A comparison of generic pressure coefficient for indoor air flow studies

D. Costola, B. Blocken & J.L.M. Hensen
Building Physics and Systems, Eindhoven University of Technology, the Netherlands

ABSTRACT: Pressure coefficients across the building envelope \(C_p\) are an important source of uncertainty in building simulation. Wind tunnel experiments are generally the primary source of \(C_p\) data, but in infiltration and ventilation studies, generic values from databases or analytical models are commonly used. Building Energy Simulation (BES) and Air Flow Network (AFN) programs include several sources of generic \(C_p\) values. Those generic values show large differences between each other, which might lead to significant differences in the simulation results depending on the type of building, the building location and the performance indicator under analysis. This paper presents a comparison between five sources of generic pressure coefficient data used for infiltration and natural ventilation studies, namely: the database provided by AIVC, that by ASHRAE and the analytical models CpCalc, CpGenerator and the model by Swami & Chandra. The first part of the paper describes each data source. In order to compare the values provided by each data source, a cubic building is adopted. We focus on three points on the façade: one at the center, one near the upper right corner and one near the lower left corner. Two different shielding configurations are considered: sheltered and unsheltered. The comparison is made for a range of wind attack angles to the façade from 0 to 180 degrees. The higher variation is found in points far from the façade center, especially when the wind is parallel to the façade. Variations in \(C_p\) from different sources are significantly higher for the sheltered than for the unsheltered case. The differences found in the \(C_p\) values indicate the uncertainty involved. This knowledge might be used to guide research on \(C_p\) for ventilation and infiltration purposes, as well as uncertainty studies in building simulation.

1 INTRODUCTION

Air infiltration and ventilation have a profound influence on both the internal environment and the energy needs of buildings (Liddament, 1986). Also, the air flow through the building envelope can cause large changes in the heat loss (Hagendorf, 1996).

Wind is an important driving force for infiltration and ventilation. Wind pressure is therefore an important boundary condition for a wide range of models, from building component heat, air and moisture (HAM) transfer models to coupled airflow network (AFN) and building energy simulation (BES) tools (Clarke, 2001).

Wind pressure is usually expressed by pressure coefficients \(C_p\), which are defined as follows:

\[
C_p = \frac{P_s - P_0}{P_d}, \quad P_d = \frac{\rho \cdot U_s^2}{2}
\]

(1)

where \(P_s\) is the static pressure in a given point at the building façade (Pa), \(P_0\) is the static reference pressure (Pa), \(P_d\) is the dynamic pressure in the upstream undisturbed flow (Pa), \(\rho\) is the air density (kg/m\(^3\)) and \(U_s\) is the wind speed at building height \(h\) in the upstream undisturbed flow (m/s).

The impact of the parameter \(C_p\) on BES results was studied by de Wit & Augenbroe (2001) and de Wit (2001). Those studies presented \(C_p\) as one of the main sources of uncertainty in BES-AFN models, because \(C_p\) uncertainty is high, and several performance indicators, e.g. energy consumption, thermal comfort and mold growth, are often very sensitive to the air change rate, which depends on \(C_p\).

Hensen (1991) described the difficulty to perform an accurate evaluation of \(C_p\). Further studies, especially on the development of analytical models for \(C_p\) prediction (Grosso, 1992; Knoll et al., 1995), could not overcome the difficulties on obtaining reliable \(C_p\) values without using expensive wind tunnel experiments. In this sense, Tuomaala (2002) stated that “there is no reliable and effective method for evaluating the value of wind pressure coefficient for complex cases.”

The difficulties in assessing reliable \(C_p\) data for BES can be explained by the wide range of influenc-
ing parameters, including wind speed, wind direction, turbulence intensity, sheltering elements (e.g., buildings, trees), building geometry, facade detailing (e.g., external shading devices, balconies) and position on the facade.

To the knowledge of the authors, there is no overview about generic pressure coefficient data for indoor air flow studies. The purpose of the present paper therefore is to provide such information and a comparison of different data sources.

This overview can be useful for the development and validation of AFN, BES and HAM models, for ventilation, infiltration and indoor air quality studies, for documentation for building certification programs and for the development of new models for $C_p$ prediction.

In this paper, primary sources of $C_p$ data are not discussed. Primary sources, such as full scale measurements, wind tunnel tests and CFD simulations, provide data for a specific building and take into account most of the parameters that influence the $C_p$ data. Data from primary sources is, in general, more accurate than secondary sources data, but their cost is also higher.

