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# A century of wind tunnels since Eiffel

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ABSTRACT

Fly higher, faster, preserve the life of test pilots and passengers, many challenges faced by man since the dawn of the twentieth century, with aviation pioneers. Contemporary of the first aerial exploits, wind tunnels, artificially recreating conditions encountered during the flight, have powerfully contributed to the progress of aeronautics.

But the use of wind tunnels is not limited to aviation. The research for better performance, coupled with concern for energy saving, encourages manufacturers of ground vehicles to perform aerodynamic tests. Buildings and bridge structures are also concerned.

This article deals principally with the wind tunnels built at ONERA during the last century. Somme wind tunnels outside ONERA, even outside France, are also evocated when their characteristics do not exist at ONERA.

## 1. From birth to first evolutions

### *1.1. Wind tunnel definition*

Wind tunnels are facilities (circular, elliptical or rectangular tunnels) in which the wind is produced by fans or by compressed air to study and measure the action of the air flow around a solid. The test section is the part of the circuit where the solid is studied. Invented in the late nineteenth century, these aerodynamic laboratories took off in the early twentieth century. The method is based on the principle of relativity enunciated by Isaac Newton in 1687: the forces exerted on a solid immersed in a fluid and the fluid are the same either the solid moves with a certain speed through the fluid at rest, or the fluid moves, with the same relative velocity to the solid that it is immobile.

In French, wind tunnel is still designated by the term “soufflerie”, which was correct for the first facilities, since a fan was blowing air upstream (relative to the direction of flow) of the test-section. The first evolution was to suck air downstream of the test section. The precursors of the other countries in the science of flight use terms that do not prejudge whether the direction of the air is moving in the circuit: *wind tunnel* in English, *Windkanal* in German, *galleria aerodinamica* in Italian, and *aerodinamicheskaya truba* in Russian [1]. Anyway, wind tunnels have largely contributed to the development of aviation, reducing the number of accidents, thus saving the lives of pilots and maintaining the equipment. They also allowed replacing the “flair” of the pioneers by the “art” of the engineers, according to the beautiful sentence by Gustave Eiffel.

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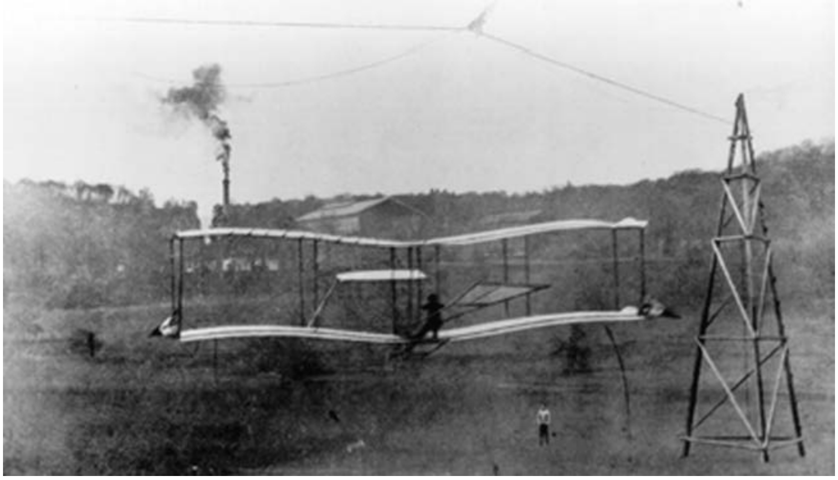


**Fig. 1.** *Aérodrome* of Captain Ferdinand Ferber in Chalais–Meudon (© ONERA).

### 1.2. Competitors for ground investigation

The wind tunnel is a very convenient experimental investigation mean, which has surpassed the alternative methods based on the direct movement of the solid in the air. However, at the beginning of the twentieth century, there was no consensus. Indeed Armand de Gramont, Duke of Guiche, who was measuring the distribution of pressure on a wing fixed on a moving car, was a detractor of Eiffel, who was using a wind tunnel. He even challenges the work of Eiffel and disapproves the transposition of the results obtained in his wind tunnel to the reality of airplanes in flight. To definitively close the controversy about the equivalence between real and relative movements – although the question had been already solved in the middle of the 19th century through the experiences of Duchemin, solving the paradox of du Buat [1] – Eiffel requests the intervention of the great mathematician Henri Poincaré. Shortly before the death of Poincaré in 1912, Eiffel received a note 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” [2].

Below are described these alternative processes existing at the beginning of the 20th century:

- Horizontal rectilinear motion
  - in 1901, a flight testing was performed by the German company Siemens on a train traveling at 160 km/h,
  - in 1909, thanks to a 1.4-km private railway track, the AeroTechnical engineering Institute (IAT) of Saint-Cyr-l'École tested wings;
  - during the first decade of the twentieth century, Armand de Gramont, duke of Guiche, tested wings in his car [2].
- Vertical rectilinear motion
  - in 1908, before the building of its first wind tunnel, Gustave Eiffel conceived a very ingenious drop test machine to study the drag of solids [2,3]. He installed the device on the eponymous tower's second floor, taking advantage of its 115 m in height. His first studies, awarded by the French Academy of Sciences in 1908, allowed him to found the fundamental laws of air resistance. In this period, with the growth of aviation, Eiffel brought new ideas and his knowledge of aerodynamics led him to understand the efforts of the air on a solid.
- Combination of the horizontal and vertical motions
  - In 1904, Ferdinand Ferber in Meudon performed a device by taking advantage of the effects of gravity to move a plane along a cable. His plane, suspended from a sliding carriage along a tensioned cable between pylons (see Fig. 1). Gustave Eiffel had also considered such a device, called *aérodrome*, from the first floor of the tower, prior to the realization of its wind tunnel.
- Circular motion:

In 1906, the AeroTechnical engineering Institute (IAT) of Saint-Cyr-l'École tested solids attached to the ends of rotary arms. This way allows access to tangential speeds all the more important that the arm is long and the speed great.

