

A comparison of RANS computations and wind tunnel tests for RMS pressures on a high-rise building model

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ABSTRACT: Five root-mean-square (RMS) pressure models are used in combination with different turbulence models to determine whether it is possible to obtain a conservative estimate of RMS pressures on a high-rise building model from a RANS calculation. When a precursor domain is used for the generation of inlet profiles the turbulent kinetic energy is severely underestimated and, as a result, all RMS models are found to be highly non-conservative, irrespective of the turbulence model which is used. Although the prescription of an ABL profile of the desired shape at the inlet or the prescription of more appropriate wall functions on the bottom of the computational domain might lead to more conservative results it is concluded that new models are needed to enable the calculation of RMS values from RANS calculations for engineering purposes.

KEYWORDS: RMS pressure model, high-rise building, RANS

1 INTRODUCTION

Although much progress has been made in recent years, the prediction of local peak wind pressures on building facades with CFD analysis has proven difficult (Stathopoulos, 1997). Time dependent techniques like DES or LES are required to obtain accurate solutions (Lim (2009)). However, these techniques are currently too expensive and complex for everyday use by construction engineers. Combined with the fact that validation of these techniques for this application is still an ongoing effort, it is unlikely that CFD analysis will be a viable alternative for building codes or wind tunnel testing in the near future. However, the application of CFD could be beneficial in the early design phase of a building, where a cheap, quick, rough estimate of wind loads is desired. A Reynolds Averaged Navier-Stokes (RANS) simulation meets these criteria.

Unfortunately, this type of simulation only provides information on the mean wind pressures. For the calculation of peak pressures, some assessment of the pressure fluctuations such as a root-mean-square (RMS) pressure is needed. A turbulence model contains some information on the fluctuating state of the flow. For example, the RMS values of the fluctuating velocity components are directly related to the square-root of the time-averaged turbulent kinetic energy. Paterson and Holmes (1989), Selvam (1992), Paterson (1993) and Richards and Wanigaratne (1993) derived models for estimating the RMS pressure from the mean turbulence characteristics of the flow. Another option, the generation of a synthetic turbulent velocity field using a stochastic model and subsequently solving the Poisson equation that governs the pressure fluctuations field (Senthoooran, 2004) is outside the scope of the current paper.

These models were developed with best agreement between calculation and experiment in mind. While this is a logical approach from a scientific point of view, for a construction engineer the most important question is whether the model will result in a safe prediction of the actual wind loads. For a safe prediction, the model needs to produce a conservative estimate. From this point of view the most appropriate model is therefore not necessarily the most accurate one.

This study investigates five RMS pressure models using three turbulence models (Standard $k-\epsilon$, Realizable $k-\epsilon$, and RNG $k-\epsilon$) for an isolated high-rise building in suburban terrain conditions. The goal of this study is to determine for the 15 combinations of turbulence and root-mean-square models whether:

- The combination of turbulence model and RMS model is conservative;
- If not, in which regions of the high-rise building model the combination is not conservative.

2 MODEL DEFINITION

2.1 Wind tunnel model

Wind tunnel experiments have been carried out in the open circuit atmospheric boundary layer wind tunnel of TNO in the Netherlands, depicted in figure 1a. It has a working section of approximately 13.5 m in length, 3 m in width and 2 m in height. The boundary layer used in this study was developed over the length of the test section using 50 mm cubic roughness elements and 6 spires located at the beginning of the test section, resulting in a wind tunnel roughness length of $z_0 = 0.0032$ m. The roughness elements extended onto the turntable to prevent the development of an internal boundary layer.

