Gustave Eiffel, a pioneer of aerodynamics

Bruno Chanetz*

Onera, 8 rue des Vertugadins,
F-92 190 Meudon, France
Fax: +33-1-46-23-51-58
and
University Paris-Ouest,
LTIE-GTE, EA 4415, 50 rue de Sèvres,
F-92410 Ville d'Avray, France
Fax: +33-1-40-97-48-73
E-mail: chanetz@onera.fr
E-mail: bchanetz@u-paris10.fr
*Corresponding author

Martin Peter

Laboratoire Aérodynamique Eiffel,
68 rue Boileau, F-75016 Paris
E-mail: martin.peter@sfr.fr

Abstract: At the beginning of the 20th century, Gustave Eiffel contributes with Ludwig Prandtl to establish a new science: aerodynamics. He was going to study the forces to which he was confronted as engineer during his life: gravity and wind.

Keywords: Eiffel wind tunnel; diffuser; laminar regime; turbulent regime; transition; drag of the sphere; Eiffel chamber.

Reference to this paper should be made as follows: Chanetz, B. and Peter, M. (2013) 'Gustave Eiffel, a pioneer of aerodynamics', *Int. J. Engineering Systems Modelling and Simulation*, Vol. 5, Nos. 1/2/3, pp.3–7.

Biographical notes: Bruno Chanetz joins Onera in 1983 as a Research Engineer. He was the Head of Hypersonic Group in 1990, Head of Hypersonic Hyperenthalpic Project in 1997 and Head of Experimental Simulation and Physics of Fluid Unit in 1998, then Deputy Director of the Fundamental and Experimental Aerodynamics Department in 2003. He was a Lecturer in Charge of the course 'Boundary Layer' at the Ecole Centrale de Paris from 1996 to 2003, then Associate Professor at the University of Versailles from 2003 to 2009. Since 2009, he is an Associate Professor at the University of Paris-West. Recently, he was interesting by the use of plasmas for aerodynamics. He is the author of 50 articles in archival journals. He is a 3AF member, member of the Aerodynamic Committee. He is also the Treasurer of the 'Aero Eiffel 100' Society.

Martin Peter joins the 'Laboratoire Aérodynamique Eiffel' as an Engineer in 1959. He becomes the Director in 1983. That same year, the 'Groupement des Industries Françaises Aéronautiques et Spatiales' (GIFAS), owner of the laboratory sold it to him. He became the Owner-Manager of the Wind Tunnel and created the 'Aérodynamique Eiffel' Ltd. In 2001, he sells the wind tunnel to the 'Centre Scientifique et Technique du Bâtiment' (CSTB) and became the Curator of the Eiffel wind tunnel. During all these years, these activities were devoted to a lot of experimental studies in different areas: cars for prestigious customers as Porsche and Peugeot; building and structures, antennas; industrial ventilation, smoke extractors and chimneys; architecture and urban climate, atmosphere and comfort, natural ventilation, pollution, studies of dispersions and recycling of effluents. He is also the President of the 'Aero Eiffel 100' Society.

1 A well filled life

Alexandre Gustave Eiffel was born in Dijon on December 15th, 1832. In 1852, he is admitted in the *Ecole Centrale des Arts et Manufactures*, now called Centrale Paris, a French engineering school where he makes his studies of engineer. In 1856, he joins the *Company of railroads François Pauwels* where he starts a prestigious career of civil engineer, essentially dedicated to the large metallic structures. At the beginning of his career, in charge of the construction of the Bordeaux metallic bridge, he becomes a remarkable technician and organiser, as well as an excellent leader.

Of her mother, an enterprising and ambitious businesswoman, he inherits an acute sense of business, which urges him to setup his own company as soon as 1866. Two years later, he is associated with Théophile Seyrig who has just completed his studies at Ecole Centrale, with the rank of ‘major’ of his promotion (top student). During the Second Empire, under the reign of Napoleon III (1852–1870), the Saint-Simonian current was still present in the Ecole Centrale whose vocation was to form entrepreneurs. At that time, the third of each promotion of engineers still became entrepreneurs. It was more than two-thirds under the previous reign of Louis-Philippe (1830–1848).

