Wind and Structures, Vol. 5, No. 2~4 (2002) 177-192
DOI: http://dx.doi.org/10.12989/was.2002.5.2_4.177

A 6 m cube in an atmospheric boundary layer flow Part 2. Computational solutions

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Abstract. Computation solutions for the flow around a cube, which were generated as part of the Computational Wind Engineering 2000 Conference Competition, are compared with full-scale measurements. The three solutions shown all use the RANS approach to predict mean flow fields. The major differences appear to be related to the use of the standard k-ε, the MMK k-ε and the RNG k-ε turbulence models. The inlet conditions chosen by the three modellers illustrate one of the dilemmas faced in computational wind engineering. While all modeller matched the inlet velocity profile to the full-scale profile, only one of the modellers chose to match the full-scale turbulence data. This approach led to a boundary layer that was not in equilibrium. The approach taken by the other modeller was to specify lower inlet turbulent kinetic energy level, which are more consistent with the turbulence models chosen and lead to a homogeneous boundary layer. For the 0^o case, wind normal to one face of the cube, it is shown that the RNG solution is closest to the full-scale data. This result appears to be associated with the RNG solution showing the correct flow separation and reattachment on the roof. The other solutions show either excessive separation (MMK) or no separation at all (K-E). For the 45^o case the three solutions are fairly similar. None of them correctly predicting the high suctions along the windward edges of the roof. In general the velocity components are more accurately predicted than the pressures. However in all cases the turbulence levels are poorly matched, with all of the solutions failing to match the high turbulence levels measured around the edges of separated flows. Although all of the computational solutions have deficiencies, the variability of results is shown to be similar to that which has been obtained with a similar comparative wind tunnel study. This suggests that the computational solutions are only slightly less reliable than the wind tunnel.

Key words: computational wind engineering; cube; turbulence modelling.

1. Introduction

At the initial stage of organising CWE2000 there was discussion on the standing of computational methods applied to problems in wind engineering. To assess progress a test case was proposed with boundary conditions closely defined. Solutions were sought from the computational wind engineering

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community by creating an element of competition and offering anonymity, if requested. It was also our intention to use standard packages and published results to assist in the assessment.

The test case selected was a cube: Silsoe Research Institute had constructed a 6 m cube as part of an experimental programme on ventilation and dispersion which included surface pressure and velocity measurements. The example of the cube is also widely used in wind-tunnel and CFD studies with results available in the literature.

This two-part paper presents the results from full-scale and wind-tunnel measurements in Part 1, followed by the comparisons with computed solutions in Part 2.

This second part attempts to answer two questions: -

What confidence can be placed on computational solutions ?

Is a computational solution as reliable as a wind tunnel ?

2. Background to CFD modelling of flow around a cube

The numerical simulation of airflow around bluff bodies in realistic engineering situations, primarily the atmospheric boundary layer(ABL), commonly called computational wind engineering (CWE) has been developing over the past thirty years. It has been stated by Murakami (1997) that CWE did not really start until the late 1980's and this is certainly when the field began to receive significant attention. Murakami (1997) highlights the particular reasons why CWE is a non-trivial problem for numerical study. To summarise: the flow obstacles always exist in the surface flow field - a region characterised by large gradients in flow parameters and high turbulence; flow obstacles of interest are primarily “bluff bodies” with sharp edges and significant local blockage, which implies complex flow fields with impingement, separation, re-attachment, circulation and both fixed and shedding vortices *etc*.

Most attempts to use computational methods for CWE have started with models of surface mounted cubes, either singularly or as a periodic array (Murakami and Mochida 1988, Baetke and Werner 1990, Paterson and Apelt 1990, He and Song 1992, Delaunay *et al*. 1995), and this test case is also typically used to evaluate the performance of new computational fluid dynamics (CFD) packages or models (Kawamoto and Tanahashi 1994, Mikkelsen and Livesey 1995, Kawamoto 1997, Lee and Bienkiewicz 1997, Tsuchiya *et al.* 1997, Thomas and Williams 1999). Various types of model or approach have been adopted and the reader is directed to the reviews of Leschziner (1995), Murakami (1997) and Stathopoulos (1997) for more details of these. In summary, however, early modelling attempts tended to use the Reynolds averaged Navier-Stokes (RANS) equations with a simple (two equation linear) turbulence model, typically the standard k-ε model of Launder and Spalding (1974). The shortcomings of this widely used and robust model were quickly made apparent, particularly its lack of roof separation zones and the associated over-prediction of suction pressures and turbulence. Artificial “fixing” of parts of the solution can be used to make improvements in the predictions of these parameters using this model. For example Paterson and Apelt (1990) used a “recirculation bubble promoter” to induce separation at the leading edge of the cube by fixing the longitudinal velocity component to zero. Wiik (1999) similarly improves the recirculation zone predictions by manipulation of the oncoming free stream turbulence level and length scale.

In an attempt to improve on this approach various options have been investigated. The simplest of these has been to make *ad-hoc* modifications to the k-ε model either by altering the constituent equations linearly (Yakhot and Orszag 1986, Tsuchiya *et al*. 1997), non-linearly (Speziale 1987, Craft *et al*. 1996) or by adding a further equation (Kawamoto 1996). These have the advantage of minimal increases in model complexity (compared to the alternatives) and therefore computing requirements but mostly at the cost of general applicability. The initially suggested general alternative was second moment closure (also called Reynolds or differential stress modelling) in which the transport equations for the six Reynolds stresses are explicitly solved and modelling is confined to the third order correlations (Kawamoto and Tanahashi 1994, Lien and Leschziner 1996). However, the improvements in fluid physics representation were found to be outweighed in practical flows by the need for complex near wall terms and numerical instability caused by the stiffness of the additional equations.

