TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
CIVIL ENGINEERING | BUDOWNICTWO

2-B/2015

OLIVIER FLAMAND[*]

SCALE QUESTIONS IN WIND ENGINEERING EXPERIMENTATION

ZAGADNIENIE SKALI W BADANIACH DOŚWIADCZALNYCH W INŻYNIERII WIATROWEJ

Abstract

Wind tunnel testing is sometimes achieved at reduced scale. Doing so, wind engineers must consider the similitude rules for giving results at full scale. These rules are deduced from the basic laws of Physics, for their theoretical part, and based on practical state of the art methods for wind tunnel application. A wide overview of this important part of wind engineering is given in this paper

Keywords: wind tunnel, reduced scale, similitude law

Streszczenie

Badania w tunelu aerodynamicznym czasami możliwe są do wykonania jedynie w skali zredukowanej. Należy wtedy wziąć pod uwagę kryteria podobieństwa dające wyniki, jak dla badań przeprowadzonych w pełnej skali. Kryteria te opierają się na podstawowych prawach fizyki, w części teoretycznej, oraz na praktycznym stanie wiedzy o stosowanych metodach – w części dotyczącej badań w tunelach aerodynamicznych. Szeroki przegląd tej ważnej części inżynierii wiatrowej przedstawiono w niniejszej pracy.

Słowa kluczowe: tunel aerodynamiczny, skala zredukowana, kryteria podobieństwa

DOI: 10.4467/2353737XCT.15.124.4161

---

[*] Centre Scientifique et Technique du Bâtiment, France.

1. Scaling in fluids mechanics

Wind engineering deals with man-made structures, works from structural engineers, architects and civil engineers that are mostly of large dimensions – this presents a problem for laboratory testing. Pioneers of fluid engineering have long faced this difficulty : how to reproduce natural phenomena on a smaller scale. Euler, in 1780, was probably the first to work seriously on scaling in engineering mechanics, this was followed by Fourier in the 1800s. In 1878, the French mathematician Joseph Bertrand was the first to demonstrate the theorem that was reused by Aimé Vaschy [1] and later popularized by Edgar Buckingham [2]. It is now known as the 'Vaschy-Buckingham' or 'Buckingham-Pi' theorem, giving the number of non-dimensional numbers necessary to describe a physical phenomenon. Because they are non-dimensional, these numbers opened the gate to dimensional analysis which gives the rules (Rayleigh's method) to be observed when transposing between a full-scale prototype and a reduced scale model.

In the 18th century, seven basic physical quantities were chosen as elementary elements, the combination of which can represent any physical quantity: length L, mass M, time or duration T, electric intensity I, thermodynamic temperature θ, number of molecules N and light intensity J.

Reynolds, Froude, Prantl, Scruton, Strouhal, Grashof, and Mach have all been immortalized by lending their names to one dimensionless quantity. Does this mean that everything has already been said concerning scale effects in wind tunnel simulations? Let's attempt to consider the practical rules and routines in scaling for wind tunnel studies.

2. Scaling practice in boundary layer wind tunnels

Boundary layer wind tunnels (BLWTs) have been used for more than 60 years for the reproduction of natural turbulent wind at a scale ranging from 1/200 to 1/3000. Prismatic blocks are placed upstream from the test area in order to generate this reduced-scale boundary layer with turbulence scales and spectra resembling the real situation as accurately as possible, using one time scale and one length scale.

It is clear that only part of the natural turbulence can be reproduced by these means, that corresponding to the input from kinetic energy, while the thermal part of the turbulence is neglected. It is commonly recognized that the BLWT [3] is efficient in reproducing a neutral atmosphere corresponding to most storm wind characteristics. It is therefore chiefly used to reproduce extreme loads due to wind on buildings and bridges etc, but it is not convenient for reproducing everyday types of wind, such as that which would be helpful in studying wind power harvesting and pollutant dispersion. Nevertheless, if the experiment is used to reproduce the local dispersion of flumes or the wake of one wind turbine impacting on a neighbouring one, all considered at a short distance, a boundary layer simulation can be very effective.

The first scale limit encountered in boundary layer wind tunnels is due to the Reynolds number. This balance of viscous forces to dynamic forces acting on flow particles is the main parameter governing the reproduction of actual loads on a model. For a geometric scale of 1/200 in air, the wind speed should therefore be 200 times higher than in reality to maintain the same value of the Reynolds number, which is clearly impossible. As a consequence, wind engineers have developed many tricks to counterbalance the effects of the Reynolds number which is 100 to 1000 times lower than the full scale one.

