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# WIND PRESSURE COEFFICIENTS :

# A COMPARISON BETWEEN PHOENICS AND WIND TUNNEL RESULTS

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Abstract

Awareness of pressure distribution around a building is particularly important when determining infiltration and on purpose ventilation through the envelope as well as induced air flow pattern within the building. The issues are multiple : occupant's comfort, energy consumption, indoor air quality and smoke circulation.

A number of multizone models have been developped but they all required the knowledge of the pressure coefficients Cp on the building facades. These coefficients depend on the site configuration (location, size and nearby obstructions), the wind direction and the size and shape of the building itself. Therefore, it will be desirable for every building to evaluate the pressure distribution. A bibliography review is presented for the determination of Cp : experimental wind tunnel measurements, regression analysis of previous experimental data, numerical simulation...

In the second part, we focuse our attention on the numerical evaluation of these pressure coefficients with the use of PHOENICS. We choose a k-ε model with a staggered grid. For a typical building configurations on an open site and for different wind directions, we compare the numerical and the wind tunnel results. They are in a fairly good agreement. This success will allow us to consider more complex and realistic building site and to compare with on-site measurements in the near future.

Contents





## 1 - Objective of work

The pressure distribution around a building is essential to determine infiltration through the envelope and to calculate airflow inside the building and therefore to evaluate the quality of the interior environment. Many parameters are involved in the evaluation of the pressure distribution : building geometry, environment (trees, other buildings...), topography, wind direction and speed.

In order to determine the pressure coefficient distribution for a building on its particular location, we can choose between a wind tunnel test or a full-scale experiment. Full-scale experiments do not allow parametric tests for optimisation studies and more critically have to be conducted a posteriori and can not be considered as a design tool. Model-scale in boundary layer wind tunnel allows this evaluation but at a high cost. A compilation of many various sources will be presented in the first part of our study. The scattering of the results is so large that a systematic approach would have to be initiated. So, we propose to include the numerical methodology in the approach. With a turbulent flow model, the velocity and pressure fields around the building facade are determined knowing the boundary conditions. Then, we can calculate the pressure distribution at a specific location such as the facades.

The results that we present here are limited to two single parallelepidic buildings on an open site. The mean pressure coefficients obtained with the PHOENICS code are compared with the bibliography data.

## 2 - Bibliography review

### 2.1 - Experimental wind tunnel measurements

Wind tunnel tests have been realized all over the world. In France, the CSTB published cartographies of wind pressure coefficients for many types of building in different surroundings and for three wind directions [1]. GAUTHIER [2] summarizes the mean pressure coefficients resulting from these tests, in terms of building's shape ratio and wind direction (table 1).

| Ratio H/l | Ratio L/l | Wind Direction | Cp for each face 1 | 2 | 3 | 4 | Cp roof |
|---|---|---|---|---|---|---|---|
| H/l<0.5 | 1<L/l<1.5 | 0 | 0.7 | -0.2 | -0.5 | -0.5 | -0.5 |
| | | 45 | 0.6 | -0.4 | 0.6 | -0.4 | -0.5 |
| | | 90 | -0.5 | -0.5 | 0.7 | -0.2 | -0.5 |
| | 1.5<L/l<4 | 0 | 0.7 | -0.25 | -0.6 | -0.6 | -0.5 |
| | | 45 | 0.6 | -0.5 | 0.6 | -0.2 | -0.5 |
| | | 90 | -0.5 | -0.5 | 0.7 | -0.1 | -0.2 |
| .5<H/l<1.5 | 1<L/l<1.5 | 0 | 0.7 | -0.25 | -0.6 | -0.6 | -0.6 |
| | | 45 | 0.7 | -0.4 | 0.7 | -0.4 | -0.6 |
| | | 90 | -0.6 | -0.6 | 0.7 | -0.25 | -0.6 |
| | 1.5<L/l<4 | 0 | 0.7 | -0.3 | -0.7 | -0.7 | -0.6 |
| | | 45 | 0.7 | -0.5 | 0.7 | -0.2 | -0.6 |
| | | 90 | -0.5 | -0.5 | 0.7 | -0.1 | -0.1 |
| 1.5<H/l<6 | 1<L/l<1.5 | 0 | 0.8 | -0.25 | -0.8 | -0.8 | -0.7 |
| | | 45 | 0.8 | -0.5 | 0.8 | -0.5 | -0.7 |
| | | 90 | -0.8 | -0.8 | 0.8 | -0.25 | -0.7 |
| | 1.5<L/l<4 | 0 | 0.7 | -0.4 | -0.7 | -0.7 | -0.7 |
| | | 45 | 0.8 | -0.6 | 0.8 | -0.2 | -0.7 |
| | | 90 | -0.5 | -0.5 | 0.8 | -0.1 | -0.1 |

