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The evolution of the application of CFD on pedestrian wind comfort in engineering practice, a validation study

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ABSTRACT

Starting in 2002, Peutz BV in the Netherlands is developing an application using CFD for the prediction of pedestrian wind comfort. The first models used the standard k-ε model and a hybrid differencing scheme and showed moderate agreement with measurement results of wind tunnel test on physical models of the same building projects. Nowadays better agreement is found using the RNG k-ε model, a second order differencing scheme (MINMOD), improved boundary conditions and an increasing number of grid cells. However, a numerical 'virtual wind tunnel' cannot yet replace a real one. But, the location of 'hot spots' can be predicted, which can be advantageous for certain projects and can be of help to the set up of measurements. For projects with a rather simple geometry CFD can even by used as an alternative for wind tunnel measurements.

1. INTRODUCTION

Peutz is a consultancy active in the fields of acoustics, industrial noise, building physics, fire safety, environmental technology and wind tunnel research. Peutz has branches in the Netherlands, Belgium, Germany, France and the United Kingdom and is involved in the design of office and

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residential buildings, railway stations, airports etc.

In Mook in the Netherlands, besides a certified acoustical laboratory and a laboratory for building physics, an atmospheric boundary layer wind tunnel is present. In the wind tunnel studies are performed with respect to:

- pedestrian wind comfort;
- dispersion of air pollution;
- mean pressures on ventilation openings for ventilation of parking garages and natural ventilation for CFD;
- forces and moments on building constructions.

This paper deals with the comparison between numerical simulation and experimental work. Numerical CFD models concerning wind around buildings and pedestrian wind comfort are tested and the results are compared with measurements on physical scale models in the wind tunnel.

The possibilities of CFD for application in the field of wind around buildings and pedestrian comfort are studied. The code Phoenics of Cham Ltd. is employed with a Cartesian mesh.

Recently, Hu and Wang [2005] showed that using CFD, an adequate prediction of street-level winds can be obtained. However, there remain some drawbacks, especially concerning the so-called Venturi-effect between tall buildings, as Blocken et. al. [2007] show. Comparison of wind tunnel measurements on pedestrian comfort with CFD predictions was investigated by a.o. Lam and To [2006], Richards et. al. [2002] and Li et. al.[2004]. Lam and To [2006] show that with the RNG k-ε model a accuracy of +/- 10% can be achieved.

2. EVALUATION OF THE WIND CLIMATE

In The Netherlands the way to evaluate the wind climate is prescribed in an official standard, the NEN 8100:2006 "wind comfort and wind danger in the built environment". The standard offers the possibility to use both wind tunnel experiments and CFD to evaluate the wind climate.

The NEN 8100 prescribes that the wind climate has to be judged after the probability of exceeding a critical wind speed of 5 m/s. Beside that criteria for wind danger are given based on the probability of exceeding a critical wind speed of 15 m/s. The criteria are summarized in table 1 and table 2.

Probability of Exceedance $P(V_{loc} > V_{threshold;wind\ nuisance})$ in percentages of the number of hours per year	Quality-level	Activity-level		
		I. Walking, normal pace	II. Walking Leisurely-strolling	III. Sitting longer time
< 2.5	A	Good	Good	Good
2.5 – 5	B	Good	Good	Moderate
5 – 10	C	Good	Moderate	Poor
10 – 20	D	Moderate	Poor	Poor
≥ 20	E	Poor	Poor	Poor

Table 1: Criteria wind nuisance according to NEN 8100

Probability of Exceedance $P(V_{loc} > V_{threshold;wind\ danger})$ in percentages of the number of hours per year	Qualification
$0.05 < p < 0.30$	limited risk
$p \geq 0.30$	dangerous

Table 2: Criteria wind danger according to NEN 8100.

According to the standard situations with an exceedance-percentage chance of $0.05 < p < 0.30$ should only be accepted if they fall within the activity-class I (walking at normal pace).

The number of wind directions tested should be at least 12. Since the Dutch standard refers to an application that provides the wind statistics at each position in the Netherlands at a height of 60 m. for 12 wind directions, usually these wind directions are tested.