The term secondary sources is used in this paper to describe those sources that were generated based on primary sources. A large number of secondary $C_p$ sources exist, which have different aims and characteristics. Databases of $C_p$ values are the most common secondary source. Those databases, which are collection of $C_p$ data, are present in several books and standards, and they provide data for a limited set of generic building configurations. Another secondary source are the analytical models, where primary data is used to derive general equations to predict $C_p$. These two types of secondary sources are discussed in sections 2 and 3. Section 4 presents comparisons of the values from each data source for the case of a cubic building model. Finally, the main conclusions are provided in section 5.

2 DATABASES

$C_p$ databases are compilations of $C_p$ data from one or more sources, where the data is classified according to some parameters, such as building shape and orientation to the incident wind.

$C_p$ databases are widely available, particularly for the calculation of wind loads on structures. Wind load standards provide $C_p$ values for unsheltered buildings with simple geometries, to be used when custom wind tunnel experiments are not available. The same approach is used in $C_p$ databases available in the ventilation and infiltration literature, e.g. the AIVC database (Liddament, 1986) or the data in the ASHRAE Handbook (ASHRAE, 2001), which are described in sections 2.1 and 2.2.

2.1 AIVC

The Air Infiltration and Ventilation Centre (AIVC) has been an international reference in the subject since its inauguration in 1979. It is an annex running under the Energy Conservation in Buildings and Community Systems (ECBCS) of the International Energy Agency (IEA).

In 1986, after a workshop about wind pressure coefficients promoted by the AIVC (AIVC, 1984), it published a compilation of $C_p$ data as part of a guide (Liddament, 1986). This publication presents tables with data for low-rise buildings, and figures with vertical profiles for high-rise buildings. The tables were compiled based on several studies, while the profiles were reproduced from Bowen (1976).

The data for low-rise buildings (up to 3 storeys) is based on the compilation of wind tunnel data published in the workshop (AIVC, 1984) and seven other bibliographical references, e.g. Bowen (1976) and Wiren (1985), but the method to compile the database is not mentioned.

The low-rise buildings $C_p$ database is presented in tables with surface averaged data, for rectangular floor plans and for 3 shielding levels: exposed, semi-sheltered (obstacles with half of the building height), and sheltered (obstacles with the same height as the building). The data is provided for wind direction sectors of 45°, for a square floor plan building, and for the long and short walls of a rectangular (1:2) floor plan building. The exact building height is not mentioned. For the facades, only the averaged value over the whole surface is provided. For the roof of the low-rise buildings, three types of averaged data are provided: a surface-average value, a value for the “rear” and a value for the “front” part of the roof. For each one of them, data is provided according to different roof pitch angle: lower than 10°, between 11° and 30° and higher than 30°.

Some details about the low-rise buildings data are not included in the publication. For the sheltered cases, the space between the building and the surroundings obstacles is not mentioned. No information is provided about the wind profile used in the wind tunnel tests.

The publication contains several warnings regarding the reliability of the data for low-rise buildings. The first page describes that “The intention of these data sets is to provide the user with an indication of the range of pressure coefficient values which might be anticipated for various building orientations and for various degrees of shielding.” All the other pages contain an explicit warning: “Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication.”

Despite the modest purpose of the low-rise buildings $C_p$ database, it has been extensively reproduced by AIVC (Orme et al., 1998; Orme, 1999; Orme & Leksmono, 2002) as well as by other publications.
about building performance (Allard, 1998; Santamouris, 1996; Clarke, 2001). The database is currently in use for the scientific community, e.g. Asfour & Gadia (2007). The confidence that is often expressed in this database seems to largely exceed the intention of the original publication, and in some cases the data is even used to calibrate coefficients in analytical models (Moeske et al, 2007).

Concerning the AIVC data for high-rise buildings, no effort was made to compile tables based on several wind tunnel tests, and only the data from one source was reproduced in the AIVC publications (Liddament, 1986). The data is presented as vertical $C_p$ profiles for two wind directions, $0^\circ$ and $45^\circ$ in relation to the normal of the longer face of the model. This angular discretization is commonly used for squared floor plan buildings, but in this case the floor plan has an aspect ratio of 1.5:1 (Orme et al, 1998), which might lead to misinterpretation by the user. The model used in the wind tunnel tests, at a scale of 1:400, has a height of 0.23 m, which represents 92 m in full scale. Data is presented for 4 different shielding levels. The comment provided to contextualize these data says that it is “showing the vertical dependency of pressure coefficients for tall buildings”. The illustrative character seems to be stronger than the informative one.

