Study on the numerical predictive accuracy of wind pressure distribution and air flow characteristics. Part 1: Optimization of turbulence models for practical use

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ABSTRACT

To evaluate wind pressure distribution on a building by using CFD (computational fluid dynamics), it has been generally practiced to use k-ε models. However, it is known that the use of the standard k-ε model has disadvantages such as overestimation of wind pressure coefficient and turbulent kinetic energy on the windward surface where wind impinges on the building. To overcome these problems, various modifications of the k-ε model have been proposed. In the present study, a number of modified k-ε models and RSM (Reynolds Stress equation Model) were applied for the estimation of wind pressure distribution on the building, which was designed in parallelepiped shape, and the characteristics in each of these models were confirmed. The results of the present study suggest that the modified k-ε model incorporating Durbin's limiter (model parameter α=0.5) showed satisfactory results for the estimation of wind pressure. In the overall evaluation, the modified k-ε model incorporating Durbin's limiter (α=0.65) and the modified k-ε model incorporating renormalization group theory (RNG) provided good results.

1. INTRODUCTION

For the estimation of wind load on a building or for the prediction of ventilation flow rate, it is essential to have the data of wind pressure distribution with high accuracy. At present, these data can be acquired by wind tunnel experiment or CFD. In wind tunnel experiment, it would be difficult to make evaluation on various shapes and to perform various case studies because of the problems in labor and cost. In this respect, the method by using CFD is applied. In particular, it appears to be practical to use k-ε model, which is inexpensive in cost and is used widely. However, it is known that the standard k-ε model commonly used has disadvantages such as overestimation of wind pressure coefficient and turbulent kinetic energy on the windward surface where the wind impinges on the building. In contrast to this, LK model (Launder and Kato, 1993) and MMK model (Murakami et al., 1996) have been proposed, but each of these models has merits and demerits and cannot be considered as optimal model for practical application. In this respect, in the present study, various modified types of k-ε models (such as RNG, incorporation of Durbin's limiter), k-ω model, Reynolds stress equation model, etc. showing satisfactory results were used, and the study was performed on the accuracy to predict wind pressure distribution on building for the purpose of proposing an optimal model suitable for practical application. In Part 1, we will study on a building of rectangular parallelepiped shape, and the characteristics of each method were confirmed. In Part 2, we study the cases where this is applied to housing models of complicated shape.

2. VARIOUS TURBULENCE MODELS AND ANALYTICAL METHODS

The turbulence models evaluated in the present study and analytical methods used are summa-

Table 1: Analytical methods.

k-ε										k-ω	
No modification	Modification of Reynolds stress term	Modification of ε equation				Modification of turbulent viscosity				SST	RSM
Standard	Quadratic	RNG	Suga		Chen	Durbin					
			Quadratic	Cubic		0.5	0.65	0.8	1.0		

rized in Table 1. Quadratic model is a model of secondary nonlinear approximation of Reynolds stress term. Similarly, cubic model is applied to a tertiary nonlinear approximation model. It is reported that these show improvement for a backward facing step flows and for a flow in the region far downstream reattachment point where the flow tends to be of simple parabolic nature (Shih et al., 1993). In Chen model, production-range time scale is introduced to ε equation for suppressing overproduction of turbulent kinetic energy. This reveals that, if production term of the turbulent kinetic energy increases, the production term of ε also increases, and this provides the effect to suppress overproduction of turbulent kinetic energy (Chen and Kim, 1987). RNG model adds the term of *R* newly to ε equation by introducing the renormalization group manipulation to N-S equation of variation value of wind velocity and by averaging the result. It is reported that excellent results are obtained for homogeneous shear flow and flow over a backward facing step (Yakhot, 1992). Durbin model gives restriction on the upper limit of turbulent time scale by using α, which is called Durbin’s limiter, as restriction to satisfy the realizability that each normal component of Reynolds stress terms is non-negative. It is reported that Durbin’s limiter has an effect to predict accurate wind pressure distribution and to suppress overproduction of turbulent kinetic energy (Durbin, 1996; Kurabuchi et al., 2004). In the standard k-ω model, (k/ω) is used to calculate turbulent viscosity coefficient (ν_t). SST (Shear Stress Transport) means the deformation of turbulent viscosity coefficient so that transport effect of the principal turbulent shear stress is taken into account. It is known that k-ω SST model improves reproduction accuracy in the adverse pressure gradient boundary layer flows (Menter, 1992). RSM does not mean modeling of Reynolds stress term but it is to close the equation by introducing a new transport equation.