3. WIND TUNNEL MEASUREMENTS

Wind tunnel investigations are performed in the Peutz wind tunnel. The wind tunnel is a so-called closed boundary layer wind tunnel, specially designed for simulating an atmospheric boundary layer. A schematic presentation of the wind tunnel is given in figure 1. At the measurement section the width of the tunnel equals 3.2 m, the height of the tunnel is 1.8 m. The models under investigation are placed on a turning table with a diameter of 2.3 m. Maximum wind speed in the tunnel above the boundary layer is about 30 m/s.

Wind speed measurements are performed using so-called NTC's. These NTC's are resistor elements with a negative temperature coefficient. These elements are operated with a constant current. The probes are calibrated in-house by determining the relation between wind speed and temperature (and corresponding resistance) of each individual probe. The probes are not direction sensitive. Since the reaction time of the probes is relatively long, only average wind speeds can be measured. For special purposes a number of fast probes is available.

In wind climate measurements usually 60 to 120 probes are used. Since most wind statistics available present data for 12 different wind directions usually measurements are performed for 12 wind directions. The scale of the models usually is in between 1:200 to 1:400. The measurement height is 1.8 m above ground level on real scale.

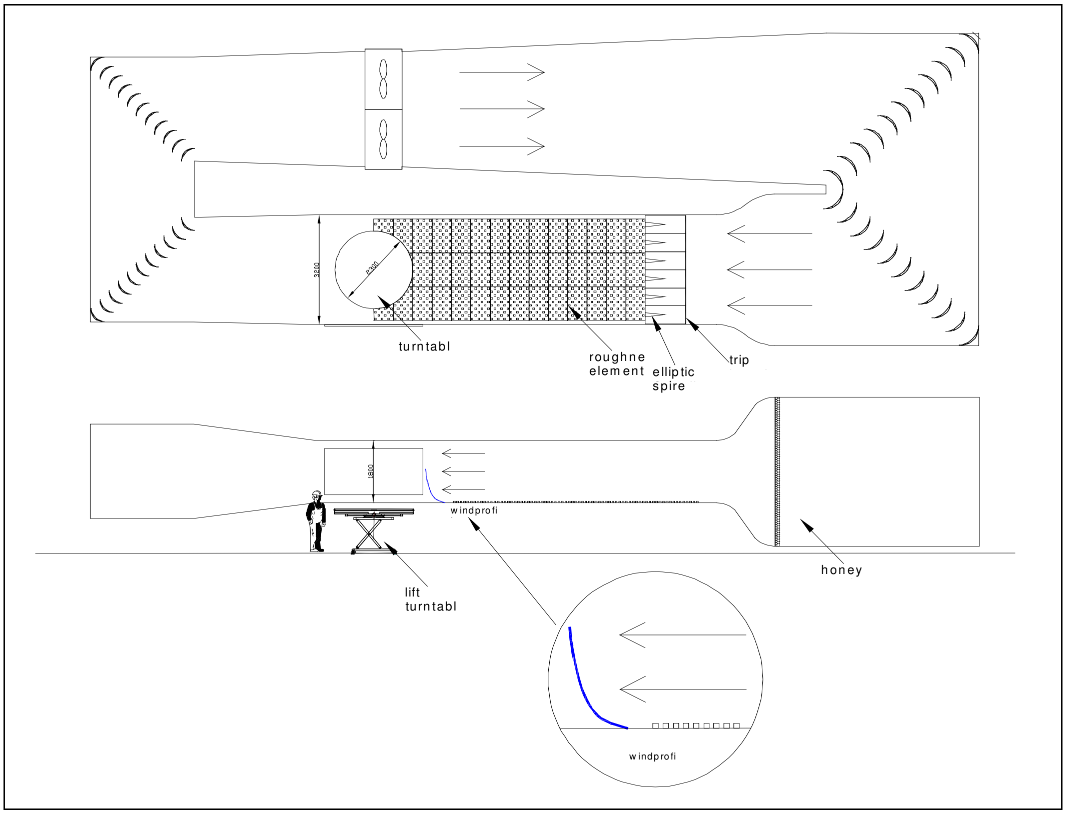

Figure 1: A schematic overview of the present wind tunnel at Peutz.

