1932), Henri Béghin (professor at the Sorbonne, member of the Academy of Sciences; 1876-1969), Henri Bénard, Noël Bernard (professor at the University of Poitiers; 1874-1911), Georges Cambefort (? -1964), Louis Dubreuil (chemist, professor at the Collège Chaptal; 1873 -1922), Georges Foulon (? -1958), Paul Langevin (he was the eldest of the promotion, as he previously graduated from the Ecole Supérieure de Physique et Chimie Industrielles de Paris (ESPCI), whose director he became in 1925, professor at the Collège de France, and member of the Academy of Sciences; 1872-1946), Henri Lebesgue (Professor of the Collège de France, member of the Academy of Sciences; 1875-1941), Pierre Massoulier (General Inspector of high school teaching in Physics and Chemistry; 1874-1961), Paul Montel (mathematician, member of the Academy of Sciences; 1876-1975), François Meynier, Lucien Patte (professor of physics at the Lycée Charlemagne) and Jules Renaud (? -1951).



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THÈSES

PRÉSENTÉES

A LA FACULTÉ DES SCIENCES DE PARIS

POUR OBTENIR

LE GRADE DE DOCTEUR ÈS SCIENCES PHYSIQUES,

PAR

M. Henri BÉNARD.

Ancien Préparateur au Collège de France.

1

1re THÈSE. — Les tourbillons cellulaires dans une nappe liquide propageant de la chaleur par convection, en régime permanent.

2e THÈSE. — Propositions données par la Faculté.

Soutenues le mars 1901, devant la Commission d'Examen.

MM. LIPPMANN, *Président.*
BOUTY, DUCLAUX, *Examinateurs.*

PARIS,

GAUTHIER-VILLARS, IMPRIMEUR-LIBRAIRE
DU BUREAU DES LONGITUDES, DE L'ÉCOLE POLYTECHNIQUE
Quai des Grands-Augustins, 55.

1901

Fig. 2.2. H. Bénard's Ph.D. thesis, published by Gauthier-Villars.

report, established after the defense, mentioned that "... *though Bénard's main thesis was very peculiar, it did not bring significant elements to our knowledge. The jury considered that the thesis should not be considered as the best of what Bénard could produce*"[6].

Once H. Bénard finished his thesis, he settled down in Paris, with a fellowship from the Foundation Thiers, and got married the same year, on December 23, to Clémentine Malhèvre (1876-1943), a few months after his mother's death. They had no children. The following year he was appointed assistant professor at the Faculty of Sciences in Lyon, where he was in charge of introductory courses. At that moment, a new experimental activity began: the observation of the fluid motion when a prismatic body is moved across a container filled with liquid. Bénard was astonished by the deformations he observed on the free surface of the liquid, which he associated with the presence of vortices in the fluid. This observation led him to build an experimental facility in the university building's basement, in order to observe the deformation of the free surface of the liquid when vortex shedding occurred.

Bénard's scientific research is marked by a specific element: the use of cinematography as an instrument of observation and measurement. In fact, in the experiment performed in the Faculty of Science in Lyon, he used the movie camera as a means of observation. He published the description of these alternating vortices in two articles in the *Comptes-Rendus Hebdomadaires des Séances de l'Académie des Sciences de Paris*, in 1908 [B12, B13]. In 1910, he was appointed professor of physics at the Faculty of Science of the University of Bordeaux, where Pierre Duhem[7] was the head of the physics laboratory [10], and carried on the analysis of the movies he had made in Lyon, particularly on the wavelength and the frequency of emission of vortices as a function of different parameters such as the velocity and the dimensions of a moving body. Simultaneously, he used a movie camera to make many movies of convection for scientific popularization. In 1914, the First World War broke out and Bénard, as a former student of the Ecole Normale Supérieure, was mobilized with the rank of officer and appointed to a military scientific commission. One of the subjects he dealt with was the improvement of the refrigeration wagons transporting meat to the front. He actually conceived new methods for the measurements of the thermal diffusivity of the wagon's walls. This work was published after the war, in 1919 [B21, B23]. Later on, he was sent to the Superior Commission of Inventions of the Ministry of War, to work on different aspects of optics. He had been interested in the

[6] *"Bien que la thèse principale de M. Bénard d'ailleurs fort curieuse, ne paraisse pas susceptible par ses développements ultérieurs, d'ajouter grand chose de nouveau à nos connaissances, le Jury a été unanime à estimer qu'il ne fallait pas prendre cette thèse comme la mesure définitive de ce que M. Bénard peut donner."*

[7] Pierre Duhem (1861-1916) was professor of theoretical physics at the University of Bordeaux from 1894 until his death. He achieved works of leading importance in the philosophy of science, historiography of science, and science itself. His interest in science was mainly directed to areas of mathematical physics, and especially thermodynamics.

wakes produced by submarines, and had studied the traces of ships in the sea and the advantages of using polarized light. Following his propositions, the National Navy Office built a periscope with polarized prisms in spath of Island, which was also provided to the Allies. Bénard also built panoramic glasses with cylindrical lenses, trying to enlarge the image in one direction, an invention that revealed itself useful for naval applications. Between 1917 and 1919, he participated in the Directorate of Inventions of the Ministry of War of which he later became head of the physics section under the direction of Jules-Louis Breton[8].

In 1922, Bénard moved from Bordeaux to Paris, where he was appointed as assistant professor at the Faculty of Science of Sorbonne University. Four years later, in 1926, he was named full professor and taught general physics to first-year students. In 1928, he became president of the French Physical Society for one year.

As far as experiments are concerned, he carried out new studies on alternating vortices and faced difficult moments in his career due to the lack of financial support. But finally in 1929, he took part in the new Institute of Fluid Mechanics, whose creation was the result of an important cooperation between the Sorbonne University of Paris and the Ministry of Aeronautics[9], and a year later, he was appointed professor of experimental fluid mechanics. In 1932, 19 persons worked in this institute, including 12 fellowships supported by the Air Ministry. They represented 11 percent of the researchers on the staff of the Faculty of Sciences in Paris [15]. Bénard was in charge of the experimental fluid mechanics laboratory, with enough room for a very important experiment on vortex shedding: on the first floor was a container with a bluff body that produced the emission of vortices, a phenomenon observed from two floors higher above by means of a movie camera.

In his laboratory at the Institute of Fluid Mechanics, Bénard was the advisor for several theses on different aspects of natural and forced convection and also

[8] Jean-Louis Breton (1872-1940), deputy of the Republican Socialist Party, was head of the War Office of Invention. The Office of Research and Inventions, established in 1922, is one of the ancestors of the present CNRS.