### 1.3. The blowing wind tunnels and the introduction of the collector

Even if the first wind tunnel known in Great Britain operated by compressed air ejector (Venham Francis, 1871, then that Horatio Phillips, 1884), the following wind tunnels used the air moved by a fan disposed upstream of the wind tunnel's test section (see Fig. 2a): Charles Renard (France, 1896), Hiram Maxim (Great Britain, 1896), Konstantin Tsiolkovsky (Russia,

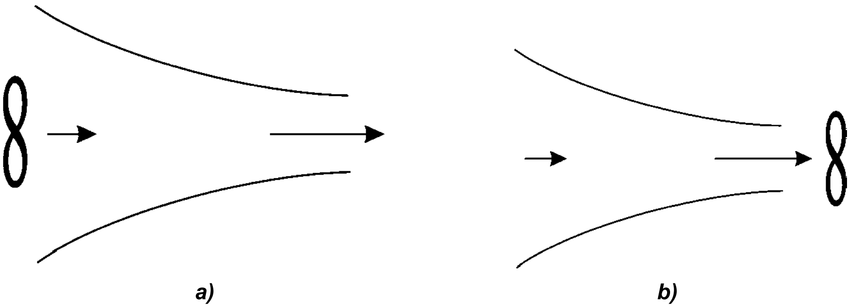


**Fig. 2.** a: Fan upstream of the model. b: Fan downstream of the model.

1897), Orville and Wilbur Wright (USA, 1901), and Auguste Rateau (France, 1909). We should also mention the wind tunnel, smoke machine built by Étienne-Jules Marey (France, 1899), which permitted the realization of the first visualizations of fluid flows [4].

A first development consists in the introduction of the collector. Disposed upstream of the test section, the convergent part increases the velocity in the test section under the mass conservation law for the flow, which is expressed for an incompressible flow, by:

$$V \cdot S = \text{constant}$$

where $V$ represents the velocity of the flow and $S$ the surface in the considered section.

### 1.4. The introduction of suction

The passage to suction is also an important step in the art of wind tunnels. The fan is now disposed downstream of the test section (see Fig. 2b) and thereby no longer interferes with the model, which is a great improvement to guarantee the quality of flow. According to this principle the following wind tunnels were conceived: Nikolai Zhukovsky (Russia, 1902), Thomas Stanton (Britain, 1903), Dimitri Riabouchinsky (Russia, 1905), Gustave Eiffel (France, 1909). Suction wind tunnels have been developed very quickly. There are currently several hundred major facilities of this kind in the world, while only less than a dozen were active before 1914.

### 1.5. Eiffel's wind tunnels and the introduction of the diffuser

In 1909, Eiffel built its first wind tunnel at the foot of the Eiffel Tower in the Champ de Mars. This facility was operational till 1911 to study aerodynamics. The air was moved by a fan driven thanks to a 50-horsepower electric motor. The first tests were to check that the principle of wind tunnel simulation – where the aircraft or its model lying in air in motion – is consistent with the reality – where the aircraft is moving in the air considered as non-moving 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 was then available for the pioneers in their conquest of air: Farman, Bleriot, Voisin, Bréguet [5].

In 1911, the municipality of Paris wanting to recover the area on which the wind tunnel is located, Eiffel had to leave the Champ de Mars. In the beginning of 1912, he installed in the district of Auteuil a new wind tunnel with increased performance, this new laboratory being inaugurated on 19 March. 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, four meters in diameter, to an outlet of two meters;
- 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;
- 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 diverging tube in order to recover pressure in front of the fan (see Fig. 3). The same 50-horsepower engine as that already used in the Champ de Mars, was used again. The wind tunnel of the Champ de Mars reached a speed of 18 m/s in a 1.5-m-in-diameter test section. With the same engine, the new wind tunnel, thanks to the diffuser, reached 32 m/s (an increase of 78% speed) in a section of 2 meters in diameter (an increase of 78% also), hence a mass flow gain of more than 200%.
- A helical fan with a diameter of 3.80 m and a weight of 8.500 kg was 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 one meter in diameter.