A separate approach to CWE which has been present since the start is the use of Large Eddy Simulation (LES) in which the Navier-Stokes equations are not Reynolds averaged but spatially filtered. Thus the entire flow physics are resolved down to the scale of the solution domain grid and only the so-called sub-grid scale (SGS) features are modelled (Murakami *et al*. 1987, Lee and Bienkiewicz 1997, Shah and Ferziger 1997, Thomas and Williams 1999). Although there is some debate about the details of this methodology, such as the most appropriate numerical schemes and SGS models, it seems it is capable of giving realistic results where RANS models do not. This, coupled with the additional complete time history of data obtained from such an approach, means that it is worth the high computational cost, although at this time perhaps not for routine engineering calculations.

Although it is often the turbulence closure model that is criticised for poor results, it should be remembered that many other factors, including the numerical scheme, domain size, grid distribution and above all boundary conditions, are critical for realistic results to be obtained. For example Hall (1997) highlighted the potential for individual users of CFD packages to make different choices when simulating the same, closely defined, situations and the widely differing results that could thereby be obtained. In this case the differences in question were mainly to do with the boundary conditions for the ABL being poorly represented, although grid and domain choices were also significant. Many of the studies cited above are not inter-comparable because of the variation in these factors. Easom (2000) has undertaken the most recent and comprehensive comparison of numerical schemes and RANS turbulence models. This work has suggested that non-linear modifications to the k-ε model are probably the most effective and efficient solution for future development, until such time as LES can be routinely applied.

Easom (2000) differs from the other cited works in one other key respect, that of validation against full-scale data. The performance of many of the cited studies has been compared purely with wind-tunnel results, most frequently Castro and Robins (1977), or indeed only with other numerical solutions. As demonstrated in Hoxey *et al*. (2000) the transition from wind tunnel to full-scale, even in this simple case, is not trivial with significant differences apparent in the results. Therefore to place the discrepancies in the results purely with the numerical models is unreasonable, especially if the precise conditions under which the experiments were undertaken have not been simulated.

It was therefore an aspiration of this conference competition to provide a detailed set of full-scale results for a cube structure with well defined boundary conditions which could be used for validation purposes with solutions from a variety of models. This data has been outlined in Hoxey *et al.* (2000) and is available from the authors for future reference.

3. The tasks

The requirements of the competition can be divided into three tasks :

3.1. Task 1: To model the atmospheric boundary layer in the absence of any obstruction

In the introduction to the competition it was stated that "There will also be a prize for the representation of the boundary layer in the solution domain i.e., its closeness of fit to the defined inlet and its stability through the solution domain with no building present". This task was primarily introduced because it had been noted that in some published CFD studies, (see for example the comments in Richards and Younis 1990), the combination of the inlet conditions, the turbulence model and the ground roughness resulted in a boundary layer which changed considerably between the inlet and the object under investigation.

The basic boundary layer parameters for the Silsoe site, which were supplied to the competitors, were as shown in Table 1. The competitors were required to provide typical inlet and outlet profiles of pressure, velocity components and turbulence.

3.2. Task 2: To model the flow around a cube with the wind perpendicular to one face

The requirements of this task were to provide pressures at various points on the cube surface, to determine velocity coefficients at a variety of points in the flow and to specify a number of separation and reattachment points.

The pressures required were :

(1) A streamwise vertical centreline section with 5 points on the windward face, 6 points across the roof and 5 points on the leeward face (16 taps). On each surface the tapping points nearest to an edge were 0.4 m from the edge and the remaining taps were spaced out at approximately 1.04 m intervals. (No taps 0.4 m above the ground)
(2) A transverse vertical centreline section with tappings in similar locations to section 1 (16 taps).
(3) A horizontal mid-height section with spacings similar to section 1, which extended around 2.5 faces (15 taps).
(4) A 4×4 grid of taps located on the roof near one corner (16 taps). The taps were positioned 0.4 m in from each edge and were 0.52 m apart in both directions.

The positions where velocities and turbulence levels were to be computed were:

Table 1 Site wind profile specification

Reference height		6 metres	
Roughness length		0.01 metres	
Displacement height		0 metres	
Turbulence Intensity (Std Dev / local wind speed)			
Height	1 m	6 m	10 m
Iu	26%	21%	19%
Iv	20%	16%	15%
Iw	8%	8%	8%
Reference Mean Wind Velocity			
u	*v*	*w*	
10 m/s	0	0	

(1) 9 m (1.5*h*) upstream, to the side and downstream of the centre of the cube at heights of 1 m, 3 m and 6 m.
(2) 600 mm (0.1*h*) away from the vertical centreline of the windward, side and leeward faces of the cube at heights of 1 m, 3 m and 6 m.
(3) 600 mm (0.1*h*) above the roof at three points. One immediately above the centre (C) and the others 2 m upstream (2 mU) and downstream (2 mD) of the centre.

The required separation/reattachment points were:

(1) The position of the windward ground separation point on the centreline.
(2) The height of the windward face stagnation point.
(3) The position of the roof reattachment on the centreline.
(4) The position of the wake reattachment at the rear of the cube on the centreline.

3.3. Task 3: To model the flow around a cube with the wind at 45^o to the faces

The requirements of this task were basically the same as for Task 2 but with the tapping and near cube velocity measuring points rotated through 45^o. The velocity measuring points that were 9 m from the centre remained upstream, to the side and downstream of the cube centre. In addition the only reattachment length required was the wake reattachment.

4. The computational solution

The response to the competition was in many ways disappointing. It seems that many computational modellers are reluctant to attempt a problem where the answers are not known in advance. In the information pack supplied to contestants, only the vertical centreline pressure profiles at 0^o and 45^o were available. In some cases the full-scale data was still being collected or processed only a week before the CWE 2000 conference and well after the submission deadline. From discussions at the conference it became apparent that a number of people/groups had begun working on this competition but were unable to complete the tasks due to time or other constraints.

