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Including Thermal Effects in CFD Wind Flow Simulations

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Abstract

The calculation of the wind field for resource assessment is done by using CFD Reynolds-Averaged Navier-Stokes simulations performed with the commercial software WindSim. A new interface has been created to use mesoscale simulation data from a meteorological model as driving data for the simulations. This method makes it necessary to take into account thermal effects on the wind field to exploit the full potential of this method. The procedure for considering thermal effects in CFD wind field simulations as well as the impact of thermal effects on the wind field simulations is presented. Simulations for non-neutral atmospheric conditions with the developed method are consistent with expected behavior and show an improvement of simulation results compared with observations.

Key Words : Atmospheric stability, CFD (Computational Fluid Dynamics), Wind farm

1. Introduction

Most numerical models used for wind field simulations do not consider thermal effects. There are three main reasons for this: (1) The mean atmosphere is neutrally stratified, (2) There are often no available temperature measurements at the site of interest, making it impossible to judge the stratification of the atmosphere for use in the simulation. (3) The simulations often show convergence problems when the temperature is included.

Nevertheless, it is well known that in some areas, especially during winter time, the mean atmospheric conditions are far from being neutral. During winter time stable stratification often occurs which can affect the wind speed and the flow behavior. Many met masts are already equipped with temperature sensors at two different heights, which can give a rough estimation of the stratification in the area of interest.

Some studies began to include stability effects, but for a long time the CFD simulations were restricted to the stable atmospheric boundary layer$^{1)}$ as these situations are much easier to handle than the cases with unstable stratification. More recent CFD works deal also with unstable atmospheric conditions$^{2)}$. In principle the CFD code is able to capture thermal effects but the choice of the turbulence model is crucial to obtain reliable results. Many studies have been carried out to improve the k-ε turbulence model used in WindSim for stratified atmospheres$^{3\sim6)}$. For the wind energy sector the stable atmospheric conditions seem to be of more importance than the unstable conditions as stable atmospheric conditions are more likely to persist for extended periods of time than unstable ones.

Today mesoscale meteorological models deliver stratification information in a relatively high resolution (1~10 km) for past decades, and also as forecasts for the next days. This information can be used to improve the CFD simulations for a specific site. The boundary conditions for the wind speed and the temperature in the CFD simulation can be taken from the meteorological model. This leads to more realistic boundary conditions than assuming neutral profiles at the boun-

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daries as it has been done so far. Every mesoscale meteorological model can be used for coupling with WindSim which has a grid width from 1~10 km and provides temperature, pressure and the three wind speed components for the CFD simulation area. The data from the mesoscale model is interpolated onto the CFD grid taking into account the difference in height between the topography data sets of the mesoscale model and the CFD model. The roughness information can be taken over from the mesoscale model or a more detailed map with the resolution of the CFD model can be used. In meteorological models temperature is also a solved-for variable which means that this additional information can be used to improve the CFD simulations. But even without the additional information of meteorological models, the consideration of thermal stratification may help to improve CFD calculations.

Following is a description of the procedure to account for thermal effects in the commercial CFD micrositing tool WindSim, and the effect of atmospheric stratification on the simulation results is assessed for artificial as well as complex real orography.

2. Influence of thermal atmospheric stratification on the wind field

2.1. Change of the wind profile shape

Dependent on the thermal stratification the atmosphere can be classified in different stability classes; neutral, stable or unstable. The behaviour of the air flow is determined by the stability: In a stable atmosphere lifted air aims to sink back into the original position as the lifted parcel is colder then the surrounding air and in unstable conditions the lifted air parcel is warmer then the surrounding air and will keep on raising. In the neutral atmosphere the air parcel remains in the height where it has been lifted to.

The wind profile develops depending on the ratio of buoyancy force to shear force. The buoyancy force is related to thermal effects and the shear force is related to the dynamical effects. In the case of high buoyancy forces, the turbulence is quite strong and therefore the shear of the wind profile is reduced in an unstable atmosphere. In a stable atmosphere, the turbulence is less than in the neutral atmosphere and the wind speed increases compared to the neutral profile (Fig. 1).

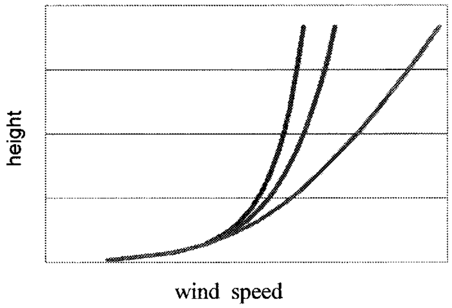

Fig. 1. Vertical wind speed profiles for unstable (left), neutral (middle) and stable conditions (right).