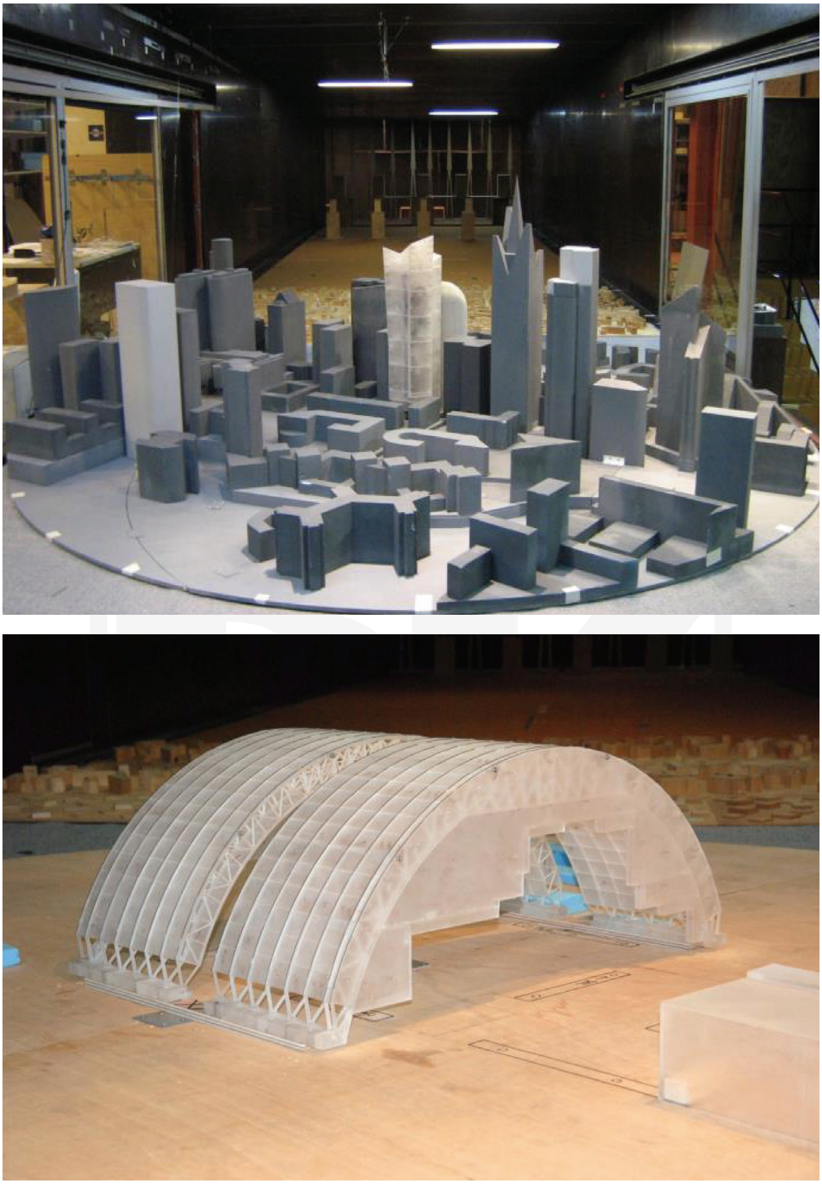

Fig. 1. A view of a BLWT operating at CSTB (top) and the case study of Novarka great arch with the Reynolds number effect on a round shape building and on a truss (bottom)

The first illustration of the Reynolds number scaling effects is given by the study of lattice structures. For elementary parts of the lattice with sharp edged profiles, it is commonly accepted that the drag force on each element does not change with a low Reynolds number. This assumption is based on drag coefficients measured on isolated squares, I, H and U-shaped beams, but is not fully verified when the lattice is so dense that it begins to behave as a mesh structure. Nevertheless, it is characteristic for rounded elements of a lattice structure that the drag force is highly dependent upon the flow regime. In such a case, there are two ways to change the lattice shape with the aim of better representing the wind loads on the model than via simply through the use of homothetic scaling. The first possibility lies in decreasing the diameter of the round bars of the lattice by the ratio of drag coefficient at full scale (say 0.6 for a given wind speed and a given roughness) to the drag coefficient at a reduced scale in the wind tunnel, (say 1.2). In practice, reducing the diameter of round bars by a factor of two is very common, and relies on the assumption of high wind speeds producing a drop in the drag force coefficient when overpassing the critical Reynolds number, usually called the drag crisis, at full scale[4]. The second possibility is to replace round bars by square bars, the thickness of which being calculated with the same ration of drag coefficient of the square compared to the drag coefficient of the circular cylinder at a given Reynolds number at full scale.

