Prediction of wind environment and thermal comfort at pedestrian level in urban area

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ABSTRACT: This paper reviews the recent developments of CWE researches for predicting the pedestrian level wind and thermal environments in urban areas. The progress of turbulence models in the last decade and their applications to the problems related to wind climate are firstly and briefly reviewed, and the results of AIJ (Architectural Institute of Japan) collaborative project of cross comparisons of CFD results of wind environments are shown. Next, recent achievements in the field of modeling canopy flows for reproducing the aerodynamic and thermal effects of trees, buildings and automobiles are outlined. Examples of numerical results with tree and vehicle canopy models are shown to demonstrate the significant effects of stationary and non-stationary subgrid scale flow obstacles on turbulent flowfield within street canyons.

KEYWORDS: pedestrian level wind environment, thermal comfort, Urban Heat Islands, subgrid scale flow obstacles, tree canopy, vehicle canopy

1 INTRODUCTION

The world's urban population was 2.9 billion (47.2%) in 2000 and is expected to rise to 5 billion (60.2%) by 2030. During 2000-2030, the world's urban population is projected to grow at an average annual rate of 1.9% [1]. In line with the rapid urbanisation and growing of urban population, there are increasing concerns on the quality of urban environment. In this respect, urban thermal environment is one of the major concerns, which had lead to numerous researches on this topic.

The urban thermal environment has been worsened by the Urban Heat Island (UHI) effects. The UHI is now regarded as one of the most serious urban environmental problems in the world. The contributing factors of UHI include less vegetation in city area, absorption of solar energy input by concrete and paved surfaces, multiple heat reflections from canyon structures of high-rise buildings, anthropogenic heat releases from air-conditioning systems, automobiles, etc. In order to reduce the UHI effects, various mitigating measures have been proposed. The most commonly applied measures include tree planting. The monetary benefits of urban trees are difficult to quantify because these trees can provide numerous private and public benefits. The latter includes improving thermal environment, reducing community noise and air pollution problems, enhancing biodiversity and meliorating aesthetics [2,3,4]. However, from engineering point of view, the existence of tree covered ground surface is one of the most essential factors to be considered in urban design. Accurate reproduction of aerodynamic effects of trees is also very significant for predicting wind environment in urban area.

Wind environment is one of the most important factors to be considered in UHI study as it has significant influence on UHI effect and outdoor thermal comfort. The conventional urban wind environment assessment methods only took into consideration the influence of topographic features and geometry of buildings (cf. Figure 1(1)). These methods may be inadequate to reflect

the real conditions of city where there are objects of various scales within the street canyons. Stationary objects (cf. Figure 1(2)) such as trees and telephone boxes, and non-stationary objects (cf. Figure 1(3)) such as moving vehicles and swinging hanging-signboards (commonly seen in Asian countries), may alter the surface roughness to certain extent, and consequently flow separation may be misplaced. In order to obtain accurate quantitative data for urban wind environment assessment, these objects must not be overlooked. In recent years, canopy models for reproducing the aerodynamic and thermal effects of trees, buildings and automobiles have been developed and applied to various problems related to urban climate. The canopy models were incorporated into the meteorological mesoscale models. The simulation methods for mesoscale and micro-scale climates were then integrated into the total simulation system using the nested grid technique.

Figure 1. Concept of wind environment assessment: from conventional approach to contemporary tactics.

The growth of CWE applications in the past decade had greatly expanded the scope of wind engineering. Now the application of CWE ranges from the microclimate around a human body to the mesoscale climate in urban area. The aims of this paper are to present the progress of CWE researches for predicting pedestrian level wind environment around buildings together with a brief review on turbulence modeling for CWE applications to problems related to wind environment and cross comparison of predicted results with various turbulence models for several test cases, and to demonstrate the significant effects of stationary and non-stationary objects (tree canopy model and vehicle canopy model respectively) on turbulent diffusion process within street canyons.

2 PROGRESS IN TURBULENCE MODELING FOR CWE APPLICATIONS OVER THE PAST 10 YEARS

2.1 Appearance of dynamic SGS models and their applications on wind engineering

The standard Smagorinsky model was widely used in the computation of LES in the CWE researches conducted in the early period. In the Smagorinsky model approach, a simple eddy-viscosity type approximation is used to simulate the subgrid scale (SGS) stress τ_{ij} in subgrid-scale. The SGS eddy viscosity, ν_{SGS} , is estimated by

$$\nu_{SGS} = (C_s f_\mu \bar{\Delta})^2 \cdot \sqrt{\frac{1}{2} \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)^2} = C(f_\mu \bar{\Delta})^2 \cdot \sqrt{\frac{1}{2} \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)^2} = C(f_\mu \bar{\Delta})^2 |\bar{S}| \quad (1)$$

where, $\bar{f}$: filtered quantities,
 $\bar{\Delta}$: the grid-filter width,
 f_μ : the wall damping function.

In the standard Smagorinsky model, one value of the Smagorinsky constant, C_s , must be selected. The Smagorinsky constant C_s was optimized from 0.1 to 0.25 for various flowfields. Since the flowfield around a bluff body involves various types of flow properties such as impinging, separation, free shear layer, vortex shedding etc., it is arduous to determine an appropriate value of C_s for analyzing the whole flowfield around the bluff body. The dynamic SGS model, which was proposed by Germano et al. in 1991 [5] and revised by Lilly in 1992 [6], successfully corrected this fault of the standard Smagorinsky model. In the Dynamic SGS model, based on the Smagorinsky model (hereafter denoted by DS model), the value of model coefficient C ($=C_s^2$) was determined as a variable of space and time following the properties of the flowfield, using two filters with different characteristic scales i.e. grid filter and test filter [5]. The details of this model are available in many papers [6-13].

It was affirmed in 1990s that the prediction accuracy of the static type Smagorinsky model could be improved by the DS model [8-11]. However, computation based on the DS model was not stable as the fluctuation of C was too large. In order to stabilize the fluctuation of C , various techniques and models had later been proposed [12-22]. When the flowfield has a homogeneous direction (e.g. channel flow), C can be calculated using the averaged quantity of the homogeneous direction. However, this technique cannot be used in many problems in wind engineering which deals with three-dimensional (3D) flow around a bluff body. To deal with such 3D flow, the Lagrangian Dynamic model proposed by Meneveau et al. [14] is useful. In this model, C is calculated using the averaged quantities along the flow path line instead of using quantities averaged over the homogeneous direction. By the advice of Prof. Squires, the present authors applied this model to flow past a square cylinder and found that this model remarkably improved on both calculation stability and prediction accuracy when a proper length scale was imposed on Lagrangian averaging [15,16].