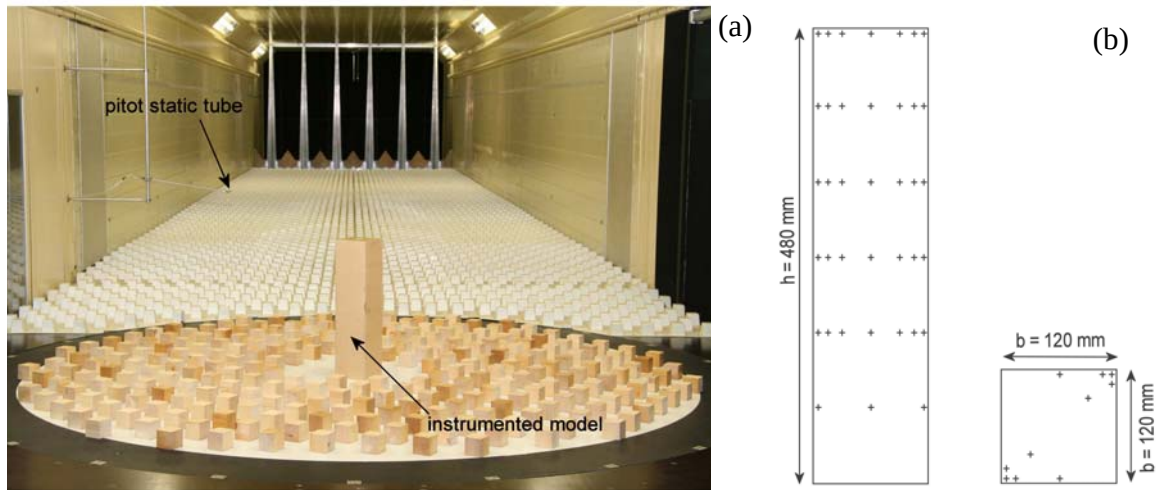


Figure 1. (a) Test configuration in the wind tunnel of TNO, (b) pressure tap distribution on the model faces

Experiments were performed on a geometrical scale of 1:250. The building model was a square cylinder with a height of $h = 48$ cm and side $b = 12$ cm. The reference model was instrumented with pressure taps at 86 locations, illustrated in figure 1b, which were sampled simultaneously. After one measurement run the model was rotated 90 degrees and a second run was performed for the same configuration, giving pressure data at 86 new locations. The total number of locations where pressure measurements were performed was therefore 172.

A hot wire anemometer was used to measure both wind speed and turbulence intensity characteristics of the boundary layer flow. Figure 2 illustrates the velocity magnitude and turbulent kinetic energy above the centre of the turntable without model present.

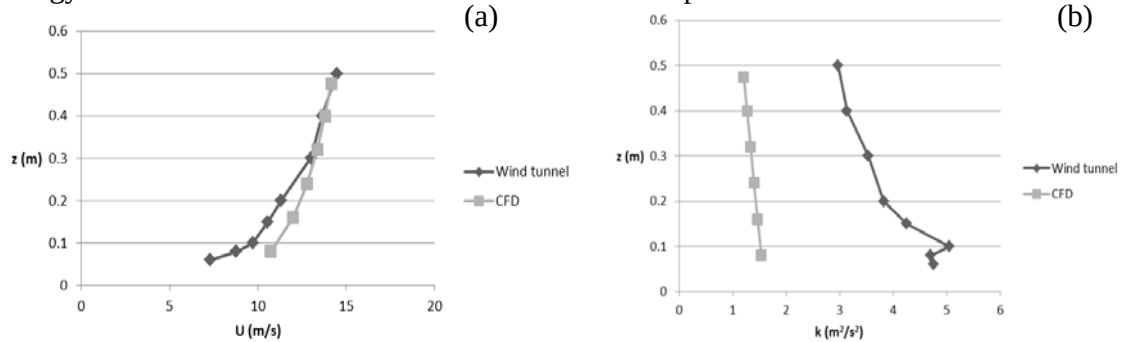


Figure 2 Approach flow profiles of (a) velocity magnitude and (b) turbulent kinetic energy

The wind speed in the wind tunnel in the presence of the model, measured with a pitot static tube, was $U_{ref} = 14.2$ m/s at model roof height ($h_{ref} = 0.48$ m). Building pressures were measured with a sampling rate of 400 Hz for a period of approximately 20.5 seconds. The pressures were converted to mean pressure coefficients, defined as

$$C_{\bar{p}} = \frac{\bar{p}}{\frac{1}{2} \rho U_{ref}^2} \quad (2)$$

in which $\bar{p}$ is the time-average of the entire measured pressure signal and ρ the air density.

