Overview of pressure coefficient data in building energy simulation and airflow network programs

Citation for published version (APA):

DOI:
10.1016/j.buildenv.2009.02.006

Document status and date:
Published: 01/01/2009

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
Overview of pressure coefficient data in building energy simulation programs

D. Cóstola*, B. Blocken, J.L.M. Hensen

Building Physics and Systems, Eindhoven University of Technology, the Netherlands

Abstract

Wind pressure coefficients ($C_p$) are influenced by a wide range of parameters, including building geometry, surrounding terrain topography, facade detailing, position on the facade and wind direction. As it is practically impossible to take into account the full complexity of pressure coefficient variation, Building Energy Simulation (BES) programs generally incorporate it in a simplified way. This paper provides an overview of pressure coefficient data and the extent to which they are currently implemented in BES programs. A distinction is made between primary sources of $C_p$ data, such as full scale measurements, reduced-scale measurements in wind tunnels and computational fluid dynamics (CFD) simulations, and secondary sources, such as databases and analytical models. The comparison between data from secondary sources implemented in BES shows that the $C_p$ values are quite different depending on the source adopted. The two main parameters causing these differences are the position on the facade and the sheltering effects. The comparison of $C_p$ data for sheltered buildings shows the largest differences, and data from different sources present different trends. The paper concludes that quantification of the uncertainty related to such data sources is required to guide future improvements in $C_p$ implementation in BES programs.

Keywords: wind pressure coefficient, building energy simulation (BES), airflow network (AFN); ventilation; infiltration; model intercomparison; building envelope

*Corresponding author: D. Costola
Building Physics and Systems, Eindhoven University of Technology, P.O. box 513, 5600 MB Eindhoven, the Netherlands.
Tel.: +31 (0)40 247 2302, Fax +31 (0)40 243 8595, E-mail: d.costola@tue.nl
1 Introduction

Air infiltration and ventilation have a profound influence on both the internal environment and the energy needs of buildings [1]. Air flow through the building envelope is also an important factor influencing building heat loss [2].

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) programs [3-6].

Wind pressure on the building envelope is usually expressed by pressure coefficients ($C_p$), which are defined as follows:

$$C_p = \frac{P_x - P_0}{P_d}; \quad P_d = \frac{\rho \cdot U_h^2}{2}$$

where $P_x$ is the static pressure in a given point at the building facade (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 $U_h$ is the wind speed at building height $h$ in the upstream undisturbed flow (m/s).

The impact of $C_p$ in BES results was studied using sensitivity analysis, identifying $C_p$ as one of the main sources of uncertainty in BES-AFN models [7-8]. The reasons are the high uncertainty associated with $C_p$ values, and the fact that several performance indicators, e.g. energy consumption, thermal comfort and mould growth, are often very sensitive to the air change rate, which depends on $C_p$.

Hensen [9] described the difficulty to perform an accurate evaluation of $C_p$. Further studies, especially on the development of analytical models for $C_p$ prediction [10,11], have not been able to overcome the difficulties in obtaining reliable $C_p$ values without using expensive wind tunnel experiments. In this sense, Tuomaala [12] 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 influencing parameters, including building geometry, facade detailing (e.g. external shading devices, balconies), position on the facade, sheltering elements (e.g. buildings, trees), wind direction and turbulence intensity.
To the knowledge of the authors, there is no overview of pressure coefficient data for indoor air flow studies in BES. The purpose of the present paper therefore is to provide such information together with a comparison of data from 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.

The paper is structured as follows. Section 2 describes the BES and AFN programs that are included in this overview, as well as the method for their selection. The sources of $C_p$ data are classified in primary and secondary sources. Section 3 provides a brief overview of primary sources: full scale measurements, wind tunnel tests and CFD simulations. Primary sources 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 the cost to obtain them is also higher. Sections 4 to 6 describe the secondary sources in detail. 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 $C_p$. Section 7 presents comparisons of the values from each data source for the simple case of a cubic building, to demonstrate the magnitude of the differences between them. Finally, the main conclusions are provided in section 8.

2 BES and AFN programs

This section presents the programs selected to take part in the present overview. It is not the intention of this selection to be complete, rather the purpose is to obtain a reliable sample of programs representing the state of the art in commercial and academic BES and AFN modelling.