Details of the three completed attempts, executed by the authors of this paper, are given in Table 2. All of these use the RANS (Reynolds Averaged Navier-Stokes) approach and are therefore mean flow calculations. While there are a number of differences between the solution methods, as might be expected from three modellers working independently, it is believed that the differences in the solutions are primarily a factor of the turbulence model chosen. The three turbulence models chosen were the standard k-ε (Launder and Spalding 1974), the MMK k-ε (Tsuchiya *et al*. 1997) and the RNG k-ε (Yakhot and Orszag 1986). Easom (2000) also investigated, amongst others, these three turbulence models and noted that when used to model the flow around a cube with the wind normal to one face, the major difference was in the roof separation behaviour. Table 3 shows a comparison of his results alongside those from the competition submissions. In both studies the standard k-ε gives no roof separation, while the MMK k-ε model gives no reattachment or marginal reattachment. The only one of the three models that gives a flow reattachment similar to the full-scale observations, is the RNG k-ε model. In addition it may be observed that in both studies the MMK k-ε model gives a very long wake. Although Easom (2000) provides a useful comparison of a number of turbulence models, it should be noted that he only had limited full-scale data for a cube, the centreline pressures mentioned earlier and some preliminary flow reattachment observations made at Silsoe, to

Table 2 Modelling details

Model Indentifier	K-E	MMK	RNG
Code	PHOENICS v3.2	CFDS CFX v4.3	Fluent v5
User experience	>5 years	>5 years	<1 year
Turbulence Model	k-ε (Launder and Spalding 1974)	MMK k-ε (Tsuchiya *et al*. 1997)	RNG k-ε with non-equilibrium wall functions (S-E Kim & D. Choudhury 1995)
Domain Size			
-x (m) +x (m) -y (m) +y (m) +z (m)	48 48 48 48 48	60 90 30 30 60	40 200 105 105 100
Mesh Type	Structured (cubic) mesh	Structured (cubic) mesh	Unstructured for region immediately surrounding cube and other structures, structured elsewere
Number of Cells			
x (streamwise) y (lateral) z (vertical)	97 97 65	55 50 37	72 62 21
Total	611585	93700	127783
Grid layout	Fine cells near cube walls, (finest 1/69 H) G.P. of 1.41 in outer region.	G.P. factors of 1.1 to 1.41 away from cube surface	Unstructured grid around cube to x=-15 m, +40 m, y=-15 m, +15, z=+25 m. Smallest cells 0.5 m horiz., 0.38 m vert. Outer region structured with 1.21 G.P. spacing in all directions.
Convective differencing scheme	Hydrid differencing (first/second order)	Curvature Compensated Convective Transport (CCCT) (third order) (Gaskell and Lau 1988)	Higher-order Upwind differencing (second order) (Thompson and Wilkes 1982)
Computer	Dell Latitude Pentium II PC 128MB RAM.	Dec Alpha	2 shared Digital Alpha Servers comprising either 2 EV6 550 MHz CPUs or 4 EV5 300 MHz CPUs, 1GB RAM each. Typically shared between 10-20 users at any time.
Number of Processors	1	1	2/4
Run Time	12 hours	8 hours	24-36 hours
Other relevant information	User Fortran coding of rough wall functions and log-law inlet velocity profile	User Fortran coding of (a) MMK model (b) Rough ground surface r=0.01 m (c) Inlet log-law profile. Symmetry was used to simplify the simulation of the 0^o case	A coupled, implicit solver was used.

compare his results with. In contrast the data collected for this competition is a far more extensive and detailed set of results.

Since it is believed that many of the differences between the solutions may be attributed to the turbulence model chosen, the identifiers K-E, MMK and RNG will be used in the remainder of this paper.

Table 3 Roof and wake reattachment positions for wind direction 0°

Model	Roof reattachment (from cube centre)		Wake reattachment (from cube centre)	
	Easom (2000)	CWE 2000 Comp.	Easom (2000)	CWE 2000 Comp.
Standard k-ε	No separation	No separation	$x/h = 2.6$	$x/h = 2.3$
MMK k-ε	No reattachment	Marginal reattachment at $x/h = 0.36$	$x/h = 3.62$	$x/h = 3.7$
RNG k-ε	$x/h = 0.34$	$x/h = -0.01$	$x/h = 3.0$	$x/h = 2.32$
Full-scale	$0.0 < x/h < 0.1$	$x/h = 0.1$	$1.7 < x/h < 1.9$	$x/h = 2.0$

5. Results and discussion

5.1. Results from Task 1 - Boundary layer modelling

Fig. 1 shows the inlet and outlet velocity and turbulent kinetic energy profiles for the three solutions. It can be seen that in all cases the inlet velocity profile was set to match a logarithmic profile with a roughness length of 10 mm (shown as the full-scale profile). With both the K-E and MMK solutions the outlet profile is very similar to the inlet profile but in the RNG solution the outlet profile is slightly fuller. The reason for this can be more clearly identified in Fig. 1b where it is clear that the RNG solution turbulent kinetic energy (TKE) profile has change more significantly. This illustrates one dilemma that faces the CWE modeller. It appears that the RNG modeller has set the inlet TKE profile so that it approximately matches the measured full-scale turbulence levels. Unfortunately this has led to a situation where the turbulence model, the inlet TKE profile and the ground roughness treatment do not create a homogenous boundary layer. This problem has been discussed by Richards and Hoxey (1993) who showed that with the k-ε turbulence model, and the standard model constants ($C_\mu = 0.09$), a homogenous logarithmic velocity profile is consistent with

$$k = \frac{u_*^2}{\sqrt{C_\mu}} = 3.33u_*^2 = \frac{3.33^*(0.4U_{ref})^2}{\left(\ln\left(\frac{z_{ref}}{z_0}\right)\right)^2} = 0.013U_{ref}^2 \tag{1}$$