2.2. Blocking / lifting effects

When a thermally stratified air mass is flowing over a hill, blocking or lifting effects can occur. In a stably stratified atmosphere, the air which rises on the windward side of the hill is prevented from lifting due to buoyancy effects and the flow will go more around the hill than over, as in the neutral case.

In the case of unstable stratification, the rising air will continue to rise after being displaced because it is then warmer than the surrounding air.

3. Equations

To be able to simulate these stability effects in the wind flow and in the wind profile, the temperature equation needs to be solved explicitly in the CFD solver, and an additional term in the momentum, the turbulent kinetic energy, and the dissipation equation has to be added. The last two equations are used in WindSim to close the turbulence model. The wind profiles given at the inlets of the simulation area need to be consistent with the stratification.

3.1. Temperature equation

To take into account stability effects in the atmosphere the temperature equation is solved explicitly. Potential temperature is used instead of normal temperature as it has the advantage that the temperature gradient is always positive in stable conditions and negative in unstable conditions. The change of the mean potential temperature $\overline{\Theta}$ is influenced by advection, thermal diffusion and turbulent heat transfer:

$$\overline{u_i}\frac{\partial\overline{\Theta}}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\alpha\left(\frac{\partial\overline{\Theta}}{\partial x_i}\right)-\left(\overline{u_i'\Theta'}\right)\right) \tag{1}$$

Here $\overline{u_i}$ is the mean speed of the i-th wind component and u_i' the perturbation from the mean wind speed. Θ' is the perturbation from the mean temperature, and α is the kinematic molecular diffusivity for heat.

The turbulence term is parameterized by a flux-gradient relationship:

$$\left(\overline{u_j'\,\Theta'}\right)=-\frac{v_t}{\sigma_\Theta}\frac{\partial\overline{\Theta}}{\partial x_j} \tag{2}$$

Where v_t is the turbulent viscosity and σ_Θ is the turbulent Prandtl number for heat.

3.2. Momentum equation

The influence of temperature on the vertical wind speed is taken into account by the Boussinesq approximation. This means that the effect of varying density is only considered in the gravitational term of the equation. By solving the temperature equation a mean temperature $\overline{\Theta}$ is obtained which differs from the reference state of the atmosphere Θ_0. This difference Θ^* is used to determine the effect of buoyancy on momentum:

$$\overline{u_i}\frac{\partial\overline{u_3}}{\partial x_i}=\frac{\Theta^*}{\Theta_0}g-\frac{1}{\rho}\frac{\partial\overline{p}}{\partial x_3}+\frac{\partial}{\partial x_j}\left(\upsilon\left(\frac{\partial\overline{u}_3}{\partial x_j}+\frac{\partial\overline{u}_j}{\partial x_3}\right)-\left(\overline{u_3'u_j'}\right)\right) \tag{3}$$

g is the gravitational constant, ρ is the density, and p is the pressure.

3.3. Turbulent kinetic energy and dissipation equation

In the equation for turbulent kinetic energy k and the equation for dissipation ε of the k-ε model an additional temperature dependent term P_b is added:

$$\frac{\partial\overline{u_i\varepsilon}}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\frac{\upsilon_T}{\sigma_\varepsilon}\frac{\partial\overline{\varepsilon}}{\partial x_i}\right)+c_{\varepsilon 1}\frac{\varepsilon}{k}\left[P_k+c_{\varepsilon 3}P_b\right]-c_{\varepsilon 2}\frac{\varepsilon^2}{k}$$

$$\frac{\partial\overline{u_ik}}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\frac{\upsilon_T}{\sigma_k}\frac{\partial\overline{k}}{\partial x_i}\right)+P_k+P_b-\varepsilon \tag{4}$$

$$P_b=-\frac{\upsilon_T}{\sigma_\Theta}g\frac{1}{\overline{\Theta}}\frac{\partial\overline{\Theta}}{\partial x_3}$$

P_k is the turbulent production term, and σ_ε, $C\epsilon 1$, $C\epsilon 2$, $C\epsilon 3$, and σ_θ are model constants. Details about P_k and the constants can be found in the article of Gravdahl[7].

3.4. Inlet wind profiles

In a model with a large extension the changes in the wind speed profile due to stability effects will develop gradually from the inflow border where a logarithmic wind profile is given when the full range of equations are applied. To be able to run smaller models it is necessary to give stability dependent wind speed profiles already at the inlet.