The company of construction Gustave Eiffel works in many countries. When the building site of the tower opens in Paris, the Eiffel Company already has an excellent reputation obtained thanks to large-scale iron and steel realisations, including the Douro viaduct in Portugal, the dome of the observatory centre of Nice, the Garabit viaduct in France and the supporting structure for the Statue of Liberty in New York harbour. After the triumph of the tower during the Universal Exhibition of 1889, Gustave Eiffel is compromised in the scandal of the Panama Canal, which darkens its last business years and has to do with his decision to definitively retire from business to devote his free time to science. At this time, he is more than 70 years old. A new career of scientist begins for him, which will last twenty years. Gustave Eiffel died in Paris on December 27th, 1923 (Marrey, 1989).

2 From the tower to the wind-tunnel

The tower has numerous detractors, mainly artists. At the origin, the tower was a provisional structure with a lifetime of twenty years. Gustave Eiffel knows that the only mean to avoid its demolition at expiration of the concession is to prove that it can have a scientific utility. Since it represents a wonderful support to make experiments, Eiffel decides to use the tower for the study of this new science: aerodynamics. At this time, various experimenters had used several testing methods: drop testing, whirling arms and rudimentary wind tunnels. Applying his engineering expertise and experience to two of these methods, Eiffel produced the most sophisticated drop test machine ever constructed and the best wind tunnel.

To study the drag of bodies, he conceives a very ingenious drop test machine, which he installs on the tower second floor, taking advantage of its 115 m height. His first studies, awarded by the Academy of Science in 1908, allow him to found the fundamental laws of the air resistance. In this period, with the growth of aviation, Eiffel brings new ideas and his knowledge of aerodynamics leads him to understand the efforts of the air on a body.

To carry out more fruitful studies, Eiffel then built the *Laboratoire du Champs de Mars* which was operational from 1909 to 1911 to study aerodynamics (Chanetz, 2009), the principle of the facility being to blow air around models of airplanes.

3 Principle of equivalence between effective and relative movements

The first tests are to check that the principle of wind tunnel simulation – where the aircraft or its model is still in air in motion – is consistent with the reality – where the aircraft is moving in air considered without motion as a first approximation. To this aim, Eiffel compares the wind tunnel results with those previously obtained with the drop test machine. This comparison being successful, Eiffel’s wind tunnel is now available for the pioneers conquering air: Farman, Bleriot, Voisin, Breguet …

However, there was not a consensus about the wind tunnel principle. Armand de Gramont, Duc de Guiche, is a detractor of Eiffel who adopts the opposite approach by measuring the distribution of pressure on a wing fixed on a moving car (Peter and Cuisinier, 2009). He even challenges the work of Eiffel and disapproves application of the results obtained in his laboratory to the reality of airplanes in flight. To settle definitively the question of equivalence between real and relative movements – although the question had been already solved in the mid 19th century through the experiences of Duchemin, raising the paradox of du Buat (Chanetz and Coët, 2004) – Eiffel requests the intervention of the great mathematician Henri Poincaré. Shortly before the death of Poincaré in 1912, Eiffel received a reply in line with his expectations: “There is no reason that the forces exerted on the plate by a uniform air flow differ from those that would occur if this plate is moving in a calm air”. Poincaré adds: “it is clear that only the relative movement is significant”.

4 Eiffel’s chamber and diffuser

In 1911, the municipality of Paris wanting to recover the area on which the wind tunnel is located, Eiffel has to leave the Champs de Mars. In the beginning of 1912, he installs in the district of Auteuil a new wind tunnel with increased performance, this new laboratory being inaugurated on March 19th (see Figure 1).