[9] The Ministry of Aeronautics, under the technical coordination of Albert Caquot, created the Fluid Mechanics Institute of Paris at the University of Paris, and gave strong financial support to scientific research in fluid mechanics, setting up the same year, four chairs, with eight professors [11,12]. The Institute in Paris was then placed under the direction of Henry Villat (1879-1972), who worked in mathematics and in theoretical fluid dynamics. A member of the Academy, Villat became its president in 1948 [13]. He maintained a close friendship with Bénard, as they were both from Normandy. Other laboratories were opened in Marseille, under the direction of Joseph Pérès (1890-1962), who moved in 1932 to the Institute in Paris [14], in Lille under the direction of Marie-Joseph Kampé de Fériet (1893-1982) while in Toulouse, activity developed with Charles Camichel (1871-1966). Five associated chairs were also created in Caen, Lyon, Nantes, Poitiers, and Strasbourg.

Fig. 2.3. Henri Bénard, Professor in Paris.

on vortex dynamics. Among his students and collaborators we can mention[10] the following. Dusan Avsec, from the Balkans, arrived in the laboratory in 1934 and worked in thermal convection of forced flows. He also studied electroconvection jointly with Michel Luntz. The latter worked on flow singularities. C. Woronetz finished his Ph.D. in thermal convection in 1934. H. Journaud did experiments on convection rolls until 1932, and his works was followed in 1936 by Victor Volkovisky who finished his Ph.D. thesis on longitudinal rolls in 1939. Paul Schwarz presented his Ph.D. thesis in 1937 on optical methods applied to the vortex shedding experiments. V. Romanovsky studied convection in muds and G. Sartory, convection induced by radiation. François-Joseph Bourrières, a former Bénard student from Bordeaux and professor at the Lycée Stanislas, did research in the Institute of Fluid Mechanics on fluid-structure interaction. Malterre worked on solitons and L. Denes, from Hungary, on thermal conductivity. André Fortier (?-1996) experimented on the viscosity of air and gases. In this group, Robert Fabre (1908-2002) and E. Drussy were technical assistants. At the same time, in the Institute, Lucien Malavard (1910-1990) and Lucien Romani (1909-1990), assistant and technician respectively, were working on electrical analogies of phenomena of fluid mechanics in the laboratory of Joseph Pérès, assistant professor. Another group in the Institute, directed by Adrien Foch (1887-1980), assistant professor, who designed a supersonic wind tunnel, included M. Dupuy, Lucien

[10] According to the information we have presently, we could not verify the full list of Bénard's collaborators and not even if the ones mentioned as such in this list, were really collaborators.

Santon who did experiments on interferometry and wind tunnels, and Charles Chartier, who accomplished a Ph.D. thesis on flow visualisation in 1937.

Henri Bénard died on March 29, 1939, at Neuilly-sur-Seine, near Paris. A. Foch, assistant professor, succeeded Bénard as professor in experimental fluid mechanics[11] at the Institute of Fluid Mechanics and Yves Rocard (1903-1992) moved from Clermont-Ferrand to Paris, in order to assume the assistantship. After the war, Y. Rocard went to the Ecole Normale Supérieure as head of the physics department, and worked in various fields of research such as semiconductors, seismology, and radio astronomy. He was one of the main leaders of

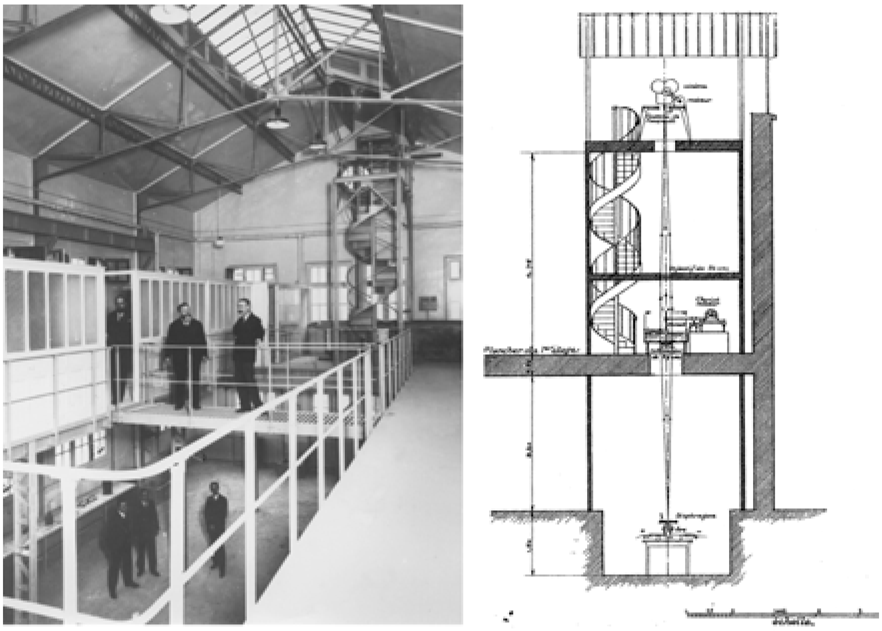

Fig. 2.4. View of the laboratory at 4, rue de la Porte d'Issy, in Paris. In the picture, from left to right, on the upper floor, D. P. Riabouchinsky, H. Bénard and H. Villat and on the lower floor, L. Santon, C. Woronetz, and H. Journaud. At right, scheme of the vortex shedding installation, observed in the back of the picture.

Dimitri P. Riabouchinsky (1882-1962) an emigrant from Russia worked in the Institute. He had previously founded a private Aeronautical Institute at Koutchino (Russia) where in 1912 he built an important wind tunnel.

the new generation of French physicists of the post-war period and reorganized research in various fields of physics. At the same time, the Institute of Fluid Mechanics, with H. Villat, A. Foch, and J. Pérès, originated many activities in

[11] Following Bénard's lectures at the Sorbonne, Léonard Rosenthal and three other students contacted A. Foch in 1939, in order to do research on the same topics. Foch told them that Bénard's subjects were exhausted and could no longer be subjects for theses! (L.R., personal communication)

mechanics, especially in aeronautical and military research. In September 1946, H. Villat presided over the Sixth International Congress of Applied Mechanics in Paris, and proposed, along with Johannes M. Burgers from Delft, the creation of a permanent organization for the science of mechanics, under the form of an International Union of Theoretical and Applied Mechanics (IUTAM).