The selection of BES programs was made based on the recent work of Crawley et al. [13]. This paper results from the collaborative work of many research groups dealing with BES, and contrasts capabilities of 20 BES programs. From those 20 programs, 7 included a fully implemented and coupled AFN [13], which requires $C_p$ data.
Stand-alone AFN tools also represent an important reference for the present paper. Firstly because some of them are coupled with BES tools, e.g. Trnsys and COMIS [14], and secondly because they may include the most advanced features which will then be implemented in BES tools. The most recent review of AFN tools was published in 1999, comparing 14 AFN programs [15]. From those, 3 programs claimed to have some data on \( C_p \): AIOLOS, COMIS and Nitecool. From this list, AIOLOS and COMIS are included in this research. CONTAM is also mentioned in [15], but at that time the version “Contam 96” did not have any \( C_p \) data. The present version (CONTAMW 2.4b) does include \( C_p \) data, and is therefore also included in the present overview.

Table 1 summarizes information about the selected programs, and the documentation used as reference for this paper. In all the cases, the “Help” available in the program interface was also considered as source of information. This set is certainly small compared to the amount of existing BES tools, but it is considered to provide a representative and general overview about the topic.

### 3 Primary sources

Primary sources are considered to be the most reliable \( C_p \) data sources. All the tools listed in Table 1 allow the input of user defined \( C_p \) data, which is most often obtained from primary sources.

In this section, a brief description of the main primary sources is provided, focusing on their advantages and disadvantages.

#### 3.1 Full scale measurements

On site full scale measurements at real building facades provide the most representative description of the pressure at the building facade. In those measurements, there is no need to reproduce boundary conditions, no scaling issues, and no physical models to be adopted. However, full scale measurements are complex and expensive, and are therefore mainly used for validation purposes.

Early full scale experiments, e.g [25], used sensors with high uncertainty for the pressure measurements, such as manometers, and for the wind speed, such as cup anemometers.

More recent experiments using ultrasonic anemometer and pressure transducers provide a large amount of high quality data about the pressure at the building facade. Raw data from full scale
measurements is some time available at the web site of some research centers, e.g

In many of the past experiments, the building is relatively unsheltered, so the approaching wind flow
can be easily measured [26-28]. The definition of proper boundary conditions is a main constraint in full
scale experiments. Data produced by several measurement campaigns can not be used for validation
purposes due to the lack of data on the approaching wind flow [29]. In the urban environment, where
many nearby obstructions are present, defining a good reference measurement location becomes a main
challenge, and this type of experiments is less commonly found in the literature.

Despite the problems associated with reference measurements, on site full scale experiments are
always useful to gain insight in the pressure variation on the building facade in space and time, which is a
main concern in the structural design. However, for ventilation and infiltration studies, the effects of
turbulence on the pressure on the building facade can be often neglected [30;31].

It is commonly assumed that the wind pressure coefficient is independent of the wind speed. This is
true when the flow around the building is Reynolds number independent and thermal processes do not
significantly influence the air flow and pressure distribution around the building. For bluff bodies with
sharp edges, the first assumption is generally true even for low velocities because of the high Re numbers
in building aerodynamics. The second assumption is not necessarily true for low wind speeds, because the
mean wind speed as well as turbulence can be significantly influenced by solar radiation [32]. This point
is not relevant for in structural aerodynamics, because there the focus is generally on strong winds under
neutral atmospheric stability; however infiltration and ventilation studies have to deal with all the range of
wind speeds. Full scale experiments conducted to assess the uncertainty in $C_p$ prediction for natural
ventilation indicated very scattered values for low wind speeds [33]. The solution adopted was to discard
from the analysis all values where the reference wind speed was lower than 4 m/s [33]. This solution
clearly compromises the applicability of the results for a large range of situations with low wind speed.

The uncertainty in the measurements is rarely the object of detailed analysis, as prescribed by ISO
[34]. $C_p$ is a derived quantity; therefore it demands measurements of several quantities: pressure on the
facade, reference velocity, and also air temperature and atmospheric pressure to obtain the air density.
Each of these parameters will contribute to the resulting $C_p$ uncertainty, not only due to the sensor
uncertainty, but also due to other sources, such as the measurement protocol. The combined uncertainty
of full scale measurements is important because it provides the limit of accuracy when these data is used for validation purposes. In the best scenario, the uncertainty on the method under validation can be described as equal to the uncertainty on the reference value, but never smaller.

