# Numerical simulation of offshore wind farm clusters

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## Summary

With the large amount of offshore wind farms to be built in the next years, clusters of wind farms will appear at favourable locations. In such clusters, the interaction between the neighboring wind farms affects the wind speed deficit and therefore the energy production of the downstream installations. In order to quantify this effect, a coupling between the microscale models of the wind farm scale and the mesoscale models of the cluster scale is needed. In the wind farm scale, a Navier-Stokes solver with k-ω turbulence closure and an actuator disk approach is used. For an accurate thrust estimation the reference velocities must be calculated at the position of each wind turbine as if the specific turbine was absent. If turbines are installed in parallel rows, as in offshore wind farms, turbine rows can be considered instead of single turbines. Instead of performing repeated simulations, turbine rows are activated successively in only one simulation in order to reduce the computational cost. To couple the predictions of this model with the cluster scale, the momentum theorem is applied to a volume surrounding the wind farm so that an equivalent thrust coefficient is estimated. Application to the Horns Rev wind farm for the western wind directions showed that the mean value of the equivalent thrust coefficient in a sector of $\pm 15^o$ is close to the equivalent thrust coefficient of the mean wind direction. Validation of the method was made by using the estimated equivalent thrust coefficients to simulate the effect of the wind farm in the cluster scale. The comparison between the velocity profiles suggests that the representation of the wind farm with an equivalent thrust coefficient in the cluster scale is acceptable.

## 1 Introduction

Due to the growing demand for offshore wind energy capacity, interactive wind farm clusters will unavoidably appear at favorable locations. The design of such clusters poses new challenges regarding the siting of the neighboring wind farms. In the context of the EERA-DTOC project new software tools will be developed and integrated for optimal design of offshore wind farms and clusters. The interaction between neighboring wind farms affects the speed deficit and the power production of the downstream installations. In order to quantify this interaction the present work aims at the coupling between the wind farm and the cluster scale through numerical simulation.

In the context of the UpWind project [1], several models were used to simulate large wind farms offshore and in complex terrain, from the simple engineering to the most advanced ones. The degree of complexity of these models started from the well known and straightforward WAsP model [2], increased to the moderately complex Ainsle-based WindFarmer [3], to the more complex WAKEFARM [4], that is based on the parabolized Navier–Stokes equations, and finally reached the advanced Fluent, 3D–NS [5] and CRES-flowNS [6] models, which solve the complete 3D Navier–Stokes equations. As regards the offshore wind farms, predictions were compared with measurements for the western wind directions at various sector widths around $270^o$ from the Horns Rev [1],[7] and Nysted [1] wind farms. Despite the fact that a thorough assessment turned out to be extremely difficult due to the large uncertainties of the measurement data due to the atmospheric conditions, results showed that wake losses in the centre of large wind farms offshore are larger than modeled using standard wind farm model parameterizations but, once corrected, model results were improved in comparison with data from existing data sets [1]. Analyses of the wind farm data also showed the primary importance of wind speed on wake development, but also that turbulence and atmospheric stability play an important role in determining the magnitude of wake losses in wind farm offshore.

From the modeling point of view, the EERA-DTOC project aims first at improving and further evaluating the numerical models in the wind farm scale, and then at coupling their results with the mesoscale models in order to simulate the interaction between neighboring wind farms in the cluster scale. In the present work, these two issues are addressed: First, the existing CFD model CRESflow-NS [6] is further developed in order to perform more accurate and fast simulations of large offshore wind farms. Then, the method is applied to the simulation of the Horns Rev wind farm. An equivalent thrust is evaluated to represent the effect of the wind farm on the downstream velocity field which acts as a momentum sink on the coarse mesoscale mesh. In this way the microscale wind farm information is transformed to mesoscale.