These models were handled on standard STAR-CD platform and with user subprograms.

3. EVALUATION METHOD

The study was performed on the building of 2:2:1 as shown in Figure 1. Calculation was made on the condition where boundary layer flow is turned to approaching flow with $1/4^{th}$ power distribution. Wind direction was set to 0 degree. Total number of meshes was set to 340,000 meshes. Evaluation was made on the maximum value and distribution configuration of wind pressure and of turbulent kinetic energy, and air flow around the building (reattachment point).

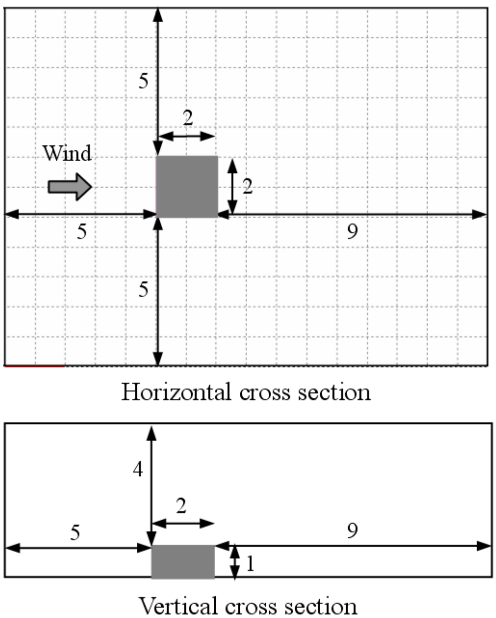

Figure 1: Calculation domain.

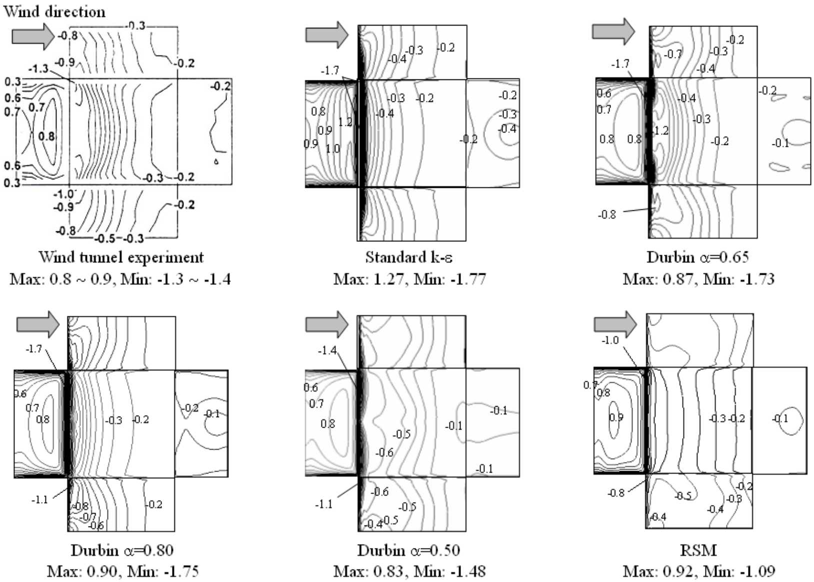

Figure 2: Comparison of wind pressure coefficient distribution.

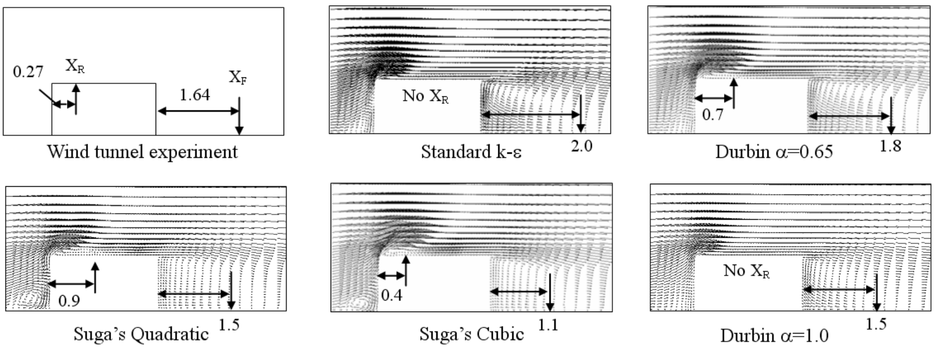

Figure 3: Comparisons of reattachment points (roof surface and wake region).