It can be concluded that full scale experiments are the primary data source that provide the most representative information; however the use of these experiments is restricted to research and validation purposes. Full scale experiments for urban environment and for low wind speeds still present limitations to be overcome by future studies, and the uncertainty of the measurements demands further attention.

3.2 Wind tunnel measurements

Wind tunnel experiments are considered the most reliable source of pressure data for buildings in the design phase. Structural engineering uses custom wind tunnel experiments to assess the wind load for a specific building, considering its geometry, surrounding and wind profile in the site. The use of wind tunnel measurements to provide BES input data however is limited due to cost, time and know-how involved in this type of experiments.

In the first half of the 20th century, knowledge on wind flow around buildings was mainly established using wind tunnel experiments [35]. In this early stage, the use of laminar uniform flows was common, and the deficiencies of this technique were not identified for many years. Later on, the comparison between wind tunnel results and full scale measurements highlighted the importance of atmospheric boundary layer turbulence and it incited the development of the boundary layer wind tunnels [25].

Nowadays, wind tunnel modelling techniques for mean pressure around buildings are widely available [29]. However, wind tunnel experiments, as any laboratory measurements, demand special care. A common exercise carried out by twelve institutions compared the wind tunnel results for the simple case of an isolated cube, for 3 wind directions [36]. Based on the standard deviation published in the paper, assuming a normal distribution and a confidence interval of 95%, it can be say that the overall variation in the surface averaged Cp values is ± 0.12 of the mean result. However, the results present some outliers, as indicated in Figure 1. The variation in the results stresses the importance of quality assurance procedures in wind tunnel experiments.

Figure 1 shows that the agreement is better for the windward surface, while the leeward surface and the roof show larger differences. Some possible explanations for the variation in the results were mentioned by the authors, such as “statistical variability of the data themselves as well as those
introduced by the measurement equipment; physical variability of the flow due to different simulation
methods, in particular regarding the structure of the simulated turbulence; different judgement on the time
and geometric scales imposed by a given wind-tunnel flow; imperfections of the model, pressure tapping
and tubing; imperfections of the software used for the data analysis; and finally, human error, lack of
accuracy and ability must not be forgotten.” [36].

A comparison between wind tunnel and full scale results for the same isolated cube case was recently
published [37]. It shows an underestimation by wind tunnel experiments at the leeward surfaces. New
wind tunnel experiments were conducted in the same study [37], paying special attention to the high-
frequency part of the turbulence spectra. The results are shown in Figure 2. The new wind tunnel
experiment shows much better agreement, even though the full turbulence spectra, and consequently the
turbulence intensity profiles, were not reproduced in the wind tunnel.

Similarly to the full scale experiments, uncertainty in wind tunnel measurements is seldom published
in accordance to the guidelines of ISO [34].

Based on the short sample of studies provided in the section, it can be concluded that wind tunnel
experiments present specific challenges. The quality of wind tunnel results is directly affected by the
history of calibration in the wind tunnel, quality assurance procedures, and the know-how of the personal
involved in the test setup and execution.

3.3 CFD

CFD has been used to study flow around buildings for more than 30 years [38], while works focused
on wind pressure on the building facade become more common about 20 years ago [39-42]. Those studies
were clearly exploratory, with no direct application in the building industry.

In the next years, CFD use increasingly grew due to the improvements in computer performance, price
reduction, and the availability of commercial CFD software. Stathopoulos provided a clear picture of
CFD “past achievements and future challenges” in a paper from 1997, which is still equally valid today in
many respects [43]. The paper expresses concern about the misuse of CFD for problems that cannot be
approached using this technique, which is still the case today considering the lack of validation in several
CFD applications. The review indicates some areas for improvement in the future. The list is reproduced
below [43]:
“(a) Numerical accuracy by using higher-order approximations coupled with grid independence checks;
(b) Boundary conditions, which depend on the specific problem under consideration so that they require good physical insight and high level of expertise; and
(c) Refined turbulence models although ad hoc turbulence model modifications are unlikely to perform well beyond the specific flow conditions for which they have been made.” [43]

It can be said that the advances in these aspects were small compared to the increase in CFD use by practitioners and researchers. Numerical accuracy and grid independence are not reported in many applications, and are not part of the editorial policy in many journals. Concerning the boundary conditions, the definition of wind profiles is often still simplistic. The turbulence profiles are included, but other features in the turbulence structure are neglected in Reynolds-averaged Navier Stokes (RANS) models. In transient simulations, such as those using Large Eddy Simulation (LES), the definition of the boundaries is even more complex. Other features related to the wind profile, such as the profile vertical displacement \((z_d)\) are rarely taken into account. The proper use of wall functions for the solid boundary in the domain floor also proved to be a source of concern [44;46].