The second limit encountered in downscaling is the blockage effect in the wind tunnel itself, especially when it is a closed loop circuit with solid walls. When the wind ‘hits’ a building at full scale, stream lines are deflected around the bluff body with no constraint in the vertical direction, and sometimes none in the lateral direction. In a wind tunnel, it is clear that the ceiling and lateral walls represent a first physical limit to the expansion of the deflected streamlines. Even if correction methods have been applied, especially in aeronautics on streamlined two dimension bodies and for the sake of measuring mean loads, these cannot be effective in boundary layer wind tunnels. The main reason is that not only is the means flow deflected here but additionally, the large eddies composing the low frequency part of the atmospheric turbulence cannot ‘develop’ vertically and laterally. Therefore, it is difficult to establish a universal limit as the effect of walls depends on the size of eddies and the shape of the structure reproduced, but a 5% to 10% blockage ratio is often taken as a maximum.

A third limit is linked with surface state characteristics and machining precision. At a scale of 1/200, a mistake of 0.1 mm on a building model corresponds to 20 cm at full scale. This means models should be machined with a precision of 1/100th mm – this is costly and in real life, often impossible to attain on complex shaped models made of easily machined materials. The best commonly available precision delivered today in 3D printing and classical machining is close to 100 microns – this limits the downscaling to 1 to 10 for a very good geometrical precision and 1 to 100 for moderately good precision. 1 to 1000 is often considered as ‘coarse’ and may be unable to deliver accurate results. The second aspect when downscaling is the surface roughness. The painted surface of a steel structure has a characteristic roughness of 10^{-6} to 10^{-7} compared to its overall size. Reproducing the same roughness in a wind tunnel on a model downscaled 1 to 100 would mean making surface state of less than 1 μm, which is the surface state of a mirror. Once again, it is at the same time very difficult and costly (if not totally impossible) to achieve such precision. In actuality, the wind engineer may find an interest in reproducing rougher surfaces in the small scale model. With respect to the aforementioned drag crisis phenomenon on circular cylinders, this can be triggered at lower wind speeds, i.e. lower Reynolds numbers, by increasing the roughness of the surface; various kinds of artificial roughening are used in the wind tunnel. These can include glued sand, added strips or ligneous material such as wood or dots. Whatever the method and it's efficiency, the aim is to counterbalance the lack of inertial forces compared to viscous forces by forcing separation to occur at a given point on the boundary layer at the skin of the model. This strategy is commonly named the 'increase of the apparent Reynolds number' and can be easily calibrated by making models of the same structure at different scales and comparing the surface pressure patterns and aerodynamic loads measured in the wind tunnel. This approach requires the use of a large wind tunnel that has the capability of testing models of the same shape with a scale ratio close to 10 without blockage effects.

As a matter of synthesis, downscaling effects are complex and cannot be restrained to simple recipes that would work in all cases. The scaling effect in wind tunnel experiment should be studied first, for instance by repeating the experiment at various Reynolds numbers. Attention must be paid to each aerodynamic phenomenon involved in a complex study: it is common that in the same study in the wind tunnel, two phenomena acting jointly will not have the same downscaling process.

3. Some examples of scaling studies in the wind tunnel

3.1. Scaling the drag of cylindrical buildings

The first need for such a scaling study appeared in the 1990s for a high rise tower in Paris, the shape of which was close to a cylinder. This tower, designed by famous architect Jean Nouvel, was named 'la Tour Sans Fins', which means 'the endless tower', because its summit was to vanish in the sky, with no clear limit, with its outer skin becoming more and more porous with altitude. The same concept is now widely seen in recent tower designs. Because the shape was not a perfect cylinder and with the aim of a 1/300 scaled model in BLWT, it was decided to make a first model 10 times the diameter of the tower model but without the same diameter to height ratio, and carefully measure the pressure pattern around it in the large, high-speed Jules Verne wind tunnel [5]. With a diameter of 0.8m and a flow speed of 80 m/s, the corresponding Reynolds number of 4.0 E^{6} was reached – this was considered high enough to be representative of the full scale value of 7.0 E^{7}. Bearing this reference pressure pattern in mind, the 1 to 300 scale model was built and tested with the same kind of flow at wind speeds corresponding to the BLWT test and with various arrangements of added roughness on the model surface. It was found that meridional strips with a thickness of 0.6 mm and a step of 15° provided the best artificial surface roughening in this case. The same question was addressed some years later for the European Launcher Ariane 4, then Ariane 5, with models at a scale of 1 to 100. Similar tests were conducted, first in a high Reynolds number condition in a large wind tunnel, then at lower wind speed in the boundary layer wind tunnel with calibration of the relevant roughening. It must be pointed out that in both cases, longitudinal strips proved to be the only efficient manner to reach the required apparent Reynolds number, while sand roughness was not rough enough.