# 2 The numerical model

## 2.1 The wind farm scale model

Navier-Stokes calculations are performed for assessing performance at the wind farm scale. Each farm is enclosed in a computational domain with assumed known inflow conditions, corresponding to the downstream conditions of the affecting upstream installations. The employed code, CRESflow-NS [6], is using the k-ω turbulence model and the actuator disk theory for the simulation of the embedded wind turbines and has been applied to the simulation of single wind turbine wakes, as well as small and large wind farms in flat and complex terrain [8],[9]. The momentum equations are numerically integrated introducing a matrix-free pressure correction algorithm which maintains the compatibility of the velocity and pressure field corrections. Discretization is performed with a finite volume technique using a body-fitted coordinate transformation on a curvilinear mesh. Convection terns are handled by a second order upwind scheme bounded through a limiter, whereas centred second order schemes are employed for the diffusion terms. Velocity-pressure decoupling is prevented by a linear fourth order dissipation term added into the continuity equation. The *k-ω* turbulence model has been suitably modified for neutral atmospheric conditions [10]:

$$\begin{aligned} &\alpha = 0.3706, \quad \beta = 0.0275, \quad \beta_* = 0.033, \\ &\sigma = 0.5, \quad \sigma_* = 0.5 \end{aligned} \tag{1}$$

According to the actuator disk approach, the rotor of each wind turbine is simulated as a disk discretized by a number of control volumes. Each control volume acts as a momentum sink through the actuator force calculated using the following relationship:

$$F = 0.5\rho\, U_{ref}^2\, C_T\, \Delta S \tag{2}$$

where $\rho$ stands for the air density, $U_{ref}$ is the reference wind speed for the thrust coefficient calculation, $C_T$ is the thrust coefficient and $\Delta S$ is the surface area of the control volume. One of the major challenges in the actuator disk theory is the determination of the reference velocity for thrust calculation.

The most accurate way is to calculate the velocity at the position of each wind turbine as if the specific turbine was absent. In offshore wind farms, wind turbines are mostly installed in parallel rows, so turbine rows can be considered instead of single turbines. A parabolic procedure is then applied: First, a run is performed without turbines to estimate the reference velocities at the positions of the first row. Then, the actuator disks are activated at the first row, and a second run is performed to estimate the reference velocities at the second row. This procedure is repeated until all turbine rows are added. However, such a procedure demands a number of independent runs equal to the number of turbine rows which is a very time consuming procedure. In the present work, only one run is performed, with a successive activation of turbine rows when a certain convergence criterion is fulfilled for the velocities at the specific positions of that row. Thus, the total computational time is significantly reduced.

## 2.2 The coupling between wind farm and cluster scale model

The target of the present work is to couple the wind farm and the cluster scale by introducing the results of the microscale model to the mesoscale model in an efficient way. Figure 1 shows two indicative meshes for the micro- and meso- scale models respectively in the xy-directions. As a result of the different scales the whole wind farm may be included in few numerical cells of the mesoscale model. In the vertical direction, mesoscale models use a finer discretization which means that more grid lines can be encountered in the space between the ground and the top height of the wind turbines.

In order to do the coupling, a volume surrounding the whole wind farm is first considered and the momentum theorem is applied by using the velocities predicted by the microscale model. A total thrust representing the effect of the wind farm is estimated which corresponds to the velocity deficit due to the presence of the wind farm. In addition, an equivalent thrust coefficient can be determined by selecting an equivalent surface area (Figure 2). A reasonable strategy is to select the equivalent surface area as shown in Figure 2, namely a yz-intersection of the surrounding volume which surrounds all the rotors visible from the upwind side of the farm. The exact position of the equivalent surface actually is not important since all parallel yz-surfaces have the same area. The estimated thrust is introduced to the coarse mesoscale mesh as a momentum sink to the numerical cells which are located closest to the middle of the wind farm (Figure 3). In this way the microscale wind farm information is transformed to mesoscale.