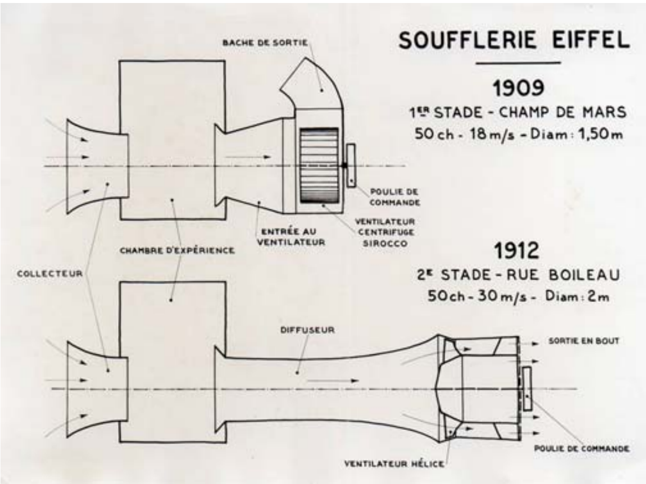
The originality of the wind tunnel at Auteuil is the presence of the following successive elements, from upstream to downstream:

- a collector or convergent, where air is accelerated from an entrance section, of four metres in diameter, to an outlet of two metres
- a closed experimental chamber where the free stream flow is produced (i.e., without walls); whereas at the time the other wind tunnels had a guided test-section or tunnel
- a recovery at the exit of the test chamber, made of a small collector whose section is larger than the section of the convergent at the test chamber entrance

- a diffuser made of a diverging tube in order to recover pressure in front of the fan
- an helical fan with a diameter of 3.80 m and a weight of 8,500 kg, specially purchased for the wind tunnel of Auteuil, the fan of the Champ de Mars wind tunnel being used for a second small wind with a collector outlet of one metre in diameter.

Figure 1 Photograph of the Eiffel laboratory © Laboratoire Eiffel (see online version for colours)

Figure 2 The diffuser: an innovation from Eiffel universally adopted © Laboratoire Eiffel



The diffuser, which is an innovation of Eiffel, was the subject of a patent dated November 28th, 1911: "Addition of a diffuser to improve the performance of a machine to produce artificial air flow." This invention is rich in consequences, as it allows to drastically reducing the power required for such a facility. The efficiency of the device comes from the Bernoulli law stating that pressure and velocity vary inversely. Indeed, by reducing the velocity, the diffuser has the effect to increase the pressure of the air exiting from the test section (see Figure 2). The pressure difference on either side of the fan is then much less than that which would exist if the fan were located directly downstream of the experimental chamber. This device leads to a reduction of the power required to extract the air. "Thus the diffuser saves money since the electric power is reduced by a factor of 3. The advantage of this recovery device is clear, which allowed us realizing the present large facility" (Eiffel, 1914). From that date all wind tunnels, will be equipped with a diffuser.

People who visited the wind tunnel in Auteuil gave him the name 'Eiffel Chamber'. Later, Gustave Eiffel will ask that the official designation: 'Aerodynamic device system Eiffel Paris' should be engraved on a marble plaque of 1 m by 0.5 m on all facilities using his technique, without asking for royalties.

5 The study of the drag of spheres

At the Auteuil laboratory, Eiffel resumed the activities undertaken at the Champs de Mars Laboratory concerning the aerodynamics of the sphere whose drag seemed to follow specific laws based on velocity. Measurements carried out at the Champs de Mars wind tunnel at a speed of 15 m/s revealed values of the drag coefficient less than half those found for lower speeds by Professor August Föppl in the Göttingen Laboratory, in Germany, headed by the famous Ludwig Prandtl. Föppl did not hesitate to write that the French colleague had committed an error. Therefore, Eiffel decided to undertake new tests with spheres of different diameters. He discovered that, for each sphere, there are two flow regimes: one at low speeds corresponding to the coefficient found in Göttingen (laminar flow) and the other, at higher speeds, corresponding to the coefficient found in the Champs de Mars facility (turbulent flow). Transition between the two regimes always occurs for the same value of the product velocity × diameter. Thus, the experimental studies carried out in his laboratory of Auteuil have first demonstrated the important role of the *Reynolds number* in aerodynamics.