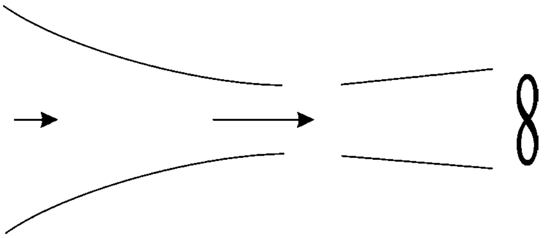


**Fig. 3.** Introduction of the diffuser between the test section and the fan.

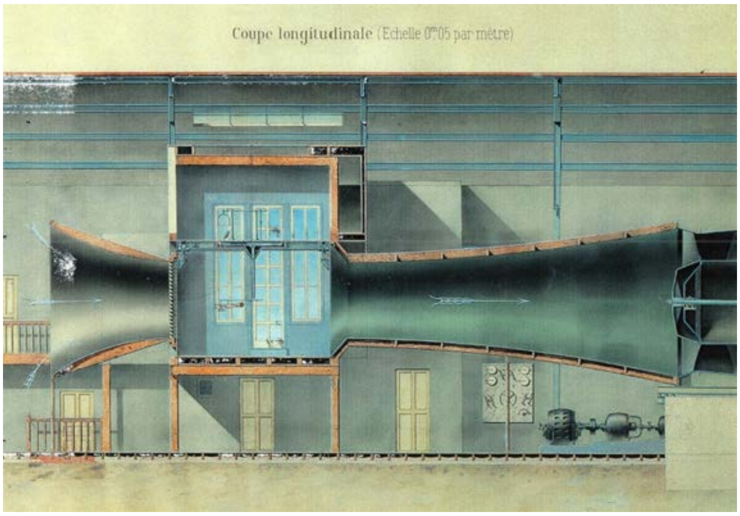


**Fig. 4.** Watercolor drawing of the Eiffel wind tunnel located in the rue Boileau (© Aérodynamique Eiffel).

The diffuser, which was an innovation of Eiffel (see Fig. 4), was the subject of a patent dated 28 November 28 1911: "The addition of a diffuser to improve the performance of a machine to produce artificial air flow". This invention was rich in consequences, as it allowed Eiffel to drastically reduce the electric 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 velocity, the diffuser increased the pressure of the air exiting the test section. The pressure difference on either side of the fan is then much less than the one that would exist if the fan were located directly just downstream of the test-section. This device leads to a reduction in the electric power required to extract the air. "Thus the diffuser saves money since power is reduced by a factor of 3. The advantage of this recovery device is clear, which allowed us to realize the present large facility" (Eiffel [5]). From that date all wind tunnels have been equipped with a diffuser. Gustave Eiffel (see Eiffel in Fig. 5) will ask that the official designation, "Aerodynamic device system Eiffel Paris" should be engraved on a 1-m-by-0.5-m marble plaque on all facilities using his technique, without asking for royalties.

### *1.6. The Prandtl wind tunnel in Göttingen*

Another major innovation consisted in making air circulate in a closed circuit. The first installation of this kind was built at the University of Göttingen, in Germany, by Ludwig Prandtl in 1909. After being sucked downstream of the test section, the air is guided through four successive bends, and then readmitted upstream of the collector. This type of wind tunnel, called Prandtl wind tunnel – or Göttingen wind tunnel – leads to a better fuel efficiency and provides controlled test conditions (pressure, temperature, humidity). Modern wind tunnels combine Prandtl's innovation (closed circuit) and Eiffel's one (diffuser).

### *1.7. The controversy between Eiffel and Prandtl concerning the drag of spheres and the irruption of the Reynolds number in aerodynamics*

At the Auteuil laboratory, Eiffel continued the activities undertaken at the Champ de Mars Laboratory concerning the aerodynamics of the drag of a sphere. The measurements carried out at the Champ 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, headed by the famous Ludwig Prandtl. Föppl did not hesitate to write that the French colleague had committed an error, but a forgivable mistake with respect to its age. Therefore, Eiffel decided to undertake new tests

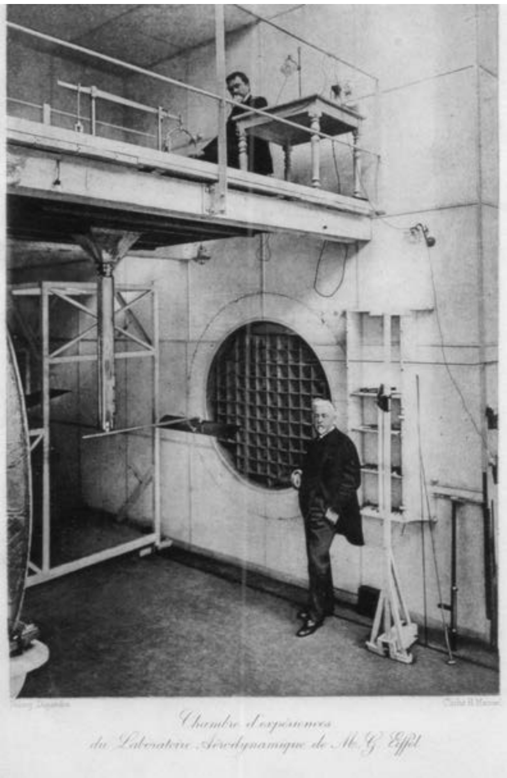


**Fig. 5.** Eiffel in the vacuum chamber of its wind tunnel in the Boileau street (© Aérodynamique Eiffel).

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 (with boundary layer separation in laminar flow) and the other, at higher speeds, corresponding to the coefficient found in the Champs de Mars facility (with boundary layer separation in turbulent flow). The transition between the two regimes always occurs for the same value of the product velocity × diameter.

If the viscosity is constant, which is the case at low velocities, this product velocity × diameter is similar to the Reynolds number:

$$Re = \rho \cdot V \cdot L/\mu$$

where $\rho$ is the density of the actual flow, $V$ its velocity, $\mu$ the air dynamic viscosity, and $L$ the characteristic length of the studied solid.

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 behavior, 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 favorable to the global drag balance, which is the sum of the friction and form drags. This phenomenon is illustrated by an old experiment carried out at ONERA in a water tunnel by Werlé [6]. Fig. 6a is relative to the case obtained for a Reynolds number based on the diameter equal to 200,000, and Fig. 6b is relative to the case of a Reynolds number equal to 300,000. One sees clearly the less perturbing wake in the second case (with a turbulent separation) than in the first case (with an earlier laminar separation) [7,8].