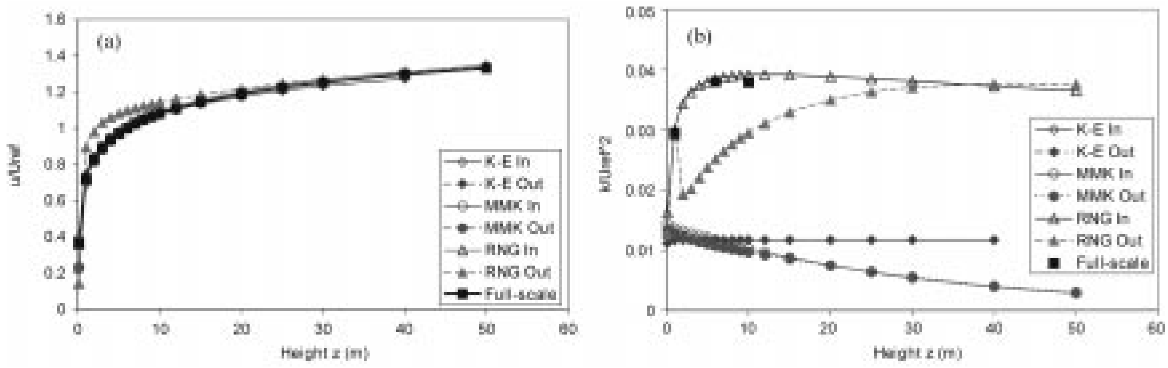

Fig. 1 Inlet and outlet profiles: (a) Streamwise velocity and (b) Turbulent kinetic energy

Values similar to this have been used with the K-E and MMK solutions and as a result more homogenous boundary layers are obtained. The problem with using the full-scale TKE levels is thought to come from the significant contributions from low frequency turbulence. The amount of this low frequency turbulence is much higher in the natural wind than in many of the flows used to develop and tune turbulence models. It is therefore appropriate, when modelling the mean flow field, to explicitly model only the high frequency turbulence and to effectively filter out the low frequency turbulence which only has a quasi-steady effect.

In addition it may be observed in Fig. 1b that there appears to be a discontinuity in the RNG solution's TKE profile near the ground. This also suggests an imbalance between the turbulence model and the wall treatment. In this regard it may be significant to note that both the K-E and MMK solutions make use of user defined Fortran to handle the rough ground surface.

5.2. Results from Task 2 - The 0^o case

Fig. 2 illustrates the pressures predicted for the 0^o case. It can be seen from both Figs. 2a and 2c that in general the windward wall pressures are well matched to the full-scale measurements. There is an indication of a slight over-prediction with the RNG solution, which may be related to the approaching boundary layer developing to a fuller velocity profile. The major differences occur in the separated flow region over the roof and along the sidewall. The K-E solution, which tends not to separate, gives a very high suction near the windward edge and then drops off too quickly. In

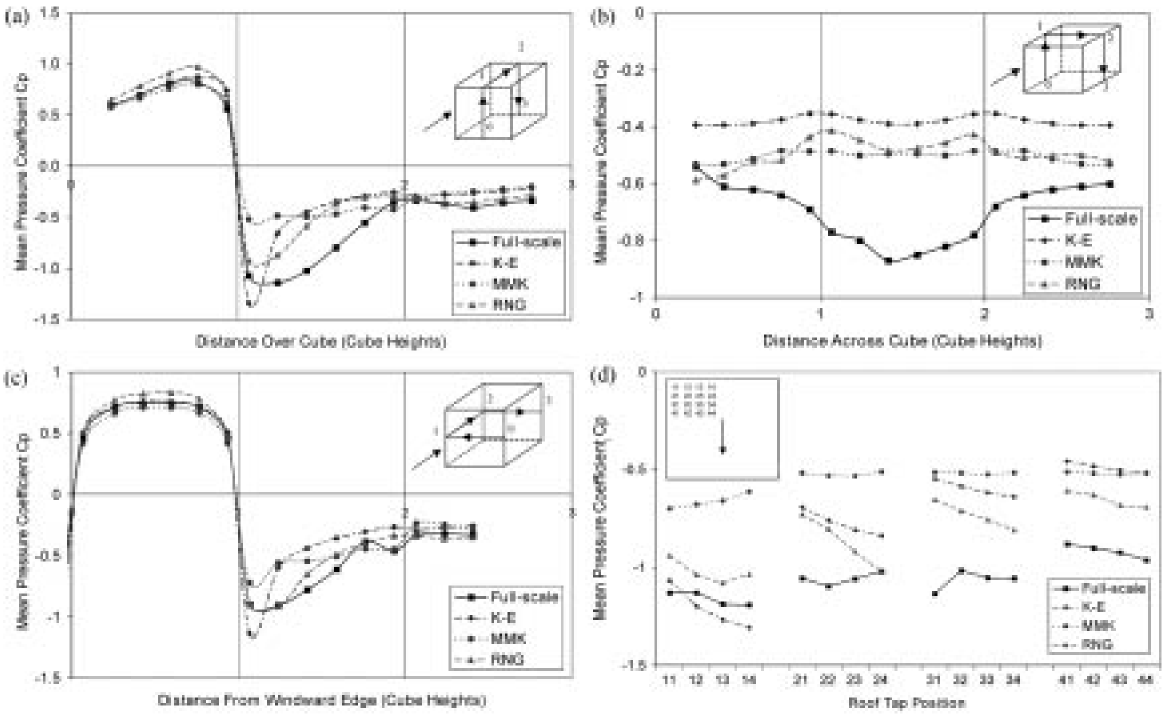

Fig. 2 Pressure coefficients for a cube with the wind normal to one face, 0^o: (a) streamwise vertical centreline section, (b) transverse centreline section, (c) mid-height section and (d) corner roof taps