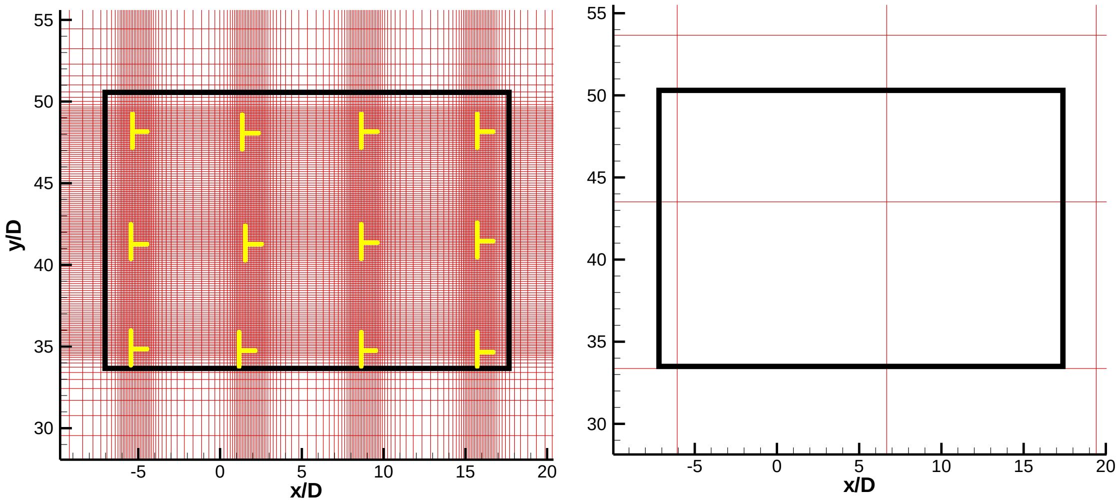


Figure 1: Indicative meshes for the wind farm scale (microscale) and the cluster scale (mesoscale) model. The black box indicates the extent of the wind farm. Wind turbines are marked with yellow color.

# 3 Application to the Horns Rev offshore wind farm

The numerical method is applied to the Horns Rev offshore wind farm [6] which comprises 80 wind turbines, arranged in a regular array of 8 by 10 turbines, with a spacing of 7 diameters in both directions. The layout of the wind farm is shown in Figure 4, where it can be seen that the direction of the N-S columns is 353°. The western wind directions are simulated by using the CRES-flowNS microscale model. For the wind directions in the range $270^o$-$285^o$, it is demonstrated that simulating the 3 northern rows 01, 02 and 03 (W-E direction) of the wind farm is sufficient, because the effect of the wakes from the rows 04-08 is negligible. Similarly, for the wind directions in the range $255^o$-$265^o$, simulating the 3 southern rows 06, 07 and 08 (W-E direction) of the wind farm is sufficient because the effect of the wakes from the rows 01-05 is negligible. The northern and southern simulated parts are indicated by the blue boxes in Figure 4.

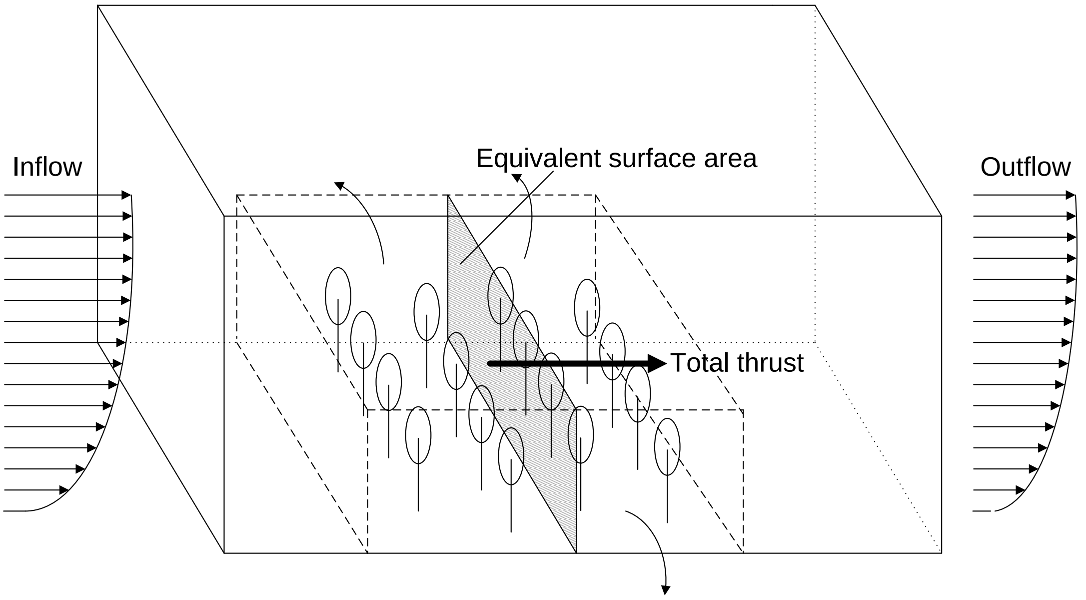


Figure 2: Calculation of the total thrust and the equivalent thrust coefficient by applying the momentum theorem to a volume surrounding the wind farm