An emblematic application of the phenomenon is given by the golf ball with dimples that trigger transition and postpone more downstream the separation of the boundary layer. The reduced wake resulting from this turbulent boundary layer promotes the penetration in the air by reduction of the global drag, which leads to an increase in 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 favorable to penetration into the air. They later discovered that the best golf balls were damaged balls whose rough envelope triggers a transition of the boundary layer [8,9].

The controversy between Prandtl and Eiffel about the drag of the sphere highlights the essential role played by exchanges between researchers for the advancement of knowledge. Thanks to these confrontations, science progresses and that was the goal pursued by Gustave Eiffel: "It is mainly the progress in aviation that I wanted by creating this laboratory where the tests

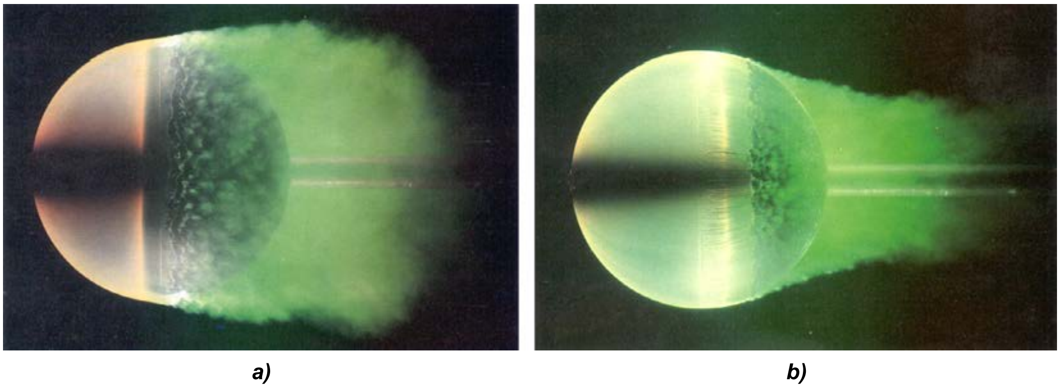


**Fig. 6.** a: Laminar regime at the boundary layer separation. b: Turbulent regime at the boundary layer separation (© ONERA).

are absolutely free, but where the results would be published, in the general interest, through reports or communications to scientific societies". Gustave Eiffel was a great 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 were to be published and accessible to all. It was truly the wind of research that was blowing at the laboratory of Auteuil under the leadership of Eiffel. He publishes *The Friction of the Air and Aviation*, a book translated into both German and English. Furthermore, its contribution to this emerging science of aerodynamics was recognized in the USA, where he received the gold medal of Langley in 1913, which had only been awarded to Wilbur and Orville Wright before.

## 2. Facilities from the beginning of the 20th century to modern wind tunnels

### 2.1. The rules of similarity

During the twentieth century, the development of wind tunnels has continued, driven by the urgent need to respect the similarity rules to ensure the validity of the tests. A first evident requirement was to have a model with the same geometric shape as the original object.

A second condition was required to meet the characteristics of the flow: the Mach number **M** has to be respected:

$$M = V/c$$

where $V$ represents the velocity of the flow and $c$ the celerity of sound.

The third similarity rule is to perform tests maintaining – as far as it might be – the Reynolds number (*Re*) of the flow.

If the air in the wind tunnel has the same characteristics as the real one (density and viscosity) and the same velocity, the Reynolds number is automatically respected in a model at the real scale. Since at the beginning of the epic of aviation, the size of aircrafts was small, the first mean to reach the convenient Reynolds number being to increase the size of the wind tunnels. The large Chalais–Meudon S1Ch wind tunnel meets these specifications.

Due to the rapid increase in aircraft size, it was not suitable to increase too much the size of the facilities. Thus, nowadays the experiments are again performed with reduced models. To respect the convenient Reynolds number, we play on the other parameters of the formula: density by pressurizing the fluid and viscosity by cooling the fluid. The F1 wind tunnel is a pressurized wind facility and the European Wind Tunnel (ETW) is a cryogenic wind tunnel.

### 2.2. The large Chalais–Meudon S1Ch wind tunnel (France)

Antonin Lapresle, collaborator and successor of Eiffel at the Auteuil wind tunnel, designed, at the request of the Air Ministry, the large Chalais–Meudon wind tunnel (Hauts-de-Seine) that had been built between 1932 and 1934 for testing full-scale airplanes (see Figs. 7 and 8). It was equipped with a collector with a reduction ratio of 3.5, with a mouth of 350 $m^2$ that captures the outside air and allows it to reach a velocity of 180 km/h in the inlet test section of 100 $m^2$. The diffuser, a giant tube shaped like a truncated cone (elliptical section, 10 m of vertical axis and horizontal axis of 18 m), is made of reinforced concrete with a thickness of 70 mm and a length of 38 meters. Downstream of the diffuser, the suction chamber, with six fans of 1,000 horsepower each, allows the air extraction. The installation, which had become obsolete, has been disused in 1977. Classified on the list of the historical monuments in 2000, this facility has tested, in many national programs, aircraft, automobiles and buildings aerodynamics [10].

