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Response to the discussion on “An improved k – ω turbulence model for the simulations of the wind turbine wakes in a neutral atmospheric boundary layer flow” by Y Yang

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The authors appreciate the comments made by the discusser on potential mistaking of the source term for the turbulence eddy dissipation rate ε in the calculation of the eddy frequency ω. For the work presented in our paper, the source term for ω was obtained by modifying the source term for ε that was proposed by Chen and Kim (1987), using the concept of the k – ω model and in a dimensionally consistent manner. The following sections explain the source term that was employed in the modified k – ω model in our paper.

Despite the fact that the standard k – ε model (Launder and Spalding, 1972) has been validated in a wide range of applications, it still fails to predict accurately flows with strong adverse pressure gradients (e.g. backward facing step). One of the applications that the standard k – ε model fails to predict correctly, as many researchers have proven such as Crespo et al. (1985), Kasmi and Masson (2008), is the simulation of wind turbine wakes. Chen and Kim (1987) have concluded that the problem with the standard k – ε model is due to the fact that the transport equation for the eddy dissipation rate is highly empirical and it does not represent the energy transfer from the large to small scales effectively. Consequently, Chen and Kim (1987) added a second time scale in the transport equation of the eddy dissipation rate to overcome this problem and they compared their model with the standard k – ε model in many different applications (e.g. backward facing step, swirling flows, turbulent boundary layer). The time scale that has been added is as follows:

$$S_{\varepsilon} = C_{\varepsilon 4} \frac{G_k^2}{\rho k} \tag{1}$$

The term G_k is the production of turbulence and is calculated as follows:

$$G_k = \mu_t S^2 \tag{2}$$

The term S is the strain rate and is defines as follows:

$$S = \sqrt{2S_{ij}S_{ij}} \tag{3}$$

Kasmi and Masson (2008) have employed the term given in equation (1) in the vicinity of the wind turbine and they showed that the results for 3 different wind turbines are significantly improved in relation to the standard k – ε model, which completely fails to predict the wind turbine wake characteristics. Unfortunately, the main issue with the Kasmi and Masson (2008) model is that it is empirical constant dependent, as some researchers have pointed out, because they validated their model with only one specific value of the relative inlet turbulent kinetic energy. This is because the time scale added by Chen and Kim (1987) in the transport equation for the eddy dissipation rate in the standard k – ε model becomes a function of the eddy viscosity, which is a function of the empirical constant C_μ which defines the relative turbulent kinetic energy of the field. In order to clarify the validity of the previous statement, the equation (1) is transformed as follows, in the standard k – ε model:

$$S_\varepsilon = \frac{\rho C_\mu^2 C_{\varepsilon 4} k^3}{\varepsilon^2}\left(\sqrt{2S_{ij}S_{ij}}\right)^4 \tag{4}$$

As seen in equation (4), the extra term is strongly dependent on the empirical constant C_μ, which defines the relative turbulent kinetic energy of the flow field.

In our paper, we have proven that similar problems to the standard k – ε model arise with the standard k – ω model (Wilcox, 1998) because the transport equation for the eddy frequency is also highly empirical and guided by physical reasoning. As in the standard k – ε model, the turbulent kinetic energy and the relative velocity at the rear of the wind turbine are both highly overpredicted by the standard k – ω model. The standard k – ω model uses the eddy frequency as the second determining variable. The standard k – ω model (Wilcox, 1998) uses the following transport equation for the eddy frequency:

$$\frac{\partial}{\partial t}(\rho\omega) + \frac{\partial}{\partial x_i}(\rho\omega u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\omega}\right)\frac{\partial\omega}{\partial x_i}\right] + \frac{\omega}{k}G_k - \rho\beta_i\omega^2 \tag{5}$$

The relationship between the eddy frequency and eddy dissipation rate is given by:

$$\omega = \frac{\varepsilon}{k\beta_\infty^*} \tag{6}$$

Consequently, the source term of equation (1), for the standard k – ω model is simply transformed as follows:

$$S_\omega = \frac{\rho C_{\varepsilon 4}}{\beta_\infty^* \omega^2}\left(\sqrt{2S_{ij}S_{ij}}\right)^4 \tag{7}$$

The empirical constant β_∞^* was given the value of unity for the simulation of both wind turbines investigated in the paper. The results have been compared with those obtained from the standard k – ω model for various freestream wind speeds and turbulence levels. The modified k – ω model showed superiority to the standard k – ω model when compared with the available experimental data for 2 different small wind turbines for both near and far wake regions. This is probably the reason why some researchers used slightly different versions for the k – ω model in order to limit the production of turbulent kinetic energy by making it a function of the dissipation. In particular, Menter (1992) used a stress limiter modification in order to control the magnitude of the eddy viscosity. The definition of the eddy viscosity was given by:

$$\nu_t = \frac{k}{\bar{\omega}} \tag{8}$$

$$\bar{\omega} = max\left\{\omega, C_{lim}\sqrt{\frac{2S_{ij}S_{ij}}{\beta_\infty^*}}\right\} \tag{9}$$

Researchers, such as Huang (1999), showed that the above modification leads to better results for incompressible flows.

Other researchers, such as Speziale et al. (1992), used the so – called cross diffusion term given by:

$$S_\omega = \frac{\sigma_d}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i} \tag{10}$$

$$\sigma_d = \left\{\begin{matrix} 0, & \dfrac{\partial k}{\partial x_i}\dfrac{\partial \omega}{\partial x_i} \leq 0 \\ \sigma_{d0} & \dfrac{\partial k}{\partial x_i}\dfrac{\partial \omega}{\partial x_i} > 0 \end{matrix}\right\} \tag{11}$$

The source term in equation (10) has been proven to improve the results for wall bounded flows (Hellsten, 2005).

All things considered, employment of source terms or modifications to the standard k – ω model can be easily made to improve the accuracy of the results. In our paper, the source term, originally proposed by Chen and Kim (1987), has been employed in the k – ω model after a transformation and it has been proven that the results are improved significantly for the simulations of 2 different small wind turbine wakes.

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