PRESSURE COEFFICIENT SIMULATED BY CFD FOR WIND-DRIVEN VENTILATION ANALYSIS

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ABSTRACT

Pressure coefficients (C_P) are fundamental to calculate ventilation rates in buildings by the airflow network models (AFN). This paper deals with the use of CFD simulation to calculate C_p, and the use of those C_p values as input in building energy simulations (BES). The commercial package CFX was used to calculate C_P for a 5-stories isolated building, typically found in social housing complexes in Brazil, The standard k-ε turbulence model was adopted. The paper describes the software settings and discusses the importance of some guidelines prescriptions as mesh independence, adopted wind profile and the use of roughness in the domain floor. The C_p values were applied in the BES-AFN model TAS for the São Paulo-Brazil climate. The main conclusion is that mesh and the adopted wind profile have a strong influence in the calculated C_p values, and the guidelines prescriptions are relevant and should be followed. The BES-AFN results show large differences depending on the source of C_p data: the CFD simulation or the generic values found in the literature. Experimental validation is recommended to assess the better C_p source for AFN model.

KEYWORDS

wind pressure coefficient, CFD, airflow network

INTRODUCTION

Wind-driven ventilation is an important strategy for passive cooling (Santamouris 1997) and for indoor air quality improving (Allard 1998). The ventilation rate is also important for the efficient energy use in buildings (Liddament 1996).

The study of wind-driven ventilation can be made by wind tunnel experiments (Carey 2005), AFN - airflow network models (Hensen 1991), and CFD simulations (Yang 2004). Each technique has some advantages and disadvantages.

Wind-tunnel experiments can reproduce many wind-driven ventilation related phenomena, but limitations due to the cost and scaling problems make those experiments rare.

The AFN is the standard model for ventilation rate calculation in many BES applications. It's used in several works like Stec (2003), Jreijiry (2003), Breesch (2005) and Wit (2001) to mention just a few ones.

The main inputs in AFN for wind-driven ventilation calculation are: wind direction and speed, opening caracteristic usually given by its discharge coefficient (C_z), and the wind pressure coefficient (C_P).

The wind data is available in weather files. A simple aerodynamic roughness correction is applied in the assumed wind profile to take in to account the effects related to its transposition from the weather station to the project site. This is an important issue, but out of its paper scope.

C_z and C_P are non-dimensional parameters, for which reference values can be found in the literature. Those values were obtained in full scale and laboratory experiments, representing high quality data. Unfortunately, their use as input in AFN model has several limitation. Those limitations are the main motivation for the research presented in this paper, which is focused only on C_p.

Pressure coefficient (C_p) is define as the non dimensional ratio between the pressure due to the wind in a point x in the building façade (P_x), and the dynamic wind pressure in the free stream region (P_d). (Etheridge and Sandberg 1996) (Awbi 1998).

$$C_P = \frac{P_x}{P_d} \tag{1}$$

The dynamic wind pressure is the force per area unit due to the wind inertia, in a plane orthogonal to wind direction, given by the following expression, where V_{ref} is the wind speed (m/s); and ρ is the air specific mass (kg/m3).

$$P_d = \frac{\rho \cdot V_{ref}^{\;2}}{2} \tag{2}$$

The wind speed varies with the height above the ground, and also the dynamic wind pressure. For C_p calculation P_d is measured at the building height.

Jreijiry (2003) remarks that "Cp depends mainly on the building shape, the wind direction and the surroundings." Hensen (1991) states that an "accurate evaluation of this parameter is one of the most difficult aspects of air infiltration modeling and, as yet, is not possible by theoretical means alone."

Similar statements can be found in many works about C_p and AFN.

The shortcut used to overcome those difficulties is presented by Jreijiry (2003): "C_p values could be found from tables or could be calculated by parametrical programs".

Several BES software with AFN, like Energy Plus, ESP-r and TAS, present some tables with C_p values and an analytical model for C_p determination.