4. CFD MODELS

In the first stage of developing our CFD application for predicting pedestrian wind comfort a model of a large part of our wind tunnel was constructed so as to be able to validate the computed atmospheric boundary layer and the resulting wind flow distribution around buildings. This first model comprises the entire (former) wind tunnel of 15 m x 3 m x 0.9 m including the development of the boundary layer by the method of Counihan. This method consists of a turbulence generator array as well as roughness elements over a length of 10 m. The roughness elements have been modeled in Phoenics as a bottom plate with a surface roughness of 3 cm applying the so-called ‘roughness wall functions’ for fully rough surfaces. Furthermore inlets have been placed at the ends of the ‘virtual wind tunnel’ with a turbulence intensity of 100 % and a uniform velocity equal to the average tunnel velocity of 8 m/s respectively. The first model uses the standard k-ε model and the hybrid differencing scheme. The total amount of grid cells was approximately 250,000. All models discussed in this article concern steady flow simulations.

The CFD model is capable of predicting the wind around a given geometry for 12 wind directions one after another. The CFD model of the wind tunnel has exactly the same size as the former wind tunnel at Mook so as to facilitate mutual comparison of the results, without need to worry about the effect of scaling and as a result of Reynolds number effects.

Since in the approach described above a large part of the computer capacity is used to compute the flow approaching the geometry of interest, a second model was build. This model contains only the measurement section (with has a diameter of 2.3 m) with velocity and turbulence profiles forced at inlets around this section.

The second model has a wind profile with again an average wind velocity of 8 m/s, but now the velocity has been distributed over the height according to a power law with a coefficient of 0.35. Furthermore the RNG k-ε model and a second order differencing scheme (MINMOD) for the three velocity components have been applied in this model. For both the turbulent kinetic energy and the dissipation a constant value is prescribed at the boundaries. The total amount of grid cells during the first tests of this model was approximately 250,000. Later versions of this latter model used more grid cells (approximately 600,000).

In the most recent versions of the model a number of improvements were applied: By using the so-called "partial solids treatment" present in Phoenics, the geometry under investigation is represented more accurate. With this feature still a Cartesian grid is used, but the cells at the building surface are cut at the surface. The inlet profiles for the velocity are prescribed using the log-law and the models are no longer scaled down to wind tunnel scale. The roughness for each wind direction can be prescribed separately. This is important if the location is situated at the shore or other location with large differences in roughness for the different wind directions. The inlet profiles for the turbulence intensity k and the dissipation ε match with the velocity profile using the equations of the k-ε theory for a stable boundary layer. The equations for the velocity magnitude U, turbulence k and dissipation ε are:

$$U(z) = U_{ref} \frac{\ln\left(\frac{z-d}{z_0}\right)}{\ln\left(\frac{z_{ref}-d}{z_0}\right)} \text{ or } U(z) = \frac{u*}{\kappa} \ln\left(\frac{z-d}{z_0}\right), \tag{1}$$

$$k = \frac{u*^2}{\sqrt{C_\mu}}, \tag{2}$$

and

$$\varepsilon = \frac{u^{*3}}{\kappa(z-d)}. \qquad (3)$$

In these equations U_{ref} is the velocity at a reference height z_{ref}, d the displacement height, z_0 the roughness height, κ the Von Karman constant, u^* the friction velocity and C_μ a model constant of the k-ε model. In the results presented, the displacement length is kept at a constant value of $-z_0$. In this way a conservative estimate for the wind climate is made. To illustrate that the boundary conditions for the turbulence intensity and the velocity profile match with the geometry under investigation, an example of a cross section of the domain showing the distribution of k and the velocity magnitude is shown in figure 2. The flow in the figures is from left to right. The small increase in velocity is caused by the fact that no displacement length was used at the inlet. A small decrease of the turbulence intensity is shown. This indicates that the CFD -model is slightly too dissipative.