It is widely known that the DS model requires the principal axes of the SGS stress term τ_{ij} be aligned with the strain-rate tensor and this brings about an excessive energy back-scattering when C becomes negative. In order to overcome this shortcoming, the Dynamic Mixed model (hereafter denoted by DM model) was proposed by Zang et al. [17] and revised by Vreman et al. [18] as a linear combination of the DS model and the scale-similarity model [19] to control the extent of excessive back-scattering. The basic equations of DM model are shown in the following equations:

$$\tau_{ij} - \frac{1}{3}\delta_{ij}\tau_{kk} = \underbrace{-2\nu_{\text{SGS}}\overline{S}_{ij}}_{\text{Smagorinsky model}} + \underbrace{B_{ij} - \frac{1}{3}\delta_{ij}B_{kk}}_{\text{scale-similarity model}} \quad (2)$$

$$= -2C\overline{\Delta}^2|\overline{S}|S_{ij} + B_{ij} - \frac{1}{3}\delta_{ij}B_{kk}$$

$$B_{ij} = \overline{\overline{u}_i\overline{u}_j} - \overline{\overline{u}_i}\overline{\overline{u}_j} \quad (3)$$

where, C in eq. (2) is given by utilizing the dynamic procedure [6]. Tominaga et al. [20-22] applied the DM model to simulate the flow past a bluff body and gas diffusion around a building. It was confirmed that this model yielded better results compared to the DS model.

Recently, Iizuka and Kondo studied the flow over a two-dimensional hill using the DS model [23]. In their results, the DS model showed very poor agreement with the experiment results. It was mainly due to the poor prediction accuracy in region near the ground surface. In order to overcome this drawback, they proposed a hybrid SGS model, i.e. a combination of static and dynamic types of the Smagorinsky model. Iizuka et al. [24] also pointed out that the DM model significantly under-predicts the mean velocity values in the central region of channel flow. Inagaki et al. [25] developed a new static type of the SGS model based on the “mixed time-scale” concept proposed by Nagano et al. [26]. The performance of this model was examined for flow over a two-dimensional hill by Iizuka and Kondo [27].

2.2 Generation of inflow turbulence for LES

For the application of LES on a flowfield with obstacles, the technique for providing the inflow boundary condition is particularly important since the inflow condition adopted is always turbulent in wind engineering. In order to generate turbulent velocity fluctuations at the inflow boundary, several techniques have been developed [28-37]. The simplest method is to store the time history of velocity fluctuations given from a preliminary LES computation [28]. Another approach is the artificial generation method in which velocity fluctuations are given by inverting the Fourier transform of prescribed energy spectrum with target turbulence intensity and length scale [29]. Methods of generating the inflow turbulence for CWE applications based on this approach were developed by Kondo et al. [30-32], Iizuka et al. [33,34] and Maruyama et al. [35]. The third method is to set the driver section at the upstream region of the main computational domain to generate the inflow turbulence. Lund proposed the method for generating 3D time-dependent turbulent inflow data for LES of spatially developing boundary layers [36]. Kataoka et al. [37] simplified Lund’s method by assuming the boundary layer thickness is constant within the driver section. This method is now widely used in LES applications on wind engineering problems [38-40].

2.3 Applications of second-moment closure models on wind engineering problems

ASM (Algebraic Stress Model) [41,42] and DSM (or RSM, Differential Second-moment Closure Model or Reynolds Stress Equation Model) [43] were applied to bluff bodies [44-47]. A number of DSM models were proposed during early 1990s. The major topic was the revision of modeling for pressure-strain correlation term, including the higher-order models proposed by Fu-Laundar-Tselepidakis (FLT model) [48] and Speziale-Sarkar-Gatski (SSG model) [49]. Concerning the wall reflection term, the present authors pointed out the shortcoming of the Gibson-

Launder model [50]. The stress normal to the wall should be suppressed in the impinging region while the Gibson-Launder model increases it [44,46]. Craft-Launder proposed a revised model in which this drawback was rectified [51].

Ooka et al. applied various DSM models to the flowfield around a cube [45-48]. Their DSM results did not show any overestimation of turbulent energy k around the frontal corner, which is peculiar to the k - ε model [55,56]. However, the lengths of separation region were overestimated in all trials of DSM. LES based on the simple standard Smagorinsky model gave much better prediction in comparison with DSM. Similar tendency of the drawbacks of DSM when applied to flow around a cube were also reported in the 6th ERCOFTAC/IAHR/COST workshop on the refined flow modeling (organized by Profs. Hanjalic and Obi, Delft, 1997 [54]). The present authors withdrew to improve the prediction accuracy of DSM applied to flow around a bluff body. Instead, the authors shifted their attention to the revision of k - ε model as described in the next section.

2.4 Revisions of k - ε models and their applications to wind engineering problems

It is widely known that the standard k - ε model has a serious drawback in over-estimating turbulence kinetic energy, k , in the flow with impinging [55,56]. Although this problem does not occur in LES computations, the computational resource required for LES is large and is still beyond the scope of practical applications in CWE. Thus, k - ε model is still favorable due to its simplicity and cost effectiveness. Several revised k - ε models have been proposed to overcome the drawback of the standard k - ε model and their performance have been tested for flow around a building, city block, actual building complex and flow over hilly terrains.

1) LK and MMK models

Launder and Kato proposed a revised k - ε model (hereafter denoted by LK model) [57,58] in which the production term P_k in the transport equation of turbulent energy k was changed from $P_k = \nu_t S^2$ to $P_k = \nu_t S \Omega$, as shown in Table 2 (in this paper, $\langle \rangle$ denotes ensemble-averaged quantities). They applied the LK model to a 2D oscillating square cylinder and obtained quite good results. With this revision, the over-estimation of k around the frontal corner was remarkably improved [57,58]. This simple revision was very successful when applied to a single 2D cylinder with wind direction of zero angle of incidence. The increase of computer processing time due to this modification was very small. The LK model is very easily modified from the original standard k - ε model and its computation stability is also very good in comparison to the non-linear k - ε models [59-61]. Thus, the LK model is often applied to the flowfield around a bluff body [62-64]. However, this model has two faults requiring revision. First, the LK model contributes to a decrease in turbulent energy k at the area where $\Omega < S$, as shown in its definitions (cf. eq. (7) in Table 1). However, it overestimates the value of P_k in comparison to the standard k - ε model where $\Omega > S$. The area $\Omega > S$ often appears around a bluff body. This drawback of the LK model became more serious in the analysis of flowfield where several bluff bodies were arranged, as the area $\Omega > S$ increased in this situation. The second drawback of the LK model is a mathematical inconsistency in the modeling of Reynolds stress $-\langle u_i' u_j' \rangle$ and P_k . In the transport equation of mean flow energy K ($= \langle u_i \rangle \langle u_i \rangle / 2$), there is a term which has the same form as that of P_k with the opposite sign. This term plays a role in transferring the kinetic energy from mean flow to turbulence. In the case of the original LK model, the term corresponding to P_k in the equation of mean flow energy K did not take the same form as P_k in the equation of turbulent energy k . This is because the LK model only revised the expression of P_k in the equation of k . Therefore, P_k in the equation of mean flow energy K and that in the equation of turbulent energy k did not appear in the same form.