2.2 CFD model

The numerical simulations were performed with the open source flow solver OpenFOAM 2.1.0. The statistically steady flow field was computed by solving the RANS equations using the simpleFoam solver for steady state incompressible flows. Three different turbulence models were employed: the standard $k-\epsilon$ model, the realizable $k-\epsilon$ model and the RNG $k-\epsilon$ model. All calculations were run until the residuals showed no further improvement. For the standard and realizable $k-\epsilon$ models residuals of approximately $1.0 \cdot 10^{-6}$ or smaller were achieved. For the RNG $k-\epsilon$ model the residuals were much higher, with a maximum of $3.5 \cdot 10^{-3}$ for the lateral velocity component in several calculations. These residuals were much reduced upon mesh refinement (see section 2.3), indicating that this effect is most likely due to a greater mesh sensitivity for this model. Since observed differences in the solution upon refinement were small the results were nevertheless considered adequately converged.

The computational domain corresponded to the wind tunnel model described in the previous paragraph. Velocity, turbulent kinetic energy and turbulent dissipation rate equilibrium profiles were generated by running a precursor computation on a periodic domain and prescribing the resulting profiles at the inlet of the model computational domain. Both the lateral boundaries and top boundaries were modeled as symmetry planes. The building surface was treated as a solid smooth wall. Standard rough wall functions based on the local velocity field (nutURoughWall-Function) were employed at the bottom of the domain.

Gauss linear schemes were used for the calculations of gradients and Gauss linear corrected schemes for the Laplacians. Furthermore linear interpolation and corrected surface normal gradient schemes were selected. For the calculation of divergence the limitedLinear2V scheme was used for the velocity field, in which the calculated face gradient is used to blend in a small amount of the solution in the upwind cell (here a multiplication factor between 0.2 and 0 was used) in order to damp high-frequency oscillations in the solution. Self-filtered central differencing was applied for the calculation of divergences for the k and ε fields. For the last divergence term, involving the effective viscosity, a Gauss linear scheme was applied.

2.3 Computational grid

The CFD model of the high-rise building had a length of ($L = 10.08$ m), a width of ($W = 3.00$ m) and a height of ($H = 2.00$ m). The domain measured $4.4 h_{ref}$ ($= 2.1$ m) upstream of the building, $16.4 h_{ref}$ ($= 7.86$ m) in the downstream direction, $3.0 h_{ref}$ ($= 1.44$ m) to each side and $3.2 h_{ref}$ ($= 1.52$ m) in the height direction. These values were chosen to enable a fair comparison with the results from the wind tunnel tests and lead to a very low blockage of 0.96 %. They also correspond with most recommendations specified in COST Action 732 (2007).