### 2.3. The F1 wind tunnel of Le Fauga–Mauzac (France)

To replace the large S1Ch wind tunnel of Chalais–Meudon, other facilities were emerging. For aerospace testing, a pressurized F1 wind tunnel was built near Toulouse, at Le Fauga-Mauzac. Operational since 1974, this tunnel closed circuit has

**Fig. 7.** View of the large S1Ch wind tunnel in Meudon (© ONERA).

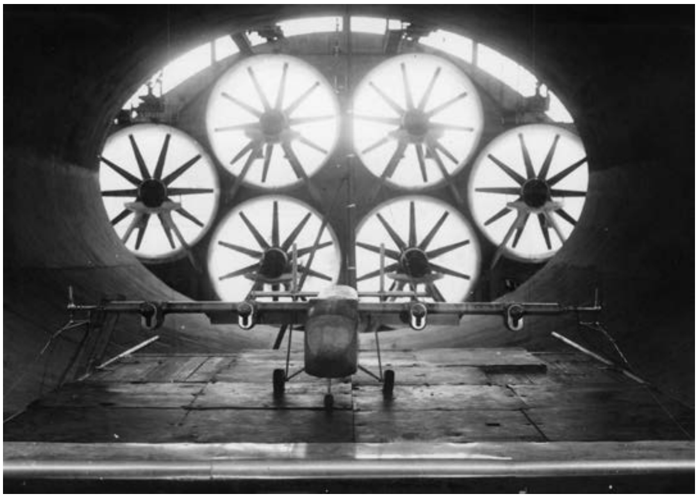


**Fig. 8.** Bréguet 940 airplane in the S1Ch Meudon test section (© ONERA).

a rectangular test section (4.5 m × 3.5 m) where the flow speed reaches 430 km/h. Pressurizing the facility (up to 3.85 bar) increases the density of the flow, hence maintaining a high Reynolds number compensating the reduced size of the model imposed by the relatively small wind tunnel size. It has not been, however, possible to save more than a factor of 4 on the Reynolds number by pressurizing, since then very large dynamic loads will appear on the structures (walls, floors).

### *2.4. The European Transonic Wind Tunnel (ETW) in Cologne (Germany)*

To obtain higher number of Reynolds, close to the one that characterizes the current large civil aircraft, we chose to play on the air's dynamic viscosity $\mu$, which is proportional to the square root of temperature. By cooling the circuit, a cryogenic wind tunnel is obtained. In such a facility, the Reynolds number increases not only due to the decrease in viscosity, since it is included in the denominator in the formula giving the Reynolds number, but cooling also induces an increase in the density via the ideal gas law:

$$\rho = p/r \cdot T$$

where $\rho$ is the density in $\mathrm{kg\,m^{-3}}$, $p$ the pressure in Pa, $r$ the universal gas constant equal to 287 $\mathrm{J\,kg^{-1}\,K^{-1}}$ and $T$ the temperature expressed in K.

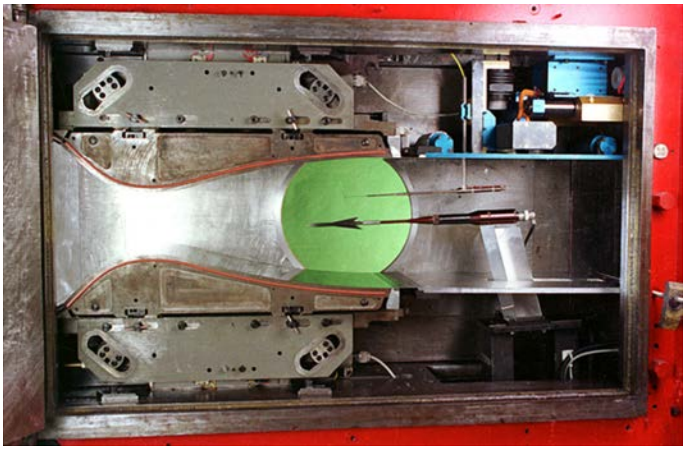


**Fig. 9.** View of the Mach 2 nozzle of the S5Ch wind tunnel in Meudon (© ONERA).

The decrease in temperature contributes also to an increase in the Reynolds number, via the increase of density. Such a system was installed in Cologne, Germany. This is the ETW wind tunnel in which the flow is at a very low temperature obtained by cooling the air by means of an internal circulation of liquid nitrogen at 100 K between the walls. This facility reached Mach 1.35. This is a transonic wind (flow velocity around Mach 1) put into operation in 1994.

## 3. Supersonic and hypersonic wind tunnels

### 3.1. *Special features of supersonic flows*

The race for speed has required the construction of more efficient facilities. This situation led to the creation of transonic wind tunnels (around Mach 1), supersonic (Mach 1 to Mach 4), and hypersonic (from Mach 5). However, supersonic flows obey laws fundamentally different from those governing subsonic flows. The Hugoniot relation distinguishes these two states. It expresses, in the absence of friction, the relationship between the Mach number $M$ of the flow, the velocity variation $\mathrm{d}V$ of the fluid along the axis of the wind tunnel and the section variation $\mathrm{d}A$:

$$\frac{\mathrm{d}A}{A} = \left(M^2 - 1\right)\frac{\mathrm{d}V}{V}$$

Thus, in subsonic flow ($M < 1$), the factor ($M^2 - 1$) is negative, which leads to opposite variations of $A$ and $V$. Thus, the speed increases in the converging sections (collector), since the section of the tunnel decreases, and decreases in diverging sections as in the subsonic diffuser described above.

However, for the supersonic flow ($M > 1$), the factor ($M^2 - 1$) becomes positive. It follows that the velocity increases in the diverging sections (since the section of the tunnel increases) and decreases in the converging sections (since the tunnel section decreases).

Another consequence of this relationship consists in obtaining the sonic flow ($M = 1$) in a minimum area section called throat. The air is moved by a fan or other means to suck the air in the circuit.