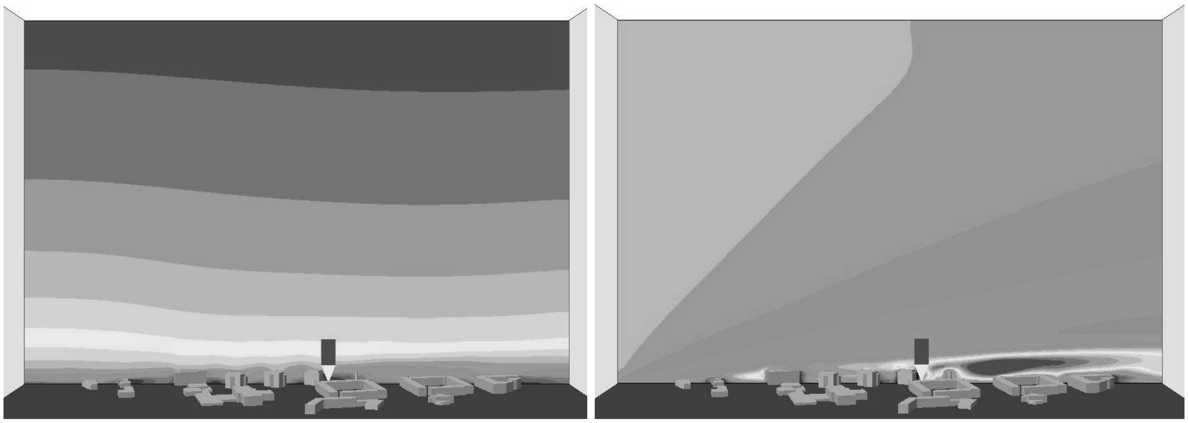

Figure 2: Velocity distribution (left) and turbulence intensity (right) in a cross section of the computational domain.

A constant pressure boundary condition is used for the outlets. With increasing computer power the amount of cells used, is increased to about 2,000,000 or more.

5. RESULTS

The first model with the developing atmospheric boundary layer is very well capable of reproducing the wind tunnel flow at the entrance of the measurement section. This means that at the measurement section the turbulence intensity at a height of 10 m (full scale) adopts the above mentioned value of 35% and that the resulting velocity profile shows to approximate the power law mentioned in the above.

The demand of CPU capacity to create the right velocity profile was relatively large (approximately 250,000 grid cells). This left too little grid cells available for the measurement section itself (approximately 150,000 grid cells). However, for rather simple rectangular building geometry's promising results were produced, even with standard k-ε model and hybrid differencing scheme. For more complex simulations no reliable results were obtained due to the lack of cells in the region of interest, in combination with the first order differencing scheme and the use of the simple turbulence model.

In the second model, with only the measurement section modeled, more grid cells are available in the region of interest. This means that in a typical street between two buildings 7 to 10 grid cells are available in the region of interest. In combination with the use of the RNG k-ε turbulence model, a second order differencing scheme (MINMOD) for the three velocity components and increasing computer power, more complex geometry's could be simulated. An example of a comparison between the results of a wind tunnel experiment and a CFD computation is shown in figure 3. The resolution of the CFD is still rather poor, and due to the Cartesian grid significant differences between the real and modeled geometry are present. The general image of the wind climate however is the same for both methods. However due to the lack of a proper boundary condition for the turbulence properties and the relative low resolution the reliability of the model is not very high.