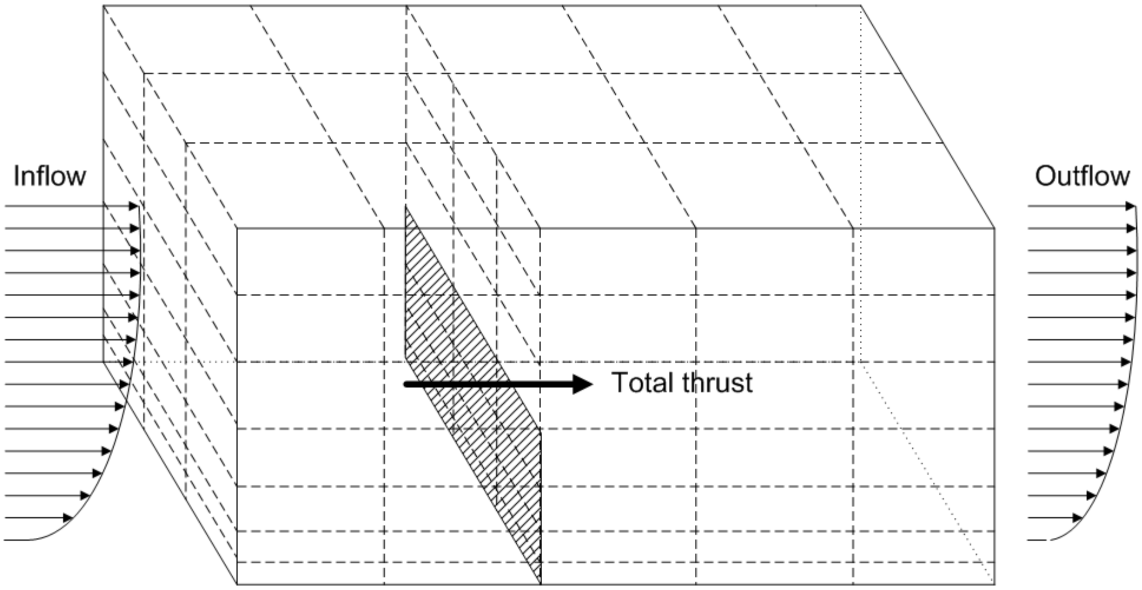


Figure 3: Coupling between the wind farm and the cluster scale models. The total thrust estimated from the wind farm model is applied to the numerical cells of the cluster scalemodel.

CRES-flowNS is used by applying the successive activation procedure of the wind turbine rows, which are the N-S columns in this case. The relative velocity errors between the current and the previous time step is calculated at the three positions of each column. When their maximum value becomes lower than $5 \cdot 10^{-6}$ the next wind turbine column is activated. For the wind direction of $273.75^{o}$, the convergence of the momentum equations is shown in Figure 5. The peaks correspond to the activation of each wind turbine column.

After convergence, the momentum theorem is applied on a volume surrounding the wind farm. This volume is a parallelepiped including all wind turbine rotors as shown in Figure 2. The total thrust of the wind farm is calculated and the equivalent thrust coefficient $C_T$ is estimated through

Equation (2) using the equivalent surface area. For the different wind directions in the range 253.75$^{o}$ - 286.25$^{o}$ the estimated thrust coefficients are given in Table 1. By averaging these values it follows that the mean equivalent $C_T$ in the sector 253.75$^{o}$ - 286.25$^{o}$ ($C_T$=0.243) is close to the equivalent $C_T$ of the mean wind direction 270.0$^{o}$ ($C_T$=0.249).