### 3.2. *Supersonic wind tunnel*

Due to the particularity of the flows, the realization of a supersonic wind tunnel requires the successive establishment of a convergent device that increases the velocity of flow to reach Mach 1 at the throat, itself followed by a diverging portion (called nozzle) within which the speed becomes supersonic. This convergent-divergent device was first designed by the Swedish engineer Carl Gustav de Laval in 1890 [8]. A Swiss engineer, Jacob Ackeret, built from this concept the first supersonic wind tunnel in 1935 [11]. One can see in Fig. 9 a view of the Mach 2 nozzle in the S5Ch wind tunnel in ONERA Meudon, into operation since 1954.

The supersonic flow has its share of mystery and it was believed for a long time that we could not reach the speed of sound, hence the usual expression “wall of sound”. This is due to the drastic increase in drag that opposes the advancement near Mach 1. Also, the increase in propulsive power planes was balanced by a corresponding increase in drag, which suggested that this barrier was impassable.

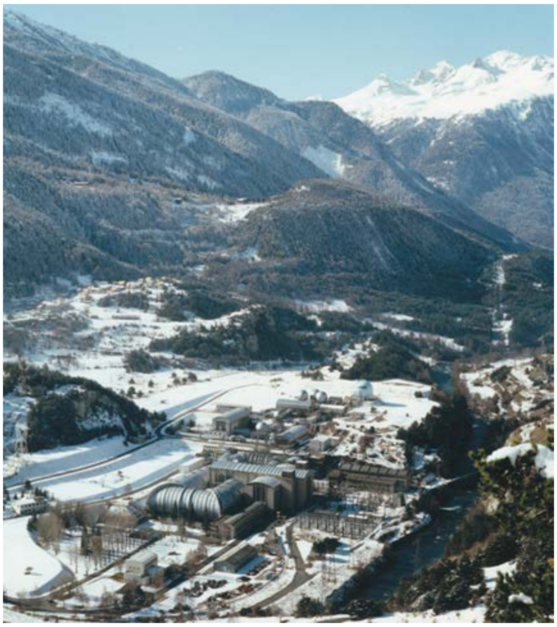


**Fig. 10.** The large ONERA S1MA wind tunnel in Modane (© ONERA).

### *3.3. Hypersonic wind tunnel*

Obtaining flows higher than Mach 4 requires a preheating of the air prior to the expansion in the nozzle in order to avoid air liquefaction. Thus flow streams from Mach 4 or Mach 5 are often called hypersonic flows, although specific hypersonic features, such as the dissociation of molecules, appear at higher Mach numbers [12].

The hypersonic domain mainly concerns the field of rockets or space vehicles. Besides the need to heat the air upstream of the nozzle, hypersonic wind tunnels also require more power to "start" the throat, i.e. to obtain Mach 1 at the throat. Indeed, it is necessary to establish a pressure difference between the upstream and downstream ends of the nozzle, sufficient to create the conditions for the ruin. Thus it is required to obtain high compression upstream or intense depression downstream, or the combination of both effects. In fact, most of the time, for hypersonic applications, one builds blow-down wind tunnels. The wind tunnels for lower Mach number are usually continuous wind tunnels, able to work during several hours. At the opposite, a blow-down wind tunnel operates for a short time (from a few seconds to a few minutes), which is determined by the capacity of the compressed air reservoirs upstream and/or the capacity of the vacuum tanks downstream.

## 4. Wind tunnels for aircraft

### *4.1. The S1MA wind tunnel in Modane–Avrieux (France)*

Among the hundreds of wind tunnels in service worldwide, the most impressive is certainly the S1MA wind tunnel at ONERA in Modane–Avrieux in Savoy, France [13–15], with a power of 88 megawatts (MW), higher than that of the *Charles de Gaulle* aircraft carrier. His performances are due to the German engineers who had started its construction in the Austrian Alps during Second World War. Unfinished at the end of the latter and considered as a compensation for war damage, it was transferred to France and was put into service in 1952 (see Fig. 10).

The air flow is provided by two wheels with a diameter of 15 meters (see Fig. 11) rotating in opposite directions and provided with metal blades (10 for one and 12 for the other). Each of these two fans is driven by a 44-MW Pelton turbine. To supply water to the turbines, 10 million $m^3$ of water per year come from the mountains thanks to several barrages operated by EDF, the French power company. Since the barrage overlooking Avrieux, a 840-meter waterfall feeds the wind tunnel through a conduct, the flow rate reaching 15 $m^3/s$. In this closed circuit wind tunnel, the speed can reach 1100 km/h (Mach 1) in the test section having a diameter of 8 meters, giving it the status of the largest sonic wind tunnel reaching the speed of sound in the world.

### *4.2. The icing wind tunnel in Capua (Italy)*

Thanks to the climate conditions prevailing in Modane due to the altitude, it was possible to study the icing phenomena that affect airplanes as they pass through the clouds. However, the S1MA wind tunnel at Modane is no longer used for

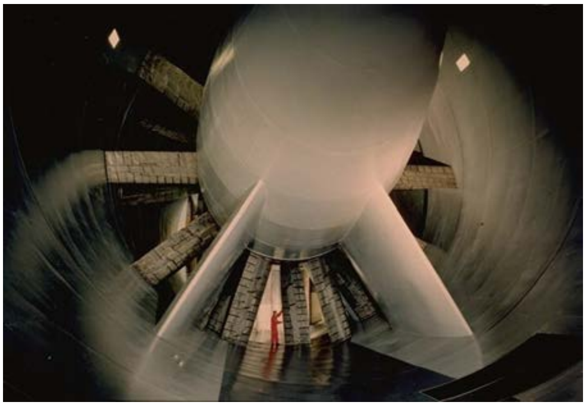


**Fig. 11.** The fan in the S1MA wind tunnel in Modane (© ONERA).

this type of test, because it could not guarantee permanent – even in winter – temperature conditions to obtain this phenomenon.