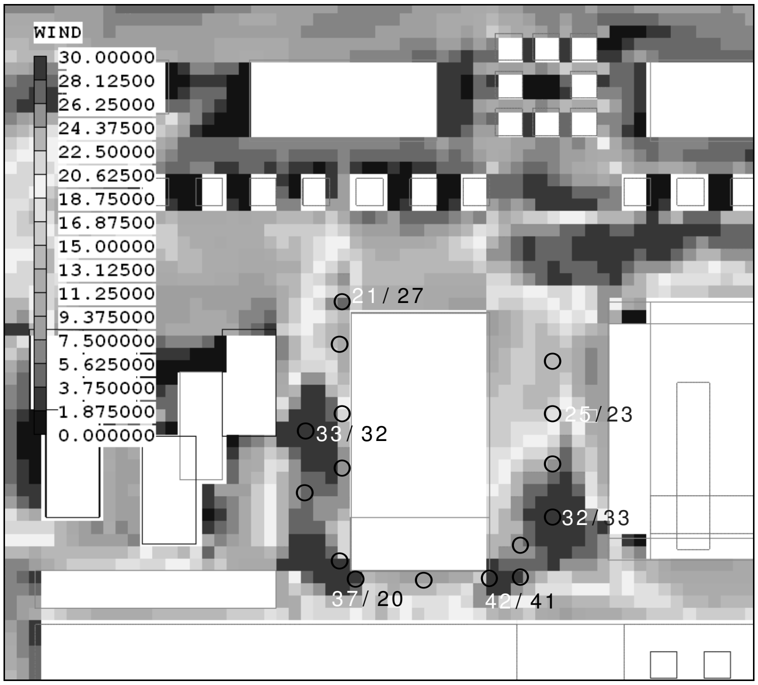

Figure 3: Comparison between the results of wind tunnel data and CFD for the second model in probability of exceedance P(Vloc > 5 m/s). White numbers CFD results, black numbers wind tunnel results.

In the present model a good agreement can be found in the predicted probabilities of exceeding the critical wind speed of 5 m/s, comparing the results of wind tunnel measurements and the results of a CFD computation. Even for a rather complex geometry like a group of high rise buildings a reasonable estimate of the wind climate can be made. A comparison between a wind tunnel measurement and a CFD computation is given in figure 4. The results of the wind tunnel measurements are indicated by the dots, with the probability of exceeding the critical wind speed printed next to it. The scale of the CFD results is limited to 20%. Above 20% the wind climate is qualified as "poor". In this case the maximum percentages in the CFD results are slightly underestimated (38% in the CFD, 44% in the measurements). In the CFD however the area in which a poor wind climate is expected is much easier to determine. An example of a velocity field, together with the grid distribution around the buildings is given in figure 5.

In order to get a better comparison between the results of wind tunnel measurements and CFD computations, the results of three different computations are presented in figure 6. The computed percentage of time an hourly averaged wind speed of 5 m/s is exceeded at a number of points is determined with both methods. The results are plotted against each other. The figure shows that for probabilities up to 40% there is a scatter in the data. On average however, the results are in good agreement. For probabilities above 40% (which occurs rarely in normal projects) the CFD results tend to underestimate the probability of exceeding the threshold value of 5 m/s.

The scatter in the data in figure 6 is quite large. Looking at the results in more detail however, reveals that the largest differences appear in the regions with high gradients in the results. The resulting differences reveal both the strength and the weakness of CFD compared to wind tunnel measurements. Due to errors in the prediction of the recirculation region behind the buildings the shape of the regions with high velocities might be not exactly correct. This is one of the disadvantages of CFD. On the other hand it also indicates the sensitivity of the exact positions of the measurement points in wind tunnel measurements. Small differences in the positions of the probes might lead to large differences in the outcome of the investigation of the wind climate.