Murakami, Mochida, Kondo et al. proposed a new revision of the k-ε model, i.e. MMK model [65], which corrected these two drawbacks in the LK model by adding the modification not to the expression for P_k but to the expression for eddy viscosity, ν_t (cf. eqs. (10)-(11) in Table 1).

Table 1. Model equations for LK and MMK models [57,58,65]

1. Standard k-ε model

$$P_k = \nu_t S^2 \quad (4) \quad (\nu_t : \text{eq.(5)}), \quad \nu_t = C_\mu \frac{k^2}{\varepsilon} \quad (5), \quad S = \sqrt{\frac{1}{2} \left(\frac{\partial \langle u_i \rangle}{\partial x_j} + \frac{\partial \langle u_j \rangle}{\partial x_i} \right)^2} \quad (6)$$

2. LK model

$$P_k = \nu_t S \Omega \quad (7) \quad (\nu_t : \text{eq.(5)}), \quad \Omega = \sqrt{\frac{1}{2} \left(\frac{\partial \langle u_i \rangle}{\partial x_j} - \frac{\partial \langle u_j \rangle}{\partial x_i} \right)^2} \quad (8)$$

3. MMK model

$$P_k = \nu_t S^2 \quad (9) \quad (\nu_t : \text{eq.(10) or (11)})$$

$$\nu_t = C_\mu^* \frac{k^2}{\varepsilon}, \quad C_\mu^* = C_\mu \frac{\Omega}{S} \quad \left(\frac{\Omega}{S} < 1 \right) \quad (10)$$

$$\nu_t = C_\mu^* \frac{k^2}{\varepsilon}, \quad C_\mu^* = C_\mu \quad \left(\frac{\Omega}{S} \geq 1 \right) \quad (11)$$

2) New k-ε models adjusting the turbulence time-scale

Recently, new types of revised k-ε models, in which the turbulence time-scale is adjusted in accordance with the property of predicted flowfield, have been proposed.

In k-ε models, the eddy viscosity, ν_t was expressed as

$$\nu_t = C_\mu k \tau \quad (12)$$

where, τ in eq. (12) is the turbulence time-scale. In the standard k-ε model,

$$\tau = \frac{k}{\varepsilon} \quad (13)$$

Durbin proposed eq. (14) for τ based on the “realizability” constraint, $0 \leq \langle u'_\alpha u'_\alpha \rangle \leq 2k$ via a bound on the time-scale, τ , where summation was not taken in $\langle u'_\alpha u'_\alpha \rangle$ [66].

The proposed bound on the time-scale is,

$$\tau = \min(\tau_u, \tau_D) \quad (14)$$

where,

$$\tau_u = \frac{k}{\varepsilon} \quad (15)$$

$$\tau_D = \frac{1}{C_\mu \sqrt{6|S|^2}} \quad (16)$$

$|S|^2 = S_{ij} S_{ij}$ and S_{ij} is the rate of mean strain tensor given by

$$S_{ij} = \frac{1}{2} \left(\frac{\partial \langle u_i \rangle}{\partial x_j} + \frac{\partial \langle u_j \rangle}{\partial x_i} \right) \quad (17)$$

The present authors applied this model to flow past a bluff body and confirmed that its result showed good agreement with experimental data in comparison with other revised k-ε models [67-69]. Nakayama, Kurabuchi, Ohba et al. also reported the high performance of this model when applied to the flow in and around a building under cross-ventilation [70]. However, Lun et

al. pointed out that this model severely overestimated the size of reverse flow region behind a two-dimensional hill [71].

Another type of revised model adjusting the turbulence time-scale was proposed by Nagano and Hattori [72]. This model introduced a mixed time-scale (τ_m), which is a harmonic balance of the turbulent time-scale τ_u : k/ε and the time-scale of mean velocity gradient. Various expressions for estimating τ_m , namely S model, Ω model and S- Ω model expressed as eqs. (18-1), (18-2) and (18-3), respectively were proposed and tested [72].

$$\frac{1}{\tau_m} = \frac{1}{2} \left(\frac{1}{\tau_u} + \frac{C_s}{\tau_s} \right) \quad (\text{S model}) \quad (18-1)$$

$$\frac{1}{\tau_m} = \frac{1}{2} \left(\frac{1}{\tau_u} + \frac{C_s}{\tau_\Omega} \right) \quad (\Omega \text{ model}) \quad (18-2)$$

$$\frac{1}{\tau_m} = \frac{1}{2} \left(\frac{1}{\tau_u} + \frac{C_s}{\tau_{S-\Omega}} \right) \quad (\text{S-}\Omega \text{ model}) \quad (18-3)$$

where,

$$\tau_s = \frac{1}{\sqrt{|S|^2}} \quad (19-1)$$

$$\tau_\Omega = \frac{1}{\sqrt{|\Omega|^2}} \quad (19-2)$$

$$\tau_{S-\Omega} = \frac{2}{\sqrt{|S|^2} + \sqrt{|\Omega|^2}} \quad (19-3)$$

$$|\Omega|^2 = \Omega_{ij} \Omega_{ij}, \quad (20)$$

$$\Omega_{ij} = \frac{1}{2} \left(\frac{\partial \langle u_i \rangle}{\partial x_j} - \frac{\partial \langle u_j \rangle}{\partial x_i} \right) \quad (21)$$

and $C_s = 0.4$

In these models, τ in eq. (12) was replaced by τ_m , derived from eqs. (18-1), (18-2) and (18-3). The performances of these models for flow over hilly terrain [71,73] and flow around a cube [74,75] have been examined by the present authors. Fig. 2 shows the vertical profiles of mean streamwise velocity at various positions over a two-dimensional hill model, in comparison with experimental results [76]. A revised k- ε model proposed by Durbin [66] and the S- Ω model proposed by Nagano and Hattori [72] were employed in this simulation. It was clearly shown that the result of Durbin model deviated from experiment in the region behind the hill. A large re-circulation occurred along the downstream of the hill. The large re-circulation zone observed behind the hill, in the case of Durbin model, is rectified by the newly proposed S- Ω model.

