

# Including thermal effects in CFD simulations

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## Summary of the work

The calculation of the wind field for resource assessment is done by using CFD RANS 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.

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 simulations were restricted to the stable atmospheric boundary layer (Huser et al. [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 (Alinot et al. [2]). 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 boundaries as has been done so far. 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 micro-siting 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

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).

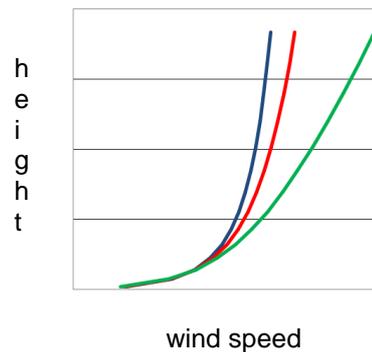


Fig. 1 : Vertical wind speed profiles for unstable (blue), neutral (red) and stable conditions (green).

### 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.

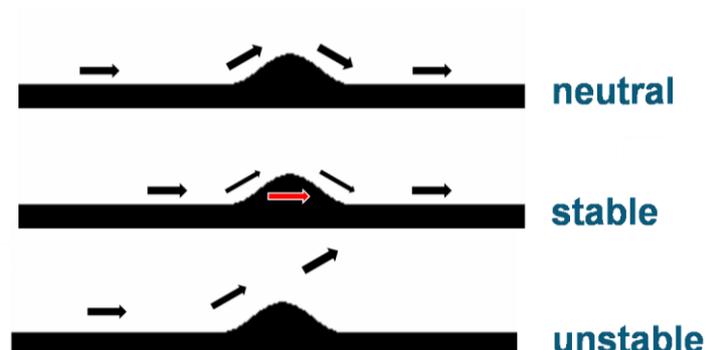


Fig. 2: Behavior of the flow for different stratifications of the atmosphere.

### 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  $\bar{\Theta}$  is influenced by advection, thermal diffusion and turbulent heat transfer:

$$\bar{u}_i \frac{\partial \bar{\Theta}}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \alpha \left( \frac{\partial \bar{\Theta}}{\partial x_i} \right) - \overline{u_i' \Theta'} \right)$$

Here  $\bar{u}_i$  is the mean speed of the i-th wind component and  $u_i'$  the perturbation from the mean wind speed.  $\Theta'$  is the perturbation from the mean temperature, and  $\alpha$  is the kinematic molecular diffusivity for heat.

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

$$\overline{u_j' \Theta'} = - \frac{\nu_t}{\sigma_\Theta} \frac{\partial \bar{\Theta}}{\partial x_j}$$

Where  $\nu_t$  is the turbulent viscosity and  $\sigma_\Theta$  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  $\bar{\Theta}$  is obtained which differs from the reference state of the atmosphere  $\Theta_0$ . This difference  $\Theta^*$  is used to determine the effect of buoyancy on momentum:

:

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

$g$  is the gravitational constant and  $\rho$  is the density.

### 3.3 Turbulent kinetic energy and dissipation equation

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

$$\begin{aligned}\frac{\partial \overline{u_i \varepsilon}}{\partial x_i} &= \frac{\partial}{\partial x_i} \left( \frac{\nu_T}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_i} \right) + c_{\varepsilon 1} \frac{\varepsilon}{k} P_k + c_{\varepsilon 3} P_b - c_{\varepsilon 2} \frac{\varepsilon^2}{k} \\ \frac{\partial \overline{u_i k}}{\partial x_i} &= \frac{\partial}{\partial x_i} \left( \frac{\nu_T}{\sigma_k} \frac{\partial k}{\partial x_i} \right) + P_k + P_b - \varepsilon \\ P_b &= -\frac{\nu_T}{\sigma_\Theta} g \frac{1}{\Theta} \frac{\partial \Theta}{\partial x_3}\end{aligned}$$

### 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:

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

Where  $\bar{u}(z)$  is the mean wind velocity in inflow direction depending on the height  $z$ ,  $\kappa$  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.  $\Psi$  is an additional term depending on the stability of the atmosphere. This term can be described by (Businger et al. 1971 [3]):

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

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

$$\Psi_m = 2 \ln \left[ \frac{1+x}{1+x_0} \right] + \ln \left[ \frac{1+x^2}{1+x_0^2} \right] - 2 \arctan(x) + 2 \arctan(x_0) \text{ for unstable conditions } \left( \frac{z}{L} < 0 \right)$$

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

To calculate the vertical velocity profiles, the wind speed at a certain height and the Monin Obukhov length have to be given. With these values the friction velocity  $u_*$  can be calculated. With  $u_*$  the boundary layer profiles of the turbulent kinetic energy  $k$  and the dissipation rate  $\varepsilon$  can be calculated from the equations given in Huser et al. (1997):

$$\begin{aligned}k &= \frac{u_*^2}{\sqrt{c_\mu}} \left( 1 - \frac{z}{h} \right)^2 \\ \varepsilon &= \frac{u_*^3}{\kappa} \left( \frac{1}{z} \right)\end{aligned}$$

where  $h$  is the height of the ABL in stable conditions and  $c_\mu$  is a constant with the value of 0.0324.