Thus the experimental study of icing now requires, for any time of the year, the use of wind tunnels specially equipped to produce airflow with water droplets. A very important test facility dedicated to this type of study is that of the Italian Aerospace Research Centre (CIRA) in Capua, near Naples. This huge facility, into operation since 1985, occupies a floor area of approximately 2,500 $m^2$, and the test section is 11.40 m long. It is equipped with a water spray system that generates various types of clouds, including reproducing the reality of flight for a civil aircraft flying at an altitude of 10 km with an outside temperature of $-50\,^\circ$C. Under these conditions, the condensation of water droplets contained in the clouds can form a layer of ice on various elements of the surface planes if precautions are not taken to prevent this phenomenon. However, it is important to maintain the original shape of the wing, optimized to ensure the aircraft's flying qualities. Therefore it is imperative to study in wind tunnels local devices that protect sensitive areas against the formation of frost.

## 5. Wind tunnels for spacecraft

### *5.1. The S4MA wind tunnel in Modane (France)*

High velocity wind tunnels are required for the specific needs of strategic missiles, rockets and space vehicles. During a re-entry, velocities encountered are in the order of 20,000 km/h. The first hypersonic wind tunnel category consists of wind tunnels called "cold", i.e. the air is heated before its expansion in the nozzle, just enough to prevent liquefaction. Thereby, the air – or any other study gas – reaches few tens of kelvins (around $-250\,^\circ$C). The S4MA wind tunnel operates on this principle since 1970. It is constituted, from upstream to downstream by:

- a compressed air tank at 270 bar,
- a Joule effect heater amount up to $1600\,^\circ$C,
- a set of three interchangeable nozzles: Mach 6.4, Mach 10 and Mach 12,
- a test chamber,
- a diffuser for compressing the air,
- a vacuum sphere for sucking the air ejected from the diffuser.

This tunnel allows runs with a duration time reaching 45 s at Mach 12. In such a "cold" wind tunnel, the simulation of real phenomena of hypersonic flight is not fully ensured, since the velocity achieved is still insufficient, although reaching 6500 km/h with a Mach 12 nozzle. Furthermore, in the reality, due to the air friction on the vehicle, which generates an intense temperature increase, the dissociation of oxygen and nitrogen molecules occurs. In a cold wind tunnel, the air temperature is too low and the air still retains its molecular structure, and is not the seat of the reactive phenomena actually observed.

The shape of the nozzle permits to obtain the desired Mach number, but the temperature conferred to the flow determines the velocity ($V$) at the nozzle outlet. This fact is due to the definition of the number of Mach ($M$), since the velocity $V = M \cdot c$, with $c$ the sound speed, which is itself proportional to the square root of the temperature.

The dependence of the Mach number on the temperature can be conveniently illustrated by the example of Concorde at its cruising velocity. He was flying at Mach 2 at 18 km of altitude, where the temperature is around $-50\,^\circ$C. Thus the aircraft velocity at that distance from the ground reached 2110 km/h. If the plane had kept the same velocity at sea level, with an outside temperature of $+20\,^\circ$C, this would lead to a supersonic flow only reaching Mach 1.7 instead of Mach 2.

**Fig. 12.** The high-enthalpy ONERA F4 wind tunnel in Le Fauga–Mauzac (© ONERA).

In fact, with a "cold" wind tunnel, one easily gets high Mach numbers, since the sound speed is low, approximately 350 km/h instead of 1200 km/h in standard conditions for temperature and pressure. Thus the resulting Mach number may be high and the gas velocity still important, but not entirely representative of the reality of an atmospheric reentry.

### *5.2. The F4 wind tunnel in Le Fauga–Mauzac (France)*

To reproduce faithfully the reality of hypersonic flights, one uses "hot" hypersonic wind tunnels, called hot-shot wind tunnel, in which the test gas is heated intensely upstream of the nozzle. But considerable powers are required to obtain the initial temperatures, i.e. stagnation temperatures, before expansion in the nozzle exceeding 2500 °C, with high pressure levels. So the run duration is extremely short. In the F4 wind tunnel, into operation since 1992 (see Fig. 12), the heating of the flow is obtained by an electric arc heater in a 15-liter chamber, filled with air, nitrogen or other test gases at a selected pressure depending on the desired final conditions. The burst of a diaphragm located at the throat allows the admission of the gas flow in the nozzle (up to Mach 20). Thus one produces pressures of several thousand bars and temperatures of 3000 to 8000 °C, for useful run duration in the order of magnitude of 100 ms. The energy required for the realization of the electric arc is obtained by means of a generator consisting of a 15-ton flywheel launched at 600 revolutions per minute, which represents an energy storage equal to 400 MJ. Since these facilities require significant energy, the test sections are of small dimensions, with a diameter of a few tens of centimeters (according to the nozzle used).