Finally, there is still no consensus on turbulence modelling for simulation of pressures on facades. It is accepted that LES can provide good results for \(C_p\) and for related natural ventilation problems, while RANS simulations present less accurate results [47-49]. Important contributions to the accuracy and reliability in CFD modelling for other applications, such as pedestrian wind comfort and pollutant dispersion, have become available in recent years [50;51].

Despite the vast increase in application of CFD to study the wind flow around buildings, it is not a common practice to use it as source of custom \(C_p\) data for BES simulation. The main reasons are the required level of expertise and the high computational cost of these simulations, when compared to the BES simulation itself. Part of those limitations can be overcome in the future by the integration of pre and post processing between BES and CFD, together with clear guidelines for such simulations. IES<VE> is the only BES tool that at present includes a prototype of this integration, but in the present state it is not yet useful, due to the limited range of options for the CFD simulation, limited grid options and lack of integration in the post processing stage. However, it does indicate a possible direction to improve the use of CFD as source of \(C_p\) data.
4 Secondary sources: general aspects

When primary sources data are not available, secondary sources provide low cost data for infiltration and ventilation studies. Table 2 presents a list of secondary sources implemented in the BES and AFN programs that were mentioned in Table 1.

Concerning building height, data for low-rise buildings is more often implemented than data for their high-rise counterparts. Concerning the data source, data provided by AIVC is included in 7 out of the 10 programs analysed in this paper.

Despite the large amount of wind tunnel data published, only two databases are used in the programs: the so called AIVC database [1;15] and the ASHRAE Handbook - Fundamentals [52]. There seems to be a clear choice for data from “safe sources”, supported by well known institutions such as AIVC and ASHRAE.

Analytical tools are less frequently included than databases, at least in BES programs. Only two BES programs provide full implementations of the analytical models “CpCalc+” or “Swami & Chandra”, while other tools require using third-party analytical tools. The equations proposed by Swami & Chandra [53] are listed in the analytical tools, but they are in fact much simpler then CpCalc+ or Cp Generator.

Each of the of secondary data sources in table 2 is discussed in the next sections.

5 Secondary sources: Databases

Cp databases are compilations of Cp 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. Cp databases are widely available, particularly for the calculation of wind loads on structures. Wind load standards provide Cp values for unsheltered buildings with simple geometries, to be used when custom wind tunnel experiments are not available. The same approach is used in Cp databases available in the ventilation and infiltration literature, e.g. the AIVC database [1] or the data in the ASHRAE Handbook [52], which are described below.

5.1 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 [54], it published a compilation of \( C_p \) data as part of a guide [1]. 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 the original publication [55].

The data for low-rise buildings (up to 3 storeys) is based on the compilation of wind tunnel data published in the workshop [54], and seven other bibliographical references, e.g. [55;56], but the method to compile the database is not mentioned.

The \( C_p \) database for low-rise buildings consists of 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 are 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-averaged 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 data for low-rise buildings are not included in the publication. For the sheltered cases, the spacing 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 [15;57;58] as well as by other publications about building performance [3;24;59]. The database is currently in use for the scientific community, e.g. [60]. The confidence that is often expressed in this database seems to exceed the intention of the original publication, and in some cases the data are even used to calibrate coefficients in analytical models [61].
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 were reproduced in the AIVC publications [1;57]. The data are presented as vertical $C_p$ profiles for two wind directions, 0° and 45° 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 [57], 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 mentions that it is “showing the vertical dependency of pressure coefficients for tall buildings”, which seems to indicate that the illustrative aspect was a priority, rather 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 3 presents an example of vertical $C_p$ profile [1] and the $C_p$ distribution over the same surface for the same experiment [57]. The figure represents a windward facade with a wind attack angle of 45°, 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 3.