## 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 4000x4000 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 2K/100m. The inflow wind direction was 270 degrees.

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 y 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). The main horizontal wind component is reduced in value especially at the hill top where one can find normally the highest wind speeds (Fig. 5).

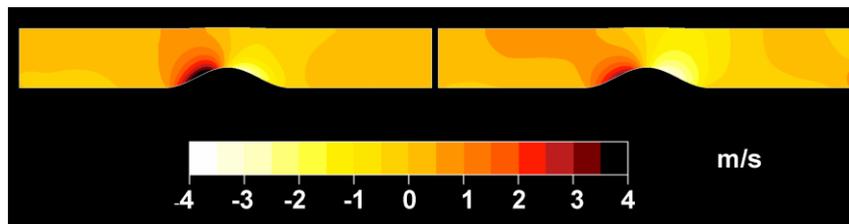


Fig. 3: W-component of the wind speed for the simulation with neutral (left) and stable (right) stratification. The wind is blowing from left to right.

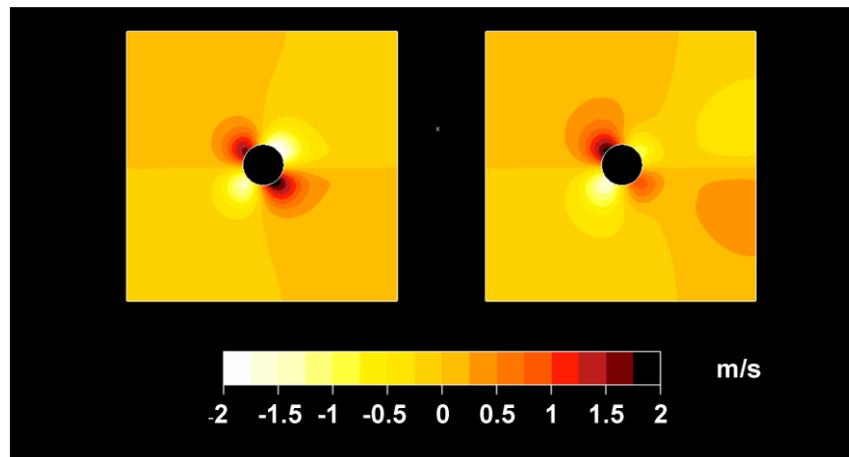


Fig. 4: V- component of the wind speed for the simulation with neutral (left) and stable (right) stratification. The wind is blowing from left to right.

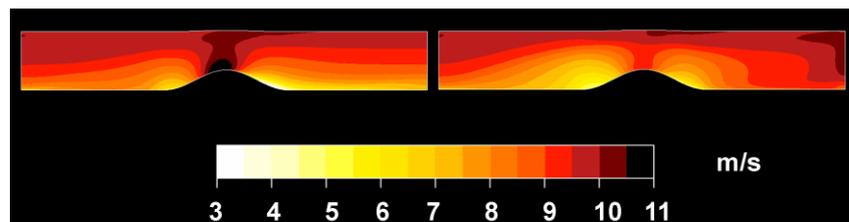


Fig. 5: U- component of the wind speed for the simulation with neutral (left) and stable (right) stratification. The wind is blowing from left to right.

#### 4.2 Real complex terrain: Hundhammerfjellet

Data from a measurement mast at Hundhammerfjellet wind farm (Norway) is used to evaluate WindSim simulations with and without consideration of stability effects (Fig. 6). 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.

From this data the atmospheric stability was calculated for the wind sectors (Tab.1). Only four sectors can be found in which the atmosphere is neutral over most of the days. In all other 8 sectors the atmosphere is stable over the whole investigation period. Simulations were performed with the default WindSim where no temperature effects were included, and with the advanced WindSim including thermal effects for all 12 sectors. The advanced simulations take into account a moderate level of stability. The results of the simulations and the measurements are 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. 7).