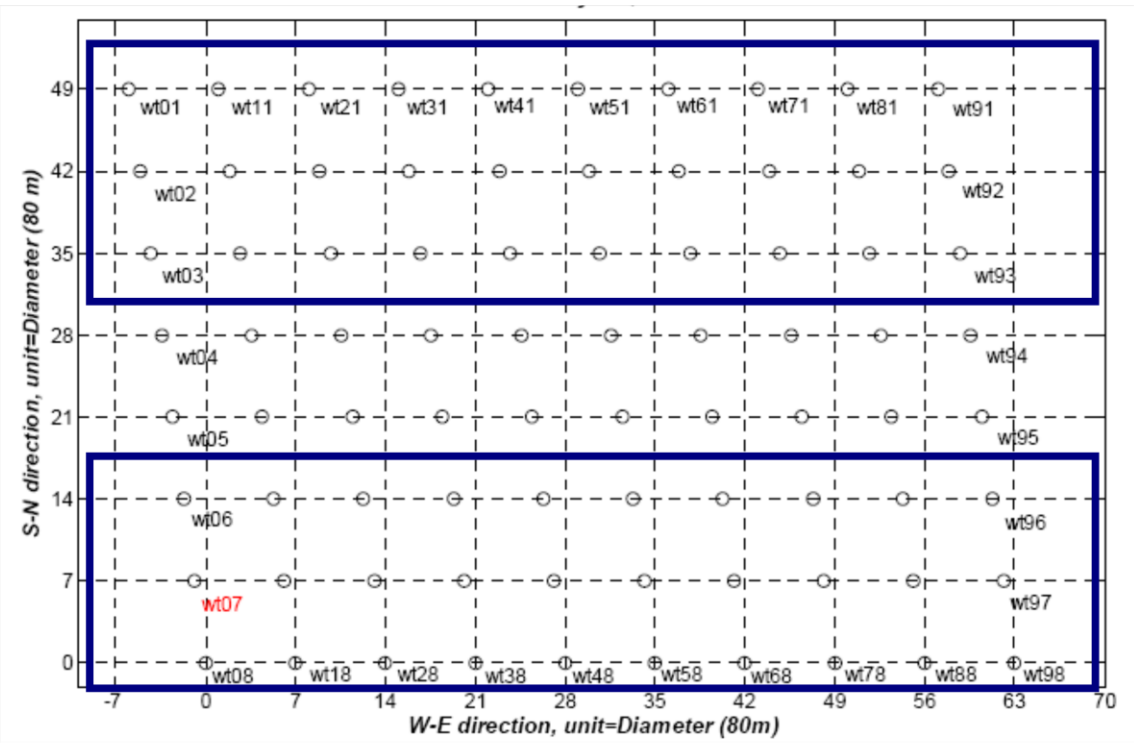


Figure 4: The layout of the Horns Rev wind farm. Internal spacing between wind turbines is 7D (diameters) in both directions. The blue boxes show the two simulated parts of the wind farm. The northern part is used for wind directions 270$^{o}$-286.25$^{o}$ and the southern part is used for wind directions 253.75$^{o}$-268.75$^{o}$