2.2 Convection Cells

In 1898, when Henri Bénard was working at the Collège de France, and trying to prepare a coherer with solid dielectrics, he observed, by chance, the presence of semiregular polygonal figures in a melted paraffin bath in which graphite dust had been incorporated. He inquired if this apparently common phenomenon had already been observed scientifically and decided to prepare laboratory experiments on thermal convection, in order to describe and measure, in a horizontal liquid layer heated from below, the convection currents that prevailed, as near as possible to their state of greatest stability. Much of his effort had been devoted to avoiding any inhomogeneity in temperature that could initiate an uncontrolled process in the movement of the liquid, a preoccupation he expressed by saying *"It is clear that, if even the littlest fluctuation or local excess of temperature, is sufficient to create a centre of ascension; how is it possible to obtain a stable regime?"* Due to the construction of an apparatus with a metal container and steam circulation, offering very homogeneous thermal conditions and a constant temperature in the lower layer of the liquid, he observed different patterns of convective movement. The main result of his observations was the discovery of a pattern of almost regular hexagonal cells, called *cellular vortices*, that is to say, a stable system with particular geometric characteristics to which he had already devoted study during his Ph.D. work. He used the expression *tourbillons cellulaires*, which were later known as Bénard cells (*cellules de Bénard.*) He insisted on the polygonal characteristics of this cellular, semi-regular vortex, due to the existence of polygons of four, five, six, and seven sides, but with a predominance of hexagons. He pointed out the difficulty of producing regular hexagons on a long surface without many defects. These cellular vortices could be generated in a steady state, under a moderate heat flux. Bénard also observed vortices in fairly volatile liquids, such as alcohol or hydrocarbon, underlying the fact that evaporation chilled the surface, causing a vertical heat flux. In order to produce a uniform thickness and to avoid evaporation problems, he worked with higher temperatures, between 50 ° C and 100 ° C, using substances which melted at 50 ° C such as wax or spermaceti, a whale oil, which melts at 46 ° C but has no significant volatility below 100 ° C. This allowed him to create liquid films of one millimeter thickness controlled to with one micron and to obtain a spread of the thin layers, which remained constant for many hours.

Bénard studied the circulation of the liquid within the convective cell. He accurately determined the pattern of the trajectory with closed streamlines, studying the warm liquid ascending through the axis of the hexagonal cell and descending along the periphery bordered by vertical planes. He observed the

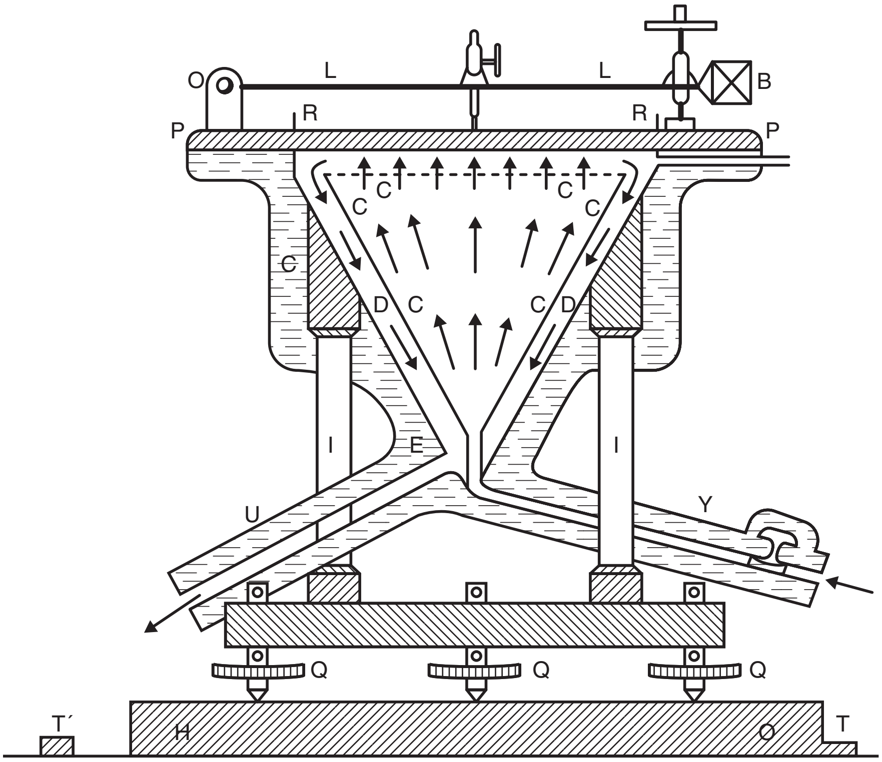

Fig. 2.5. Apparatus used by Bénard, during his Ph.D. work.

formation of a convective structure with different polygonal structures tending to a hexagonal one as a limit state, with extremely slow deformations, up to the point at which it reached a very regular shape that allowed him to measure the distance between the vertical axes of two contiguous hexagonal cells. Bénard, impressed by the periodicity discovered, studied the geometrical characteristics of these convective structures using different methods, and more precisely, the relation between the wavelength and the thickness of the liquid layer [18].

Bénard described two other types of cellular vortices that appeared in his experiments. The first one was the *tourbillons en bandes* or convective rolls, to update the expression, in a stable permanent regime whenever the heat flux is small. Later, he used Rayleigh's expression *striped-vortices* to define the phenomenon, as well as *cellular vortex of the second kind*. He tended to use the concept of *tourbillons en bande* in order to point out the fact that the structure exhibited the same spacing between strips, that is, a constant wavelength. He described a third regime called *tourbillons en chaine* or *vortex worm*. This regime, unstable and turbulent, is formed in liquids that evaporate in open air and when the heat flux is important. Cinematography was particularly useful in studying this régime. His study was mostly performed with experiments on free surfaces. Afterward, his colleague and collaborator Jean Camille Dauzère[12] became interested in experiments with an upper covered rigid surface.

One of the characteristics of Bénard's thesis work, developed in a relatively short period of time, is the enormous number of experimental methods used for the observation of the cell structures. Visualizations were achieved projecting fine licopodium grains on a free surface and drawing their trajectories on the free surface. He could also observe the border of the hexagonal cells by means of the reflecting particles of graphite powder or aluminium. As the convective

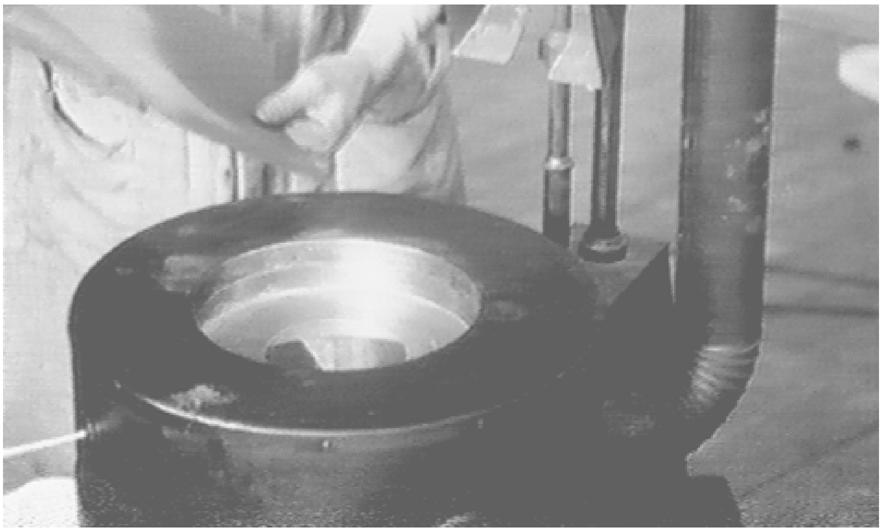

Fig. 2.6. Picture from one of the Bénard's movies, when the operator (Bénard himself?) introduces the particle tracer in the container.