The tables are made based on wind tunnel experiments. They present an average C_p value for each façade, for simple building shapes and surroundings. Due to the average, important information about C_p is lost. An example of this data loss is presented below. The Figure 1 shows wind tunnel data of C_p distribution before averaging for one face of a cubic model. The angle between the wind direction and the surface normal is 35º. The range of values goes from 0 to 0.7, and the average value is approximately 0.4. Considering this example is reasonable to ask if the average value should be used as input in AFN models to predict the flow rate inside the building. Hien (1999) says that "such wall averaged values of C_p usually do not match the accuracy required for multi-zone air flow models."

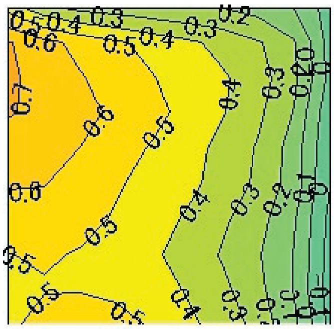

Figure 1 Example of Cp distribution before averaging (Anon A)

The other limitation of the C_p tables is the small number of building and surrounding shapes that is available. In general, only very simple forms, like cubes and parallelepipeds with flat or slope roof can be found. The real buildings have complex geometries, architectural elements in the façade, balconies, overhangs and other geometrical features that make them different from those presented in the tables. In this case it's also reasonable to ask if C_p data for a cube can describe the C_p distribution in a real buildings with complex geometry, like the one in Figure 2.

The analytical models can overcome the average limitation, but they can't handle complex building forms and surroundings.

Those features may explain why C_p in presented by WIT (2001) as one of the main sources of uncertainty in BES-AFN models.

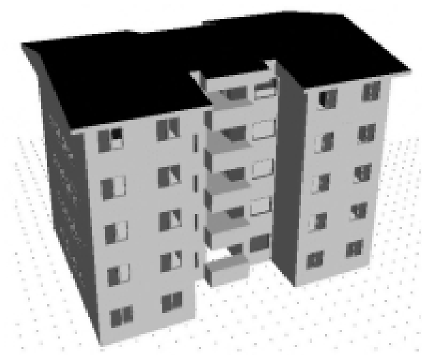

Figure 2 Perspective of the simulated building

In face of the limitations of C_p provided by tables and analytical models, CFD presents an alternative to assess C_p values.

Huanga (2007) presents C_p calculations for a high rise building by CFD, using different turbulence models. It concludes that the use of Large Eddy Simulation – LES – "can give satisfactory predictions for mean and dynamic wind loads on the tall building". Although LES provide a good agreement, its use is serious limited by the high computational resources demanded. For this reason, LES is not included in this study.

Huanga (2007) says that the RANS models present "encouraging results in most cases and has the advantage of providing rapid solutions." The results aren't averages over the surface, and the main features of building and surrounding geometry can be modeled. Based on the results presented by Huanga (2007) and Yang (2004), it seems reasonable suppose that CFD simulations with RANS models can improve the quality of C_p data for AFN, when compared with tables and analytical models.

The setup of a CFD simulation involves several decisions. Guidelines like COST (2004) recommend time consuming tests, as the mesh independence and stability of profiles in the empty domains. They stress the importance of convergence, y^+ values just to mention a few examples. The correct choice of mean wind speed profiles and turbulence intensity is also presented as a key component for a successful CFD simulation.

The careful setting presented in the guidelines contrasts with the information presented by several works which don't mention mesh independence, wall treatment, inlet wind profile, convergence and so on. Facing this contradiction, the novice in CFD has to make a choice: simple simulations providing fast results but neglecting the guidelines, or complex and time consuming simulations following them.

The second option seems more reasonable, although the large number of example choosing the simple simulation approach. The objective of this paper is to test some of the guidelines prescriptions, in order to assess its adoption impact in the calculated C_p values.

Three CFD simulation settings are presented and discussed: mesh independence, wind profiles applied as boundary condition and roughness adoption in the domain floor.

In the second part of the paper, the C_p values produced by the CFD simulation are applied as boundary conditions in the BES-AFN commercial package TAS (EDLS, s.d.). The intention in this part is two fold. Firstly, the BES-AFN simulation aims to bring back the paper focus from the Cp and CFD to the air change rate in the building interior. Secondly, it intends to compare, for the study case, the BES-AFN results using Cp by CFD simulation versus those results obtained using Cp by tables. If the BES-AFN results are the same in both cases than the CFD simulation is useless, but a difference in the results can lead to a future validation to assess which result presents a lower uncertainty.