The example of the sphere reveals the complexity of the boundary-layer behaviour, which sometimes leads to paradoxical laws. The laminar boundary layer generates a lower friction drag than the turbulent one, but its earlier separation leads to a more disturbed wake, which is the origin of a form (pressure) drag larger than in the turbulent case. Therefore, by triggering transition, one reduces more the drag due to the wake than one increases the friction drag due to a more important turbulent boundary layer on the sphere. The turbulent regime is more favourable to the global drag balance, which is the sum of the friction and form (pressure) drags. The two situations are illustrated in Figure 3 showing visualisations obtained in a water tunnel. The first picture (on the top) shows the flow around a sphere with a laminar separation and the second picture (below) the flow with a turbulent separation, the wake resulting from the second situation being less disturbing than the first one (Lengrand and Chanetz, 2005–2006).

The golf ball with dimples that trigger transition and postpone more downstream separation of the boundary layer gives an emblematic example. The reduced wake resulting from this turbulent boundary layer promotes penetration in air by reduction of the global drag, which leads to an increase of the golf ball range. At the origin, the inventors of golf manufactured leather balls, taking care to place the seams on the back to have a smooth envelope favourable to penetration into air. They later discovered that the best golf balls were damaged balls whose rough envelope triggers transition of the boundary layer.

Figure 3 Visualisations of the flow around a sphere in laminar regime (top) and in turbulent regime (below) © Onera (see online version for colours)

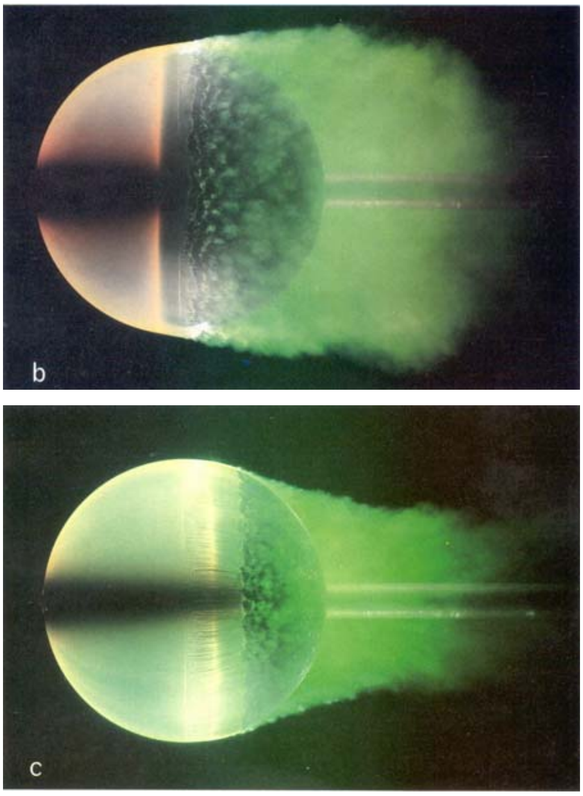


Figure 4 Gustave Eiffel and his collaborator Antonin Lapresle © Laboratoire Eiffel

6 A researcher who communicates and publishes

The controversy between Prandtl and Eiffel about the drag of the sphere highlights the essential role played by exchange between researchers for the advancement of knowledge. Thanks to these confrontations, science progresses and that was the goal aimed by Gustave Eiffel: "It is mainly the progress in Aviation that I wanted by creating this laboratory where the tests are absolutely free, but where the results would be published – in the general interest – either through reports or communications to scientific societies."

Gustave Eiffel was a true researcher who has not played the role of a suspicious inventor against potential competitors. He offered all manufacturers the means to test their models free of charge, if their results would be published and accessible to all. It was truly the wind of research, which was blowing at the laboratory of Auteuil under the leadership of Eiffel, a retired captain of industry.

He publishes *The Friction of the Air and Aviation*, a book translated into German and English. The author recalls (Eiffel, 1914) that the results were much appreciated because they were published at a time when the science of Aviation had the greatest need of experimental data. Its contribution to this emerging science of aerodynamics was recognised in the USA, where he received the gold medal of Langley in 1913, previously given only to Wilbur and Orville Wright.