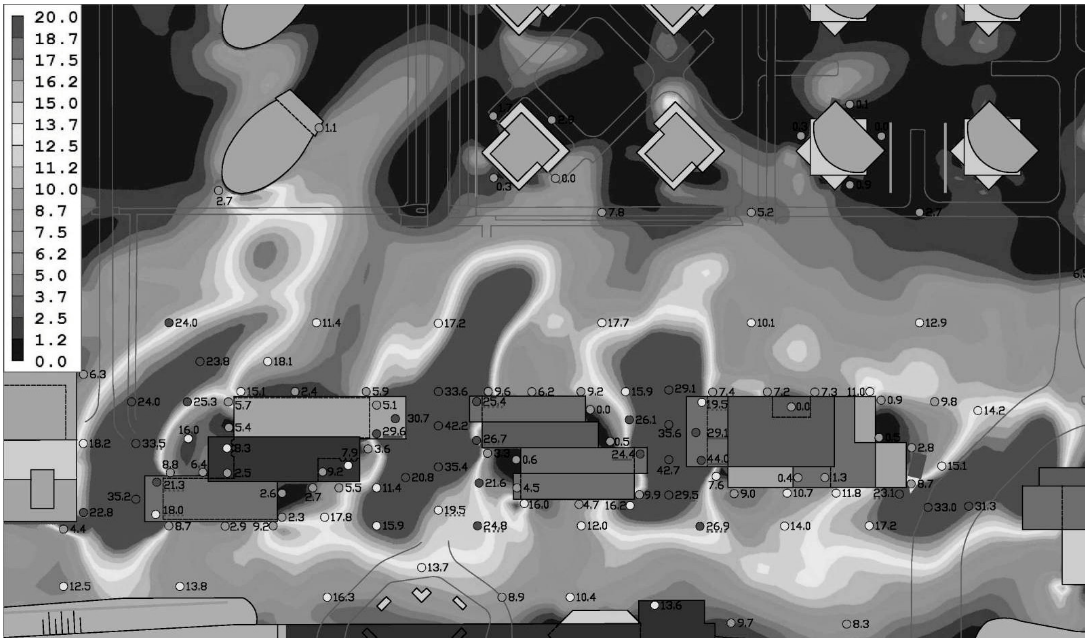

Figure 4. A comparison between a wind tunnel measurement and a CFD computation of the expected exceedance probabilities around a group of buildings. The dots and printed numbers refer to wind tunnel measurements.

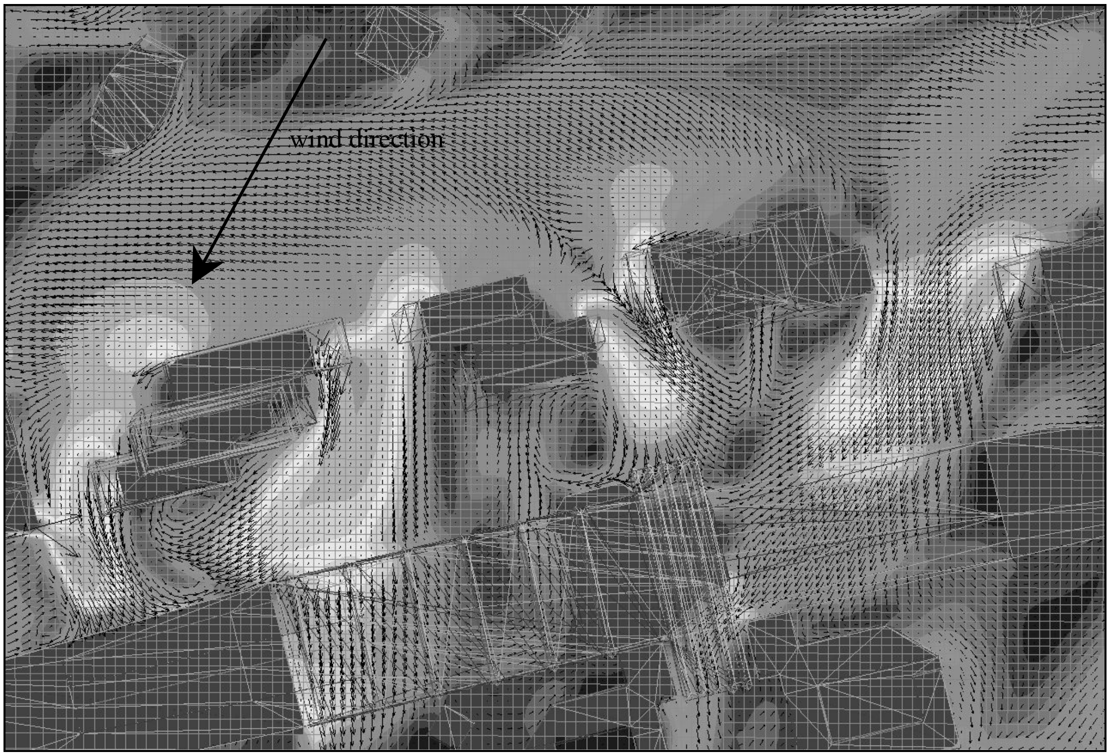

Figure 5: Velocity distribution and grid around a set of high rises. Wind is coming from North-northeast (30 degrees).