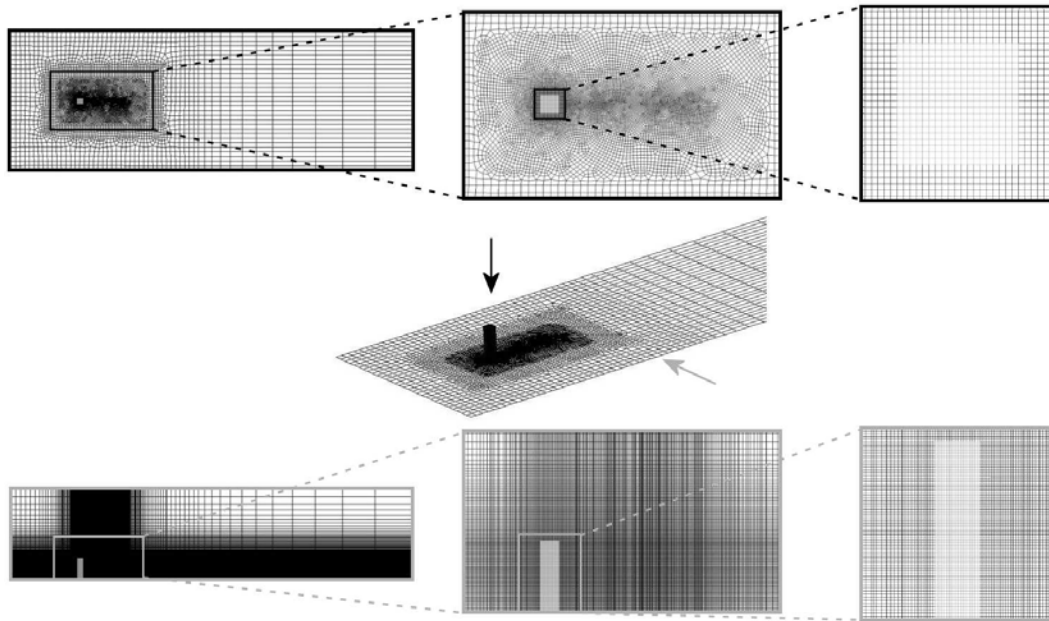


Figure 3 Coarsened mesh (top view in black, side view in grey).

Purely hexahedral meshes were created using Gambit 2.4.6. A coarsened version of the mesh used in the calculation at a zero degree angle of attack is depicted in figure 3. The mesh was successively refined towards the building surfaces and in the wake of the building. This was done by specifying the desired cell size on the building surface and in the wake, meshing the ground plane using a quad pave scheme and extruding the resulting surface mesh in the vertical direction. The smallest cell size at the building surface was approximately 5 mm in each direction, leading to a y^+ range of $1.03 \leq y^+ \leq 310.74$ for all calculations with a mean value of $y^+ = 79.02$. The number of cells over the building surfaces was 24 in the streamwise and spanwise directions and 88 over the building height. The total number of cells used was 2,219,268.

For a mesh refinement study a coarser and a finer mesh with 369,078 and 5,747,816 cells, respectively, were also used. From this study it was concluded that the average difference between $C_{p,mean}$ values calculated for the medium and fine meshes was very small: 0.59 % for the standard $k-\varepsilon$ model, 1.14 % for the realizable $k-\varepsilon$ model and 0.87 % for the RNG $k-\varepsilon$ model. Close to building edges differences up to nearly 100 % were observed owing to the numerical difficulties in modeling sharp corners. Since large near-wall gradients exist for the turbulent kinetic energy the average differences for calculated k values were substantially larger: 6.37 % for the standard $k-\varepsilon$ model, 15.41 % for the realizable $k-\varepsilon$ model and 23.52 % for the RNG $k-\varepsilon$ model. Local differences up to 212 % were observed.

Nine more angles of attack were calculated, ranging from 5 to 45 degrees at 5 degree intervals. Both the resolution near the building as well as the total number of cells in these nine meshes were similar to those for the 0 degree angle of attack medium resolution mesh.

2.4 RMS pressure models

Various models have been developed for determining the RMS pressures in a RANS simulation. Paterson and Holmes (1989) published the first formula for prediction of RMS pressure coefficients. Starting from Bernoulli's equation and using experimental results, they obtained:

$$C_{p,RMS} = \frac{2 \left[k/3 + 0.816 |C_{p,mean}| U_o \sqrt{k_o} \right]}{U_h^2} \quad (2)$$

Here U_o and k_o are the mean velocity and turbulent kinetic energy of the approach flow at the height of interest, $C_{p,mean}$ is the local mean pressure coefficient, k is the local turbulent kinetic energy and U_h is the mean reference velocity at building height. The part proportional to k is associated with small-scale local pressure fluctuations in a flow free of mean velocity gradients, the part containing U_o is a 'quasi-steady' term associated with the amplification of upwind pressure fluctuations by velocity gradients.