motion in the liquid layer changed the pressure, the free surface was no longer flat. Therefore Bénard used the reflection produced on the deformed free surface as a concave mirror in the middle of the cells to visualize them. The best images of the polygonal structure were taken with optical transmission where the light is transmitted across the liquid layer and reflected on a steel mirror on the bottom of the recipient. He had recourse to Schlieren or Foucault's method of beam deflection on a disturbed surface to distinguish hills from valleys and to identify the rising and descending streams. This method allowed him to obtain very accurate free surface measurements. We should also note Bénard's ability

[12] C. Dauzère (1869-1944) was a professor of physics at the Lycée of Agen, in the south of France, and later in Toulouse. His first experiments were performed in Agen and published in 1907. During 1913-1914 he spent one year doing experiments on solidification in the industrial chemistry laboratory of Professor Charles Fabre in Toulouse and defended a Ph.D. thesis in Paris in 1919. He assumed the direction of the Pic du Midi Astronomical Observatory in 1920 until 1937, where he became interested in thunderstorms and hail [17].

to measure thickness differences of 1 micrometer for liquid layers of 1-millimeter thickness of spermaceti at an average temperature of 100 °C. With the interference fringes obtained with a first beam reflected on the upper free surface and a second one crossing the layer, reflected on the steel mirror in the bottom of the layer, Bénard succeeded to plot the isotherms, separated by 0.1 °C, within the convective cell.

In 1916, Lord Rayleigh (J.W. Strutt, 1842-1919) published in *Philosophical Magazine* a paper about the stability of a fluid layer subjected to a vertical gradient of temperature, referring to "*the interesting results obtained by Bénard*". In this article, Lord Rayleigh, considering a fluid with symmetrical free - free horizontal boundary conditions, got results on the critical temperature difference necessary to produce a convective motion. From the analysis of stability, he determined the wavelength of convective cells on the instability threshold, equal to two times the thickness. The fact that this article had been published during

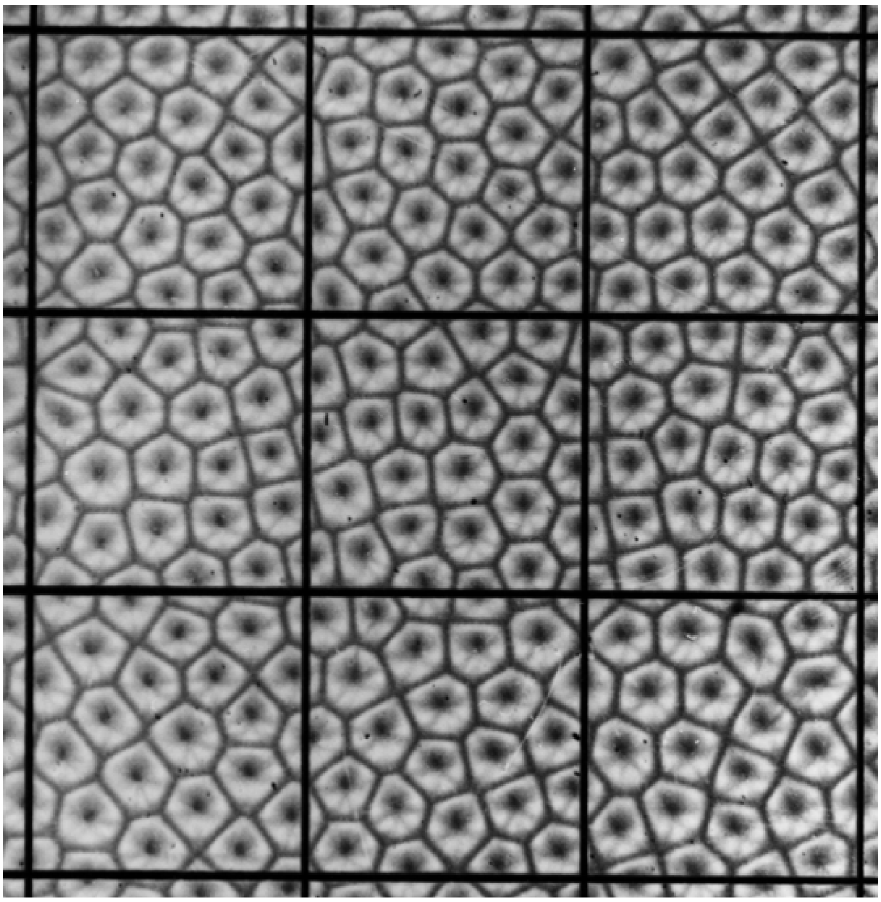

Fig. 2.7. Convection cells.

the war prevented Bénard from reading it before Lord Rayleigh's death, a fact he regretted because he was no longer able to discuss it with him. Several years later, in 1928 and 1934, Bénard tried to compare the predicted onset values, especially those from the new calculations from Jeffreys' work on asymmetrical rigid - free limit conditions. These conditions corresponded to the experiments he had done with a free surface. For an hexagonal structure, Bénard concluded that the theoretical value of the critical wavelength, equal to two times the thickness, was very close to the value he had obtained in his experiments. He discovered strong discrepancies between predicted and measured onset values, which were understood several years later. Myron J. Block realized experiments in 1956 [19] (similar to the ones of Bénard), and suggesting that the buoyancy could not be, in this experiment, the driving mechanism of the convection, considered that the Bénard cells are produced by variations in the surface tension with temperature. In 1958, Pearson [20] introduced the concept of surface tension gradient instability (Marangoni effect). Six years later, Nield [21] proved that the combined effect of buoyancy and Marangoni's effect caused the instability. The physical mechanism, actually responsible for the convective motion considered by Rayleigh's theoretical analysis, is the buoyancy, that is to say, the Archimedes force[13]. Bénard cited only two references as previous work on cellular convection.

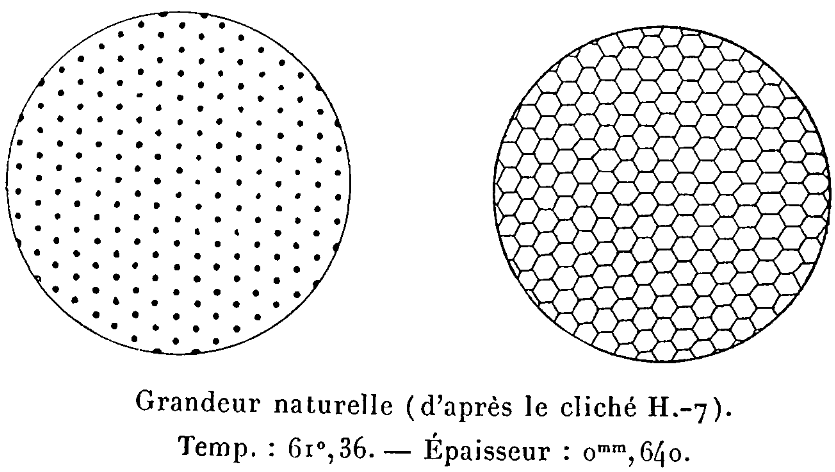

Fig. 2.8. Cells visualization by reflection and transmission: Temperature = 61,36 ° C, thickness = 0,640 mm.