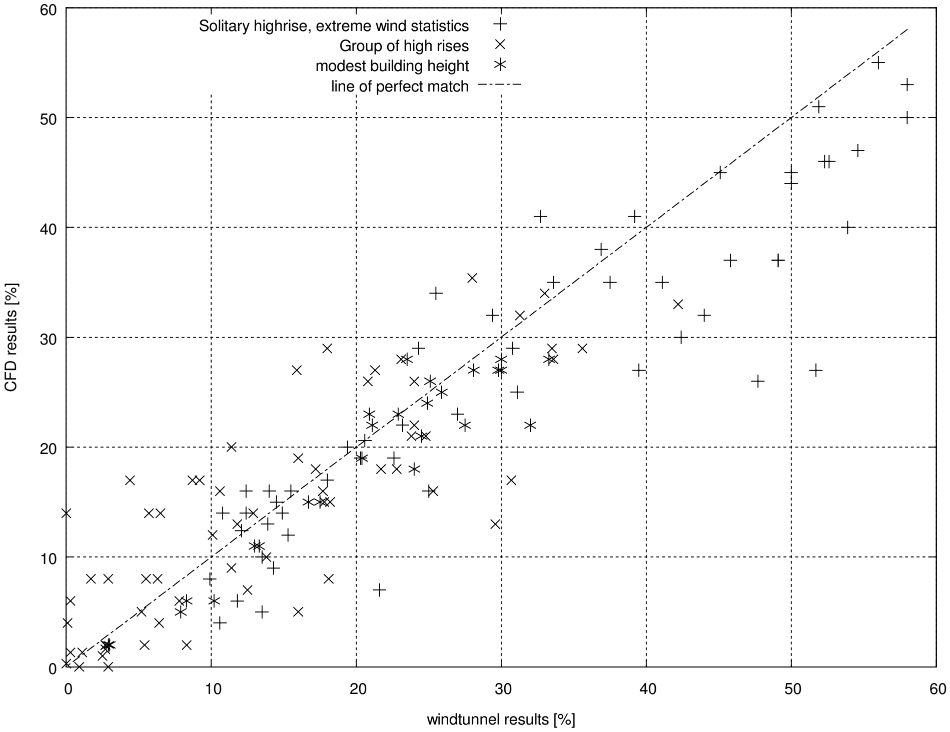

Figure 6: A numerical comparison between reported probabilities of exceedance from wind tunnel measurements and CFD computations for three different situations.

In cases of a complicated geometry in engineering practice a wind tunnel measurement is still preferred. With the present computer power available the CFD model becomes too large and the computations too time consuming to be competitive with the wind tunnel. Especially if the local effects of e.g. screens and canopies have to be determined, more grid cells are needed.

Phoenics offers the possibility of local grid refinement. This feature might be used in the future to determine the effects of local measures.

6. CONCLUSIONS AND FUTURE WORK

From comparing the results of recent CFD models with measurements in the wind tunnel it can be deduced that the numerical approach is promising.

A numerical ‘virtual wind tunnel’ cannot yet replace a real one.

For projects with a rather simple geometry CFD can by used as an alternative for wind tunnel measurements for prediction of pedestrian wind comfort.

In order to get a reasonable performance a very fine grid with typically 7 to 10 grid cells or more per street between buildings should be applied.

Furthermore, the RNG k-ε model should be used in combination with second order numerical differencing schemes (MINMOD) for the velocities and a high number of grid cells (approx. 2,000,000) should be applied.

Further work will involve validation on cases with a more complex geometry. By means of local grid refinement the applicability of CFD on testing the effect of local measures like screens and canopies will be evaluated.

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