METODOLOGY

In this research the commercial CFD package CFX was used for to provide C_p values for the commercial BES-AFN TAS, by EDSL.

The building studied in this research is a typical social housing 5-stories Brazilian example. Those buildings are usually constructed in arrays. The isolated building was adopted due to the lack of computational resources as well as a pilot case. A 3D model used produced in the BES software is presented in Figure 2, and the floor plan is presented in the Figure 3.The balcony in the figure 1 is closed by windows, so the building is a closed volume.

The simulations were carried out in a INTEL Pentium 2 Ghz, with 1Gb of RAM.

The wind direction was discretized in 30 degrees interval, resulting in 12 directions (COST, 2004) for each simulation setup described in the Table 1.

The C_p values were calculated to the windows central point in the ground floor and in the upper floor, as described in the Figures 4 and 5.

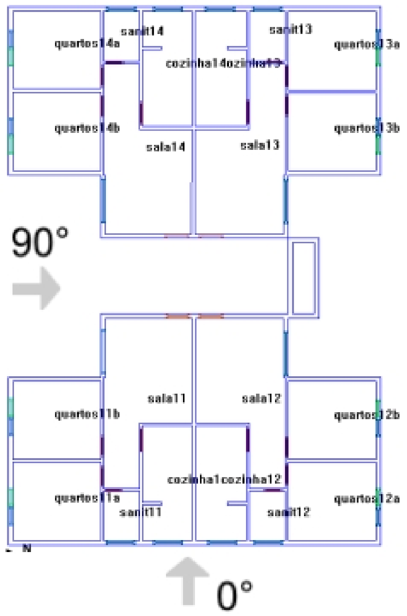

Figure 3 Floor plan of the simulated building

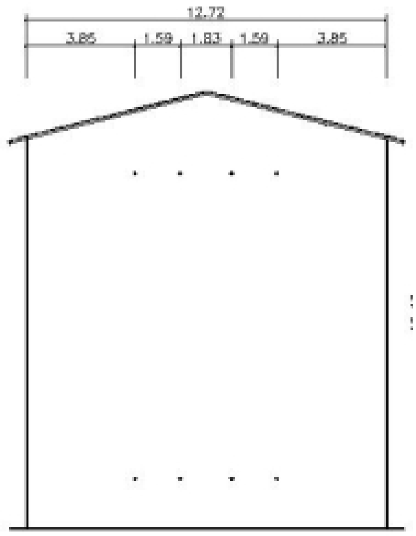

Figure 4 Points for Cp calculation on short façade

A second order discretization scheme was adopted, as prescribed by CFX (2003) and COST (2004).

The mesh was composed by a prism layer in the domain “floor”, and an unstructured tetrahedral mesh in the rest of the domain. The unstructured meshes has a higher diffusivity (COST, 2004), but it was adopted due to the complex building geometry.

Three meshes were created to this model: the course one with approximately 400 000 elements, the medium composed by 750 000 elements and a fine one 1 000 000 elements. The Table 1 describes which mesh was used for each simulation. The fine mesh is presented in the figures 6 and 7.