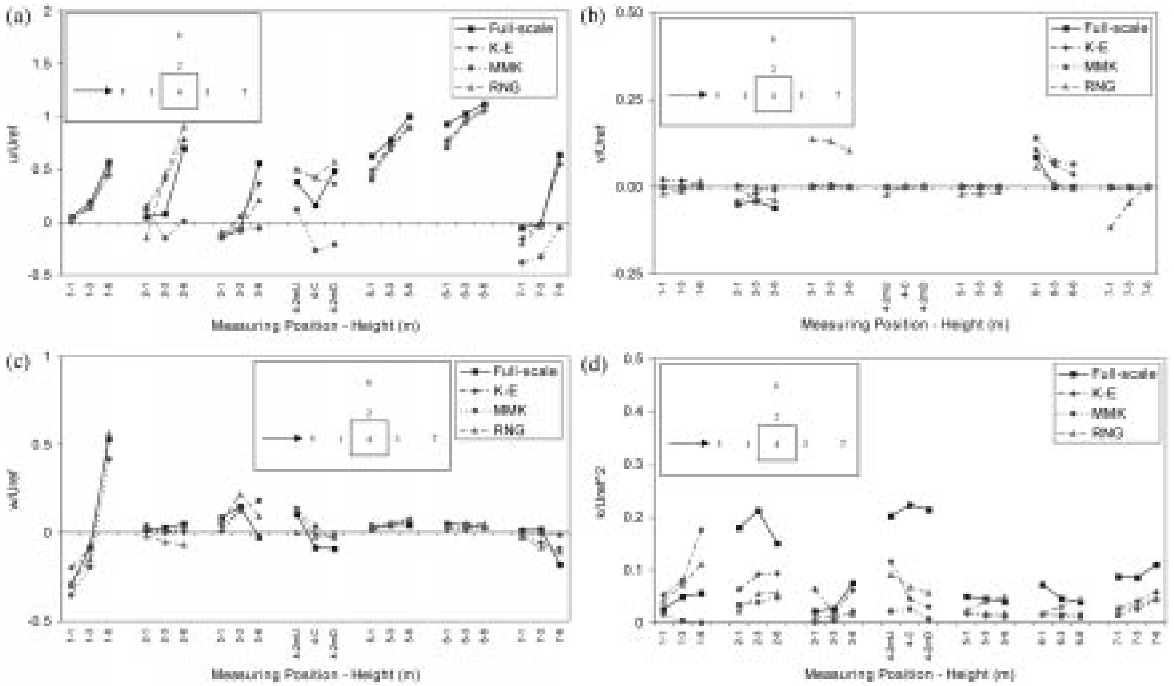

Fig. 3 Velocity coefficients around the cube with the wind normal to one face, 0^o: (a) streamwise u / U_{ref}, (b) transverse v/U_{ref}, (c) vertical w/U_{ref} components and (d) turbulent kinetic energy k/U_{ref}^2

contrast the MMK model, which separates too vigorously, generally under-predicts the suctions. Even the RNG solution, which most closely matches the shape of the full-scale results, under-predicts the highest suction and drops off too rapidly across the roof. In all cases the largest differences occur in the middle of the roof, which shows up very clearly in the transverse section data of Fig. 2b. This can also be seen with the roof corner taps in Fig. 2d. Here the K-E and RNG solutions are close to the full-scale data for the row of taps near the windward eaves (positions 11-14), but the differences are significant in rows 3 (31-34) and 4 (41-44), particularly for the K-E solution. All the solutions and the full-scale data show a weak suction on the leeward surface.

While there are significant difference in the pressure distributions there appears to be better agreement between the full-scale and CFD solutions for the velocities. In Fig. 3a there is general agreement between full-scale measurements and the K-E and RNG solutions for the u velocity components. All measuring positions show increasing velocity with height and reversed velocities (< 0) at the 1 m and 3 m heights in the two downstream positions (positions 3 and 7). This shows that the wake extends at least 1.5h downstream of the cube centre. The major differences in Fig. 3a occur with the MMK solution. This shows negative velocities at the 3m height along the side (position 2), at the 6 m height at the two downstream positions (3 and 7) and above the roof, both at the centre and 2m downstream. All of these are consistent with separation regions that are more extensive than the full-scale situation or the other solutions.

The transverse velocities shown in Fig. 3b can in general be expected to be near zero, with the exception of positions 2 and 6. For these two positions there is general agreement, with a small velocity component towards the building at position 2 and a component away from the building at position 6, which is strongest at the lowest height. In addition with the RNG model there are opposing transverse components at the two downstream locations. This asymmetry in the wake flow may have been caused by explicit modelling of adjacent buildings. The RNG solution was the only one to explicitly model these buildings. The K-E solution was a full 3D solution but the other buildings were considered to be sufficiently distant to be ignored and the MMK solution used a centreline symmetry plane to reduce computational costs and hence forced the centreline velocities to zero.

Once again there appears to be good agreement with the vertical velocities in Fig. 3c. In all cases there is a high vertical component near the windward eaves (position 1, height 6) and a moderate vertical velocity immediately behind the cube (position 3, height 3). On closer inspection it may be observed that the roof velocities (position 4) reveal the differences in roof separation behaviour. With both the RNG solution and the full-scale measurements there is an upwards component at the upstream location (4-2 mU), which is only 1 m downstream of the windward eaves, and downward components at the centre (4-C) and downstream (4-2 mD) positions. In contrast the K-E solution shows almost no vertical component at any of these positions, which is consistent with no flow separation. The MMK solution on the other hand shows upward components at both the upstream and centre locations, indicating a large separation region above the roof.

Although there is generally reasonable agreement with the velocity components this cannot be said for the turbulence levels shown in Fig. 3c. Many years ago it was recognised (see for example Murakami and Mochida 1988) that the standard k-ε tended to over-predict the generation of turbulent kinetic energy around the windward eaves of the cube and this is still the case in these results (position 1, height 6). As a consequence, Tsuchiya *et al.* (1997) developed the MMK k-ε model as a method of redressing this problem by modifying the k-ε model in regions of high vorticity. However it appears from Fig. 3d that the implementation used in the MMK solution is too effective and reduces the windward eaves turbulence well below the measured value. Although the k-ε model may over-predict the turbulence levels near the windward eaves, it appears from these