The first one came from E.H. Weber, who, in 1855, had described polygonal structures in drop dissolutions. Later, M.O. Lehmann gave a thermal origin of this phenomenon. He also referred to A. Guébhard, who, in 1897, observed vortex

[13] In fact, C. Dauzère [22] described that when he was boiling wax mixed with water, he observed a very different stability in respect to Bénard's observations. He provided an explicit explanation of this situation by the fact that the composition of the liquid modifies the surface tension and, consequently, the stability.

motion in an abandoned bath of film developer. Bénard some time later found a work by James Thomson (Lord Kelvin's brother; 1822-1892) published in 1882, entitled *On Changing Tessellated Structures in Certain Liquids.* This study dealt with the cooling of saponaceous water and the apparition of polygonal prisms.

The observation of symmetry and periodicity of the cellular vortices induced Bénard, like many other physicists of his time, to compare it with other structures observed in nature or even in life. But he knew that the thermoconvective explanation was not valid for the origin of most of the hexagonal structures observed in nature. In the thirties, he discussed the difference between living tissue and hexagonal structures, the last ones being formed by one layer of cells, and the former by several layers of superposed cells and wrongly mentioned the analogy between these latter cells and the annular cells (or Taylor-Couette rolls) observed by Geoffrey I. Taylor (1886-1975) in 1923, rolls he considered as superposed cells.

After Paul Idrac's work in 1920 [16], meteorologists became interested in the existence of convective rolls of hundreds of meters in diameter in the atmosphere[14]. The only model for understanding cloud structure was the one transverse to the wind and formed by shear layer instabilities ("Helmholtz waves" as they were called at that time). The presence of thermoconvective longitudinal rolls parallel to the wind, was a subject that Bénard promoted. He directed experiments related to this explanation, performed by his students Journaud, Avsec and Volkovisky at the Institute of Fluid Mechanics, experiments in which the fluid layer heated from below is put in motion by an inclined plane or a moving band. Dauzère observed through experiments on solidified wax that it solidifies first at the top of the border of the hexagonal convective cell because of the presence of cold currents inside the cell. From this observation and by analogy, Bénard provided a theory on the relief of craters on the moon, explained as some sort of slow cooling and solidification of surface layers of the moon minerals instead of the impact of meteorites. He also published a paper [B16] where he speculated about the analogy between cellular vortex patterns and fracture patterns in soil[15]. Bénard was aware of Jansen's observations in 1896 at the Paris Observatory about sun granulation and subscribed to a convective theory to explain these patterns. Also several scientists tried to study the polygonal shape of the granules, immediately related to turbulent convection in terms of Bénard's hexagons. Today, the role of these convective mechanisms is accepted, in the structure of solar granulation (see Chapter 6 of this book).

[14] Schereschewsky said that Bénard probably discussed these ideas with Idrac (1885-1935) when they worked together during the war, at the Commission of the Inventions [3].

[15] In a personal reprint of this paper, Bénard mentioning hand-script, "*Ne pas diffuser*" (not to be distributed), suggesting that he was aware of the risk of this speculation.

2.3 Vortex Shedding in Bluff Bodies

In 1898, Bénard began to be interested in experimental hydrodynamics, as he was collaborating with Marcel Brillouin at the Collège de France, on the viscosity of liquids. When he opened his laboratory at the Faculty of Science in Lyon, he began in 1904, an experiment on an obstacle, an elongated lamina, moving in the bottom of a rectangular container of 1.35 m x 0.35 m filled with a layer of 0.12 m. of water. He observed the deformation of the free surface, associated with the presence of a double trail of alternating vortices in the wake and carried out very meticulous experiments in order to obtain accurate measures of geometrical and kinematical properties. In order to study the deformation on the free liquid surface produced by pressure variation due to the existence of vortices, he used the same Schlieren optical method that had been used in thermal convection. Therefore, he was able to follow the position of the center of rotation of each vortex. Facing some technical difficulties in photographing these capillary ripples in the interface, he decided to use a movie camera, equipped with a motor, developed by Louis Lumière (1864-1948). He could then film the vortex shedding for a period of several seconds and in November 1908, he published the papers [B12,B13] in which he described two results: the existence of an alternating row of vortices and the fact that the distance between them depended only on the transverse size of the bluff body[16]. By that time, he had already analyzed more than 30,000 images from which he obtained the law of frequency as a function of velocity, as well as the geometrical characteristics of the vortex emission.

He kept on studying the results of the films from Lyon until 1925. An analysis of Bénard's laws can be found in Provansal's contribution, chapter 10 of this book. After his 1908 papers, Bénard continued to process the pictures of his experiments performed during 1908 and 1909, and in 1913 he published two new papers [B17,B18]: the improvement due to the use of the movie camera made possible the observation of the center of vortices and the precise determination of their velocity and of the distance between them. The meticulosity of the data analysis of the 133 films[17] on vortex shedding experiments that he produced, among which, after several years of research, he retained only 71, must be highlighted. From there he obtained spatio-temporal diagrams, one of which is shown in Provansal's contribution.

The analysis of this complete data set ended with four papers published in the *Comptes-Rendus de l'Académie des Sciences de Paris* in 1926 [B28-B31]. In these papers, by analyzing the period fluctuations, estimated to be between

[16] He later recognized that it was a speedy study and that the first one contained a drawing mistake (the sense of the vortex's rotation was inverted), mistake he corrected in 1913 [B17].

[17] During the Second World War, in June 1940, the German army held the buildings of the Institute of Fluid Mechanics in Paris. L. Malavard and L. Romani, from Pérès' laboratory, succeeded, in extremis, in taking away a rheological calculator to the Free Zone[12]. One day, the German soldiers threw in the dustbin Bénard's experimental movies on vortex shedding in order to use the cupboard in which they had been stored (R. Fabre, personal communication).

five and ten percent, Bénard performed ingenious statistical analyses of a great number of measures taken in order to obtain the law of the frequency as a function of the flow velocity. As he himself recalled, the main purpose of his thesis work on thermal convection was to measure with precision the periodicity of cellular structures. He showed the same interest when he began to study the alternating vortices behind a bluff body: his fundamental aim was to measure the frequency of emission of vortex shedding. This explains not only the use of the camera as a method of measurement, but also the great effort spent on data analysis for several years in order to obtain the laws of the variation of the frequency with the physical parameters of the experiment. The subject had become a wide topic of investigation in hydrodynamics. In Toulouse (France), C.H. Camichel, M. Teissie-Solier, L. Escande, and T. Dupin were specifically working on vortices emitted by circular cylinders. In 1928, Bénard published two other papers [B37, B38] in which he compared his observations with those of the Toulouse group, particularly on the similar properties of the law of frequency of the vortex shedding as a function of the Reynolds' number, that is to say, the nondimensional value of the fluid velocity. He expressed the frequency with the Strouhal number S[18] , which was the adequate frequency parameter he had already proposed several years earlier. Bénard did not observe a minimal Reynolds number for vortex shedding and concluded wrongly, as we now know, that there is no critical parameter for vortex shedding. In addition, he questioned the existence of similarity when comparing the results obtained with cylinders and laminas.