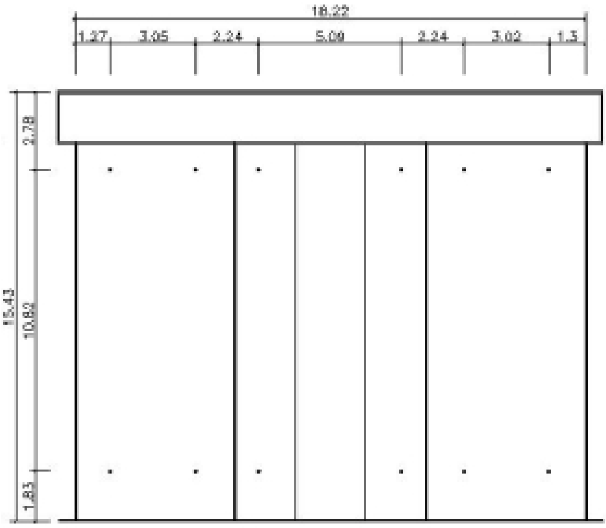

Figure 5 Points for Cp calculation on long façade

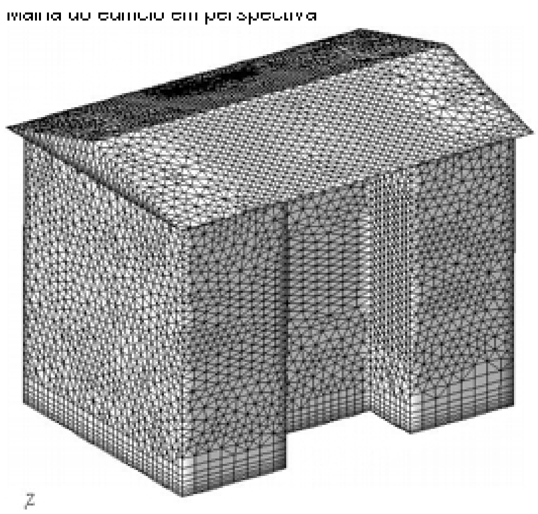

Figure 6 Surface mesh in the building

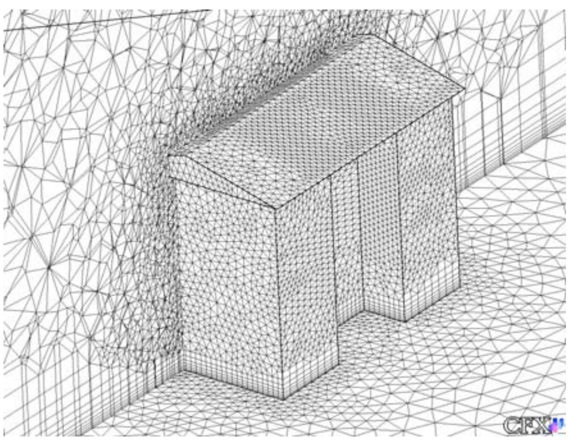

Figure 7 Mesh in the building surface, domain floor and in a slice plan

Due to limitations in the computational resources, the standard k–ε was used in the simulations, as in YANG (2004). COST (2004) recommend the use of Reynolds Stress Models, while consultancies still use k–ε for daily simulation (HARRIES, 2005). It isn't clear the impact in the final uncertainty in the BES results due to the use of 2 or 6 equations models.

The domain size allows a blockage of 3%. A downstream distance of 10 times the building height was adopted (COST, 2004) and the domain is 5 times higher than the simulated building.

It was used a cylindrical domain with a "free slip" boundary condition in the top, and wall functions in the solid boundaries. No roughness was applies to the building faces, which were modeled as smooth. The Table 1 describes the domain floor setting in the different simulations.

The wind velocity was imposed in the inlet and outlet, using a logarithm profile for neutrally stratified atmosphere (STULL, 1998), with 5% of turbulence intensity. This practice goes against the recommended setting, where the velocity is fixed only in the inlet and outlet has a zero pressure boundary. The use of velocity boundaries in the inlet and outlet can mask some effects of short downstream distance in the domain, but it simplifies the simulations settings via bat file. As said about the turbulence model the impact in the uncertainty is not clear yet and it reflects a common practice.

Table 1 – Simulation Summary

Setting	**Mesh**	**Boundary condition in the domains floor**	**z_0 used in the inlet and outlet mean wind speed profile**
A1	Course	Smooth	0,1
A2	Medium		
A3	Fine		
B1	Fine	Smooth	0.001
B2			0.01
B3			0.1
B4			0.3
C1	Fine	Smooth	0.1
C2		Rough z_0=0.1	

COST (2004) and CFX (2003) recommend a RMS value equal or lower than10^{-4}, which was adopted in the simulations.

The recommend values for y^+ is between 30 and 100 for wall function, but the values obtained in the simulations with the fine mesh were around 600.