S- Ω model was incorporated into the Local Area Wind Energy Prediction System (LAWEPS) developed by Murakami, Nagano, Mochida, Kato, Kataoka, Otuka et al. [73]. The project for developing LAWEPS was funded by the New Energy and Industrial Technology Development Organization (NEDO) of Japan. The project commenced in 1999 and completed in 2003 [Note 1].

Figure 2. Comparison of mean streamwise velocity around a 2D hill model [71,73]

3) Revision of k-ε model incorporating the buoyancy effects on turbulent diffusion

In recent years, the quality of outdoor thermal environment has been regarded as important as that of indoor thermal environment, and a lot of CFD analyses of outdoor thermal environment have been conducted. Since the temperature difference between urban surfaces is significantly large, the effects of buoyancy on turbulent diffusion should be carefully considered for this type of analysis, and the conventional k-ε models based on the Eddy-Viscosity Concept is clearly inadequate. The present authors have adopted the WET model proposed by Launder [77] and the revised k-ε model including buoyancy effects as shown in Table 2 for the analysis of outdoor climate [78]. The revised k-ε model in Table 2 was derived from the simplification of WET model.

Table 2. New model for sensible and latent heat fluxes including buoyancy effects [78]

$$1. \text{ Sensible heat flux : } -\langle u'_3 \theta' \rangle = \frac{\nu_t}{\sigma_\theta} \frac{\partial \langle \theta \rangle}{\partial x_3} + \frac{k}{\varepsilon} C_{\theta 3} g_3 \beta \langle \theta'^2 \rangle \quad (22)$$

$$2. \text{ Latent heat flux : } -\langle u'_3 q'_w \rangle = \frac{\nu_t}{\sigma_w} \frac{\partial \langle q_w \rangle}{\partial x_3} + \frac{k}{\varepsilon} C_{\theta 3} g_3 \beta \langle \theta' q'_w \rangle \quad (23)$$

q_w : mixing ratio of total water

$$g_3 = -9.8 \text{ m/s}^2, C_{\theta 1} = 0.25, C_{\theta 3} = 0.25, \sigma_\theta = 0.5, \sigma_w = 0.5$$

2.5 AIJ collaborative research project

- cross comparisons of CFD results of wind environment at pedestrian level -

Recently, the prediction of wind environment around a high-rise building using CFD technique was being carried out at the practical design stage. However, there were very few studies examined its accuracy, including the velocity distribution at pedestrian level. Hence, a working group for CFD prediction of wind environment around buildings, which consisted of researchers from several universities and private companies [Note 2], was organized in the AIJ (Architectural Institute of Japan). During initial stage of that project, the working group carried out cross comparisons of CFD results of flow around a single high-rise building block placed within the surface boundary layer and flow within a building complex in an actual urban area, obtained from

various $k-\varepsilon$ models, DSM and LES [67-69,80-84]. Fig.3 illustrates six test cases for these cross comparisons. They were done in order to clarify the major factors which affect the prediction accuracy. In order to assess the performance of turbulence models, the results should be compared under the same computational conditions. Special attentions were paid to this point in this project. The computational conditions, i.e., grid arrangements, boundary conditions, etc., were specified by the organizers. Contributors were requested to follow the conditions. Here results of two cases, Cases A and E, are shown.

Figure 3. Six test cases for comparison.

1) Test Case A (2:1:1 shaped building model)

Outlines of the computed cases for 2:1:1 shaped building model (Test Case A) are listed in Table 3. Nine groups have submitted a total of eighteen datasets of results. The performance of the standard $k-\varepsilon$ and five types of revised $k-\varepsilon$ models was examined. Furthermore, Differential Stress Model (DSM) [45], Direct Numerical Simulation (DNS) with third-order upwind scheme [85] and Large Eddy Simulation (LES) using the Smagorinsky subgrid-scale model [87] were also included in the comparison exercise.

The predicted reattachment lengths on the roof, X_R , and that behind the building, X_F , were given for all cases as shown in Table 3. In the results of the standard $k-\varepsilon$ (KE1~8), the reverse flow on the roof, which was clearly observed in the experiment, was not reproduced. On the other hand, the reverse flow on the roof appeared in the results of all the revised $k-\varepsilon$ models (LK1, RNG1, MMK1, RNG1, LK2, LK3, MMK2, DBN) though its size was a little larger than that of the experiment. In the DSM result, the separated flow from a windward corner was predicted too large, and does not reattach to the roof. The result of LES without inflow turbulence (LES1) can reproduce the reattachment on the roof, but X_R is somewhat overestimated in this case. On the other hand, the result of LES with inflow turbulence (LES2) shows close agreement with the experiment.

The reattachment length behind the building, X_F , was evaluated larger than the experiment in all cases by the standard and revised $k-\varepsilon$ models. It is surprising to see that there were significant differences in X_F values between the results of the standard $k-\varepsilon$ model. As was already noted, the grid arrangements and boundary conditions were set to be identical in all cases, and QUICK scheme was used for convection terms in many cases. The reason for the difference in

X_F values predicted by the standard $k-\epsilon$ models is not clear, but it may be partly due to the difference in some details of numerical conditions, e.g. the convergence condition, etc. The results of the revised $k-\epsilon$ models except for the Durbin's model were in the tendency to evaluate X_F larger than the standard $k-\epsilon$. This discrepancy was improved in LES and DNS computations. On the other hand, DSM greatly over-estimated X_F . The over-estimation of reattachment length behind a three-dimensional obstacle was also reported by Lakehal and Rodi [63].

The size of the recirculation region behind the building is strongly affected by the momentum transfer mechanism in the wake region, where vortex shedding plays an important role. Thus, the reproduction of vortex shedding is significantly important for accurate prediction of X_F value. However, none of the $k-\epsilon$ models compared here could reproduce vortex shedding. This results in underestimation of the mixing effects in the lateral direction causing a large recirculation region behind the building.