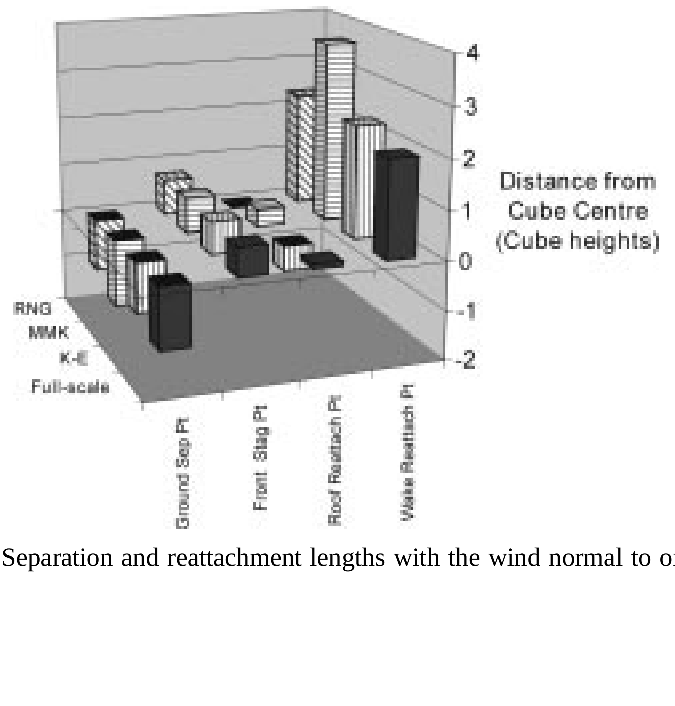

Fig. 4 Separation and reattachment lengths with the wind normal to one face

result that the more obvious discrepancy is the failure of all of the solutions to match the very high turbulence levels along the side of the cube (position 2), across the roof (position 4) and to a lesser extent in the wake (position 7). Observation of the flow in these regions suggests that these high turbulence levels are associated with the highly fluctuating separation zones.

Fig. 4 shows a comparison of the flow separation/reattachment lengths. There is general agreement on the position of the windward ground separation point and the height of the stagnation point. The comparison of the roof reattachment points is a little kind on the K-E solution since the length shown is -0.5h, which is the windward edge (that is: no separation). It is also kind to the MMK solution, where the centreline velocities near the roof were in the streamwise direction beyond x/h = 0.36, although negative velocities existed in the flow above these at higher heights. It is therefore debatable whether the flow had really reattached. Certainly the wake length behind the cube is excessive with the MMK solution.

5.3 Results from Task 3 - The 45^o case

Fig. 5 shows the pressure coefficients for the 45^o case. In general the CFD solutions are much closer to the full-scale measurements, however, as seen from Figs. 5a and 5c, the high suctions which occur along the windward edges of the cube are generally under-predicted. With this orientation there is little difference between the three solutions. All of them show some degree of asymmetry in Fig. 5a and show higher positive pressures, than measured in full-scale near the windward edge, in

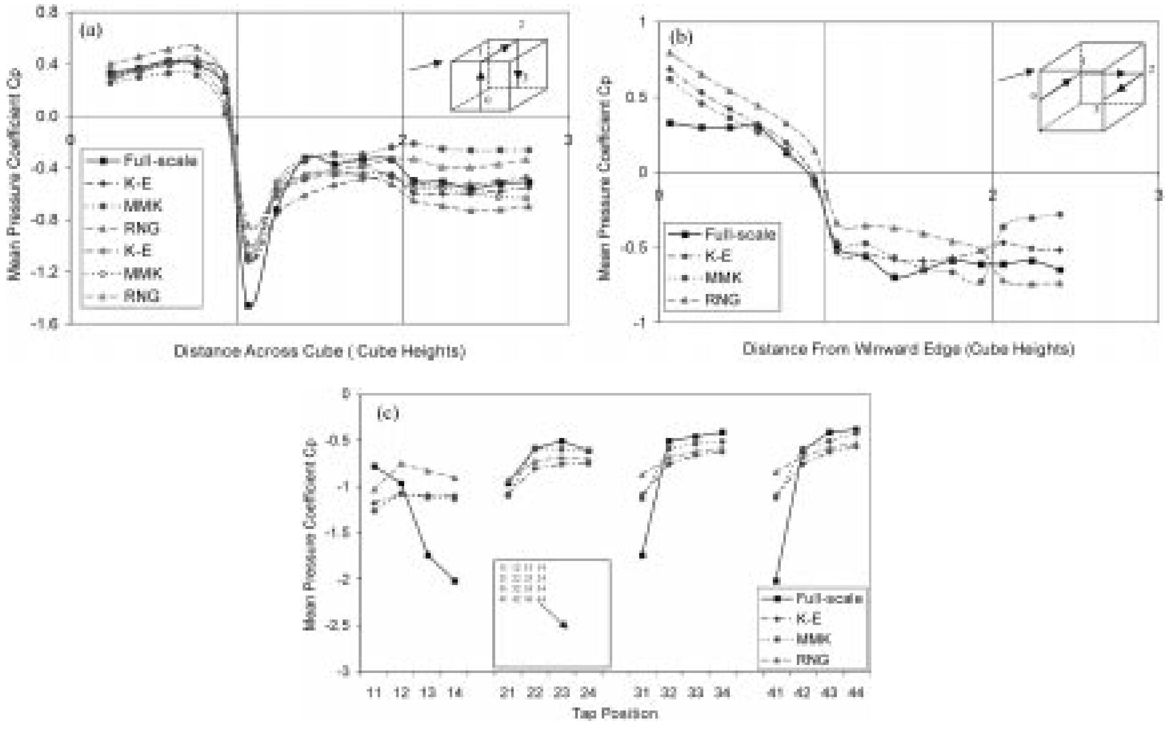

Fig. 5 Pressure coefficients for a cube with the wind at 45^o to the faces: (a) vertical centreline sections in both directions, (b) mid-height section and (c) corner roof taps