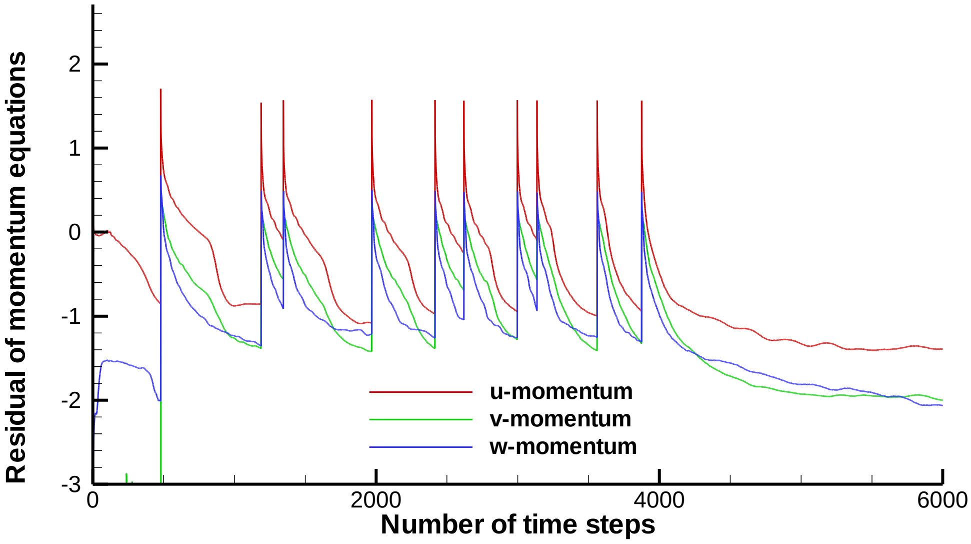
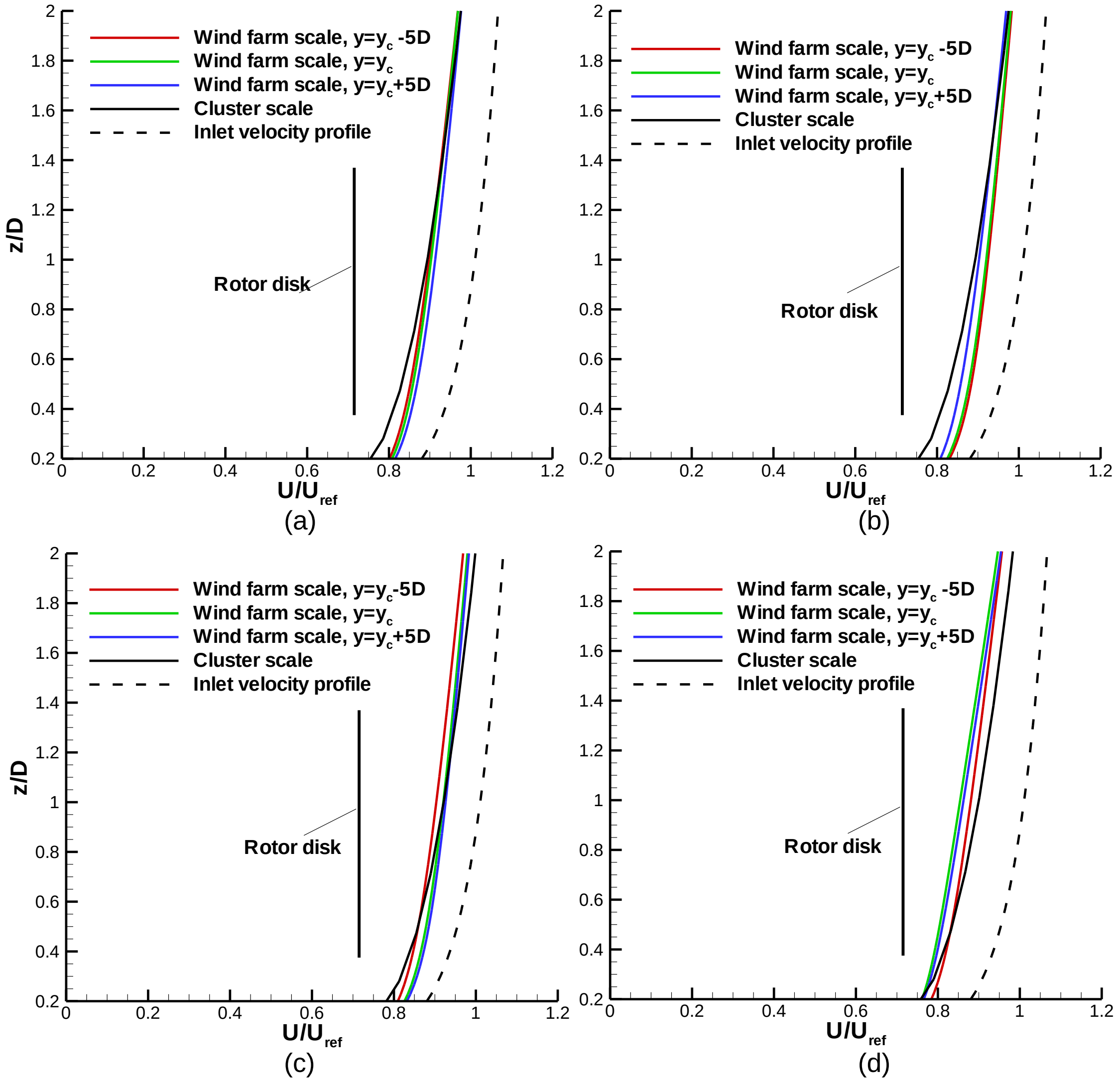