Applying a similar procedure as Paterson and Holmes (1989) to derive equation (2), Selvam (1992) deduced an alternate equation for the RMS pressure coefficients:

$$C_{p,RMS} = \frac{2 |C_{p,mean}| [1.414 U_h \sqrt{k_h} + k_h]}{U_h^2} \quad (3)$$

in which U_h and k_h are the mean velocity and turbulent kinetic energy in the approach flow at building height.

Paterson (1993) derived a second model for large Reynolds numbers from the stream-wise component of the Navier-Stokes equations:

$$C_{p,RMS} = \frac{8k_o^2}{U_o^4} + \frac{8C_{p,mean}^2 U_o^2 k_o}{(U_o^2 + 2k_o - 2k)^2} \quad (4)$$

According to Paterson, results obtained with equation (4) were in better agreement with full-scale and wind tunnel results of the TTU experimental building than results using equation (2). Richards and Wanigaratne (1993) derived a similar equation as Paterson and Holmes' (1989) equation (2), but suggested it should be more of the form

$$C_{p,RMS} = \frac{2 \left[Ek_o^2 + 0.816^2 \cdot C_{p,mean}^2 \cdot U_o^2 k_o \right]^{\frac{1}{2}}}{U_h^2}, \quad (5)$$

This is a variation on equation (2) where the local turbulent kinetic energy term was replaced with a function of the approach flow turbulence, Ek_o^2 . $E \approx 0.5$, which was determined through investigation of the value of $C_{p,RMS}$ in regions where $C_{p,mean} \approx 0$. Richards and Wanigaratne (1993) developed an additional model through consideration of the flow oriented with respect to the mean stream lines:

$$C_{p,RMS} = 2 \left[\begin{aligned} & Ek_o^2 + (U_o^2 \sigma_{uo}^2 + Ek_o^2) \cdot \left((1-F) + F \frac{C_{p,mean} U_h^2}{U_o^2 + 2k_o} \right)^2 \\ & + \left(\frac{U_o^2 \sigma_{uo}^2 + Ek_o^2}{(U_o^2 + 2k_o)^2} + 0.25 \right) F^2 \left(\frac{\partial C_{p,mean}}{\partial \theta} \right)^2 U_h^4 \frac{\sigma_{vo}^2}{U_o^2} \end{aligned} \right]^{\frac{1}{2}} / U_h^2. \quad (6)$$

In which $\sigma_{uo} = \sqrt{u_o'^2}$, $\sigma_{vo} = \sqrt{v_o'^2}$. A value $F = 0.64$ was found through investigation of the relationship between $C_{p,RMS}$ and $C_{p,mean}$ for a dataset of wind tunnel measurements.

2.5 Comparison of wind tunnel measurements and CFD results

In all locations where a comparison between wind tunnel measurements and CFD results could be made, the five RMS models presented in the previous section were applied to the CFD results for all three turbulence models, leading to a total of 15 combinations. The evaluation of the term $\partial C_{p,mean} / \partial \theta$ in equation 6 was done in a central differencing fashion using the results of the calculations at a ± 5 degree angle of attack with respect to the evaluated angle. In this it was assumed that the units of θ are degrees, as is common in the field of wind engineering, although this was not specified in the original paper. The terms σ_{uo} and σ_{vo} were derived from the calculated Reynolds stresses.

At each pressure tap point the difference between wind tunnel data and the computational result for the mean and RMS pressure coefficients was determined as

$$\Delta C_p = |C_{p,CFD}| - |C_{p,WT}| \quad (7)$$

While it is possible to define a quality parameter which is directly related to these difference data, this would lead to a dependence on the choice of measurement locations. In order to overcome this problem the data were interpolated on a regular grid measuring 111 points in the

streamwise and spanwise directions and 396 points in the height. While this approach makes the results dependent on the interpolation method, it reduces the chosen dependence on the pressure tap positions. The interpolation was performed using the Matlab gridfit routine using a triangular interpolation scheme and a smoothness parameter of 1 in the streamwise and spanwise directions and 2 in the height direction. No extrapolation was performed.