Lord Rayleigh stated in a paper dated 1915 [23], relating to Aeolian sound[19] and the emission of alternating vortices produced by the wind on cables, that Bénard's work had pointed out that the Strouhal's number is actually a function of the Reynolds number. Although Bénard was not the first scientist to observe vortices behind a bluff body, he may be considered as the first one to have obtained experimentally the laws characterizing their periodicity. He did not know if previous work had been done on the same phenomenon, but some years later, he discovered H.R.A. Mallock's[20] paper published in 1907 [24], to which he referred as the first work achieved on alternating vortices in fluids. He also mentioned [B41] many times the similar emission of vortices observed by Etienne Jules Marey,[21] who was certainly the pioneer of visualization tech-

[18] $S = fd/U$, where f is the frequency, U the fluid velocity, and d the typical size of the object.

[19] Since ancient times, it has been observed that wind causes vortex-induced vibrations of the wires of an Aeolian harp. In 1878, Strouhal found that the Aeolian tunes generated by a wire in the wind were proportional to the wind velocity divided by the thickness of the wire.

[20] Indeed, in this paper Henry Reginald Arnulph Mallock (a consulting engineer working in various branches of physics who invented and improved many instruments of high scientific value), drew different possibilities of vortex emission including the alternate raw.

[21] Étienne-Jules Marey (1830-1904) French physician, inventor, and photographer, specialized in human and animal physiology. He held the chair of Natural History of

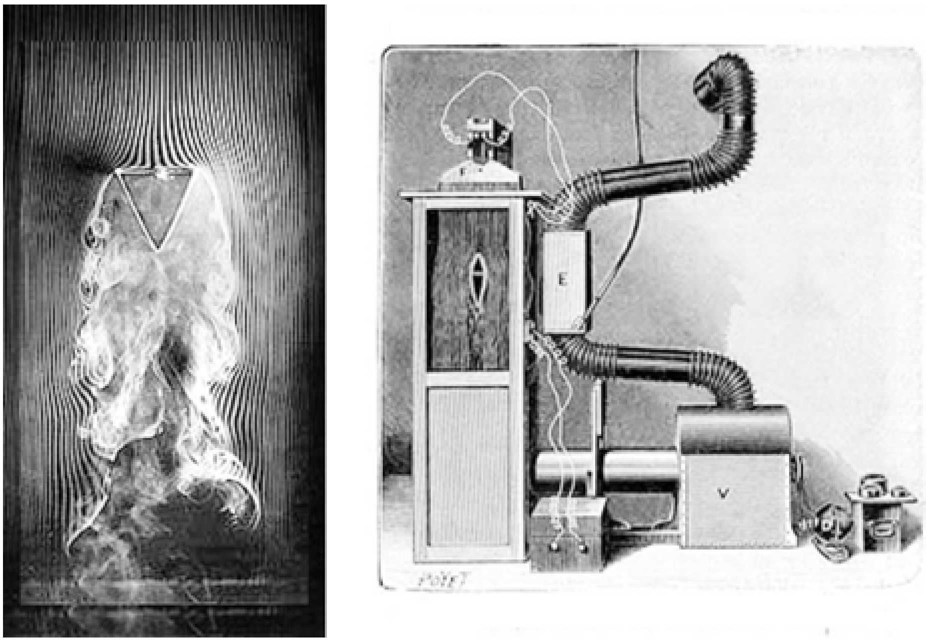

Fig. 2.9. A typical Marey's image of coherent structures (a) observed in his wind tunnel (b), published in 1901.

niques in modern fluid mechanics [25]. In 1911 and 1912 Theodor von Kármán (1881-1963) published two papers about his work on the stability of alternating vortices in a street formation achieved at the University of Gottingen. Ludwig Prandtl(1875-1953), a professor of applied mechanics, had founded a school of aerodynamics and hydrodynamics there that had acquired a world reputation, which was acquired as well by the activity in theoretical physics with Max Born, with whom von Kármán collaborated in 1912 on lattice vibrations and their connection with specific heat. He demonstrated that the distance between vortices in the street, divided by the breadth of the street was equal to 1/0,238, in order to ensure stability.[22] This theoretical work, with H. Rubach's experiments [26], had important consequences and even today, the phenomenon known as alternating vortex shedding produced by a bluff body is often referred as the *von Kármán's street.*

Of course, Henri Bénard reacted to von Karman's supposed paternity on the alternating vortex emission by moving bodies in fluid even if they referred to one

Organized Bodies at the Collège de France from 1868 until his death. He is mainly known for his photographic experiments on the study of motion. In 1890, Marey continued to study aerodynamics by building a wind tunnel and taking pictures of coherent structures!

[22] T. von Kármán relates in his book [27] how he got interested in the subject, after L. Prandtl's suggestion.

of his 1908 papers [B12]. This is the reason why, for several years, Bénard argued indirectly, trying to demonstrate that von Kármán's and Rubach's theoretical results were idealistic and far from real conditions. An example can be found in the paper he published in 1926 entitled, "*About the Inaccuracy for Fluids in Real Conditions of the Kármán's Theoretical Laws Regarding Alternated Vortex Stability*"[B29]. Actually, Bénard experimentally showed that the dimensionless frequencies measured with the Strouhal number S, vary with the velocity of the object, whereas von Kármán's result could imply that Strouhal number is constant. As part of this polemic, Bénard insisted on the role played by the camera, an instrument that could reduce the fluctuations on period measurements and allow for better statistics. He quoted in a sarcastic way the 1912 von Kármán and Rubach paper: "*The authors said that it could be possible to use the cinematography*, [an obvious reference to his own work], *but such a method has no important advantage in respect with the method they used"*, and adding that the authors, giving results on only two experiments, counted vortices with a clock in hand, observing departure and arrival, "*method already used for horse racing, but which lacks precision for a 3 centimetres race course*" [B49]. In 1926, Bénard and von Kármán met at the Second International Congress of Applied Mechanics in Zurich. Bénard said[23] that von Karman kindly consented to him that the accuracy of the few experiments made by Rubach and himself in 1912 could not be compared to Bénard's ones. Moreover, Kármán declared that he never claimed paternity of the alternated vortex, with an exception, for the theory on its stability. As Bénard told the story, von Kármán declared pettishly that the expression *Kármánsche Wirbelstrasse* (Kármán Vortex Street) could be easily replaced by the *rue des tourbillons de Bénard* (Bénard Vortex Street). Kármán's version, in his book *The Wind and Beyond* [27], placed the same discussion in 1930 (the Third International Congress of Applied Mechanics held in Stockholm?) in the course of which he declared he would accept to call it *Kármán Street* in Berlin and London, and *rue de Bénard* in Paris.[24] Even if both said that the problem

[23] *"M. Th. von Kármán a bien voulu m'accorder très aimablement que les quelques expériences faites par Rubach et lui en 1912 ne pouvaient au point de précision être comparées aux miens. D'autre part, il a déclaré n'avoir jamais réclamé la priorité en ce qui concerne les tourbillons alternés, sauf pour sa théorie de leur stabilité. Il a ajouté avec humeur que l'expression die Kármánsche Wirbelstrasse pourrait sans incovenient être remplacée par la rue de tourbillons de Bénard. Mais, comme moi-même, M. Kármán trouve plus sérieux que la question de priorité, mon désaccord expérimental avec la loi de similitude dynamique, intangible aux yeux des hydrodynamiciens"* [B49].