Figure 5: Convergence of the momentum equations for the 273.75$^{o}$ wind direction. The appearance of peaks indicate the activation of each wind turbine column.

| Wind direction | Equivalent $C_T$ | Wind direction | Equivalent $C_T$ |
|---|---|---|---|
| 253.75 | 0.225 | 271.25 | 0.236 |
| 256.25 | 0.239 | 273.75 | 0.248 |
| 258.75 | 0.263 | 276.25 | 0.178 |
| 261.25 | 0.274 | 278.75 | 0.254 |
| 263.75 | 0.277 | 281.25 | 0.246 |
| 266.25 | 0.254 | 283.75 | 0.232 |
| 268.75 | 0.230 | 286.25 | 0.233 |
| 270.0 | 0.249 | | |

Table 1: Equivalent thrust coefficients of the Horns Rev wind farm for the various western wind directions.



(a)

(b)

(c)

(d)

Figure 6: Comparison of the velocity profiles between the wind farm and the cluster scale models 35D downstream of the Horns Rev wind farm. The three profiles of the wind farm scale model correspond to three different lateral positions, one in the center (y= $y_c$) and the other two at 5D from both sides of the central position. (a) Wind direction 258.75$^o$, (b) Wind direction 263.75$^o$, (c) Wind direction 276.25$^o$ and (d) Wind direction 281.25$^o$

In order to validate the method the equivalent thrust coefficients should be applied to the mesoscale model and the velocity profiles should be compared at the same positions downstream of the wind farm. In the present work the microscale model with a coarse mesh is used instead of a mesoscale model. The velocity profiles are compared at three positions located approximately 35D downstream of the last wind turbine of the wind farm. The y-coordinates of these positions are selected one in the center of the wind farm ($y=y_c$) and the other two at 5D from both sides of the central position ($y=y_c \pm 5D$). The comparison for 4 wind directions ($258.75^o$, $263.75^o$, $276.25^o$ and $281.25^o$) is shown in Figure 6, where the inlet velocity profile has been also plotted. It can be observed that the velocity profiles calculated from the cluster scale model (microscale model with coarse mesh) using the estimated equivalent thrust coefficients are close the profiles calculated from the wind farm scale model (microscale model with fine mesh). Therefore, the representation of the wind farm with an equivalent thrust coefficient can be considered acceptable.

# 4 Conclusions

The coupling between the wind farm and the cluster scale was investigated in the present work. First, an accurate and cost efficient method was developed for the determination of the wind turbine reference velocities in a wind farm simulation, so that the thrust is well estimated when the actuator disk theory is used. This method activates successively the parallel wind turbine rows of an offshore wind farm when a specific criterion for the convergence of the reference velocities is satisfied. Application was made to the Horns Rev offshore wind farm for the western wind directions by simulating two parts of the farm, each one comprising 30 wind turbines, a northern part for the sector $270^o$-$286.25^o$ and a southern part for the sector $253.75^o$-$268.75^o$.

Next, a method was developed for the estimation of an equivalent thrust coefficient which can be used to represent the effect of a wind farm in the cluster scale. This method applies the momentum theorem to a volume surrounding the wind farm in order to calculate the total thrust and then estimates the equivalent thrust coefficient using an equivalent surface area. Application was made to the simulation of the Horns Rev offshore wind farm for different wind directions. It was shown that the mean value of the equivalent thrust coefficient in the sector $253.75^o$ - $286.25^o$ is close to the equivalent thrust coefficient of the mean wind direction $270^o$. Furthermore, the method was validated by using the estimated equivalent thrust coefficients to simulate the effect of the wind farm in the cluster scale model. Instead of a mesoscale model, the miscroscale model with a coarse mesh was used. The comparison between the calculated velocity profiles from the wind farm and the cluster scale models was good suggesting that the representation of the wind farm with an equivalent thrust coefficient in the cluster scale is acceptable.

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