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

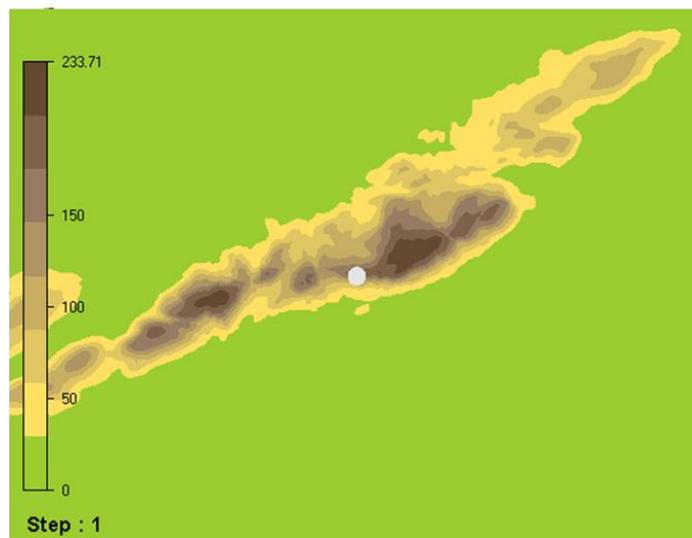


Fig. 6: Hundhammerfjellet area. The met mast is marked by a grey dot.

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

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

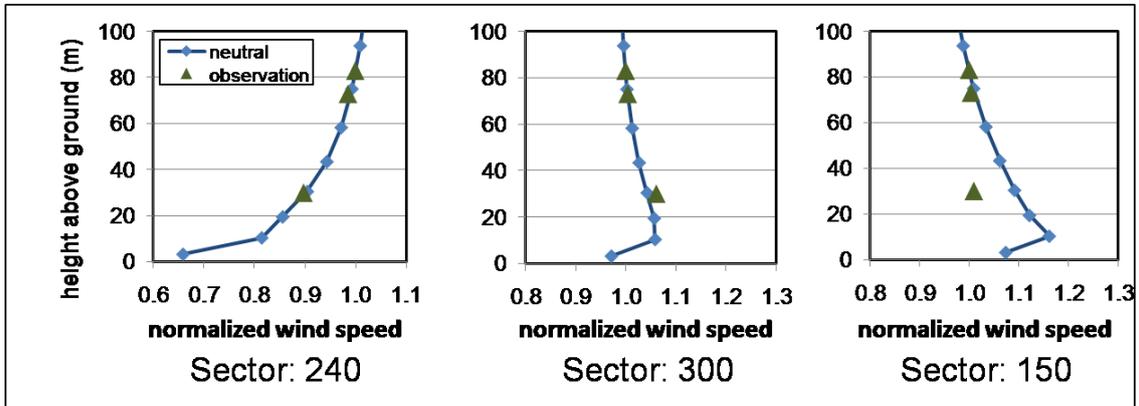


Fig. 7: Simulations without consideration of thermal effects (blue) and measurements (green) for sectors with neutral (left, middle) and stable (right) stratification.

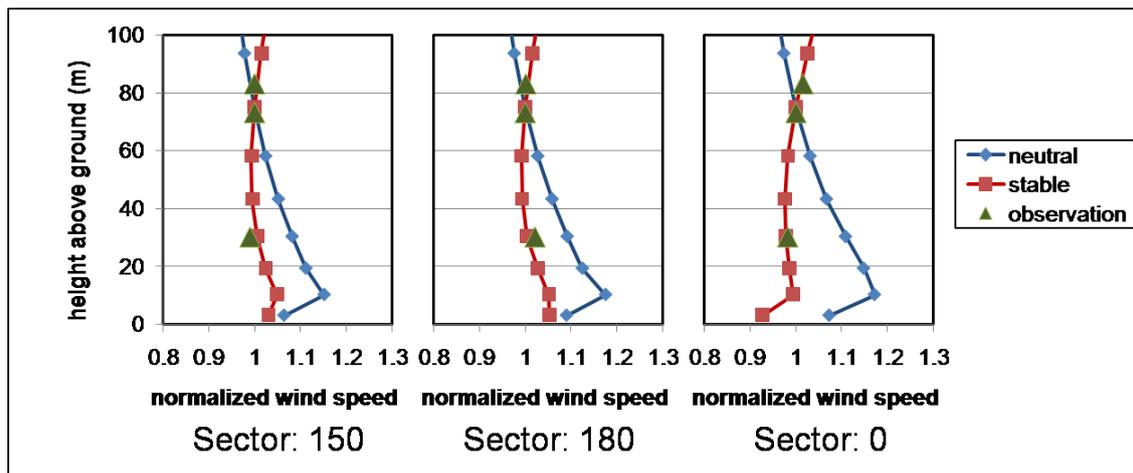


Fig. 8: Simulations with (red) and without (blue) consideration of thermal effects, and observations (green) for sectors with stable stratification.

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

The method shows the expected results and blocking effects of mountains in stable atmospheric conditions can be simulated. When compared with measurements, the simulation results with thermal effects fit better than without for cases with known stable conditions. The developed method can be used also for the coupling of WindSim with mesoscale meteorological models.

## 6 Acknowledgement

The authors want to thank the Nord-Trøndelag Elektrisitetsverk for providing the measurement data.

## 7 References

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