Table 3. Computed cases for 2:1:1 shaped building model (Test Case A)

Affiliation	CASE	Software	Turbulence model	Scheme for convection terms	Computational method and time integral scheme	X_R^*/b	X_F^*/b
A	KE1	STREAM ver.2.10	$k-\epsilon$ (standard)	QUICK	SIMPLE,steady solution		2.54
B	KE2	STREAM ver.2.10	$k-\epsilon$ (standard)	QUICK (1st-order upwind for k and ϵ)	SIMPLE,steady solution		1.66
C	KE3	STREAM ver.2.10	$k-\epsilon$ (standard)	QUICK	SIMPLE,steady solution		2.00
	LK1		$k-\epsilon$ (LK) ⁵⁷⁾			0.87	2.98
D	KE4	STREAM ver.2.10	$k-\epsilon$ (standard)	QUICK	SIMPLE,steady solution		2.00
	RNG1		$k-\epsilon$ (RNG) ⁸⁶⁾	QUICK		0.50	2.80
E	KE5	STAR-LT ver.2.0	$k-\epsilon$ (standard)	QUICK	SIMPLE,steady solution		2.20
F	MMK1	Homemade	$k-\epsilon$ (MMK) ⁶⁵⁾	QUICK	MAC, unsteady solution with implicit scheme	0.65	2.72
G	KE6	FLUENT ver.5.0	$k-\epsilon$ (standard)	Central	SIMPLE,steady solution		2.41
	RNG2		$k-\epsilon$ (RNG) ⁸⁶⁾			0.58	3.34
	KE8	Homemade	$k-\epsilon$ (standard)	QUICK	HSMAC, unsteady solution with implicit scheme		2.70
	LK2		$k-\epsilon$ (LK) ⁵⁷⁾			0.58	3.19
	LK3		$k-\epsilon$ (modified LK) ⁸⁸⁾			0.53	3.11
	MMK2		$k-\epsilon$ (MMK) ⁶⁵⁾			0.52	3.09
	DBN		$k-\epsilon$ (Durbin) ⁶⁶⁾			0.63	2.70
	DSM		DSM ⁴⁵⁾			>1.0	4.22
	LES1		LES(without inflow turbulence) ⁸⁷⁾	Second-order centered difference	SMAC, Convection terms: Adams-Bashforth scheme Diffusion terms: Crank-Nicolson scheme	0.62	1.02
	LES2		LES(with inflow turbulence) ⁸⁷⁾			0.50	2.10
H	KE7	Homemade	$k-\epsilon$ (standard)	QUICK	HSMAC, unsteady solution with implicit scheme		1.98
I	DNS	Homemade	DNS ⁸⁵⁾	3rd-order Upwind Scheme	Artificial compressibility method, explicit	0.92	2.05
Experiment [89]						0.52	1.42

* X_R : Reattachment length on the roof

* X_F : Reattachment length behind the building

2) Test Case E (building complex in actual urban area)

Prediction accuracy for wind environment within an actual building complex, located in Niigata City, Niigata Prefecture, Japan, was examined in this test case. The prediction was carried out by three different codes for comparison, namely a homemade CFD code and two commercial CFD codes. The computational conditions are given in Table 4. In order to reproduce the geometries of the surrounding building blocks, data from an identical CAD file was used. This CAD file was produced from the drawing of the experimental model.

Table 4. Computed cases for building complex in actual urban area (Test Case E)

CFD Code	Code O	Code M	Code T
	Self-made code	Commercial code	Commercial code
Computational method and time integral scheme	Overlapping structured grid	Structured grid	Unstructured grid
	Artificial compressibility	SIMPLE, steady state	SIMPLE, steady state
Turbulence model	Standard k- ϵ	Standard k- ϵ	Standard k- ϵ
Scheme for advection term	3 rd -order Upwind	QUICK	MUSCL(2 nd -order)
Grid arrangements

Although CFD simulations have been performed for sixteen different wind directions, only the wind distributions for wind directions of NNE and W, which are the prevailing wind directions in Niigata City, are shown here. Since there were no clear differences observed between the horizontal distributions of scalar velocity near ground surface as predicted by the three CFD codes, only the results with Code T were presented (cf. Fig. 4). This figure illustrates the horizontal distributions of scalar velocity near ground surface ($z=2\text{m}$). The values in Fig. 4 are normalized by the velocity value at the same height at inflow boundary. Fig. 5 shows a comparison of CFD results with wind tunnel experiments. It was found that the scalar velocity predicted by all CFD codes tends to be smaller in the wake region compared to the experimental value. This discrepancy is mainly due to the fact that k- ϵ model cannot reproduce the vortex shedding from tall buildings, similarly as in Test Case A. This problem is absent in LES results but the computational cost for adopting LES is still beyond the scope of practical applications. In order to overcome this drawback, the adaptation of Hybrid RANS/LES and DES (Detached-Eddy Simulation) [90-93] would be needed. The current state of these approaches will be shown in the invited lectures at this conference by Profs. Hanjalic and Squires [94,95].

Figure 4. Distributions of scalar velocity near ground surface around building complex [79-84]

Figure 5. Comparison of scalar velocity value for each measurement[79-84]

3 MODELLING OF SMALL SCALE FLOW OBSTACLES

3.1 Various subgrid-scale obstacles in real situations

The real situations of environment in street canyons are influenced under the interaction of various objects, both stationary and non-stationary. In most of the previous CFD simulations of flow around buildings, only the influences of topographic features and building geometry were considered (cf. Figure 1(1)). At the height of pedestrian level, influences of small obstacles such as trees (stationary) and automobiles (non-stationary) are significant (cf. Figures 1(2) and 1(3)). Their effects have been neglected in most of the studies in the conventional way of CFD prediction of wind environment, but modeling on the effects of such subgrid scale flow obstacles have been investigated in recent years by many researchers.

Figure 7. Flowchart for assessing outdoor human comfort based on CFD [78,108,111].

This 3D canopy model employed the k - ε turbulence model with extra terms (cf. Table 5) added into the transport equations, to simulate the aerodynamic effects of trees. The term F_i included in the i component of momentum equation denotes the drag force. F_k and F_ε added, respectively, into the transport equations of turbulent energy, k , and energy dissipation rate, ε , to represent the effects of trees on turbulent flowfield. These extra terms were derived by applying the spatial average to the basic equation [97]. The radiative heat transport was computed using the method based on Monte-Carlo simulation [112]. The solar and longwave radiant fluxes incident to the plant canopy were calculated by assuming a decay rate of $\{1 - \exp(-k' a(x_1, x_2, x_3) l)\}$, where k' is the absorption coefficient and l is the length by which radiant flux passes through the plant canopy. The mean leaf surface temperature of the plant canopy was estimated using the heat balance equations listed in Table 6. In the heat balance equation (27), the heat conductivity term is neglected as heat capacity of leaf was negligibly small.