4. COMPARISON AND EVALUATION OF THE RESULTS

4.1 Wind pressure coefficient distribution

Figure 2 shows the distributions of wind pressure coefficient. Comparison was made with the results of available wind tunnel experiment (Murakami et al., 1996). In the standard k-ε model, the reproducibility was poor for the maximum value, the distribution configuration on windward surface and roof surface as in the previous experience. The distribution configuration on lateral surface was relatively satisfactory, while minimum value was underestimated. Durbin model (α=0.65) showed good results in the maximum value, the distribution configuration on windward surface and roof surface, while the results of distribution on lateral surface was not satisfactory. In the distribution on lateral surface, the results of Durbin model (α=0.80) was relatively good. Durbin model (α=0.5) and RSM model showed the results with the highest reproduction accuracy.

4.2 Reattachment point of separation air flow

From the viewpoint of the evaluation of wind environment near the building, it is important whether the reattachment point is present or not and how long is the distance to it. Figure 3 shows the comparisons of reattachment points of roof

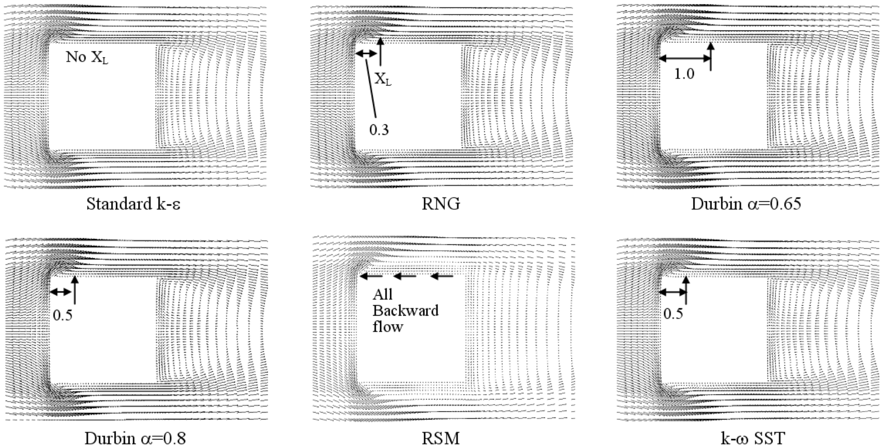

Figure 4: Comparison of reattachment point (lateral surface).

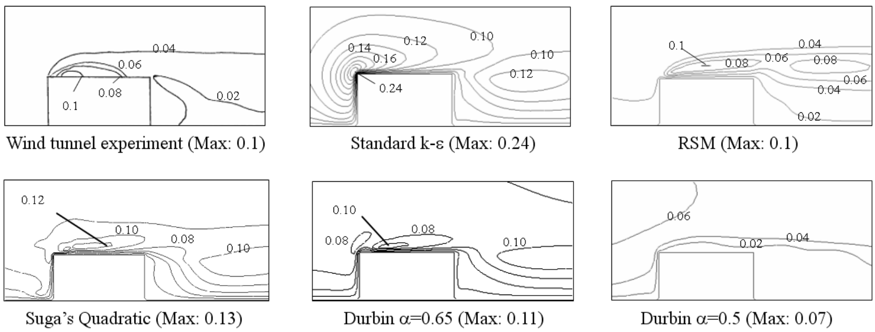

Figure 5: Comparison of turbulent kinetic energy distribution.

surface and wake region. Only in Durbin model (α=0.5, 0.65), Suga’s Quadratic model and Suga’s Cubic model, the reattachment on roof surface of the building was appeared. However, on the distance of the reattachment point, the results were not satisfactory in almost all models. In all models, reattachment on wake region was appeared. In particular, Durbin model (α=0.65, 1.0) and Suga’s Quadratic model showed good results.

In almost all models, the reattachment on lateral surface on building was appeared. The results are given in Figure 4. Since there is no data of wind tunnel experiment, it is difficult to evaluate exactly. Though, the variation in each value is small.