TABLE 1 : Cp from GAUTHIER

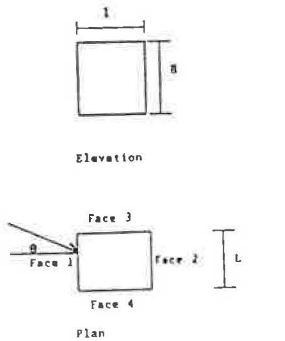



FIGURE 1 - Building geometry

## 2.2 - Regression analysis

Many wind pressure data resulting from on-site experiments or from tests in boundary layer wind tunnel are available in the world. ALLEN [3], SWAMI & CHANDRA [4], ANSELME [5,6] have conducted regression analysis and curve fitting in order to obtain analytical formulation for the pressure coefficient in terms of shape ratio, wind direction, wind profil, and environment.

WALTON [7] proposed a very simple formulation for the mean pressure coefficient in terms of wind direction θ which is a compromise between the formulation.

$$Cp = 0.75 - 1.05 \frac{\theta}{90} \quad \text{pour } \theta < 90°$$

$$Cp = 0.45 - 0.15 \frac{\theta}{90} \quad \text{pour } \theta > 90°$$

The variation of the pressure coefficient with the wind direction according to the different formulations is presented for a seven-storeyed building in the next figure. We can notice that all the formulation give different extremal values and that the curve shape is not in agreement. The scattering of the data is quite large and some unphysical phenomena happen such as non symetry of the Cp variation with the wind direction, a Cp maximum at a wind direction non orthogonal to the facade.