[24] *I never asked to have my vortex theory named after me, but somehow the name remained. There is always some danger in such matters, especially as one grows in fame or importance. In 1930, almost two decades after my paper was published, a French professor named Henri Bénard popped up at an international congress and protested the name Kármán Vortex Street. He pointed out that he had observed the phenomenon earlier and that he had taken pictures of alternating vortices before I did. He was right, and as I did not wish to fight over names I said: "All right, I do not object if in London this is called Kármán Vortex Street. In Berlin let us*

of priority was not important, Bénard's insistence in spreading, even at the Paris University Council, the discussion which had taken place in Zurich in 1926, has to be underlined. His colleagues took care of his claim, as did H. Villat who, in a report to the Science Academy, criticized the fact that in a recent book Joukowski had dedicated a full chapter to von Karman, without any mention of Bénard's experiments. This attitude of Bénard about the conflict of paternity of the vortex street has to be placed in the general context of the First World War. We must keep in mind that in the immediate postwar period, scholars of the victorious powers developed an attitude of refusal towards German scholars and several academies of science decided to boycott the Germans from 1919 up to 1926 [29] . For example, French scientists refused to attend the conference on hydrodynamics and aerodynamics held in September 1922 in Innsbruck and organized by Levy and von Kármán. It is worthwhile to quote Marcel Brillouin (who had a great influence on Bénard's formation) who refused the invitation on August 8,1922, with a provocative letter: "*Since German scientists and professors have not understood that they would not be bound to pay if they had not committed systematic devastations, and because they have done it, they have to pay; my esteem for them is still insufficient to shake hands with, no matter their scientific value*". Therefore, the strong insistence of Bénard to fight against von Kármán's priority (this is just a hypothesis) could have been fed by the strong chauvinistic climate of the time.[25] Even in 1924, the French were absent from the First International Congress of Applied Mechanics at Delft [30-32], organized by Burgers and Biezeno, under the impetus of von Kármán.[26] In addition, these years were characterized by two opposite styles of making science, especially in mathematics: the "modern" or formalist one represented by Gottingen University and Hilbert and the "conservative" or intuitive one by Poincaré and French science. Chauvinism of the time tried to transform this difference into a controversy.[27]

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call it Karmansche Wirbelstrasse, and in Paris, Boulevard d'Henri Bénard". We all laughed heartily and Bénard and I became good friends"[27]. About the same event, von Karman said: ... *Bénard did a great deal of work on the problem before I did, but he chiefly observed the vortices in very viscous fluids or in colloidal solutions and considered them more from the point of view of experimental physics than from aerodynamics* [28].

[25] At that time, Paul Langevin was one of the few scientists in France who adopted a definite position against this boycott and tried to develop scientific cooperation with German scientists, in the first place, with A. Einstein [6].

[26] In 1913, von Kármán became director of the Aachen Aerodynamics Institute and in 1930, he moved to Caltech, in the USA. In 1937, he visited the Institute of Fluid Mechanics in Paris and after the Second World War played an important role in the French–American relationship. As an American delegate and Chairman of the AGARD (a scientific advisor group of NATO) he frequently visited Paris and developed a friendship with J. Pérès, L. Malavard, and other French scientists.

[27] But, irony of history, after 1933, these qualifications changed. In France, the Bourbaki group became the symbol of modern mathematics and, in Germany, formalism was attacked as a "Jewish science".

Fig. 2.10. H. Bénard (1) during the Third International Congress of Applied Mechanics , at Cambridge in 1934. Also attending this meeting were G.I. Taylor (2), L. Prandtl (3), and J. Burgers (4)*(IUTAM).*

2.4 Bénard and Cinematography

Of course, Bénard was not the first one to use the cinematograph in science and we recall pioneers such as Étienne-Jules Marey, Georges Demenÿ, Lucien Bull, Louis and Auguste Lumière, and Georges Méliès [33]. But Bénard was one of the first to use it, a Lumière-Carpentier camera, as a scientific instrument, in 1907 in Lyon for his first experiments on vortex shedding. Before this, in 1900, he used a chronophotographic apparatus, supplied by L. Gaumont to take pictures each five seconds of the turbulent vortex. Bénard not only used cinematography as a technique of observation and measurement, but also as a means for scientific popularization, which perhaps is the least known aspect of his work. We have found in the archives of the Gaumont company, in the Joinville studios founded by Léon Gaumont in 1895 near Paris, a series of seven films[28] produced by Bénard and Dauzère between June and October 1913, entitled "*The Cellular Vortices*", as part of another series called "*Cinematography Applied to the Study of Physical Science*". On April 18, 1914, Dauzère and Bénard presented the films

[28] *Les tourbillons cellulaires: Particules solides et méthodes optiques* (H. Bénard, 8'28"); *Les tourbillons cellulaires du spermacéti: Leur régularisation progressive enregistrée par les méthodes optiques* (H. Bénard, 3'46"); *Les chaînes de tourbillons cellulaires de l'éther* (H. Bénard, 11'45"); *Les tourbillons cellulaires de l'éther: Relief de la surface libre* (H. Bénard, 5'49"); *Tourbillons cellulaires isolés: Observation par la méthode optique en lumière réfractée* (C. Dauzère, 4'40"); *Les deux espèces de tourbillons cellulaires* (C. Dauzère, 4'2"); *Solidification cellulaire* (C. Dauzère, 4'48").

in the amphitheatre of the Conservatoire des Arts et Métiers de Paris, to the French Physical Society. This series of films has been listed in the Gaumont catalogue since July 1914. We do not know if the films were actually shown in the schools, because the ones we have found were too long and lacked mounting and editing work, which leads us to think they were not considered, from the production point of view, as finished. The most important thing to emphasize is the interesting booklet [B19] added to the distribution of the films, probably meant for teachers, with a very synthetic description of convective motion phenomena intended for a wide public. In these films, the observation methods are explained and comments are developed on the analogies between convective motion and the biological phenomena, calling attention on the extraordinary beauty of descriptive physics. It is important to observe that the movies were produced by the Gaumont series on education. In fact, offering movies on craftwork, hygiene, zoology, and physics, Léon Gaumont considered himself a progressive educator, who thought that cinematography was an important educational support. In addition, Bénard participated in scientific popularization activities such as exhibitions. For instance, he presented a special convection container shaped to project a shadowgraph image on at exhibitions on physics [B42]. One of his assistants, M.R. Fabre told us that he built a wood model of a hexagonal cell representing convective motion that he showed in different activities and exhibitions.