To evaluate the performance of different models from a comparison between wind tunnel data and CFD calculations three quality parameters were defined: the fraction of all locations where the evaluated parameter is underpredicted, the average amount of underprediction per underpredicted location and the overall average amount of underprediction. The latter thereby equals the product of the former two.

A comparison of the wind tunnel and computational results is made for four angles of attack (0° , 15° , 30° and 45°). The three quality parameters defined above, derived for each of the wind directions, are averaged to produce an overall quality estimate. Evaluation of the quality parameters is performed on the interpolated grid.

3 RESULTS

In figure 2 the turbulent kinetic energy and velocity magnitude profiles which were measured in the empty wind tunnel are compared with the profiles calculated in the precursor domain of the CFD calculation. The calculated turbulent kinetic energy is lower than the wind tunnel result by a factor of roughly 2.5 to 3. A clear difference between the velocity magnitude profiles can also be observed, especially close to the ground.

The three quality parameters defined in section 2.5, evaluated for every combination of turbulence model and RMS model, are presented in tables 1-3. In these tables the root mean square pressure models are abbreviated as P&H (Paterson and Holmes, equation 2), S (Selvam, equation 3), P (Paterson, equation 4) and R&W 1 and 2 (Richards and Wanigaratne, equations 5 and 6).

Table 1. Fraction of underpredicted locations. For the abbreviations of the RMS pressure models see text.

Turbulence model	$C_{p,mean}$	$C_{p,RMS}$ (P&H)	$C_{p,RMS}$ (S)	$C_{p,RMS}$ (P)	$C_{p,RMS}$ (R&W 1)	$C_{p,RMS}$ (R&W 2)
Standard k- ϵ	0.3551	0.9880	0.6819	0.9999	0.9987	1.0000
Realizable k- ϵ	0.4386	0.9988	0.8178	1.0000	0.9995	1.0000
RNG k- ϵ	0.4251	0.9990	0.8102	1.0000	0.9996	1.0000

Table 2. Average amount of underprediction per underpredicted location. For the abbreviations of the RMS pressure models see text.

Turbulence model	$C_{p,mean}$	$C_{p,RMS}$ (P&H)	$C_{p,RMS}$ (S)	$C_{p,RMS}$ (P)	$C_{p,RMS}$ (R&W 1)	$C_{p,RMS}$ (R&W 2)
Standard k- ϵ	0.0878	0.0829	0.0732	0.1387	0.0979	0.1226
Realizable k- ϵ	0.0744	0.0950	0.0686	0.1454	0.1045	0.1259
RNG k- ϵ	0.0934	0.0970	0.0702	0.1458	0.1046	0.1263

Table 3. Overall average amount of underprediction. For the abbreviations of the RMS pressure models see text.

Turbulence model	$C_{p,mean}$	$C_{p,RMS}$ (P&H)	$C_{p,RMS}$ (S)	$C_{p,RMS}$ (P)	$C_{p,RMS}$ (R&W 1)	$C_{p,RMS}$ (R&W 2)
Standard k- ϵ	0.0312	0.0819	0.0499	0.1387	0.0978	0.1226
Realizable k- ϵ	0.0326	0.0949	0.0561	0.1454	0.1045	0.1259
RNG k- ϵ	0.0397	0.0969	0.0569	0.1458	0.1046	0.1263

As will also be concluded in section 4 it can immediately be seen from table 3 that the best results are obtained when the model of Selvam is used in combination with the standard k- ϵ model. In order to understand the reason for this, the average amount of underprediction in $C_{p,RMS}$ values for this combination of models is plotted at 0 and 45 degree angles of attack in figure 4 and figure 5, respectively. In these figures bright green represents a conservative estimate (no underprediction).