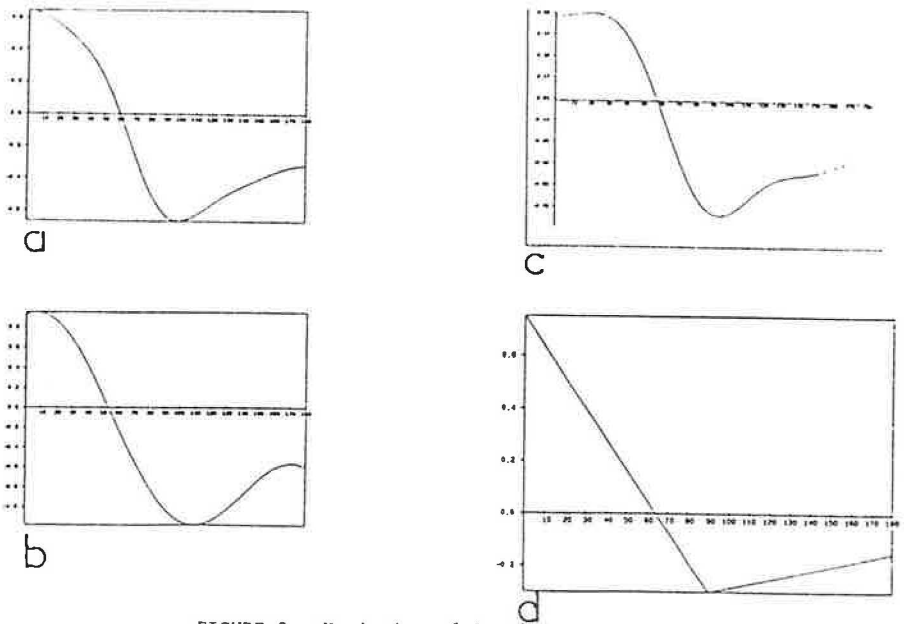


FIGURE 2 : Variation of Cp with the wind direction
a) Allen, b) Swami, c) Anselme, d) walton



## 2.3 - Numerical simulation

The simulation of the flow field around buildings with a turbulence model has been presented in many papers for the purpose of pedestrian's comfort or flow analysis but only a few studies have been conducted to calculate the pressure distribution on the building.

Al-SANEA [8], using the PHOENICS code and a k-ε model of turbulence, has calculated for two wind directions the pressure coefficients on a building - 50 m x 10 m and 10 m heigth with inclined roof - which is isolated or surrounded by a group of buildings of the same type and spacing. This paper demonstrates the feasibility of computer determination of the pressure coefficient but no validation of the results is exposed.

HÄGGKVIST [9] studing the pressure field around the same building with the same code concluded that the differences between simulation and wind tunnel test are essentially quantitative because of the uncertain and not well controled boundary conditions - velocity and turbulence intensity -. The pressure level on the frontal wall shows a strong sensivity to the velocity distribution. However, the pressure field is generally good from an engineering point of view. If an exact value is expected, it is necessary to improve our knowledge of the boundary conditions.

MATHEWS [10,11] has demonstrated that the determination of the pressure coefficient for ventilation studies is possible with a numerical code based on a k-ε model of turbulence. He has simulated with success the flow around a tall and a long building in a open site but no validation with the pressure coefficients obtained in wind tunnel or in situ for the same cases is presented.

MURAKAMI has experimented two models of turbulence : a LES model which leads him to conclude at a good correspondance between numerical simulation and wind tunnel experiments [12,13]. With a fine mesh resolution and a k-ε model of turbulence, the numerical simulation reproduces quite well the pressure field but the prediction of the flow field in the wake is difficult to reproduce precisely. This code is powerful to analyse the flow field in a complicated urban site [14] for wind engineering design.

PATERSON [15,16] has compared his k-ε model computation with Castro's experiments. He has concluded that the numerical pressure coefficients are in a good agreement with the experimental results for the leeward and windward faces and that the velocity profiles around the building are similar. On the other side, the agreement is better with the wind tunnel tests than with the experimental studies. An important limitation of this code is the restriction at wind direction perpendicular at one face of the building.

We notice that few studies have tried to tackle this difficult problem. Previous successful attempts lead us to conclude at the feasibility of solving such a problem with a k-ε model. However, a research effort should be initiated to give experiences and to derive a numerical guideline to solve various configurations. Our study us part of this effort. After a study of the grid dependance, we focused on the determination of the pressure coefficient distribution on a simple building with various wind directions which are not perpendicular to one face of the building but without success at the present time. We hope to present sucessful results at the conference.

## 3 - Description of simulated phenomenon

The flow around a building is supposed to be turbulent, incompressible, steady and without temperature gradient. The building is an obstacle that can't be crossed by the flow. We consider that all the random fields - pressure and velocity - can be severed in a mean component and a fluctuated one according to the Reynolds decomposition.