More recent AIVC publications do not include reproduction of the profiles or surface distributions for high-rise buildings, and present only the data for low-rise buildings [15;58]. The reproduction of the high-rise building data by others is also less common, e.g. [62], and it is used merely to exemplify the complex distribution of $C_p$ over the surface.

5.2 ASHRAE

The ASHRAE handbook [52] is not a ventilation oriented document like the AIVC publications, so it only presents condensed information about $C_p$ in the chapter dedicated to the 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, with different floor plan aspect ratios and pitch roofs are included with different angular discretizations.

An important difference between the AIVC and the ASHRAE handbook data is the attention given to building 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.

6 Secondary sources: Analytical models

The analytical models consist of a set of equations and coefficients to calculate $C_p$ for a specific building configuration [10;11;53;63]. 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 were 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., facade aspect ratio, position at the facade, building aspect ratio, position and size of the surrounding buildings, wind direction and aerodynamic roughness. The applicability of the derived functions depends on the quality and variety of the $C_p$ experimental data used in the regression, as well as on the parameters considered in the analysis. Regarding the experimental data, several authors [10;53] 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 guide 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.

6.1 The model by Swami & Chandra (1988)

The model proposed by Swami & Chandra [53] 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:

\[
NC_p = \ln[1.248 - 0.703 \cdot \sin(\theta/2) - 1.175 \cdot \sin^2(\theta/2) + 0.131 \cdot \sin^3(\theta/2) + 0.769 \cdot \sin^4(\theta/2) + 0.07 \cdot G \cdot \sin^2(\theta/2) + 0.717 \cdot \sin^4(\theta/2)]
\]

(2)

where \(NC_p\) 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 \(NC_p\), considering \(NC_p\) equal to 1 when the wind is orthogonal to the surface. It is therefore necessary to know a priori the \(C_p\) value for wind orthogonal to the surface. The model suggests \(C_p = 0.6\) for this case, 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.

The model calculates \(C_p\) for building with rectangular floor plan, and sheltering effects are not considered in detail. 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 [56;64], which focused on infiltration calculations assuming cracks that are homogeneously distributed over the building facades. This assumption however is not valid for many 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, including data from buildings with different heights and different roof pitch angles, and that fact that 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.
6.2 CpCalc+ (1992)

CpCalc+ [10] was developed within the COMIS workshop [4] and the European project AIOLOS [24], with the intention to provide results for sheltered buildings, that could not be obtained with the model by Swami & Chandra. Compared to this model [53], further experimental data were used to take into account sheltering effects, and also new parameters were added, such as the power-law exponent of the mean wind velocity profile, the plan area density, the relative building height to the surrounding buildings, the frontal aspect ratio and the position at the facade. Sheltering effects are considered using the “plan area density”, where the individual sheltering effects of each building are not taken into account. 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 mentions that the methodology is the main result, rather than the equations themselves. This is due to the lack of consistent experimental data, which is considered the main obstacle for a more comprehensive analysis.

6.3 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” [11]. 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 dimensions (length-width-height) and taking into account the effects of the surrounding terrain by wind profile corrections. The main improvement is situated in the way in which sheltering is taken into account. The model considers discrete block shaped obstructions instead of the neighbourhood plan area density. Unfortunately, the model was not developed in the English language. A comparison between C_p Generator results and experimental data for that specific low-rise building shows that they “are closer to reality than simulations carried out with C_p values from the AIVC tables” [33]. Nevertheless, the results show large deviations from full scale experimental data for some points and wind directions [33].

7 Comparison of C_p data features
Table 3 presents the summary of the characteristics described in the previous section. 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 of 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 sheltering effects are treated in different ways by each data source presented in Table 1. These aspects are discussed in the subsections below.

7.1 Variation across the facade

Table 3 shows that the variation across the facade is only 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 are made here. An arbitrary terrain type, suburban environment, is chosen for this comparison, and the corresponding wind profile parameters for the analytical models are obtained in the program documentation. A power-law wind profile exponent (\(\alpha\)) of 0.22 was used for \(\text{CpCalc+}\), while an aerodynamic roughness length (\(z_0\)) of 0.5 m was used for the \(\text{Cp}\) Generator. For the AIVC database and the model by Swami & Chandra for low-rise buildings, only surface averaged values are used in the comparisons, because those data sources do not provide values for specific points at the facade. Figure 4 presents the data for three points on the facade of a low-rise cubic building (10x10x10 m³). The data from the different sources show a similar pattern, and the range of deviation in the results for the middle point (A) is 0.4, which might be considered high, given the simple building geometry. For 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 4 (D) shows the differences in \(\text{Cp}\) values compared with the surface averaged values of the AIVC. As reported by Ref [65], 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 \(\text{Cp}\) usually do not match the accuracy required for air flow calculation models.”