The use of vertical profiles for the high-rise building data might lead to misunderstandings, because in some cases the “vertical dependency” is not the main aspect in the $C_p$ distribution over the surface. Figure 1 presents an example of vertical $C_p$ profile published by Liddament (1986) and the $C_p$ distribution over the same surface for the same experiment, published by Orme et al (1998).

![Figure 1. Example of vertical profile of $C_p$ values for a high-rise building surface (Liddament, 1986), and the $C_p$ distribution over the same surface (Orme et al, 1998).](image)

The figure represents a windward facade with a wind attack angle of $45^\circ$, and the profile is based on the average of the three values at the same level. The surface distribution shows a clear vertical dependency of $C_p$, but it also shows a horizontal dependency which is as pronounced as the vertical one for this specific surface and wind attack angle. This dependency is omitted in the vertical profiles, like the one in Figure 1.

More recent AIVC publications do not include reproduction of the profiles or surface distributions for high-rise buildings, presenting only the data for low-rise buildings (Orme, 1999; Orme & Leksmono, 2002). The reproduction of the high-rise building data by others is also less common, e.g. Santamouris (2006), and it is used only to exemplify the complex distribution of $C_p$ over the surface.

### 2.2 ASHRAE

The ASHRAE handbook (ASHRAE, 2001) is not a ventilation oriented document like the AIVC publications, so it only presents condensed information about $C_p$ in the chapter dedicated to airflow around buildings. Different from the AIVC low-rise building database, the ASHRAE handbook only reproduces data from primary sources, rather than compile several data in a single database.

The publication provides data for low and high-rise buildings, presenting examples of $C_p$ distribution over the surface as well as surface averaged data. The building geometries are simple parallelepipeds, and different floor plan aspect ratios and pitch roofs are included with different angular discretizations. Averaged data is presented for flat roofs with different aspect ratios. Pitched roofs are not considered.

An important difference between the AIVC and the ASHRAE handbook data is the attention given to the obstruction effects: ASHRAE does not present data for sheltered buildings, although it provides correction values for the reference wind speed based on sheltering factors. As in the AIVC database, there is no information about the wind profiles used in the experiments.

### 3 ANALYTICAL MODELS

Analytical models are composed of a set of equations and coefficients to calculate $C_p$ for a specific building configuration (Grosso, 1992; Knoll et al, 1995; Eldin, 2007). They represent a user friendly way to access the large amount of empirical data used in the model formulation.

Analytical models for $C_p$ prediction were developed based on wind tunnel and full scale experiments. They aim to provide $C_p$ data for a broader range of building configurations, considering obstructions, the effect of different wind profiles and the $C_p$ variation across the facade.
None of the models presented here provide the uncertainty in their predictions. For some of them, correlation coefficients are provided, but it is not possible to calculate the prediction uncertainty using only this value. Therefore, it is not possible to assess the quality of their results to predict $C_p$ values for new building configurations.

Analytical models are developed using regression techniques to analyse a large amount of $C_p$ data. The result is a function where the $C_p$ value depends on a set of parameters considered in the regression, e.g., wind direction, aerodynamic roughness, facade aspect ratio, position at the facade, building aspect ratio, and the position and size of the surrounding buildings.

The applicability of the derived functions depends on the $C_p$ data and the parameters considered in the regression analysis. Regarding the experimental data, several works (Grosso, 1992; Swami & Chandra, 1988) point to the lack of data for complex shapes such as L-shape or U-shape. Regarding the parameters, two considerations are important. Firstly, the available data guides the parameterization, because the chosen parameter needs to be covered by the range of experiments. So, some parameters cannot be considered because of lack of data. Secondly, there is a trade off between precision and complexity. More precise equations tend to demand more parameters, but the increment in the precision does not necessarily justify the use of very complex formulae. The correct choice of which parameters to include in the regression analysis can be made based on sensitivity analysis.

In the following sections, the main features of three analytical models are presented.

3.1 Swami & Chandra (1988)

The method proposed by Swami & Chandra (1988) provides one simple equation for low-rise buildings and another for high-rise buildings. The low-rise building equation is presented below, as an example:

$$\text{NC}_p = \ln[1.248 - 0.703 \cdot \sin(\theta/2) - 1.175 \cdot \sin^2(\theta/2)]$$

$$+ 0.131 \cdot \sin^3(\theta/2) + 0.769 \cdot \sin^4(\theta/2)$$

$$+ 0.07 \cdot G^2 \cdot \sin^5(\theta/2) + 0.717 \cdot \sin^6(\theta/2)]$$

(2)

where $\text{NC}_p$ is the normalized pressure coefficient, $G$ is the natural logarithm of the floor plan aspect ratio and $\theta$ is the wind attack angle. The equation adopts a normalized pressure coefficient $\text{NC}_p$, considering $\text{NC}_p$ equal to 1 when the wind is orthogonal to the surface. It is therefore necessary to know a priori the $C_p$ value for the orthogonal surface. The paper suggests the value of 0.6 to the $C_p$ for the orthogonal surface, but it indicates that the value can vary from 0.19 to 0.91, depending on the wind profile, building height, roof pitch and floor plan aspect ratio.