### 3.1 - Model equations

The equations governing the flow are obtained from the equations established in fluid mechanics by using the Reynolds decomposition. The continuity equation for the mean movement is :

$$\frac{\partial \overline{U_i}}{\partial x_i} = 0$$

The Navier-Stokes equation is now :

$$\overline{U_j} \frac{\partial \overline{U_i}}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \overline{P}}{\partial x_i} + \nu \frac{\partial^2 \overline{U_i}}{\partial x_j \partial x_j} - \frac{\partial \overline{u_i u_j}}{\partial x_j}$$

A turbulence model is required to calculate the Reynolds stress tensor which appears in the Navier-Stockes equation. This term associated which the fluctuation motion represents the interaction between the mean and fluctuating flieds. The turbulence viscosity is introduced in order to evaluate the Reynolds stress tensor in terms of gradient of velocity :

$$\overline{u_i u_j} = -\nu_T \left( \frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i} \right) + \frac{2}{3} k \delta_{ij}$$

$$k = \frac{\overline{u_i u_i}}{2}$$

When the Reynolds number of the flow is high, the turbulence viscosity can be exprimed in terms of turbulence kinetic ernegy and dissipation rate :

$$\nu_T = C_\nu \frac{k^2}{\varepsilon}$$

$$\varepsilon = \frac{\nu}{2} \overline{\left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)^2} \quad \text{in the general case}$$

$$\varepsilon = \nu \overline{\frac{\partial u_i}{\partial x_j} \frac{\partial u_j}{\partial x_i}} \quad \text{if the Reynolds number is suffisantly high}$$

The closure of the system of equations requires the determination of equations for k and for $\varepsilon$. These equations introduce new terms which are modelled in the zone where the Reynolds number is high [17].

$$\overline{U_j} \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\nu_T}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + \nu_T \left( \frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i} \right) \frac{\partial \overline{U_i}}{\partial x_j} - \varepsilon$$



$$\overline{U_j} \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\nu_T}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right) + C_1 \left( \frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i} \right) \frac{\partial \overline{U_i}}{\partial x_j} \frac{\varepsilon}{k} - C_2 \frac{\varepsilon^2}{k}$$

Near the wall, the Reynolds number is low and particular phenomena appear such a laminarization of the flow. "Wall function" are also used to simulated this effet, and the constants which have been introduced are expressed in terms of Reynolds number [18,19].

This equations system is solved by using the general computer solver PHOENICS [20], based on a control volume technique developped by Patankar.

### 3.2 - Boundary conditions

The wind profil at the inlet of the simulated domain is considered to be steady, the wind direction is parallel to the floor. We impose the wind profil reproduced during the wind tunnel tests. So, the vertical profil of the horizontal velocity follows a logarithmic law of an open site [21]:

$$\frac{U_z}{U_0} = 0.202 \text{ Log} \left( \frac{Z}{0.07} \right)$$

and the turbulence intensity can be approximated by :

$$I_z = \frac{0.202 \ U_0}{U_z} = \frac{\overline{u_z u_z}^{\,0.5}}{U_z}$$

So we deduce that :

$$k = (0.202 \ U_0)^2 / 2$$

$$\varepsilon = \frac{Z}{\kappa \ k^{1.5}}$$

On the floor and on the wall of the building, we imposed a no slip condition and a wall condition. Out of the simulated domain the wind flow must be non disturbed by the obstacle, so we impose a zero gradient of all the fields at the side, the top and the outlet exepted for the wind velocity in the vertical direction.

### 3.3 - Mesh distribution

The calculation domain is so large that no interaction between recirculation zones and the boundary conditions can exist. It is about 5 building heights (H) in height, 1.65 building length (L) in the perpendicular direction to the wind direction and 8.5 building width (l) in the wind direction with 0.625 l before the building and 275/40 l after it (cf. figure 3).

Three meshes have been tested in our studies : a regular spacing mesh (1), and two irregular spacing meshes (cf table 2), in order to determined which mesh dividing realizes the better compromise between accuracy and low CPU time.

We did not take in account symetry because we wanted to test the capability of the code to handle such symetries.