7.2 Sheltering effects

Table 3 shows the differences in approaches to model the sheltering effect. These approaches can be classified in three categories. The first category considers each surrounding building individually to
provide the combined sheltering effect (marked with “x” in Table 3). The second category considers an averaged effect of the surrounding buildings, with just a global description of the obstacle height and horizontal distribution (marked with “p”). The last category adopts simplified correction factors (marked with “s”). In order to present the different results obtained using categories one and two, the same building and facade positions of Figure 4 were used, but now this building is considered to be surrounded by similar buildings in an infinite regular array with a horizontal spacing of 10 m. The results are shown in Figure 5. 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. This might seem logical, given the effect of channelling of wind flow through the building group. The range of the results is wide, implying high uncertainty associated with C_p values for sheltered buildings. Figure 5 only considers sheltering by neighbouring buildings, but several low-rise buildings, such as L-shape or U-shape buildings, can provide shelter to themselves [53]. In those cases, the uncertainty might be even higher.

Table 4 details the method to calculate the sheltering effect as implemented in each program. The first three lines describe the three data sources used in Figure 5. The first option is to use C_p results from wind tunnel experiments, like in the AIVC database. Another solution is the use of parameters to describe the surrounding area, like the “neighborhood density” in CpCalc+ or the position of a “discrete obstruction” in C_p Generator. Those methods try to take into account the specific impact on the C_p value, instead of adopting a more pronounced simplification like the other methods listed in the table. The simplified correction factor models are described below.

IES <VE> adopts the AIVC database, but the data for high-rise sheltered buildings do not comply with the original source. Data analysis revealed that arbitrary correction factors (0.66 and 0.33) are applied to the data for fully exposed buildings to obtain values for semi-exposed and sheltered buildings respectively. The documentation does not mention this procedure. SUNREL adopts a similar method, applying correction factors according to the shielding classification. Tas assumes that C_p for any sheltered facade is equal to the C_p value from the leeward facade of the unobstructed building [19]. The orientation of the sheltered facade relative to the wind direction is not taken into account. The comparison of leeward data in Figure 4 with sheltered data in Figure 5 shows that this approach is not preferable, as it can provide underpressure instead of overpressure. ASHRAE [52] describes a method to take into account the sheltering effect by correcting the reference wind speed. This method is not implemented in any of the
studied programs. All those methods consider a uniform sheltering correction for all points at the building facades, while in reality the extent of sheltering can be different for different parts of the facade. Stand-alone AFN tools, which are focused on the ventilation modelling, do not include those simplifications, which can be interpreted as an indication of the less good performance of those approaches.

8 Conclusions

The present research provided an overview of wind pressure coefficient data in building energy simulation programs. Some points can be highlighted from the findings described in the previous sections.

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

Databases are the most common data source in BES. Analytical tools are rarely found and are poorly integrated with BES programs. CFD is still a promise for the future regarding its integration with BES tools.

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.

Acknowledgements

This research is funded by the “Institute for the Promotion of Innovation by Science and Technology in Flanders” (IWT-Vlaanderen) as part of the SBO-project IWT 050154 “Heat, Air and Moisture Performance Engineering: a whole building approach”. Their financial contribution is gratefully acknowledged.
References


[18] Integrated Environmental Solutions, MacroFlo Calculation Methods - <Virtual Environment> 5.6, n.d.

[19] EDSL, TAS Theory, EDSL, n.d.