These stability dependent wind speed profiles at the inlet can be described by adding a stability dependent term to the logarithmic law:

$$\overline{u}(z)=\frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right)-\Psi_m\left(\frac{z}{L},\frac{z_0}{L}\right)\right] \tag{5}$$

where $\overline{u}(z)$ is the mean wind velocity in inflow direction depending on the height z , κ is the von Karman constant with a value of 0.4, z_0 is the roughness length depending on the land use, u_* is the friction velocity and L is the Monin-Obukhov length. Ψ is an additional term depending on the stability of the atmosphere. This term can be described by[8] :

$\Psi_m=-4.7\left(\frac{z}{L}-\frac{z_0}{L}\right)$ for stable conditions $(\frac{z}{L}>0)$

$\Psi_m=0$ for neutral conditions $(\frac{z}{L}=0)$

$$\Psi_m=2\ln\left[\frac{1+x}{1+x_0}\right]+\ln\left[\frac{1+x^2}{1+x_0^2}\right]-2\arctan(x)+2\arctan(x_0) \tag{6}$$

for unstable conditions $(\frac{z}{L}<0)$

with

$$x=\left[1-\left(15\frac{z}{L}\right)\right]^{1/4}$$

and

$$x_0 = \left[1-\left(15\frac{z_0}{L}\right)\right]^{1/4}$$

To calculate the vertical velocity profiles, the wind speed at a certain height and the Monin-Obukhov leceth have to be givecleWith these values the friction velocity u_* to be gcalculatedleWith u_* the boundary layer profilesthe Moniturbulect kinetic ecergy k and the dthsipation rate ε can be calculated from the equations given in Huser et al. [1]:

$$k = \frac{u_*^2}{\sqrt{c_\mu}}\left(1-\frac{z}{h}\right)^2 \qquad (7)$$

$$\varepsilon = \frac{u_*^3}{\kappa}\left(\frac{1}{z}\right)$$

where h is the height of the ABL in stable conditions and c_μ is a constant with the value of 0.09.

4. Examples

4.1. Artificial orography: cosine hill

Simulations were performed for a cosine hill with a height of 200 m and a length at the surface of 800 m. The hill was centered in an area of 4,000 × 4,000 m with 40 m grid width. To investigate the pure effect of the thermal stratification the inlet wind speed profile was the same for the neutral and the stable case and only a linear potential temperature gradient was given in the stable case with an increase of potential temperature of 2 K/100 m. The inflow wind direction was 270 K. The inlet wind speed profile is a logarithmic wind profile with a roughness of 0.03 m and a wind speed of 10 m/s at 500 m.

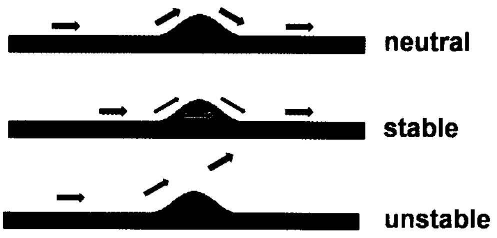

Fig. 2. Behavior of the flow for different stratifications of the atmosphere.

The vertical component of the wind speed shows a significant decrease at the windward side of the mountain for the stable atmosphere (Fig. 3). The lifting of air is reduced. The v component of the wind speed increases at the same side which means that the wind is blowing more around the mountain in the stable atmosphere (Fig. 4).

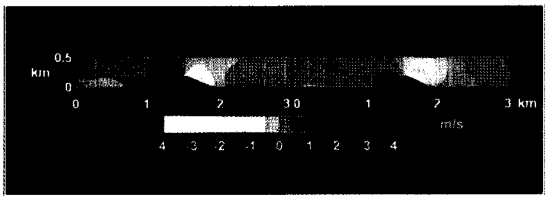

Fig. 3. W-component of the wind speed for the simulation with neutral (left) and stable (right) stratification. The wind is blowing from left to right.

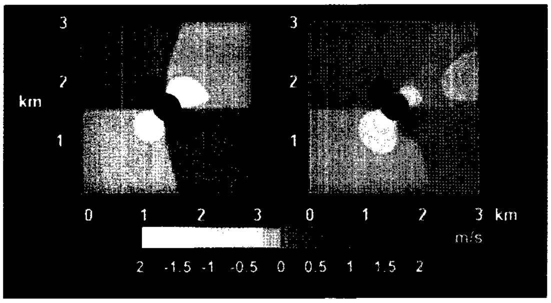

Fig. 4. V-component of the wind speed for the simulation with neutral (left) and stable (right) stratification. The wind is blowing from left to right.