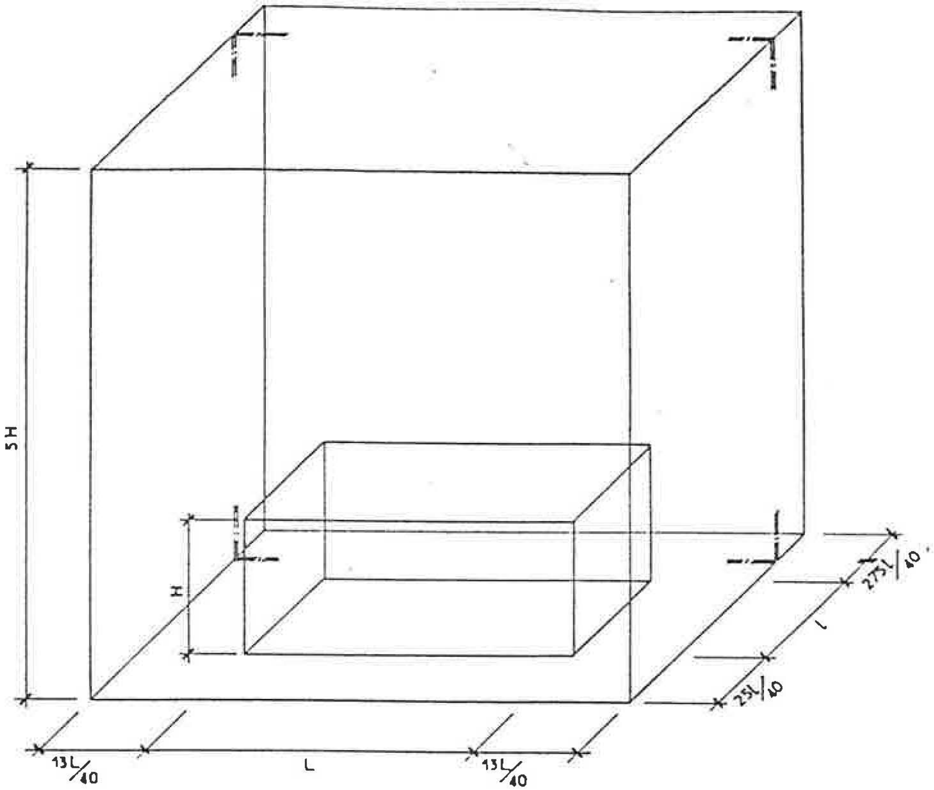



FIGURE 3 : Calculation domain

| | Number of discretisation points | Smallest mesh | Largest mesh |
|---|---|---|---|
| Mesh 1 | 20 x 35 x 51 | 3m x 3m x 3m | 3m x 3m x 3m |
| Mesh 2 | 36 x 24 x 34 | 0.45 x 1.31 x 0.9 | 0.9 x 11.375 x 18 |
| Mesh 3 | 46 x 48 x 43 | .225 x .656 x .45 | 0.9 x 5.6875 x 18 |

TABLE 2 : Mesh spacing characteristics



## 4 - Presentation of the results

### 4.1 - Simulated cases

The simulated building is a seven-storeyed building with a flat roof, 21m high and 18mx18m in plan, in an open site. Only two wind directions are studies - 0° and 45° - because of the symetry. A model of this building at a 1/150 scale has been studied in the boundary layer wind tunnel of the CSTB where a wind characteristic of a wind of a open site has been reproduced by using a subtle dosing of the ground roughness and of the vortex generators [21]. Two facades of the model have been equipped with scanivalves which permit the measure of the pneumatic average pressure coefficient on a area.

### 4.2 - Typical input and output

In appendix listings of a typical input and of the corresponding output have been reprinted. The methods of pairs is used so that it is easy to change the mesh dividing. The pressure coefficient is calculated by using a special function in ground. To simulate the wind profil special functions are used : GRND2, GRND3, GRND4, included in ground. All the listings of the functions written for our study have been reprinted in appendix.