## 6. Wind tunnels for ground vehicles

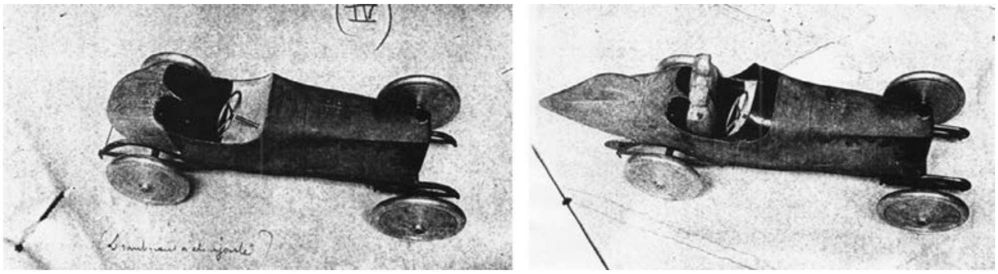
### *6.1. Cars in wind tunnel: a long-standing idea*

Testing cars in a wind tunnel is not a new idea. In 1914, Peugeot passed a car in the Eiffel wind tunnel located in the rue Boileau, in Paris. The left view (Fig. 13a) is relative to the first model tested and the right view (see Fig. 13b) is relative to the model improved after wind tunnel tests. To decrease the aerodynamic drag, the back shape of the car has been largely modified.

With the requirements for reducing pollutant emissions, these tests are more and more relevant. Indeed the aerodynamic drag becomes important from a 90 km/h cruise velocity. A gain of 10% in the aerodynamic drag leads to a decrease in consumption of 0.3 to 0.4 liters per 100 km on the highway at 130 km/h.

### *6.2. The S2A wind tunnel in Montigny-le-Bretonneux (France)*

In 2003, to meet the needs of the automobile industry, a highly advanced wind tunnel, with a capacity of 3.8 MW, was put into service in Montigny-le-Bretonneux (Yvelines, France) by an economic interest grouping involving Peugeot, Renault, and the "Conservatoire national des arts et métiers" (CNAM). This wind tunnel and aeroacoustics (S2A) reaches a velocity of 240 km/h in a test section of 24 m$^2$, allowing one to study aerodynamics and acoustics on vehicles at scale 1 (see Fig. 14).



***a) Before wind tunnel tests.*** ***b) After wind tunnel tests.***

**Fig. 13.** Peugeot model tested in 1914 in the Eiffel wind tunnel (© Laboratoire Eiffel). a) Before wind tunnel tests. b) After wind tunnel tests.

**Fig. 14.** S2A wind tunnel in Montigny-le-Bretonneux (© GIE S2A).

For the simulation of the ground effects, this wind tunnel is equipped with a central moving carpet under the vehicle, which rolls at the same wind tunnel velocity.

## 7. Wind tunnels for buildings

### *7.1. The Eiffel wind tunnel in Paris (still in service)*

Stadiums, bridges or towers, all these works have in common their gigantism. Wind effects on these structures are the subject of extensive studies. Gustave Eiffel wind tunnel ever works, principally in this domain, since the French Scientific and Technical Centre for Building (CSTB) bought the facility in 2001. Also added to the wind resistance for buildings, a lot of other studies have been undertaken in the facility, such as effluent dispersion in nature, active cooling (with pumps to move air), passive cooling (without pumps), which are subject of extensive research in the current context.

### *7.2. The Jules Verne wind tunnel in Nantes (France)*

CSTB operates also, since the end of the last century an exceptional large facility: the Jules Verne climatic wind tunnel in Nantes (see Fig. 15). This tunnel was conceived to study the combined effects of wind and other climatic parameters (rain, sand, sun, snow, temperature...) on building elements, but also on vehicles or other system submitted to extreme climatic conditions. This installation consists of two concentric rings. A dynamic circuit occupies the outer ring, where six fans deploy a 3-MW total energetic capacity, a velocity of 100 km/h reached in the 100-m$^2$ test-section of 100 m$^2$ and 280 km/h in the "high-velocity" 30-m$^2$ test section. The wind tunnel can simulate heavy rain (rainfall up to 200 mm/h) and sandstorm. The thermal circuitry occupies the inner ring and simulates the temperature ($-2\,^\circ$C to $+50\,^\circ$C), fog, ice, snow, sunshine and all types of rain. The velocity reaches 140 km/h using a fan with a 1.1-MW electric power. Heat exchangers with a cooling capacity of 2 MW ensure the control and the variation of the temperature till 15 °C/h. The models of the bridges of Normandy and Millau have been tested in wind tunnels.

**Fig. 15.** The "Jules Verne" wind tunnel in Nantes (© CSTB).

## 8. Conclusion

In the 1980s, the advent of computers with large computing capabilities, in conjunction with the development of numerical methods, augured the disappearance of wind tunnels. However, the abandonment of these aerodynamic ground laboratories is still not in the agenda. Yet thanks to the evolution of computing, Computational Fluid Dynamics (CFD) has now reached a high degree of confidence, so that the researcher in aerodynamics considers that it is an excellent good means to understand the physical reality as well as the measurements acquired during flight tests or in wind tunnels.

Parallel to the development of theoretical models, another breakthrough, almost as spectacular, took place in the experimental area with the development, thanks to laser sources, of a set of optical means to explore complex flows [16–18]. With this breakthrough of metrological means, wind tunnels allow one today to assess the validity of the theoretical models proposed in fine physical flows. Moreover, taking advantage of the constantly improved reliability of digital means, the concept of computer-aided wind tunnels was born. This process aims to correct the results of tests by the results of numerical calculations in conjunction with the tests in the same wind tunnel environment. The characteristics of the test are taken into account in order to determine the effect of the walls, the effect of the support and, more generally, of anything that could affect the experiment. Hence, calculation and experiment will still bring a mutual support in the years to come.

Furthermore, the numerous wind tunnel construction projects in emerging countries show that the use of experiment in the aerodynamics domain is still relevant. This article has been principally devoted to ONERA wind tunnels. To have more information about aerodynamic research in France, see [19] and in foreign countries, the reader is referred to [20].

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