Table 5. Additional terms for tree canopy [108]

F_i	$-\eta C_f a(x_1, x_2, x_3) \langle u_i \rangle \sqrt{\langle u_j \rangle^2}$	(24)
F_k	$\langle u_i \rangle F_i$	(25)
F_ε	$\frac{\varepsilon}{k} C_{p\varepsilon} F_i$	(26)

η : green coverage ratio,
 C_f : drag coefficient,
 $a(x_1, x_2, x_3)$: leaf surface area density,
 $\langle \rangle$: ensemble-average

Table 6. Heat balance equations of plant canopy [108]

$S_P + R_{DP} + H_P + LE_P = 0$	(27)
$H_P = A_P \alpha_C (T_{aP} - T_P)$	(28)
$LE_P = A_P \alpha_W \beta_P L (f_{aP} - f_{sP})$	(29)

where,

S_P	: absorbed solar radiation flux on leaf surfaces	[W]
R_{DP}	: absorbed longwave radiation flux on leaf surfaces	[W]
H_P	: sensible heat on leaf surfaces	[W]
LE_P	: latent heat at leaf surfaces	[W]
L	: latent heat of water vaporization	$(2.5 \times 10^6 \text{ [J/kg)})$
A_P	: leaf area at tree crown (A_P is twice the product of the volume of tree crown and the leaf area density of tree crown)	$[\text{m}^2]$
α_C	: convective heat transfer coefficient on leaf surfaces	$[\text{W}/\text{m}^2\text{K}]$
T_P	: leaf surface temperature	[K]
T_{aP}	: air temperature in the mesh including tree crown	[K]
α_W	: convective moisture transfer coefficient on leaf surfaces	$[\text{kg}/(\text{m}^2\text{sPa})];$ $(\alpha_W = 7.0 \times 10^{-6} \alpha_C)$
β_P	: moisture availability on leaf surfaces	[-]
f_{aP}	: water vapor pressure in the mesh including tree crown	[kPa]
f_{sP}	: saturation water vapor pressure on leaf surface temperature	[kPa]

Results with this model were given by Yoshida et al. [108]. Based on the similar approaches, various studies have been conducted in recent years to investigate the effects of planted trees on outdoor thermal environment and optimize their shapes, densities and layouts [113-115].

3.2.2 Optimization of tree canopy model for reproducing the aerodynamic effects

Recently, the present authors carried out a series of numerical studies to examine the accuracy of the existing canopy models in reproducing the aerodynamic effects of trees, and to optimize the model coefficients included in them [73,109,110]. The canopy models adopted in these studies used the revised k- ϵ model, which based on a “mixed time-scale” concept (S- Ω model), as a base, with extra terms added into the transport equations as shown in Table 5. The additional terms contained four parameters, C_{pe} , η , a and C_f . “ C_{pe} ” was regarded as a model coefficient in turbulence modelling for prescribing the time-scale of the process of energy dissipation in the canopy layer, whilst “ η ”, “ a ” and “ C_f ” were the parameters which should be determined according to the conditions of trees. The choice of C_{pe} value included in F_ϵ (cf. eq. (26) in Table 5) affects much on the prediction accuracy [110], and considerable difference was observed between the values adopted in the previous researches [96-108]. The C_{pe} was optimized by the present authors and predicted results were compared with experimental results. Figure 8 shows an example of such comparison. The value of 1.8 was selected for C_{pe} as a result of a series of numerical experiments. The tree canopy model developed here was incorporated in the LAWEPS [73,117]. A five-stage nesting grid system was adopted in the LAWEPS. The largest domain (1st Domain) covered an approximate region of a scale about $500 \text{ km} \times 500 \text{ km}$ in horizontal directions, and 10 km in vertical direction. The smallest domain (5th domain) occupied region of about $1 \text{ km} \times 1 \text{ km}$. Figures 9(1) and 9(2) compare the vertical velocity profiles predicted by LAWEPS with the tower observations at Shionomisaki Peninsular, Wakayama, Japan [117]. It can be seen that the results of numerical prediction show very close agreement with the observations.

Figure 8. Comparison of normalized vertical profiles of mean streamwise velocity behind pine trees (H: a height of tree, U_H : inflow velocity at a height of H) [109,110].

Figure 9. Comparison of vertical velocity profiles above Shionomisaki Peninsular, Wakayama, Japan (Dec.15th, 15JST, 2001) [117].

The present authors have lately carried out an extensive review on tree canopy models. Four types of canopy models were selected for investigating the aerodynamic effects of trees on wind environment at pedestrian level. The model coefficients adopted in the extra term added to the transport equation of energy dissipation rate, ε , were optimized by comparing the numerical results with field measurements. The four selected tree canopy models [96-101,107] are based on k- ε model as given in Table 7.

Table 7. Additional terms in various tree canopy models

	F_i	F_k	F_ε	
Type A	$\eta C_f a \langle u_i \rangle \sqrt{\langle u_j \rangle^2}$	$\langle u_i \rangle F_i$	$\eta \frac{\varepsilon}{k} \cdot C_{pe1} \frac{k^{3/2}}{L} \quad \left(L = \frac{1}{a} \right)$	Hiraoka [97] : $C_{pe1}=0.8 \sim 1.2$
Type B		$\langle u_i \rangle F_i$	$\frac{\varepsilon}{k} \cdot C_{pe1} F_k$	Yamada [96]: $C_{pe1}=1.0$ Uno et al. [98]: $C_{pe1}=1.5$ Svensson [99]: $C_{pe1}=1.95$
Type C		$\langle u_i \rangle F_i - 4\eta C_f a \sqrt{\langle u_j \rangle^2}$	$\frac{\varepsilon}{k} \left[C_{pe1} \langle u_i \rangle F_i - C_{pe2} \left(4\eta C_f a \sqrt{\langle u_j \rangle^2} \right) \right]$	Green [100]: $C_{pe1}=C_{pe2}=1.5$ Liu et al. [101]: $C_{pe1}=1.5, C_{pe2}=0.6$
Type D		$\langle u_i \rangle F_i - 4\eta C_f a \sqrt{\langle u_j \rangle^2}$	$\eta \frac{\varepsilon}{k} \cdot C_{pe1} \frac{k^{3/2}}{L} \quad \left(L = \frac{1}{a} \right)$	Ohashi [107]: $C_{pe1}=2.5$

The same forms of “ F_i ” were used in all the tree canopy models, and two types of modeling were proposed for F_k . For Types A and B in Table 5, F_k was expressed as follows:

$$F_k = \langle u_i \rangle F_i \quad (\langle \rangle : \text{ensemble-average}) \quad (30)$$

In Types C and D, F_k is modified to include an additional sink term, i.e.