### 4.3 - Grid independence

The comparison between the results obtained with the three mesh dividings let us to consider that a regular spacing of the mesh give no satisfying values for the pressure coefficient. But the pressure coefficients calculate with the mesh 2 and 3 are similar (cf Table 3). So we can conclude that a very fine mesh dividing is not necessary in order to obtain good results. The computation effort for the mesh 3 is about 6 times the computation effort for the mesh 2, which is about 2.5 CPU day.

| | Face 1 | Face 2 | Face 3 | Face 4 | Roof |
|---|---|---|---|---|---|
| Mesh 1 | 1.18 | -0.20 | -0.28 | -0.30 | -0.32 |
| Mesh 2 | 0.62 | -0.21 | -0.36 | -0.36 | -0.45 |
| Mesh 3 | 0.65 | -0.21 | -0.36 | -0.37 | -0.48 |

TABLE 3 : Cp values calculated with the three meshes

## 5 - Discussion of results

### 5.1 - Mean pressure coefficients

We verify that the mean pressure coefficients are symetrical. So in the future we would reduce the simulation domain by using the symetrical properties of the case. The mean pressure coefficient is always in the range of the bibliography values. This confrontation doesn't allow us to propose a conclusion because of the dispersion of the values (cf Table 4).

| Incidence vent 0 | Façade 1 | Façade 2 | Façade 3 | Façade 4 |
|---|---|---|---|---|
| Simulation | 0.62 | -0.21 | -0.36 | -0.36 |
| Gauthier | 0.7 | -0.25 | -0.6 | -0.6 |
| Annales ITBTP | 0.60 | -0.40 | -0.80 | -0.80 |
| Swami | 0.94 | -0.60 | -1.01 | -1.01 |
| Walton | 0.75 | -0.15 | -0.30 | -0.30 |

TABLE 4 : Comparison of the differents Cp values

### 5.2 - Contours of pressure coefficients

From the refined meshing - 100 points of discretisation - we can get the distribution of pressure coefficients all over the facade and a specific area of the building, a "paving". This information is required because during a wind tunnel analysis we get only the pressure coefficient on a "paving" that usually corresponds to a apartment.

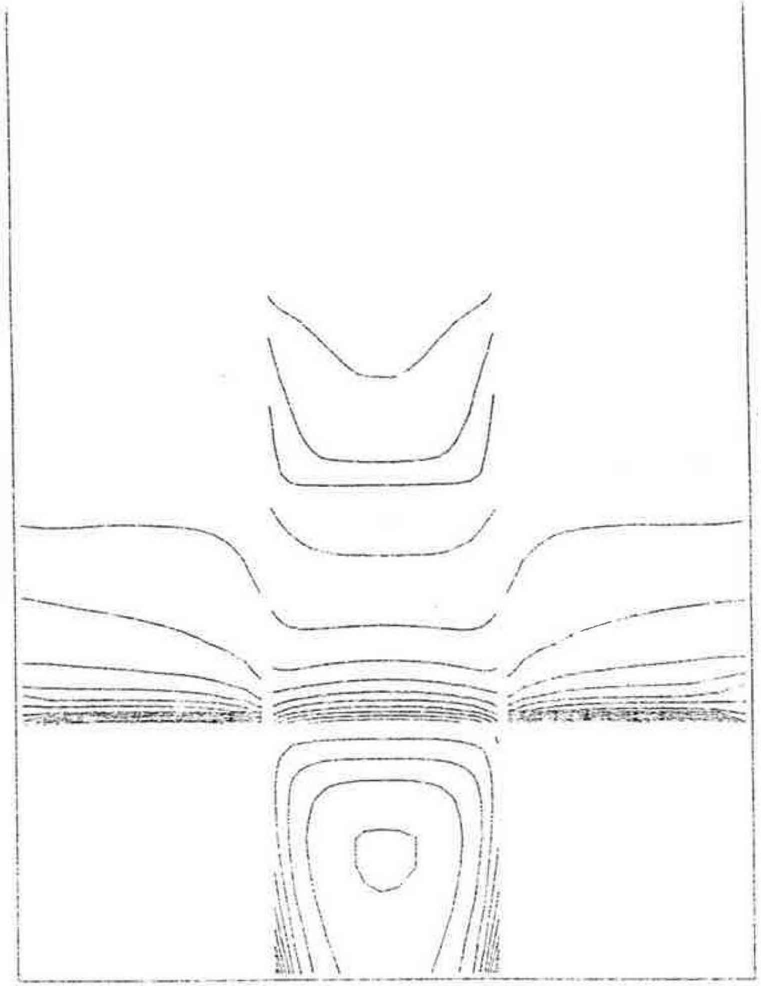
Figure 4 is the plotting of pressure coefficient contours. We notice that the figure is symetrical and that the contours are contracted near the edges of the building facades. The pressure coefficient is most sensible at the horizontally position than at the height.