The integration of BES and CFD for C_p calculation is poor, since the tools don't share any information automatically (geometry, reference height, C_p results). In this work, only the preprocessing was done manually. All the simulation and post-processing was automated, so the C_p input file was ready for use in the BES model.

CFD RESULTS ANALYSES

The simulations settings A1, A2 and A3 aim to study the mesh dependency in this model. Russell (2002) states that "Ignorance of mesh dependency can sometimes be an embarrassment in numerical calculations." The results confirm the importance of mesh independence test.

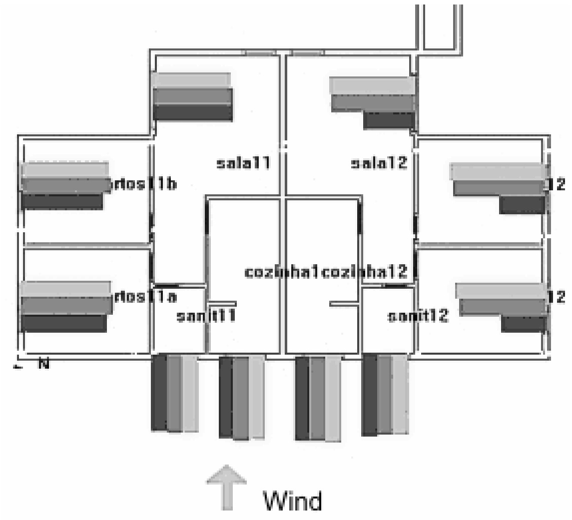

Figure 8 Comparison of Cp for different meshes. Wind direction equal to 0°

The Figure 8 shows a comparison of some Cp values for a single wind direction (0º), in the windward apartments in the ground floor. The bars length corresponds to the C_p value. The dark bars present the course mesh results, which exhibit a large and unexpected asymmetry. The C_p wind tunnel results for symmetric buildings, like those presented by LIDDAMENT (1996), are in general symmetric too. The medium grey bars present a medium mesh, and the light gray correspond to the fine mesh results. The comparison between the medium and the fine mesh shows that the mesh independence was obtained in this sample.

The simulations settings B1 to B4 present a comparison of different wind profiles as boundary condition. The effect of this parameter variation is presented in Figure 9 for the windward face. The windows centers are marked for reference. It's clear that beside a similar distribution, the variations of C_p in the points of interest is up to 0.35 or 50% (as in the comparison of the first and the last figures for the ground floor windows).

The simulation settings C1 and C2 intend to study the impact of different boundary conditions in the domain floor.

The results were compared for each window in the ground and upper floors (40 points) for each simulated direction, subtracting the value from C1 to C2. The Figure 10 presents a histogram of those differences. In most of the cases (350 out of 480) the values don't show a large difference (less than 0.1). Based on this one could conclude that the C_p value in this model is not sensitive to the roughness in the domain floor.

COST (2004) recommends the use roughness in model floor upstream and downstream, but not between the buildings. Blocken (2007) demonstrates the inability of the wall functions in keep the inlet velocity and turbulence profiles in an empty domain. This indicates that changes in the result might not be related to the simulated building but with the domain itself. As a conclusion, it can be said that this topic remains open, but at least the model studied isn't very much sensitive for this parameter.