7 His collaborators: Leon Rith and Antonin Lapresle

Leon Rith and Antonin Lapresle, who worked with Gustave Eiffel, greatly contributed to his research activity: "All these experiments were undertaken, like the previous one, with the assistance of my staff: Mr. Rith, engineer of Arts and Manufactures, and Mr. Lapresle, a former student of the *Ecole Supérieure d'Electricité*. Today, I am pleased to have once again the opportunity to thank them" (Eiffel, 1914).

Rith had considerable influence in the creation of the famous wind tunnel that served as a model for all those around the world. On the problems of stability of airplanes, too complex to be solved by a mathematical approach, Eiffel identified the key variables for equilibrium during a stable horizontal flight (weight of the airplane, power of the engine, velocity and angle of incidence). To facilitate the interpretation of the test results, Léon Rith developed the mode of representation known as the *logarithmic polar* universally adopted for solving problems related to aircraft and propellers. Eiffel wrote in 1914: "I find that this method is very convenient and will render useful services in the study of airplanes."

8 A facility often copied

The Eiffel facility is rapidly recognised in France and all over the world. In 1914, the Aero Technical Institute (IAT) in Saint-Cyr-l'Ecole undertook the construction of a wind tunnel using the new device developed by Gustave Eiffel.

In 1929, Albert Caquot, General Technical Director at the Ministry of Air, asked Antonin Lapresle to build the large wind tunnel of Chalais-Meudon (Coët and Chanetz, 2008). Antonin Lapresle notes on March 14th, 1929: "We keep the general arrangements of the Eiffel wind tunnels" (see Figure 5).

The Eiffel wind tunnel has been copied abroad, a large number of wind tunnels being then built all over the world: Rome, Moscow, Stanford, Dayton, Tokyo. However, the will of Eiffel has not been respected, the marble plaque stating 'aerodynamic device system Eiffel Paris' having been affixed nowhere.

Figure 5 The diffuser of the large Wind Tunnel of Onera Chalais-Meudon designed by Antonin Lapresle © Onera (see online version for colours)

9 The Eiffel wind tunnel today

In 1921, two years before his death, Gustave Eiffel offered the exploitation of the wind tunnel to the *Services Techniques de l'Aéronautique* (STAé).

In 1929, *Le Groupement des Industries Françaises Aéronautiques et Spatiales* (GIFAS) took in charge the exploitation of the wind tunnel.

In 1983, Martin Peter bought the wind tunnel and created the company *Aérodynamique Eiffel*.

In 2001, Martin Peter sold the laboratory to the *Centre Scientifique et Technique du Bâtiment* (CSTB).

In 2012, a century after its inauguration, the aerodynamic laboratory of Gustave Eiffel is still in operation and continues to provide to the industry an important scientific contribution to the aerodynamics of vehicles, industrial ventilation and building engineering.

References

Chanetz, B. (2009) '1909, la soufflerie Eiffel', La Science au Présent, ISBN: 978-2-85229-516-2.

Chanetz, B. and Coët, M-C. (2004) 'Souffleries aérodynamiques', *Encyclopaedia Universalis*, Cd-rom 10.

Coët, M-C. and Chanetz, B. (2008) 'Meudon, de l'aérostation à l'aérospatial', La revue pour l'histoire du CNRS no. 20, printemps.

Eiffel, G. (1914) 'Nouvelles recherches sur la résistance de l'air et l'aviation faites au laboratoire d'Auteuil', Dunot, H. and Pinat, E. (Eds.).

Lengrand, J-C. and Chanetz, B. (2005–2006) 'Cours de couche limite', Ecole Centrale Paris 3ème année d'étude, M.A.E. Air Espace (édition).

Marrey, B. (1989) 'Gustave Eiffel, une entreprise exemplaire', *Histoire d'entreprise*, ISBN: 2-907904-00-0.

Peter, M. and Cuisinier, J-P. (2009) 'Eiffel, la bataille du vent', Editions CSTB, ISBN: 978-2-86891-344-9.