### Table 1. BES and AFN program

<table>
<thead>
<tr>
<th>Program</th>
<th>Type</th>
<th>Version</th>
<th>Documentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESP-r</td>
<td></td>
<td>11.3</td>
<td>[3;9;16]</td>
</tr>
<tr>
<td>EnergyPlus</td>
<td></td>
<td>2.0.0.025</td>
<td>[17]</td>
</tr>
<tr>
<td>IES &lt;VE&gt;</td>
<td></td>
<td>5.6</td>
<td>[18]</td>
</tr>
<tr>
<td>Tas</td>
<td>BES</td>
<td>9.0.5</td>
<td>[19]</td>
</tr>
<tr>
<td>BSim</td>
<td></td>
<td>4.6.7.12</td>
<td>[20;21]</td>
</tr>
<tr>
<td>IDA ICE</td>
<td></td>
<td>3.0 (15)</td>
<td>-</td>
</tr>
<tr>
<td>SUNREL</td>
<td></td>
<td>-</td>
<td>[22]</td>
</tr>
<tr>
<td>CONTAMW</td>
<td></td>
<td>2.4b</td>
<td>[23]</td>
</tr>
<tr>
<td>AIOLOS</td>
<td>AFN</td>
<td>1.0</td>
<td>[24]</td>
</tr>
<tr>
<td>COMIS</td>
<td></td>
<td>3.2</td>
<td>[4;14]</td>
</tr>
</tbody>
</table>
Table 2. $C_p$ database and analytical models implemented in BES and AFN software

<table>
<thead>
<tr>
<th>Database</th>
<th>ESP-&lt;i&gt;r&lt;/i&gt;</th>
<th>EnergyPlus</th>
<th>IES &lt;VE&gt;</th>
<th>Tas</th>
<th>BSim</th>
<th>IDA ICE</th>
<th>SUNREL</th>
<th>CONTAMW</th>
<th>AIOLOS</th>
<th>COMIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIVC Low-rise</td>
<td>x</td>
<td>x</td>
<td>p</td>
<td>p</td>
<td>?</td>
<td>?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIVC High-rise</td>
<td>p</td>
<td>p</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASHRAE Low-rise</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASHRAE High-rise</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Analytical model

<table>
<thead>
<tr>
<th>Swami &amp; Chandra</th>
<th>Low-rise</th>
<th>x</th>
<th>p</th>
<th>p2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CpCalc+</td>
<td>x</td>
<td>x</td>
<td>x1</td>
<td></td>
</tr>
<tr>
<td>Cp Generator</td>
<td>x1</td>
<td>x1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- x – Implemented
- p – Partially implemented
- ? – Not clearly mentioned in the documentation

Notes:
1. Not implemented in the software. It is indicated as $C_p$ source in the software documentation.
2. Table with results based on the analytical equation.
### Table 3. Database and analytical model features

<table>
<thead>
<tr>
<th>Primary sources</th>
<th>Low-rise</th>
<th>High-rise</th>
<th>Low-rise</th>
<th>High-rise</th>
<th>Low-rise</th>
<th>High-rise</th>
<th>CpCalc+</th>
<th>Cp Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topographic effects</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effect of surrounding terrain (smooth, rural, suburban, urban)</td>
<td>x</td>
<td></td>
<td></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 p p s s s s p x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></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>
</tr>
<tr>
<td>Size of direction sectors (degrees)</td>
<td>c 45 90 c c c c</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variation across the facade</td>
<td>x s x x x</td>
<td></td>
<td></td>
<td></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>
</tr>
</tbody>
</table>

x – Fully able to model  
 p – Partially able to model  
 s – Simplified model  
 c – Custom
Table 4. Methods to model sheltering effects

<table>
<thead>
<tr>
<th></th>
<th>ESP-r</th>
<th>EnergyPlus</th>
<th>IES &lt;VE&gt;</th>
<th>Tas</th>
<th>BSim</th>
<th>IDA ICE</th>
<th>SUnREL</th>
<th>CONTAMW</th>
<th>COLOMOS</th>
<th>COMIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_p$</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Neighborhood density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discrete obstruction</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Correction factor on $C_p$</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copy data from the leeward facade</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Correction factor on flow rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Correction factor on wind speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Comparison of different wind tunnel experiments, after Ref. [36].

Figure 2. Comparison of different wind tunnel experiments with full scale results, after Ref. [36;37].
Figure 3. Example of vertical profile of $C_p$ values for a high-rise building surface [1] (left), and the $C_p$ distribution over the same surface [57] (right).
Figure 4. $C_p$ for an unsheltered low-rise cubic building as function of wind angle of attack ($\theta$): (A) middle of the facade, (B) lower left corner, (C) upper right corner, (D) range of data for the points A, B and C.
Figure 5. Sheltered building: $C_p$ from different sources, and different points in the facade.