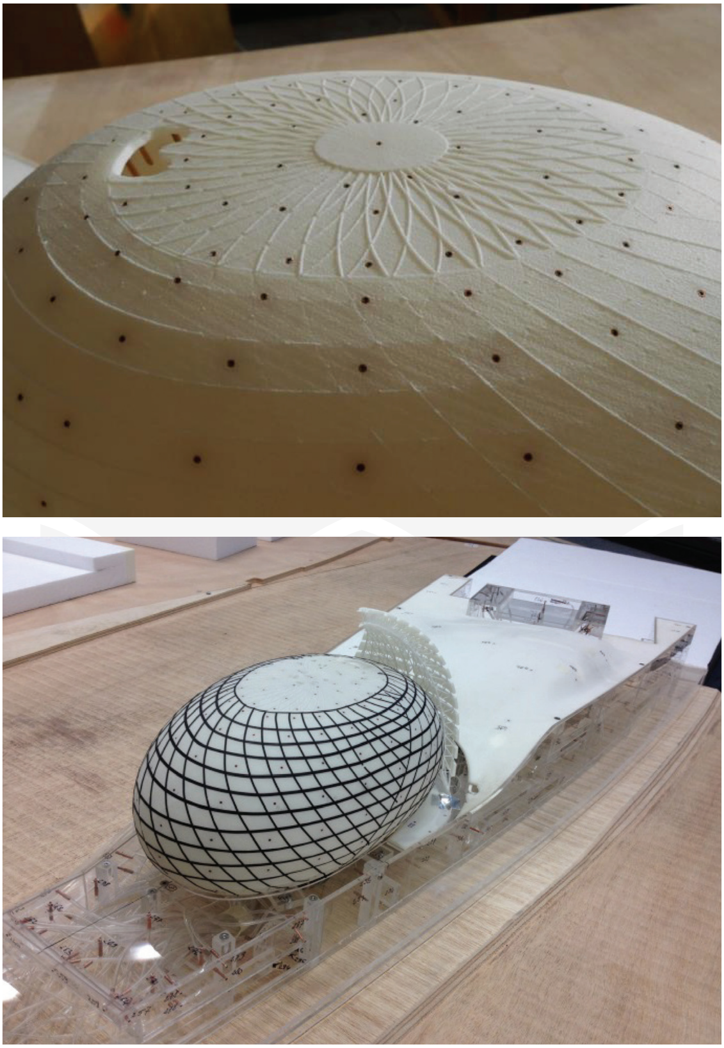

Fig. 2. Extra trips on a powder sintered model for reaching the right roughness in BLWT

3.2. Scaling the porosity of cladding elements

There are a series of recent cases of high-rise buildings incorporating sun shades for the reduction of solar energy input in summer time. Architects also try to use these external structures to give the building a unique appearance, changing the shape and size of these elements across the façade, requiring the design engineer to carefully design them. Due to their exposure at the façade, they are subject to high wind loads, sometimes in accelerated flow areas.