### 5.3 - Comparison of the calculated Cp with the wind tunnel Cp

During the wind tests the pressure coefficient on "paving" representative of a flat was mesured. So we have seven Cp for each wind direction, corresponding at the seven floors of the building. We compare the mesured Cp on a "paving" with the calculated one on the middle point of the "paving". We consider that the pressure has linear variations in each direction of discretisation

The comparison is difficult because the standart deviation of the results in wind tunnel is large, sometimes a half of the mean value and in some critical cases it is greater than the mean value. The pressure coefficient resulting from the simulation is always include in the interval of mean value - standart deviation, mean value + standart deviation, excepted for top of the lateral face. (cf figure 5 and table 5)





| | Cp max | Cp min |
|---|---|---|
| Face 1 | 0.70 | 0.16 |
| Face 2 | -0.16 | -0.36 |
| Face 3 | -0.16 | -1.42 |
| Face 4 | -0.16 | -1.40 |
| Roof | -0,16 | -1.20 |

FIGURE 4 : Cp Contours - Wind direction 0°

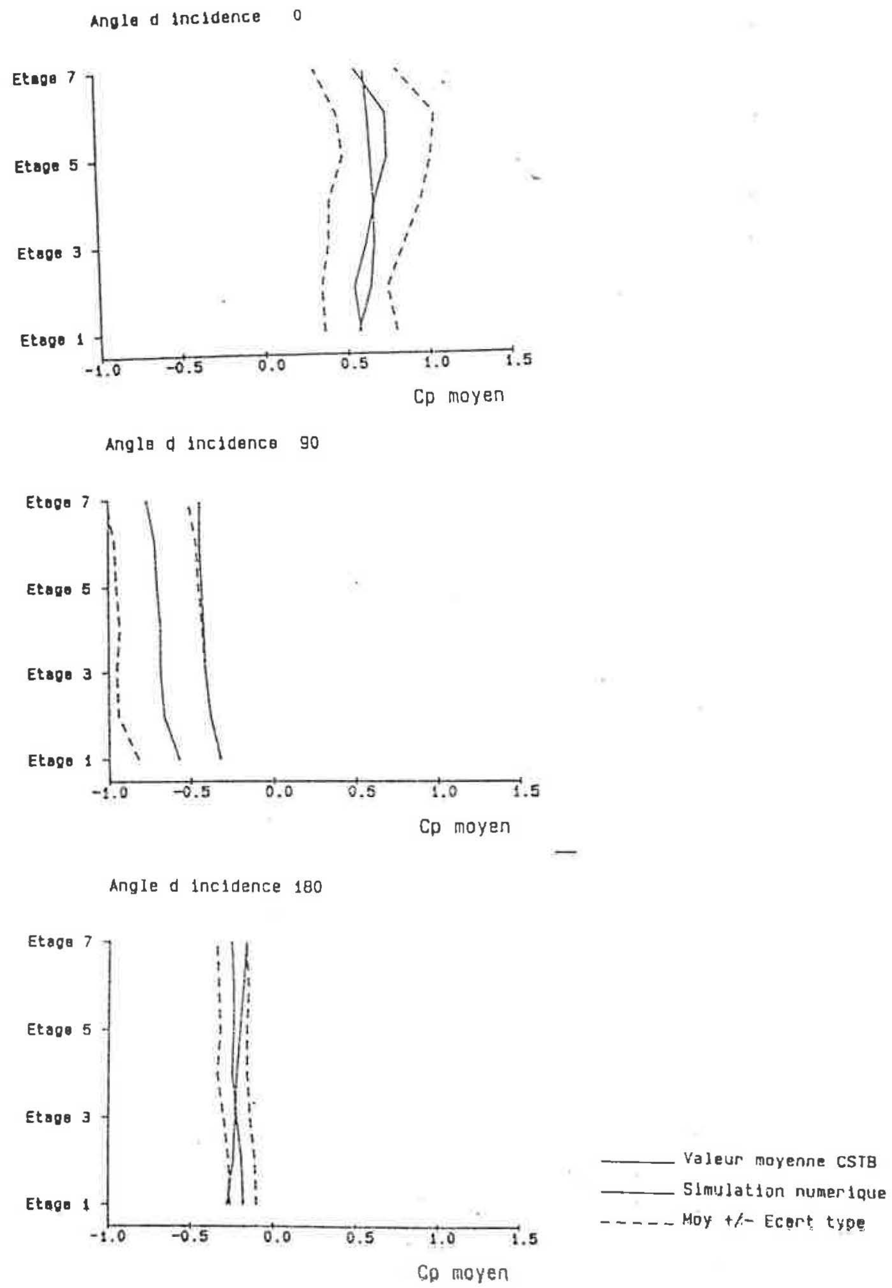



FIGURE 5 : Variation of Cp with the heigth