4.3 Turbulent kinetic energy

The results in the turbulent kinetic energy distribution of wind tunnel experiment and CFD are shown in Figure 5. In the models such as the standard k-ε model, the peak value is found on front edge of roof surface of the building. On the other hand, in the models such as RSM, Suga’s Quadratic model, and Durbin model (α=0.65), the maximum value was confirmed on roof surface of the building just as in the results of the experiment.

4.4 Comprehensive evaluation

The results of evaluation on all models are summarized in Table 2. Also, the features of each model found are given in the remarks column. In the reproducibility of wind pressure coefficient, Durbin model (α=0.5) and RSM provided the most satisfactory evaluation results. In the overall evaluation, RNG model and Durbin model (α=0.65) showed good reproducibility as a whole and provided the highest evaluation results.

Table 2: Comprehensive evaluation.

Evaluation item (results of wind tunnel experiment)			Wind pressure coefficient (Cp)				Turbulent kinetic energy		Reattachment point			Comments
			Max (0.8~0.9)	*1 (○)	*2 (○)	*3 (○)	Max (0.1)	*4 (○)	X_R *5 (0.27)	X_F *6 (1.64)	X_L *7 (No data)	
k-ε	Standard		1.27	×	×	○	0.24	×	-	2.0	-	- Reproducibility was poor in all cases.
k-ε	Quadratic		0.90	○	×	○	0.18	×	-	2.0	0.5	- Maximum Cp was comparatively lower. - No item showed extremely poor reproduction accuracy.
k-ε	Suga	Quadratic	1.12	-	-	-	0.13	○	0.9	1.5	1.2	- Cp showed disturbed distribution configuration, and it was impossible to have accurate evaluation.
k-ε	Suga	Cubic	1.17	-	-	-	0.20	○	0.4	1.1	0.7	
k-ε	RNG		0.97	○	×	○	0.15	×	-	1.9	0.3	- Maximum Cp was comparatively lower. - No item showed extremely poor reproduction accuracy.
k-ε	Durbin	0.5	0.83	○	○	○	0.07	×	1.8	3.2	1.1	- No turbulent kinetic energy due to the building occurred. - Reproduction accuracy was comparatively high.
k-ε	Durbin	0.65	0.87	○	○	×	0.11	○	0.7	1.8	1.0	- Reproduction accuracy was high in whole.
k-ε	Durbin	0.8	0.92	○	×	○	0.13	×	-	2.2	0.4	- No item showed extremely poor reproduction accuracy.
k-ε	Durbin	1.0	1.00	○	×	○	0.24	×	-	1.5	-	- The characteristics similar to those of standard k-ε model.
k-ε	Chen		1.01	×	×	○	0.16	×	-	2.1	0.4	- The characteristics similar to those of standard k-ε model.
k-ω	SST		1.32	×	×	×	0.24	×	-	2.4	0.5	- The characteristics similar to those of standard k-ε model.
RSM			0.92	○	○	○	0.10	○	-	2.4	-	- Reproduction accuracy was high except the position of reattachment point. - Calculation time required was 2.5 times as long as that of k-ε model.

*1: The maximum value on windward surface is distributed near the center of it.
*2: The minimum value on roof surface is distributed at left and right of the front edge of it.
*3: The minimum value on lateral surface is distributed on fore upper part of it.
*4: The maximum value is distributed slightly rearward than the front edge.
*5: Distance from front edge.
*6: Distance from leeward surface.
*7: Distance from windward surface.

5. CONCLUSIONS

The findings obtained from the present study were as follows:

- In the reproduction accuracy of wind pressure coefficient distribution, Durbin model (α=0.5) and RSM model showed the results with the highest reproduction accuracy.

However, it was found that Quadratic model, RNG model, and Durbin model (α=0.65, 0.8) also have considerably high reproduction accuracy enough to be suitable for practical application.

- In the results of turbulent kinetic energy, Durbin model (α=0.65), Suga’s Quadratic model, and RSM showed high reproduction accuracy.
- Regarding the distance of reattachment point of separation air flow, the results were not satisfactory in all of the models. On roof surface of the building, reproduction was observed in Durbin model (α=0.5, 0.65), Suga’s Quadratic model, and Suga’s Cubic model, but these results showed higher value than the results of wind tunnel experiment.
- In the overall evaluation, it appears that RNG model and Durbin model (α=0.65) showed the highest reproduction accuracy.

In Part 2, we study the cases where Durbin model and RNG model are applied to housing models of complicated shape.

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