$$F_k = \text{Production } (P_k) - \text{Dissipation } (D_k) \quad (31)$$

Where, P_k : production of k within canopy ($= \langle u_i \rangle F_i$)
 D_k : a sink term to express the turbulence energy loss within canopy [100]

In Types A and D, F_ε is modeled by using the length scale “ L ” within canopy.

$$F_\varepsilon \propto \frac{1}{\tau} \left(\frac{k^{3/2}}{L} \right) \quad (\text{here } \tau = k/\varepsilon \quad \text{and} \quad L = 1/a) \quad (32)$$

On the other hand, F_ε is given by the following relation in Type B

$$F_\varepsilon \propto \frac{1}{\tau} F_k \quad (\text{here } \tau = k/\varepsilon) \quad (33)$$

In Type C, the term corresponding to the sink term in eq. (31) is added for the expression of F_ε .

$$F_\varepsilon = \text{Production } (P_\varepsilon) - \text{Dissipation } (D_\varepsilon) \quad (34)$$

$$P_\varepsilon \propto \frac{1}{\tau} P_k, \quad D_\varepsilon \propto \frac{1}{\tau} D_k$$

As seen in Table 7, the additional terms contain five parameters, two model coefficients, C_{pe1} and C_{pe2} , η , a and C_f . Results with Type B and Type C models will be compared with measurements in the presentation at this conference by the present authors [110].

3.3 Modeling for aerodynamic effects of vehicle canopy [118,119]

Recently, the present authors developed a simulation method named ‘vehicle canopy model’ to predict the effects of moving automobiles on flow and diffusion fields within street canyons [118,119].

3.3.1 Outline of vehicle canopy model

In this model, the effects of each individual moving automobile were not directly modeled, instead, the total effects of all the moving automobiles on the street were considered as a whole. The aerodynamic effect of the moving automobiles was modeled based on the methodology of canopy model. The proposed vehicle canopy model was derived based on the k - ε model, in which extra terms were added into the transport equations. Similarly to the tree canopy model [96-101,107,110], the extra term “ $-F_i$ ” was added in the momentum equation, cf. Table 8, which produced the effect of moving automobiles on velocity change. This “ $-F_i$ ” was defined as a function of wind velocity $\langle u_i \rangle$ in the tree canopy model (cf. Tables 5 and 7). In modeling vehicle canopy, $\langle u_i \rangle$ was replaced by the relative velocity between wind velocity and moving speed of automobiles (cf. Figure 10). In order to simulate the effects of moving automobiles on turbulence increase rate and energy dissipation rate, additional terms “ $+F_k$ ” and “ $+F_\varepsilon$ ” were included in the

transport equations of turbulent kinetic energy, k , and energy dissipation rate, ε . Table 8 describes the function of these extra terms [118,119].

Figure 10. Relationship between wind velocity and moving speed of automobiles.

Table 8. Additional terms for vehicle canopy model [118,119]

F_i	$\frac{1}{2} C_{f-car} \frac{A_{car}}{V_{cell}} (<u_i> - u_{i-car}) \sqrt{(<u_j> - u_{j-car})^2}$	(35)	C_{f-car} : drag coefficient of automobiles A_{car} : sectional area of automobiles observed from i direction [m ²] V_{cell} : volume of one computational mesh [m ³]
F_k	$(<u_i> - u_{i-car}) F_i$	(36)	u_{i-car} : moving speed of automobiles [m/s]
F_ε	$\frac{\varepsilon}{k} \frac{k^{3/2}}{L} C_{\varepsilon-car}$	(37)	L : length scale for canopy layer $C_{\varepsilon-car}$: ratio of turbulence scale of automobiles

3.3.2 CFD analyses of flowfield in real situations in street canyon

By using the proposed vehicle canopy model, the flow and diffusion fields within Jozenji-street in Sendai, Japan, Figure 11, were predicted. The accuracy of CFD analyses was confirmed by comparing the simulation results with the field measurement results conducted by the present authors [113,120]. Details of the numerical settings can be obtained from [118,119].

Figure 11. Actual urban space; Jozenji street, Sendai, Japan.

All the test cases are shown in Table 9. Horizontal distributions of wind velocity vectors at a height of 1.5m for Case 1 are illustrated in Figure 12. A comparison of the results of turbulent kinetic energy, k , between field measurements and CFD analyses in Jozenji-street is given in Table 10. In the cases without automobiles (Cases 1 and 2), k values were largely under-predicted

in comparison with the measurement results. However, the magnitude of k due to turbulent diffusion generated by moving automobiles was well reproduced in Case 3-2, especially on the southern sidewalk.

Figure 12. Horizontal distributions of wind velocity vectors (without trees and automobiles, 12:00a.m. on August 3rd at a height of 1.5m) [118,119].

Table 9. Test cases for vehicle canopy model [118,119]

	Roadside trees	Effects of moving automobiles on turbulent diffusion process
Case 1	Without	Without automobiles
Case 2	Present situation	Without automobiles
Case 3-1	Present situation	$u_{car} = 0$ [km/h]
Case 3-2	Present situation	$u_{car} = 15$ [km/h]

Table 10. Comparison of turbulent kinetic energy, k [m^2/s^2] [118,119]

Measuring points	Result of field measurement	Results of CFD analyses			
		Case 1	Case 2	Case 3-1	Case 3-2
Northern sidewalk	0.44	0.06	0.07	0.02	0.22
Southern sidewalk	0.27	0.12	0.03	0.03	0.25

3.4 Modeling for aerodynamic and thermal effects of building canopy [123,127]

Temperature increase due to urbanization is becoming very serious in Japan. City administrators and urban planners are now willing to adopt countermeasures that can mitigate the problem of UHI effects. Various urban planning scenarios have been proposed to minimize the impact of urbanization on urban climate. Since mid-1990s, a lot of numerical studies of mesoscale climate in urban areas have been carried out by many researchers [121-126].

Historically, one-dimensional heat balance model was usually adopted for the ground boundary conditions of mesoscale climate analysis. In this conventional model, a roughness parameter was employed in order to present the effect of the building complex. As the vertical grid size adjacent to the ground surface must be made several times larger than the roughness length in the conventional model, physical phenomena within the surface layer could not be estimated. Furthermore, the definition of surface temperature is vague in the conventional model because its relationship with ground, roof and wall surface temperature is unclear. Therefore, it is necessary to include the effects of urban canopy precisely in order to analyze the thermal environment at pedestrian level in an urban area. On the other hand, the one-dimensional urban canopy model was also commonly used to analyze urban thermal environments. Although this model can predict the thermal environment at pedestrian level easily, it is not possible to consider the effects of local climate due to the limitation of the assumption of a horizontally homogeneous flow and temperature field.