## 6 - Conclusions

The simulation of the tridimensional flow field around an isolated building allows us to determine numerically the pressure coefficients. The pressure distribution on the different facade of an isolated building is in a good agreement with the wind tunnel results. A comparison with the pressure coefficient measured in the full-scale test building of the CERUG* will be done in a near future. This building site is a realistic and more complex site.

* CERUG is the research center of Gaz de France situated at Plaine Saint Denis in the suburbs of PARIS.

| α | | Etage 1 | Etage 2 | Etage 3 | Etage 4 | Etage 5 | Etage 6 | Etage 7 | Toit |
|---|---|---|---|---|---|---|---|---|---|
| 0 | M cstb | 0.58 | 0.55 | 0.63 | 0.69 | 0.77 | 0.77 | 0.59 | -0.86 |
| | σ cstb | 0.22 | 0.20 | 0.23 | 0.28 | 0.27 | 0.30 | 0.25 | 0.26 |
| | M simul | 0.57 | 0.65 | 0.68 | 0.68 | 0.67 | 0.66 | 0.64 | -0.45 |
| 90 | M cstb | -0.57 | -0.66 | -0.68 | -0.68 | -0.70 | -0.71 | -0.76 | -0.87 |
| | σ cstb | 0.25 | 0.28 | 0.27 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| | M simul | -0.32 | -0.38 | -0.41 | -0.42 | -0.43 | -0.44 | -0.44 | -0.45 |
| 180 | M cstb | -0.18 | -0.19 | -0.22 | -0.25 | -0.24 | -0.24 | -0.25 | -0.39 |
| | σ cstb | 0.08 | 0.08 | 0.08 | 0.09 | 0.08 | 0.09 | 0.09 | 0.15 |
| | M simul | -0.28 | -0.24 | -0.23 | -0.21 | -0.20 | -0.18 | -0.16 | -0.21 |

TABLE 5 : Comparison of mesured and calculated Cp

ACKNOWLEDGMENTS

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