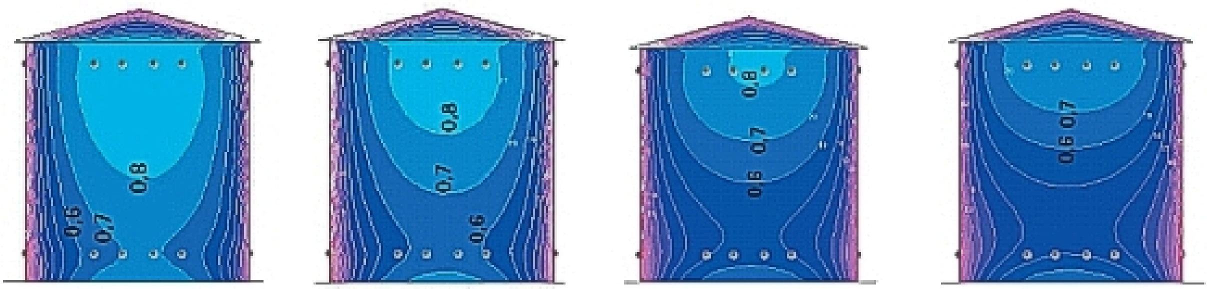

Figure 9 C_p Distribution in the windward facade, for different inlet wind profiles, corresponding to the follow roughness respectively (0.001) (0.01) (0.1) (0.3). Wind direction equal to 0°

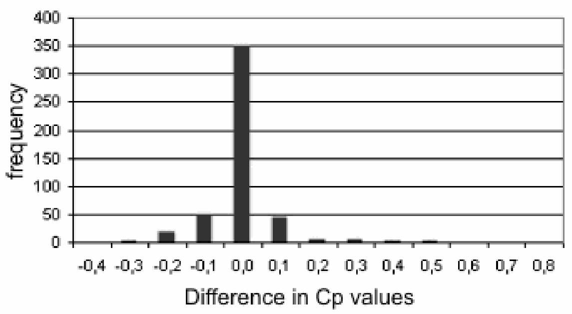

Figure 10 Histogram of C_p difference with and without roughness in the domain floor. Results for the 12 simulated directions (ingles, decimal pt)

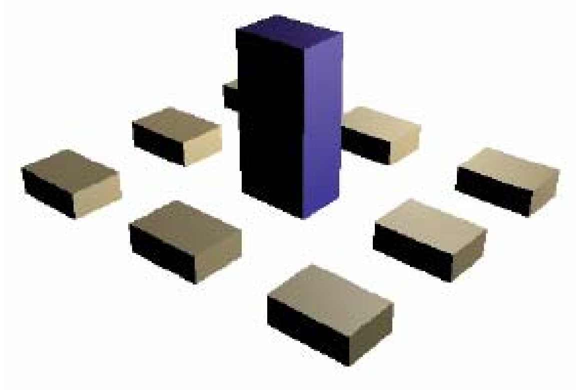

Figure11 Model used on TAS-NG Cp values

BES SIMULATION USING CP BY CFD

The C_p results for simulation setting C1 were used as input in the commercial BES-AFN package TAS (EDSL, s.d.). The intention was to compare the results for internal dry bulb temperature and flow rate for some rooms, using two different inputs: the standard generic C_p values provided with the BES model, and the C_p values obtained by CFD simulation. The simulations were carried out for a typical year in São Paulo city, Brasil.

The C_p value provided by TAS-NG were obtained in a wind tunnel experiment with a parallelepiped model of 11:7.6:23cm, with surrounding neighbors of 1/6 of its height, distant each other of 1/3 of the model height (EDSL, s.d.). The Figure 11 was made for this paper, based on this description. This geometry is completely different of the case under analyses in this paper.

The same ventilation schedules was adopted in both simulations, as well as the same discharge coefficients to the openings.

As usual, the amount of data generated in the simulation is huge, so a few samples were present here. The Figure 12 presents the calculated flow rate, for the days 1 and 2 of January, for four rooms in the ground floor. The left chart shows the total flow rate, while the right chart present the hourly values for just one room. The difference in the mean rate is from 5% to 120%, while the hourly values present differences up to 600%.

The Figure 13 shows the same comparison of the previous figure, but now concerning to the dry bulb temperature. In this case the variation is minimal, because it's lower than the overall uncertainty in the simulation.