Among the most spectacular contributions of Bénard and his team was the one at the Universal Exposition of Paris in 1937, called "Exposition Internationale des Arts et Techniques dans la vie moderne", which took place in the building later called the Palais de la Découverte, the first interactive science museum in the world. In the meteorology pavilion, Bénard's team presented experiments on convective cell production, where an air current was heating from below (what could be called the) and showing the longitudinal convective rolls, analogue to the clouds, in order to explain the morphology of different clouds: cirrocumulus, altocumulus and stratocumulus. It is worth mentioning that the presentation said, "*This organized pre-turbulent state, extremely important as a transition from the laminar regime to the turbulent chaotic regime, has been experimentally characterized at the stand on Meteorology, heating from below the air contained in a glass channel where the bottom is made from a mobile metallic tape and the other walls from glass*". Visualizing the air trajectory with smoke, very beautiful cellular vortices were obtained with the static tape and, with the tape in movement, longitudinal rolls were produced. In the same stand, experiments were presented by Bénard's students, M. Luntz and D. Avsec who displayed electroconvective cellular vortices generated by a vertical gradient of electric potential. The exposition catalogue explained that the photos chosen by Bénard showed the most characteristic analogy between clouds in and , as well as the granulations of the solar photosphere with . Actually, during the 1930s, Bénard worked with the Commission of Atmospheric Turbulence, presided over by Philippe Wherlé, director of the National Meteorological Office, and a team of meteorologists and physicists. All together, they performed experiments on air with André Japy as pilot, showing the analogy between convective rolls and parallel cirrus bands, a topic which became the subject of one of Bénard's last works [B47, B48].

2.5 Physics and Dynamical Systems

Bénard was a council member of the French Physical Society and president from 1928 to 1929, following Louis Lumière and preceding Jean Perrin, Nobel Prize in Physics in 1926. In his investiture address, Perrin recognized Bénard's role, "*He has given to hydrodynamics the methods of the Physics, doing so, he discovered and studied phenomena not foreseen by theoreticians*". Bénard himself confessed in 1929, in his inaugural address in the Institute of Fluid Mechanics of Paris [B41], that after his earlier work, he became interested in hydrodynamics and adding that "*he was like Monsieur Jourdain, who was writing prose without knowing it.*" In the same speech, he said that he had studied the classical treatises of Lamb and Basset, comparing them with Lord Kelvin's and Lord Rayleigh's, which he considered to have been written by physicists who had maintained their link with reality. From his point of view, Lamb and Basset's treatises were concerned with pretty much theoretical and mathematical physics and did not deal enough with experiments: there were no pictures, so one was led to the wrong conclusion that physics was nothing but equations. He therefore had the idea of making a photo album on fluid motion with images taken from photographs and films in order to illustrate theoretical works. (This was actually done many years later in Van Dyke's famous Album of Fluid Motion).

Because Bénard's works inspired, as shown in these proceedings, most of the modern experimental works on dynamical systems and , one should quote a very interesting work performed by Bénard's group, in this direction. François-Joseph Bourrières (1880-1970), who was a former undergraduate student of Bénard and Duhem in Bordeaux,[29] collaborated in Bénard's laboratory in the Institute of Fluid Mechanics, on the subject of fluid–structure interaction. Bénard explained that he trained him in "*the experimental and rational analysis of the phenomena of and oscillation existing in real fluid mechanics*" a topic on which he had already drawn attention after 1900. Indeed, one of Bourrières' subjects was the study of the movements of the free end of a flexible rubber tube, inside which a fluid was circulating. Bourrières described spontaneous oscillations as well as

[29] The role of fluctuations in dynamical systems was Duhem's concern. In 1898, W.S. Franklin wrote in the Physical Review [34] a review of Duhem's book, titled *Traité élémentaire de mécanique chimique* published a year before in Paris. Impressed by Duhem's analysis, he said ," *A state of unstable equilibrium is produced by the heating of the lower strata of the atmosphere. An infinitesimal action as the waving of a fan, may precipitate a sweep,.... in other words, an infinitesimal cause may produce a finite effect. Long range detailed weather prediction is therefore impossible...* ***the accuracy of this prediction is subject to the condition that the flight of a grasshopper in Montana may turn a storm aside from Philadelphia to New York."*** This reference is cited by R.C. Hilborn in a very recent study of the evolution of the notion of sensitive dependence on initial conditions and chaos [35].

more complex ones. In order to study the phenomenon through experiments, he attached a little lamp at the extremity of the tube and took pictures, with an open shutter, of their trajectory. He then could display a very clear picture of a limit cycle and the attraction to this cycle limit during transitional phase and perturbations. Bourrières published this experiment in 1939, with a foreword by Bénard [36], in which the latter exposed the nonperiodic form the movement could take, from whatever initial conditions, and how these conditions led the system to a limit cycle, referring to the concept of self-oscillations due to Alexandr A. Andronov (1901-1952) [37]. As it is known, one of great achievements of Andronov, who belonged to the group on nonlinear dynamics formed in Moscow around Leonid I. Mandelstam (1879-1944), was to demonstrate, in the late 1920s, the connection between Poincaré's limit cycles and a whole range of practical oscillatory processes.

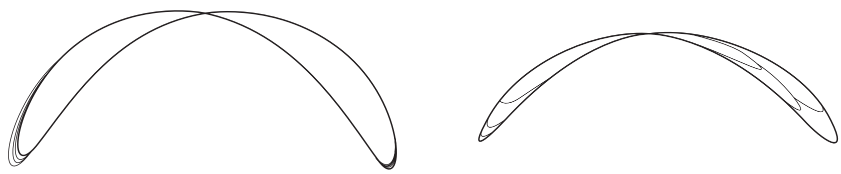

Fig. 2.11. Physical limit cycle and transients, in Bourrières' experiment [36].

2.6 Conclusion

This scientific biography provided us with the opportunity to bring to light the remarkable homogeneity of Henri Bénard's works in experimental hydrodynamics, especially on the study and recording of the movement of liquids through optical means. On two occasions he discovered, in this field, new phenomena or phenomena hardly suspected before him. He found the geometric or kinematics laws of convective cells in 1899 and of the alternating vortex shedding behind bluff bodies in motion, in 1906 to 1907. These studies, realized at the very beginning of his career, were actually his most important contributions.

This scientific biography, allows us to guess how, in France after the Second World War, experimental fluid dynamics, topics belonging to physics, withdrew from it but, in the late seventies, came back, exactly around the topics Bénard had previously explored.

Far from being a review of Bénard's experiments, this biography nevertheless permits us to understand the context his work was achieved in as well as the limits its developments had suffered. Some science historians are nowadays wondering at the gap between founding works such as Bénard's and modern studies on physical hydrodynamics in dissipative structures. We hope this chapter will contributes to the reduction of this very gap.

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