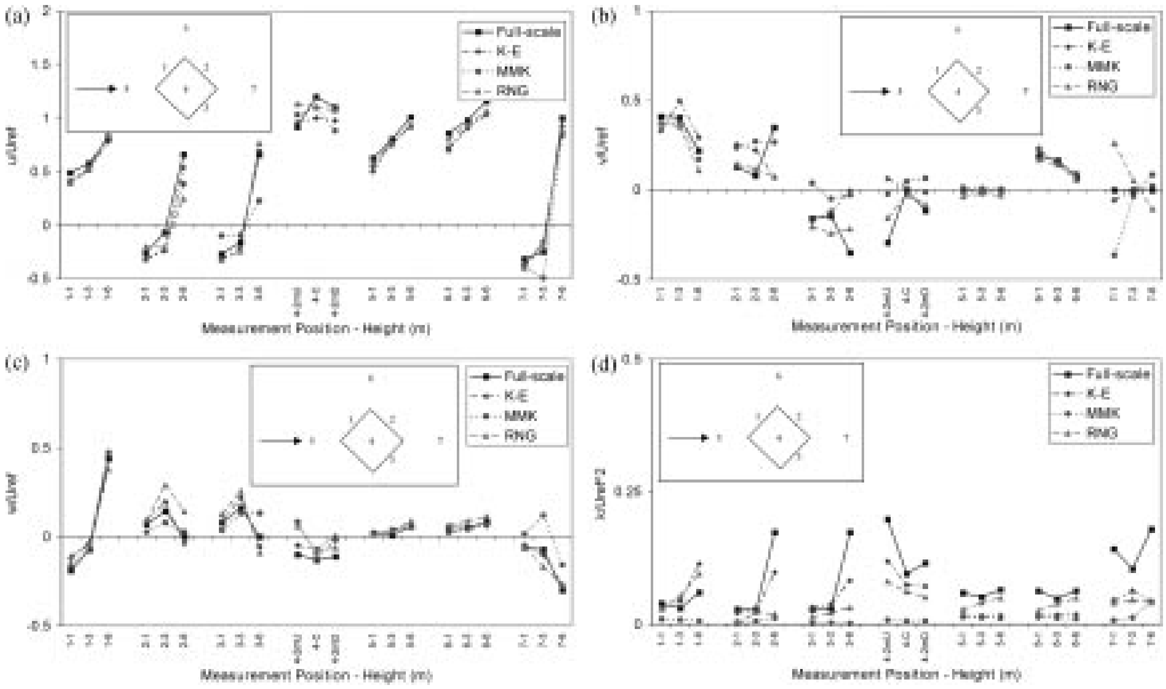

Fig. 6 Velocity coefficients around a cube with the wind at 45^o to the faces: (a) streamwise u/U_{ref}, (b) transverse v/U_{ref}, (c) vertical w/U_{ref} components and (d) turbulent kinetic energy k/U_{ref}^2

Fig. 5b. Once again the RNG solution tends to give slightly higher positive pressures than the other solutions.

In general there is good agreement between the solution and the full-scale measurements of velocities (Figs. 5a-c). The one exception to this is with the transverse velocities in Fig. 5b where the solutions show varying degrees of asymmetry in the wake (positions 2,3 and 7). Once again the solutions tended to under-predict the high levels of turbulence measured, these were at 6m in the lee of the cube (positions 2 and 3), across the roof (position 4) and at all heights 1.5h downstream (position 7). It may be noted that the K-E solution came closest to matching these turbulence levels.

Fig. 6 shows the wake reattachment lengths, where the K-E and RNG solutions give lengths that are very similar to the measured length. The MMK solution is again the longest, but, in contrast to the other results, the predicted length is shorter than for the 0^o case. This may be associated with the flow being attached at the leeward edge of the roof in all solutions.

6. Overall assessment

In order to make an overall assessment of the solutions, Table 4 gives the average magnitude of the differences between the computational solution values and those from the full-scale measurement. With both the pressures and the velocities, typical values are of order one, and so it appears that the prediction of velocities (typical error in $u \approx 0.1$) is in general more accurate than pressures (typical error ≈ 0.2). This is not surprising, since the quadratic relationship between pressures and velocities means that any error in velocity will lead to twice that error in pressure. The situation is somewhat

Table 4 Average magnitude of coefficient differences

Pressure coefficient Differences - 0 degrees						
	K-E	MMK	RNG	WT 5	WT 10	WT Mean
Vert Sect	0.18	0.19	0.14	0.12	0.25	0.15
Trans sect	0.32	0.19	0.21	0.07	0.37	0.18
Horiz Ring	0.11	0.09	0.05	0.07	0.18	0.11
Corner	0.31	0.49	0.23			
Pressure Coefficient Differences - 45 degrees						
Vert Sect 1	0.09	0.16	0.15			
Vert Sect 2	0.09	0.09	0.12			
Horiz Ring	0.10	0.13	0.21			
Corner	0.35	0.27	0.37			
Velocity Coefficeint Differences 0 degrees						
u/U_{ref}	0.11	0.25	0.13			
v/U_{ref}	0.02	0.01	0.04			
w/U_{ref}	0.04	0.05	0.05			
k/U_{ref}^2	0.06	0.08	0.06			
Velocity Coefficient Differences - 45 degrees						
u/U_{ref}	0.08	0.13	0.10			
v/U_{ref}	0.09	0.11	0.07			
w/U_{ref}	0.04	0.06	0.06			
k/U_{ref}^2	0.04	0.07	0.05			
Separation/Reattachment Length Differences (Cube Height)						
Ground Separation Point	0.23	0.13	0.18			
Front Stagnation Point	0.07	0.15	0.15			
Roof Reattachment Point	0.57	0.28	0.08			
Wake Reattachment Point	0.40	1.77	0.43			
45 deg Wake Reattachment Point	0.10	0.31	0.07			

different with the prediction of turbulent kinetic energy levels, since typical magnitudes of k/U_{ref}^2 are only of the order of 0.1 and so the typical error, which is about 0.05, is half of the typical value.