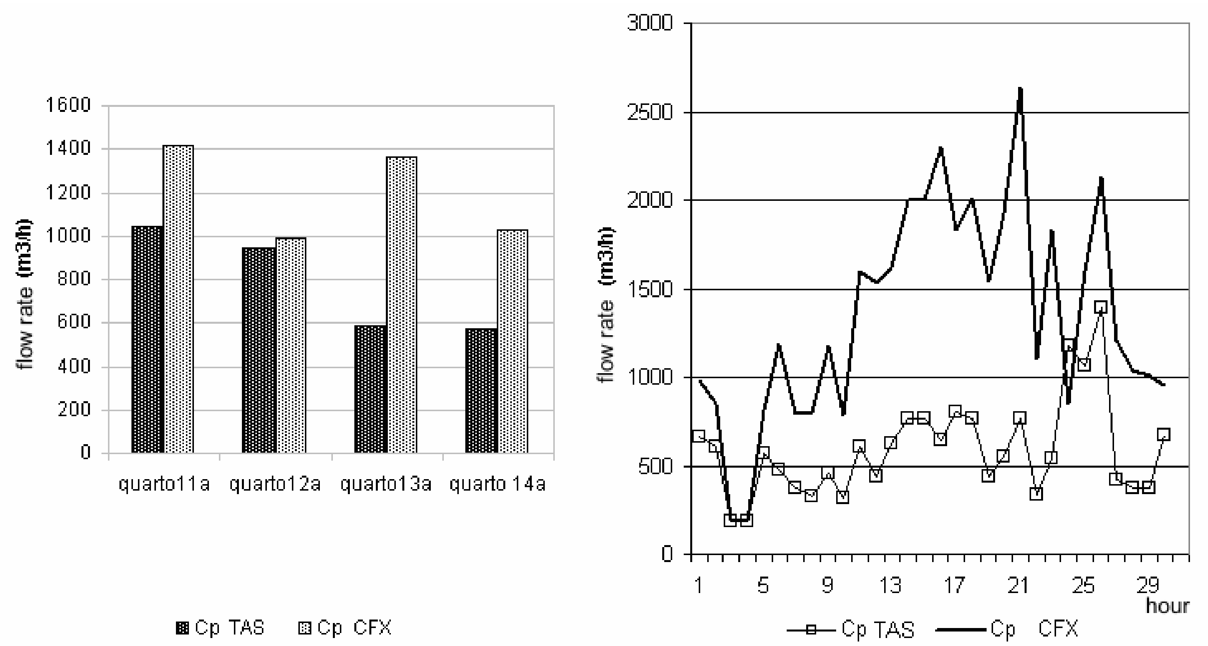

Figure 12 Calculated flow rate using different C_p values (left: total values; right: hourly values)

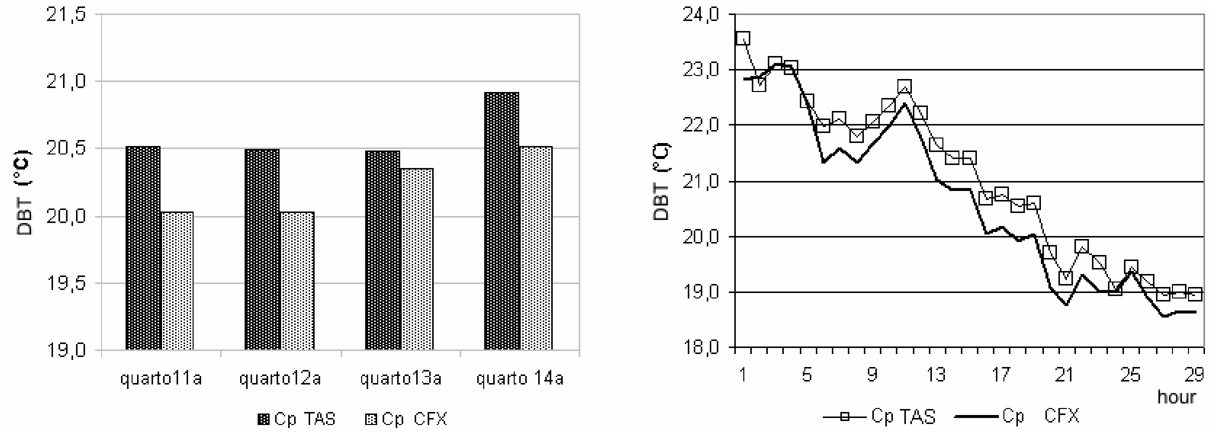

Figure 13 Calculated DBT using different Cp values (left: total values; right: hourly values)

CONCLUSION

The first conclusion of this work deals with the strong relation between the CFD simulation settings and the C_p results. Some guidelines orientations regarding mesh independence, wind profiles, and domain floor were tested, and the model show sensibility in the three cases. The conclusion for the studied building is that the guidelines should be followed, otherwise the predicted C_p value might presents deviations up to 50%, like those presented in Figures 8 and 9.