In both cases the building has a rectangular floor plan, and no shielding effects are considered on $C_p$. A shielding correction factor is proposed, to be applied directly to the calculated flow rate.

The equation for low-rise buildings provides surface averaged $C_p$. The decision to neglect the variation of $C_p$ over the surface was based on early studies (Wiren, 1985; Swami & Chandra, 1987), which focused on infiltration calculations assuming cracks that are homogeneously distributed over the building facades. This assumption is clearly not valid for ventilation calculations, and may also be invalid for some infiltration calculations.

The equation has two parameters: wind direction and building floor plan aspect ratio, and has a correlation coefficient of 0.8. This result is good, considering the broad range of data analysed, which includes data from models with different heights and different pitch roof angles, and these parameters are not used in the analytical model.

The equation for high-rise buildings does not provide surface averaged values but includes the position at the facade as an additional parameter. Correlation coefficients are not provided.

3.2 CpCalc+ (1992)

CpCalc+ (Grosso, 1992) was developed within the COMIS workshop (Feustel, 1999) and the European project AIOLOS, described in (Allard, 1998), with the intention of providing results for sheltered buildings, that could not be calculated using the method of Swami & Chandra (1988).

Compared to the Swami & Chandra model, further experimental data was used to take into account the sheltering effect, and also new parameters were added, e.g., the power-law exponent of the mean wind velocity profile, the plan area density, relative building height to the surrounding buildings, the frontal aspect ratio and the position at the facade.

In order to allow for the higher number of parameters, a parametrical approach was used, based on successive independent corrections for each parameter. This approach creates a much more complex model, based on several tables with coefficients for each correction. The author points out the methodology developed as the main result, rather than the equations themselves. This is due to the lack of consistent experimental data, considered the main obstacle for a more comprehensive analysis.

It is important to point out that the sheltering effects are considered using the “plan area density”, where the individual sheltering effects of each building are not taken into account.
3.3 $C_p$ Generator

The $C_p$ Generator has been developed in the last 30 years to "predict the wind pressure coefficients, $C_p$, on the facades and roofs of block shaped buildings" (Knoll et al, 1995). The tool is a web-based application (http://cpgen.bouw.tno.nl), developed by the Dutch institution TNO.

The $C_p$ Generator has a similar approach and similar capabilities as CpCalc+, predicting point values on the facade and also on the roof, dealing with low-rise and high-rise buildings with user-defined proportion (length-width-height) and taking into account the effects of the surrounding roughness by the use of wind profile corrections. The main improvement is in the sheltering effect calculation, where it considers discrete block shaped obstructions instead of the neighborhood plan area density. Unfortunately, the model was not developed in the English language.

A comparison between $C_p$ Generator results and experimental data shows that they "are closer to reality than simulations carried on with $C_p$ values from the AIVC tables" (Heijmans & Wouters, n.d). Nevertheless, the results show large deviations from the full scale experimental data (Heijmans & Wouters, n.d).

4 DATA COMPARISON

Table 1 presents a summary of the characteristics described in the previous section.

Table 1. Database and analytical model features

<table>
<thead>
<tr>
<th>Topographic effects</th>
<th>Primary sources</th>
<th>Low-rise</th>
<th>High-rise</th>
<th>ASHRAE</th>
<th>High-rise</th>
<th>Low-rise</th>
<th>High-rise</th>
<th>CpCalc+</th>
<th>$C_p$ Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of surrounding terrain (smooth, rural, suburban, urban)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effect of immediate surroundings (local sheltering by buildings, etc)</td>
<td>x</td>
<td>p</td>
<td>p</td>
<td>s</td>
<td>s</td>
<td>s</td>
<td>s</td>
<td>p</td>
<td>x</td>
</tr>
<tr>
<td>Building configuration (building geometry and facade detailing)</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size of direction sectors (degrees)</td>
<td>c</td>
<td>45</td>
<td>90</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td></td>
</tr>
<tr>
<td>Variation across the facade</td>
<td>x</td>
<td>s</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncertainty</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

x – Fully able to model
p – Partially able to model
s – Simplified model
c – Custom

The first conclusion is that none of the databases or analytical methods can handle the effects of the site topography, building facade detailing or inform about the uncertainty relative to the provided data.