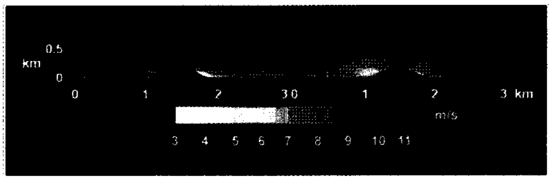

Fig. 5. U-component of the wind speed for the simulation with neutral (left) and stable (right) stratification. The wind is blowing from left to right.

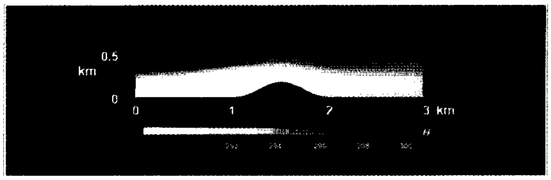

Fig. 6. Temperature distribution for stable stratification.

The main horizontal wind component u is reduced in value especially at the hill top where one can find normally the highest wind speeds (Fig. 5). The temperature distribution shows a lifting of the cold air on the wind-ward side of the hill in stable conditions (Fig. 6).

4.2. Real complex terrain: Hundhammerfjellet

Data from a measurement mast at Hundhammerfjellet wind farm in Norway is used to evaluate WindSim simulations with and without consideration of stability effects (Fig. 7). In this area the atmosphere is often stable stratified. Wind speed measurements for 30, 73 and 83 m height, and temperature measurements for 50 and 83 m are available for the period from April 2006 to January 2007.

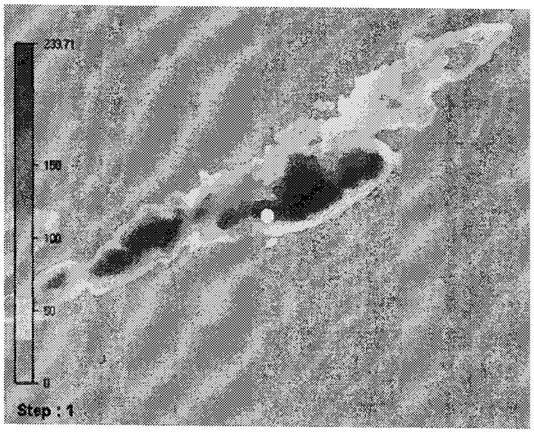

Fig. 7. Hundhammerfjellet area. The met mast is marked by a white dot.

From this data the atmospheric stability was calculated for the wind sectors (Table 1). Only four sectors can be found in which the atmosphere istmosphereover mosteof the days. In erreother 8 sectors the atmosphere isthereoveover the whole invesdag days period. Simulatays there performed he atthe defaultund iSim where no temperature effect there d cluded,tmosphe atthe asvmoced nd iSim d cludd gtthermereeffect tfor erre12 sectors. The asvmoced simulatays terke d to account a moderate leveleof stability. The resultseof the simulatays tmospthe measurement tmre scaled against the wind speed in 73 m to compare the relative behavior of the wind profile.

The default simulations show good results for the neutral sectors, but large deviations from the observations can be seen for the sectors with stable atmospheric conditions (Fig. 8).

For the sectors with stable atmospheric conditions, the simulations with the advanced WindSim show much better results than the default WindSim when compared to the observations (Fig. 9).

The better fit of the advanced WindSim in stable atmospheric conditions can be explained as follows: For the wind directions with stable stratification where the wind is blowing almost perpendicular to the long hill axis the default WindSim produces to high speed-up close to the surface at the hill top where the met mast is positioned. This high speed up cannot be seen in the measurements. In the advanced WindSim simulation with stable atmosphere this speedup is prevented as the flow goes more around the mountain then over it due to the blocking effect and the simulation results fit well with the observations in the 30 m measurement height.

From this comparison it can be concluded that the inclusion of temperature effects in wind field simulations can enhance the simulation results markedly.

5. Conclusions

Thermal atmospheric stratification can now be considered in CFD wind field calculations with the commercial software WindSim. The temperature equation is solved explicitly and the wind profiles at the inlets are calculated to be stability dependent. This can be of importance in areas where the atmosphere is non-neutrally stratified during large parts of the year,

Table 1. Wind sectors with neutral (n) and stable (s) stratification

Sector (degree)	0	30	60	90	120	150	180	210	240	270	300	330
Stability	s	s	s	s	s	s	s	n	n	n	n	s