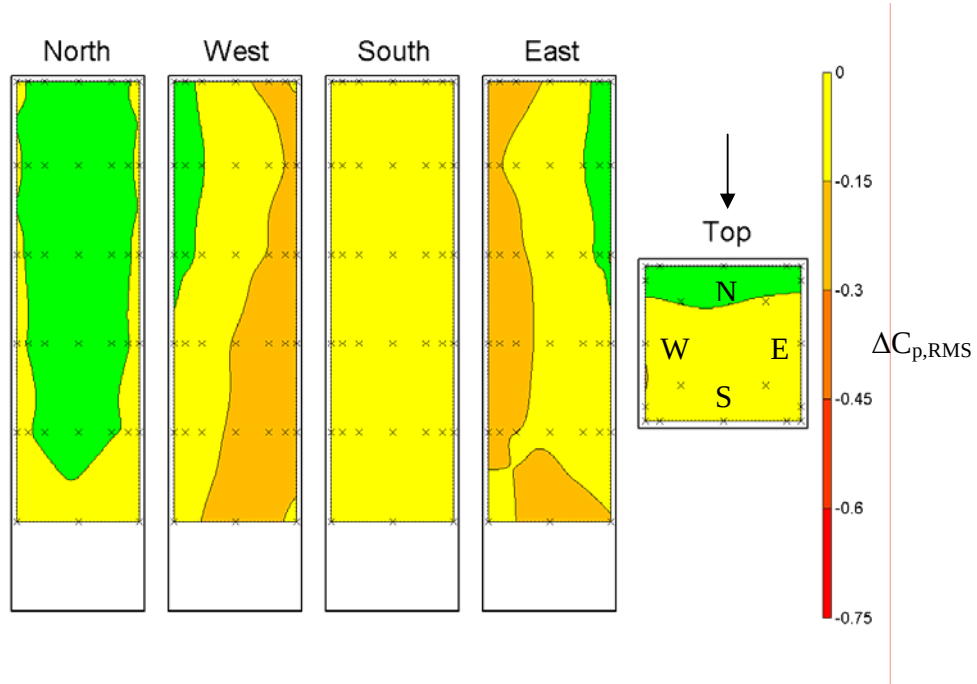


Figure 4 Amount of $C_{p,RMS}$ underprediction as a function of location for the model of Selvam using the standard k- ϵ turbulence model. 0 Degree angle of attack.

4 DISCUSSION

It can be seen from table 1 that the underprediction fractions for all RMS models are much larger than 0.5, indicating that none of the models are conservative. Both the models of Paterson and Holmes and that of Paterson perform especially poorly in this respect, leading to an underprediction for (almost) every location. Also apparent is the fact that, for the case considered here, the influence of the RMS model which is chosen is much more important than the turbulence model. The differences between the turbulence models show that the standard k- ϵ model is the most conservative which might be due to the well-known overprediction of turbulent kinetic energy in stagnation areas for this model. All papers where these models were introduced exclusively used the standard k- ϵ model.

The average amount of underprediction per underpredicted location is given in table 2. Again, although the differences between the results of the three turbulence models are not negligible they are much larger when different RMS models are compared. The least amount of underprediction is found using the model of Selvam whereas that of Paterson again performs poorly.