Although the average pressure difference is often less than 0.2, it is the failure of all the solutions to predict the high suctions in the centre of the roof for the 0^o case, and along the windward edges for the 45^o case, which are of particular concern from a design point of view. From an overall assessment of pressure predictions it appears that the RNG solution is most accurate with the 0^o case, but there is little to choose between them in the 45^o case. The better performance of the RNG solution in the 0^o case is obviously linked to the more realistic modelling of flow reattachment, both on the roof and in the wake.

In the introduction it was stated that this paper would attempt to answer two questions : -

What confidence can be placed on computational solutions ?

Is a computational solution as reliable as a wind tunnel ?

The first part of which has been answered in the detailed comparisons of section 5. However, in order to answer the second part it is necessary to have some assessment of the reliability of wind tunnel data. Fortunately the comparative wind tunnel study reported by Hölscher and Niemann (1998) used a test case very similar to the present competition. In their study 12 laboratories conducted 15 wind tunnel studies of a 50 m cube in a suburban boundary layer. Since the cube

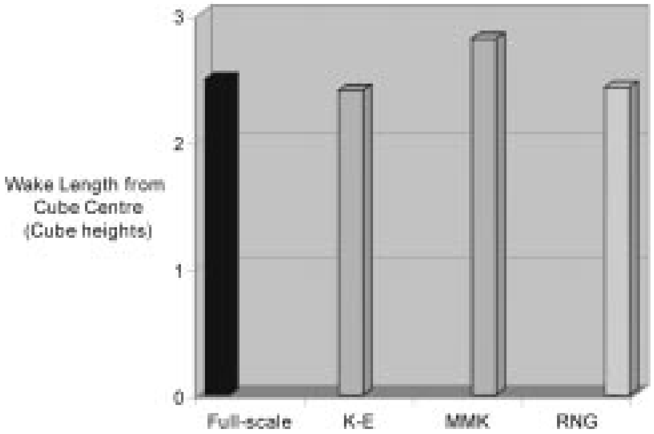

Fig. 7 Wake reattachment length with the wind at 45° to the cube faces

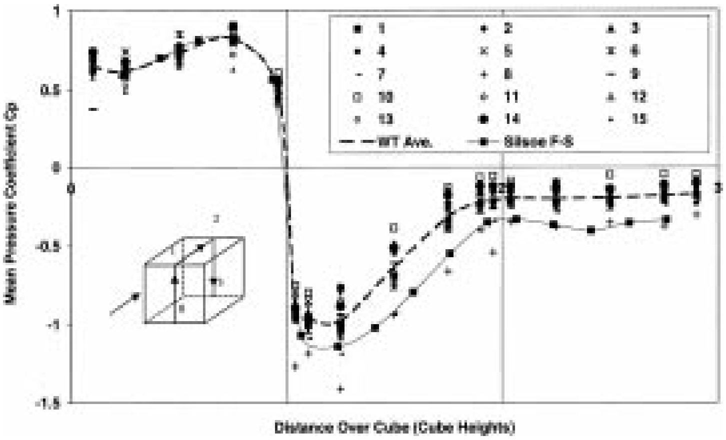

Fig. 8 Streamwise vertical centreline section pressure coefficients from the Wintechnologische Gesellschaft comparative testing program (Hölscher and Niemann 1998) and the Silsoe full-scale test. Wind normal to one face, 0°

height and the roughness length are both larger than the Silsoe situation, both the Jensen number (h/z_0) and the turbulence intensity at cube height are of the same order. In addition the authors have kindly made available more details of the individual tests than are available in the published paper. Fig. 8 shows the vertical centreline section data from the 15 individual wind tunnel tests along with the average of the 15 tests and the Silsoe full-scale data. It may be noted that there is generally good agreement on the windward wall, but as with the computational modelling there is considerable spread in the roof pressures. In general the shape of the distribution is similar to the full-scale measurements but the majority of the tests tend to under-predict the roof pressures.

Further the data available has made it possible to estimate the magnitude differences between wind tunnel and full-scale for three of the sets of pressures obtained for the 0° case. These results are shown in the last three columns of Table 4. The three columns are for wind tunnel test 5, which overall seemed to be closest to the full-scale data, wind tunnel test 10, which had the greatest differences, and the average of the 15 sets of differences. Comparing these differences with the computational solutions shows that the K-E solution differences are of the same order as the worst of the wind tunnels, while the MMK and RNG solutions have differences of the same order as the average of the 15 wind tunnel tests. Hence it would appear that the computational solutions are slightly less reliable than a wind tunnel, but both methods can give quite a broad range of answers.

7. Conclusions

Computation solutions for the flow around a cube, which were generated as part of the Computational Wind Engineering 2000 Conference Competition, have been compared with full-scale measurements. The three solutions shown all used the RANS approach to predict mean flow fields. The major differences appeared to be related to the use of the standard k-ε, the MMK k-ε and the RNG k-ε turbulence models.

The inlet conditions chosen by the three modellers illustrated one of the dilemmas faced in computational wind engineering. While all modeller matched the inlet velocity profile to the full-scale profile, only one of the modellers chose to match the full-scale turbulence data. This approach led to a boundary layer that was not in equilibrium. The approach taken by the other modeller was to specify lower inlet turbulent kinetic energy levels, which are more consistent with the turbulence models chosen and lead to a homogeneous boundary layer.

For the 0^o case, wind normal to one face of the cube, it was found that the RNG solution was closest to the full-scale data. This result appears to be associated with the RNG solution showing the correct flow separation and reattachment on the roof. The K-E solution showed no separation on the roof, while the MMK solution showed excessive separation.

For the 45^o case the three solutions were fairly similar. None of them correctly predicted the high suctions along the windward edges of the roof.

In general the velocity components were more accurately predicted than the pressures. However in all case the turbulence levels were poorly matched, with all of the solutions failing to match the high turbulence levels measured around the edges of separated flows.

Although all of the solutions have deficiencies, comparison with a similar wind tunnel study has shown that the computational solutions are only slightly less reliable than the wind tunnel.

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