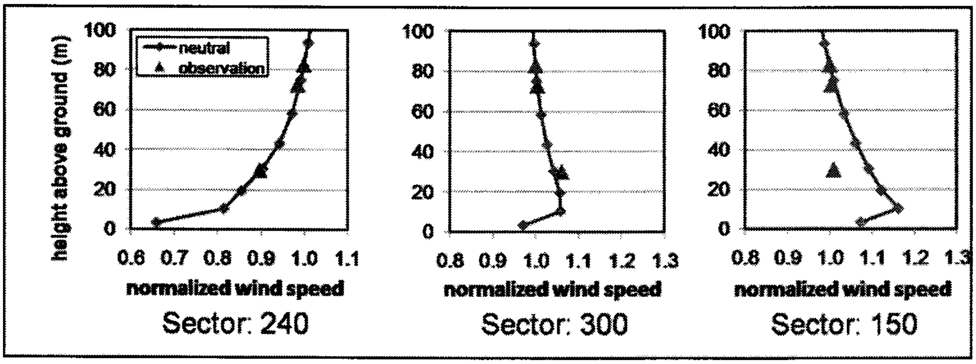

Fig. 8. Simulations without consideration of thermal effects (line with diamonds) and measurements (triangles) of wind speed for sectors with neutral (left, middle) and stable (right) stratification. The wind speed is normalized against the measured wind speed in 73 m.

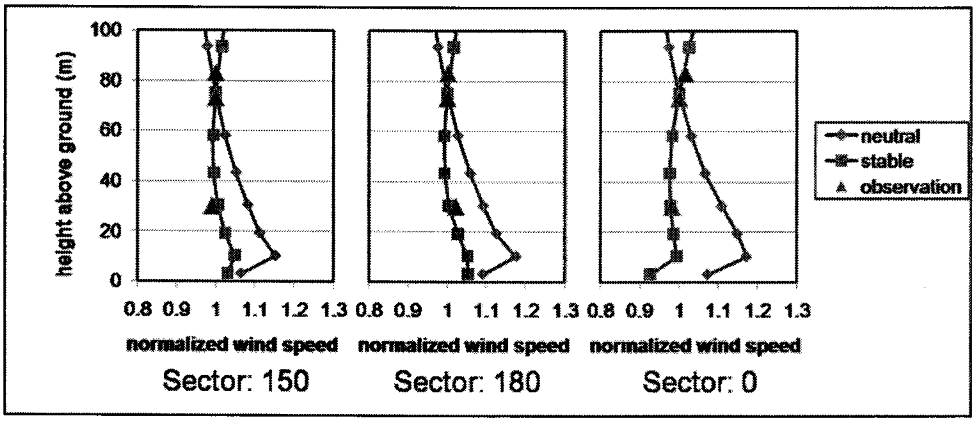

Fig. 9. Simulations with (line with rectangles) and without (line with diamonds) consideration of thermal effects, and observations (triangles) of wind speed for sectors with stable stratification. The wind speed is normalized against the measured wind speed in 73 m.

e.g. in regions with snow cover during winter time.

The method shows the expected results and blocking effects of mountains on the wind flow in stable atmospheric conditions can be simulated. When compared with measurements, the simulation results for wind speed with thermal effects fit better than without thermal effects for cases with known stable conditions.

The developed method can be used also for the coupling of WindSim with mesoscale meteorological models.

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References

1) Huser A., Nilsen P. J., Skåtun H., 1997, Application of k-ε model to the stable ABL: Pollution in complex terrain, J. Wind. Eng. Ind. Aerodyn., 67&68, 425-436.
2) Alinot C., 2003, Analyse aérodynamique des parcs éoliens immerges dans une couche limite terrestre ayant différentes conditions de stabilité thermique, Ph.D. Thesis, University of Quebec, Canada.
3) Duynkerke P., 1988, Application of the E - ε turbulence closure model to the neutral and stable atmospheric boundary layer, J. Atmos. Sci., 45, 865-880.
4) Thanh V., Ashie Y., Asaeda T., 2002, A k-ε turbulence closure model for the atmospheric boundary layer including urban canopy, Boundary Layer Meteor., 102,

459-490.

5) Apsley D. D., Castro I. P., 1997, A limited-length scale k- ε model for the neutral and stably-stratified atmospheric boundary layer. Boundary Layer Meteor., 83, 75-98.

6) Baklanov A., 2000, Application of CFD methods for modelling in air pollution problems: possibilities and gaps, J. Environmental Monitoring and Assessment, 65, 181-189.

7) Gravdahl A., 1998, Mesoscale modeling with a reynolds averaged navier stokes solver, 31th IEA Experts Meeting, Risoe Denmark.

8) Businger J., Wyngaard J., Izumi Y., Bradley E., 1971, Flux-Profile Relationships in the Atmospheric Surface Layer, J. Atmos. Sci., 28, 181-189.