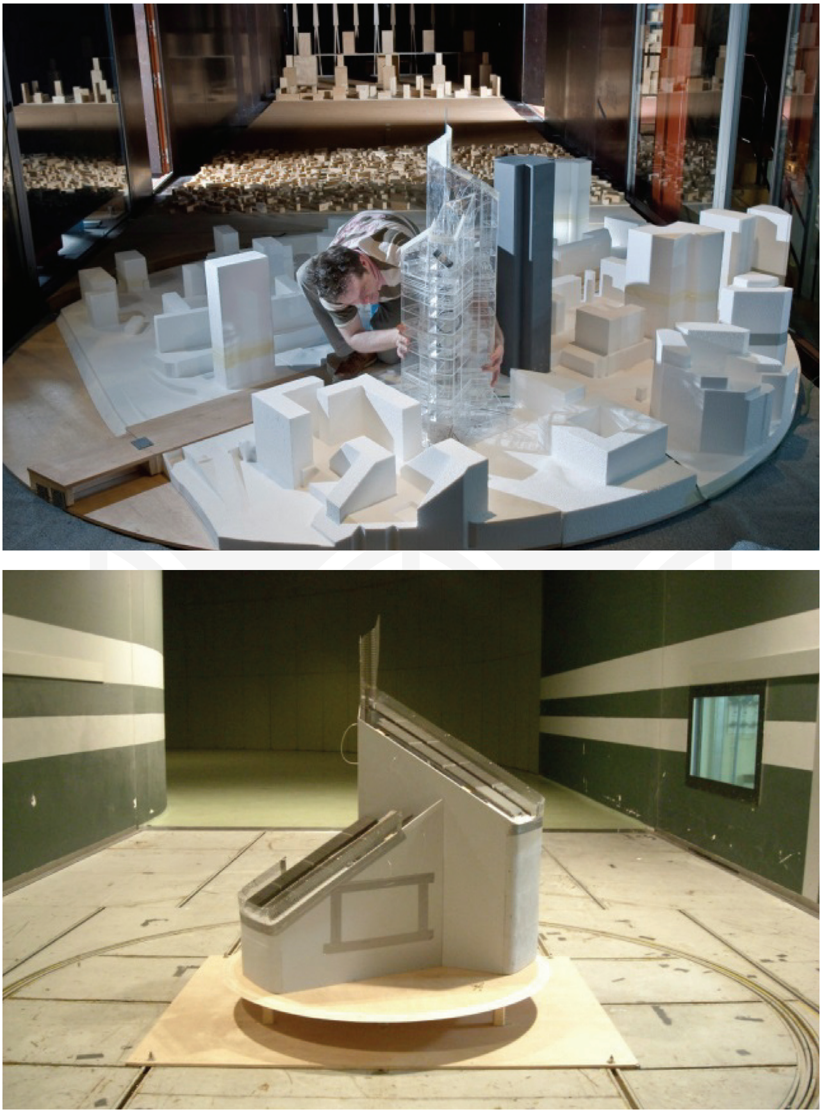

Fig. 3. High rise building scaled 1/200 in BLWT (top) and model of the top of the same tower at a 1/50 scale in a high-speed wind tunnel (bottom) for measurements at a high Reynolds number

At the usual scale of buildings in BLWT; typically from 1/200 to 1/500, it is rather difficult to reproduce the detailed shape and porosity of the shades. The porosity of these screens is especially poorly represented at a very reduced scale because the viscous part in the Reynolds number is considerably increased. Therefore, the classical BLWT model is used to determine global wind forces and flow fields around the building in its environment and a second model of the façade is usually built, at a larger scale, say 1/50, for the fine modelling of wind loads on the shading structures.

3.3. Scaling snow in climatic wind tunnel

There are many questions raised by the researchers involved in the investigation of snow loads. Failures induced by snow ingress in systems, snow accretions on structures and vehicles are efficiently studied by full scale approaches either outdoor or in laboratory environment. On the other hand, questions dealing with large environments, typically interaction between various structures and their surroundings can only be studied with reduced scale models. Snow accumulation around buildings belongs to this category. Reliable experimental modelling in the wind tunnel depends on geometric, dynamic and kinetic criteria: snow particles (shape, density, velocity, drag, lift, liquid water ratio) and wind (temperature, speed, turbulence) must be modeled. Experiments are commonly based on theoretical approaches first introduced by Kind [6] and Iversen [7].

Since a thorough examination of similitude criteria reveals incompatibilities, choices have to be made according to their relevance. Snow particles are usually modelled using sand, sawdust or glass balls which do not reproduce all inter-particle forces. However, it is advisable to use a model particle which reproduces the shapes and stacking up of actual snow particles. From this point of view, artificial snow, although scarcely used as a model particle in the wind tunnel, is the most appropriate choice.