Recently, Ooka et al. [123] developed a comprehensive urban canopy model that considers the following five factors in dealing with building complex: (1) wind reduction by the building

complex, (2) production of turbulence by the building complex, (3) solar radiation (short-wave) heat transfer inside and outside the building complex, (4) long-wave radiation heat transfer inside and outside the building complex, and (5) sensible and latent heat transfer from the building surfaces. The urban canopy model developed in their study was incorporated into the meteorological mesoscale model [123]. The effects of plant canopy as illustrated in Figure 6 were also considered. Concerning the modeling of aerodynamic effects of the building canopy, i.e. (1) and (2), Prof. Maruyama developed a building canopy model [127], which has been widely used by many researchers. He also provided detailed database obtained by a series of wind tunnel tests to determine the model coefficients included in his model.

4 INTEGRATION OF CWE SIMULATIONS WITH VARIOUS SCALES

CWE applications now cover various phenomena in various scales ranging from microclimate around a human body to regional climate (cf. Figure 13). These phenomena of various scales are related and coupled to each other. Research efforts, thus, should be devoted to develop a method for integrating the sub-models into a comprehensive and total simulation system. For this purpose, it is necessary to develop a new software platform which not only can handle many sub-systems for analyzing each scale phenomena but also can integrate them for evaluating the total urban climate. Figure 14 illustrates the concept of the platform proposed by Murakami, Mochida, Ooka et al. [128-130].

A number of case studies based on the proposed Software Platform were presented by Prof. S. Murakami and the present authors [129,130]. It was pointed out that CWE is now in the process of growing from a tool for analysis to the tool for environmental design.

Figure 13. Various scale phenomena related to wind climate [128,129].

Figure 25. Prototype of software platform for the total analysis of urban climate [128,129].

5 CONCLUDING REMARKS

This paper reviewed the progress in CWE researches over the past 10 years primarily achieved by the researchers in the field of environmental engineering. The first part of the paper outlined the progress in turbulence modeling for predicting turbulent flow around buildings and wind environment in building complex. In 1990s, many researches were carried out to examine the performance of the dynamic LES models based on the Dynamic Smagorinsky type, Dynamic Mixed type, Lagrangian Dynamic type, etc. Various methods for generating inflow turbulence for LES were developed during the same period. Presently researches to improve the prediction accuracy of k - ε models are still continued. The performance of various revised k - ε models was examined for flow around a bluff body, city building blocks, actual building complex and flow over hilly terrains. It was confirmed that the revised k - ε models which were proposed to correct the drawback of the standard k - ε model that severely over-predicts the turbulence energy, k , around front corners could undoubtedly improve the prediction accuracy for predicting the strong wind in separated flow regions around front corners. However, all revised k - ε models over-predicted the sizes of reattachment lengths behind buildings and under-predicted the velocity values in the wake regions. This discrepancy is mainly due to the fact that all k - ε models could not reproduce the vortex shedding from buildings. This problem was not observed in LES results but computational cost for LES is still beyond the scope of practical applications. In order to overcome this drawback, the adaptation of Hybrid RANS/LES and DES (Detached-Eddy Simulation) would be needed.

The latter part of the paper described the recent and future trends of numerical modeling for predicting the wind and thermal environment as well as turbulent diffusion process in real urban space where there exist various small subgrid scale flow obstacles. The conventional approach in numerical modeling is generally carried out based on static condition (i.e. stationary objects such as buildings). This method may be erroneous when applying to real situation where dynamic condition exists (i.e. non-stationary objects such as automobiles). In recent years, canopy models for reproducing the aerodynamic and thermal effects of trees/buildings/automobiles have been developed and applied to various problems related to urban climate. This paper demonstrated some of the results regarding this subject. The research studies emphasised on the significance of the effects of stationary and non-stationary objects (tree canopy model and vehicle canopy model respectively) on turbulent flowfield within street canyons.

As indicated in Section 4 in this paper, the development of the total simulation system integrating the sub-model for the phenomena with various scales makes it possible to carry out total analysis of urban climate which composes of many elements and controls by many interacting physical processes at various scales. CWE is now in the process of growing from a tool for analysis to a tool for environmental design. However, a lot of improvements and revisions are still required before the turbulent flow phenomena in urban areas can be accurately reproduced. Hence, fundamental research efforts to improve the prediction accuracy should be continued.

Acknowledgements

This paper reviewed the recent progress in CWE applied on environmental problems. Many topics included in this report are the results of collaborations extended over years with Prof. S. Murakami (Keio University), Prof. Y. Tominaga (Niigata Institute of Technology), Prof. R. Ooka (IIS, University of Tokyo), Dr. S. Iizuka (National Institute of Resources and Environment), Prof. S. Yoshida (Fukui University), Dr. K. Kondo (Kajima Corporation), Dr. K. Sasaki (Shimizu corporation) and Dr. T. Shirasawa (Tokyo Inst. Polytechnics). The authors are grateful for

their valuable contributions. The assistance in preparing this manuscript by Mr. K.Takahashi (Tohoku University) is gratefully acknowledged.

[Note 1]: The works involved in this project are divided into three phases. During the initial phase of the study, a multi-step wind simulation with nesting method was designed. In the second phase of the work, each sub-model was coded and evaluated. Data of observations and experiments were obtained in parallel and used for verification with computation. In the final phase of the project, the performance of the entire simulation system, LAWEPS, was tested and examined by comparing its results with measured data [73,117].

[Note 2]: The CFD Working Group members are: A. Mochida (Chairman, Tohoku Univ.), Y. Tominaga (Secretary, Niigata Inst. of Tech.), Y. Ishida (I.I.S., Univ. of Tokyo), T. Ishihara (Univ. of Tokyo), K. Uehara (National Inst. of Environ. Studies), R. Ooka (I.I.S., Univ. of Tokyo), H. Kataoka (Obayashi Corp.), T. Kurabuchi (Tokyo Univ. of Sci.), N. Kobayashi (Tokyo Inst. Polytechnics), T. Shirasawa (Tokyo Inst. Polytechnics), N. Tuchiya (Takenaka Corp.), Y. Nonomura (Fujita Corp.), T. Nozu (Shimizu Corp.), K. Harimoto (Taisei Corp.), K. Hibi (Shimizu Corp.), S. Murakami (Keio Univ.), T. Yamanaka (Kajima Corp.), R. Yoshie (Tokyo Inst. Polytechnics), M. Yoshikawa (Taisei Corp.).

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