Particularly, it's recommended that future CFD simulations for C_p determination spend some energy to define the z_0 values.

The second conclusion is related to the large deviation in the flow rate results depending on the C_p source: tables or CFD simulation.

Both the C_p sources have limitations. The tables are available just for simple building shapes and present average values for the whole façade. The CFD simulation using RANS is affordable and can overcome those deficiencies, but it presents deviations from the experimental results. Validation is necessary to assess which of the two C_p souces is the best input for AFN models.

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ANNEX 1 – C_P VALUES FOR A WIND PROFILE WITH Z_0= 0.1

	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
sala11	–0,61	–0,06	0,60	0,79	0,69	0,24	–0,42	–0,53	–0,62	–0,14	–0,53	–0,23
cozinha 11	0,70	0,57	–0,07	–0,59	–0,47	–0,37	–0,08	–0,43	–0,59	–0,65	–0,07	0,53
quarto a11	–0,65	0,15	0,61	0,17	–0,07	–0,14	–0,76	–0,24	–0,46	–0,34	–0,58	–0,41
quarto b11	–0,63	0,25	0,63	0,49	0,10	–0,10	–0,61	–0,39	–0,52	–0,15	–0,58	–0,53
sanitario11	0,65	0,63	–0,08	–0,56	–0,43	–0,34	–0,14	–0,46	–0,60	–0,62	–0,13	0,42
sala 14	–0,56	0,26	0,67	0,79	0,62	0,12	–0,28	–0,29	–0,58	–0,17	–0,51	–0,48
cozinha 14	–0,16	–0,42	–0,49	–0,84	–0,05	0,60	0,71	0,51	–0,11	–0,56	–0,56	–0,39
quarto a14	–0,34	–0,18	–0,07	0,09	0,63	0,13	–0,59	–0,44	–0,64	–0,42	–0,42	–0,23
quarto b14	–0,40	–0,16	0,10	0,47	0,65	0,24	–0,54	–0,59	–0,66	–0,54	–0,46	–0,35
sanitario 14	–0,21	–0,39	–0,47	–0,88	–0,05	0,66	0,66	0,40	–0,18	–0,53	–0,58	–0,42
sala 41	–0,56	0,27	0,71	0,82	0,80	0,15	–0,46	–0,47	–0,59	–0,19	–0,53	–0,40
cozinha 41	0,87	0,67	–0,03	–0,40	–0,51	–0,43	–0,40	–0,47	–0,54	–0,74	–0,05	0,63
quarto a 41	–0,61	0,09	0,78	0,57	0,14	–0,12	–0,47	–0,54	–0,60	–0,40	–0,60	–0,52
quarto b41	–0,58	0,20	0,68	0,71	0,30	–0,10	–0,55	–0,48	–0,58	–0,43	–0,61	–0,55
sanitario 41	0,84	0,74	0,03	–0,35	–0,50	–0,39	–0,39	–0,50	–0,57	–0,62	–0,12	0,52
sala 44	–0,54	0,07	0,77	0,82	0,74	0,29	–0,45	–0,47	–0,58	–0,19	–0,53	–0,41
cozinha 44	–0,38	–0,45	–0,51	–0,57	–0,01	0,70	0,88	0,59	–0,09	–0,58	–0,51	–0,43
quarto a44	–0,42	–0,16	0,09	0,54	0,80	0,05	–0,46	–0,55	–0,64	–0,39	–0,58	–0,49
quarto b44	–0,50	–0,13	0,27	0,74	0,71	0,23	–0,50	–0,60	–0,66	–0,41	–0,55	–0,43
sanitario 44	–0,38	–0,42	–0,50	–0,52	0,04	0,77	0,85	0,48	–0,17	–0,50	–0,54	–0,45