Table 1

Similitude parameters for particles transport and accumulation with D_p particle diameter, L reference length, g gravity, ρ fluid density, ρ_p particle density, u_t^* threshold friction velocity, u^* friction velocity, u reference wind velocity

D_p/L	Geometric ratio particle length/building
$u_t^{*2}/D_p g\left(\rho/(\rho_p-\rho)\right)$	Froude number for particle friction threshold
$u_t^{*2}/Lg\left(\rho/(\rho_p-\rho)\right)$	Froude number for friction on the building
u^*/u_t^*	Threshold speed/friction speed ratio
u^*/u	Friction/fluid speed ratio
$u^2/D_p g\left(\rho/(\rho_p-\rho)\right)$	Froude number for particle transport
u^2/Lg	Conventional Froude number
ρ_p/ρ	Particle/fluid density ratio

A noticeable disagreement of the prototype and model Froude number, based on the threshold friction velocity weighted by the particle/fluid density ratio, indicates that the trajectory of the model particle is different from that of the natural snow particle. According to Kind [6], if the Froude number is not conserved, it is particularly important to verify that the saltation length, which represents 10 times the saltation height, is shorter than the model reference length and the typical size of snow drifts. In practice, this may be verified with moderately reduced scale models.

In the same way, the forces on particles are better modeled if the Reynolds number based on the saltation height is greater than 30.

Regarding the suspended particles, the particulate Froude number, weighted by the density ratio, is the parameter which allows assessment of the similarity of the transport mechanism, globally around the building or locally which drives the accumulation process. Finally, a choice has to be made between the saltation mechanism (close to the ground surface) or long distance transport processes.

In practice, the wind engineer settles simple rules for common applications, essentially considering the simulation of the drifting volume v_0. The basic similitude parameter is v_0/L^3, where L is the reference length of the structure, which leads to the simple criteria

$$\left(1-\frac{u^*}{u}\right)\left(\frac{u^2}{Lg}\right)_p=\left(1-\frac{u^*}{u}\right)\left(\frac{u^2}{Lg}\right)_m \tag{1}$$

where indexes p and m stand respectively for the prototype and the model. This relationship does not imply any constraint regarding particle density and size. Hence, the model particle scale does not interfere with the drifting volume simulation.

The experiment duration, which is a main parameter of reduced scale simulation, can be calculated according to several dimensionless time numbers. Various expressions can be found in literature. Each of the dimensionless times of Table 2 leads to a different snowstorm duration and there is no real agreement about what criteria should be used.

Table 2

Dimensionless time used to assess the equivalent snow event duration

ut/L
$\rho/\rho_p . ut/L$
$1/2\,\rho/\rho_p\, u^2/gL\left[1-u_0/u\right]ut/L$
$tQ\eta/\rho_p L^2$

Therefore, it is quite advisable to rely on the measurement of a real outdoor accumulation if available – this can be compared to its wind tunnel counterpart.

Fig. 4. Testing snow accumulation in the climatic wind tunnel at full scale (top) and reduced scale (bottom)

4. Conclusion

It was exposed in this keynote lecture that downscaling in wind tunnel always leads to making choices. Because every part of aerodynamic forces cannot be faithfully reproduced, the wind engineer must in practice give advantage to the main phenomenon with respect to the final need. Because scale effects are mostly complex, it proved useful in many cases to calibrate the scaled simulation by comparison with a full-scale reference. In practice, such a strategy is highly recommended.

References

[1] Vaschy A., *Sur les lois de similitude en physique*, Annales Télégraphiques, Vol. 19, 1892, 25-28.

[2] Buckingham E., *On physically similar systems. Illustrations of the use of dimensional equations,* Physical Review, Vol. 4, 1914, 345-376.

[3] Davenport A.G., Vickery B.J., Holmes W.H., *The structural and environmental effects of wind on buildings and structures*, Post graduate course of the University of Sidney, School of Civil Engineering, Sydney 1975.

[4] Roulle C., *Reproduction du régime hypercritique sur formes rondes en soufflerie à couche limite atmosphérique*, CSTB report n°EN-ADIM 80-20L, 1980.

[5] Lemoult B. et al., *Caractérisation des efforts aérodynamiques développés sur un cylindre en régime supercritique, simulation en soufflerie*, CSTB report n°EN-SC 90.11-C, 1990.

[6] Kind R.J. *A critical examination of the requirements for model simulation of wind induced erosion deposition phenomena such as snow drifting*, Atmospheric Environment, Vol. 10(3), 1976, 219-227.

[7] Iversen J.D., *Drifting snow similitude*, Proc. ASCE, Journal of Hydraulics Division, Vol. 105, 1979, 737-753.

[8] Delpech P. et al., *Snowdrifting simulation around antarctic buildings*, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 74-76, 1988, 567-576.