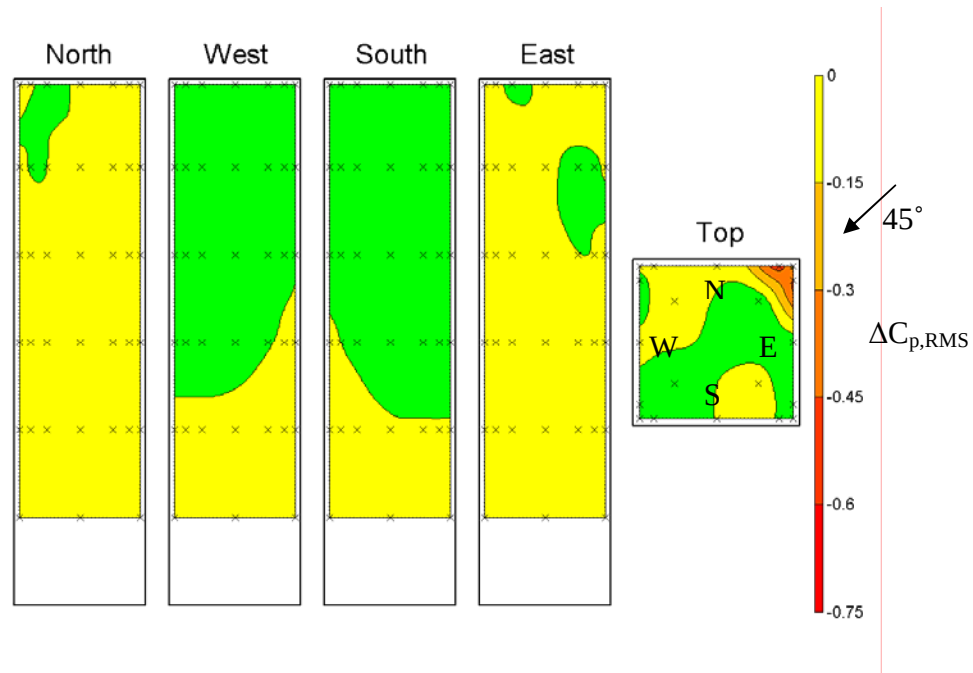


Figure 5 Amount of $C_{p,RMS}$ underprediction as a function of location for the model of Selvam using the standard $k-\epsilon$ turbulence model. 45 Degree angle of attack.

Combining the data in tables 1 and 2 by taking the product of both, the data in table 3 are derived. The values represent an average amount of underprediction for the selected model when overprediction is neglected. The best results are obtained when the model of Selvam is used in combination with the standard $k-\epsilon$ model, leading to an average amount of underprediction of $C_{p,RMS}$ of 0.0499. The worst results are obtained by combining the model of Paterson with the RNG $k-\epsilon$ model in which case the average amount of underprediction is almost three times as high.

The difference between the velocity magnitude and turbulent kinetic energy profiles for the wind tunnel and CFD datasets observed in figure 2 is caused by the wall functions used at the bottom of the CFD computational domain and in the absence of more appropriate wall functions cannot be avoided completely (Blocken, 2007; Kalkman, 2011). The effect of this discrepancy on the quality parameters given in tables 1-3 was therefore estimated through another analysis using the linearly interpolated wind tunnel dataset for the terms U_0 , U_h , k_0 and k_h , resulting in a change of 30.5 ± 38.0 %. The most conservative model is again found to be Selvam's. However, although the results of this reanalysis are considerably more conservative even this model still underpredicts RMS pressure values on 32.6 % of the inspected surface area.

5 CONCLUSION

The observation that the RMS pressure models introduced by Paterson and Holmes (1989), Selvam (1992), and Paterson (1993) are generally non-conservative has already been made by the respective authors. Richards and Wanigaratne (1993), however, showed by comparison with data from the Silsoe building that their models performed rather well. In this paper it is shown that

this is no longer the case when they are applied to a high-rise building model. A very likely source of discrepancy is the mismatch between wind tunnel and CFD inflow profiles. As an alternative to the precursor simulation method used in the present investigation one could prescribe an ABL profile of the desired shape, in disregard of the fact that it will not be maintained throughout the computational domain. Another possible explanation for the relatively poor performance of the model derived by Richards and Wanigaratne for the present case is that the factors E and F , which were determined from a fit to the Silsoe building data set, are not universally applicable. Although the mathematical basis for the model introduced by Selvam (1992) is not completely clear it does seem to have a wider range of application. From figure 4 and figure 5 it can be observed that, away from reattachment zones and areas affected by corner vortices, it does not perform too poorly. Nevertheless, it is still non-conservative and therefore not applicable in an engineering context. New models are therefore required.

The effect of the turbulence model on the performance of the RMS model is comparatively minor. Future work should therefore focus on deriving an equation for the RMS pressures from first principles. Closure should be obtained with modelling assumptions also used in the turbulence models. RSM models could be helpful for this.

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