Another feature that is similar in most data sources is the size of the wind direction sectors. In most sources, the user can choose the number of the wind direction sectors. Only the AIVC database has a fixed angular discretization in 45° intervals.

The variation across the facade and the effects of the immediate surroundings are treated in different ways by each data source present in Table 1. These aspects are discussed in the subsections below.

4.1 Surface discretisation

Table 1 shows that the variation across the facade is fully considered only by some analytical methods, but most of the BES programs adopt only database values. In order to analyse the importance of the variation across the facade, some comparisons were made.

An arbitrary terrain type, suburban environment, was chosen for this comparison, and the wind profile parameters for the analytical models were obtained in the program documentation. A power-law wind profile exponent ($\alpha$) of 0.22 was used for CpCalc+, while an aerodynamic roughness length ($z_0$) of 0.5 m was used for the $C_p$ Generator.

Concerning the AIVC database and the Swami & Chandra model for low-rise buildings, only the surface averaged values are used in the comparisons, because those data sources do not provide values for specific points on the facade.

Figure 2 presents the data for a low-rise cubic building (10 m x 10 m x 10 m) for a point in the middle of the facade. The data from the different sources show a similar pattern, and the range of deviation in the results is 0.4, which might be considered high, given the simple building geometry.
Figure 3 presents data for the same building, for a point in the lower left corner (x = 1 m, y = 1 m). The data again show a similar pattern, but the deviations go up to 0.5 for a wind attack angle of 80°.

Figure 3. Unsheltered low-rise building: variation of $C_p$ with wind attack angle for a point in the lower left corner.

Figure 4 shows data for the same building, for a point in the upper right corner (x = 9 m, y = 9 m) which presents also a similar trend in the difference between the models.

Figure 4. Unsheltered low-rise building: variation of $C_p$ with wind attack angle for a point in the upper right corner.

Figure 5 presents the data from Figures 2, 3 and 4 in a single graph. It shows the differences in $C_p$ values compared with the surface averaged values of the AIVC. As reported by Feustel et al. (2005), the use of surface averaged values was one of the main motivations for the development of analytical methods, as “From experience we know that wall-averaged values of $C_p$ usually do not match the accuracy required for air flow calculation models.”

Figure 5. Range of $C_p$ data for 3 points at the facade of an unobstructed building using different $C_p$ sources

4.2 Sheltering effect

Table 1 shows the heterogeneity of approaches to model the sheltering effect on $C_p$ predictions. Those approaches can be classified in three groups. The first one considers each obstruction effect individually and then sums their effects (marked with “x” in Table 1). The second uses an averaged effect of the surrounding buildings, considering just a global description of the obstacle height and horizontal distribution (marked with “p”). The last approach adopts simplified correction factors (marked with “s”).

Figure 6. Sheltered building: Pressure coefficients from different sources, and for different points at the facade.
In order to present the different results obtained using approaches one and two, the same building and facade position of Figure 2, 3 and 4 were used, but now surrounded by similar buildings in a regular array with a horizontal spacing of 10 m. The results are shown in Figure 6.

While the AIVC data display only a small variation of $C_p$ values with the angle of attack, the analytical methods provide very different results as a function of this angle. The range of the results is wide, implying that high uncertainty is associated with $C_p$ values for sheltered buildings.

Figure 6 only considers the sheltering by neighbouring buildings. But, as pointed by Swami & Chandra (1988) several low-rise buildings, such as L-shape or U-shape buildings, can provide shelter to themselves. In those cases, the uncertainty might be even higher.

5 CONCLUSIONS

This paper provided an overview of generic pressure coefficient data as boundary conditions for indoor air flow studies in buildings. The following conclusions are made:

- Warnings in the original data sources are not reproduced with the data, which might lead to misunderstandings when using the data.

- Data describing the same building present large variations depending on the data source, even for simple configurations like fully exposed cubic buildings. Sheltered buildings and especially points near the facade corners present even higher variations. The same applies to complex building geometries, which are not included in existing secondary databases.

- The uncertainty associated with the analysed data sources is high. Therefore, the quantification of those uncertainties using empirical data for a broad range of cases is an important topic of future research.

- This overview may be used to guide future efforts in the development of BES and HAM programs. It will also assist future studies dealing with ventilation simulation, particularly those focused on the impact of $C_p$ data sources in the overall simulation uncertainty.

REFERENCES


Orme, M.L. 1999. Technical Note 51 - Applicable models for air infiltration and ventilation calculations, AIVC.


