

École polytechnique de Louvain

LES investigation of the effects of a linear shear on anisotropic turbulence from the Mann generator

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Chapter 1

Introduction

1.1 Motivations

As the world tends towards a greener energy production, wind turbines have become a popular choice for renewable energy. The wind energy industry and installed capacity has been growing rapidly in the past few years [1] as shown in Figure 1.1.

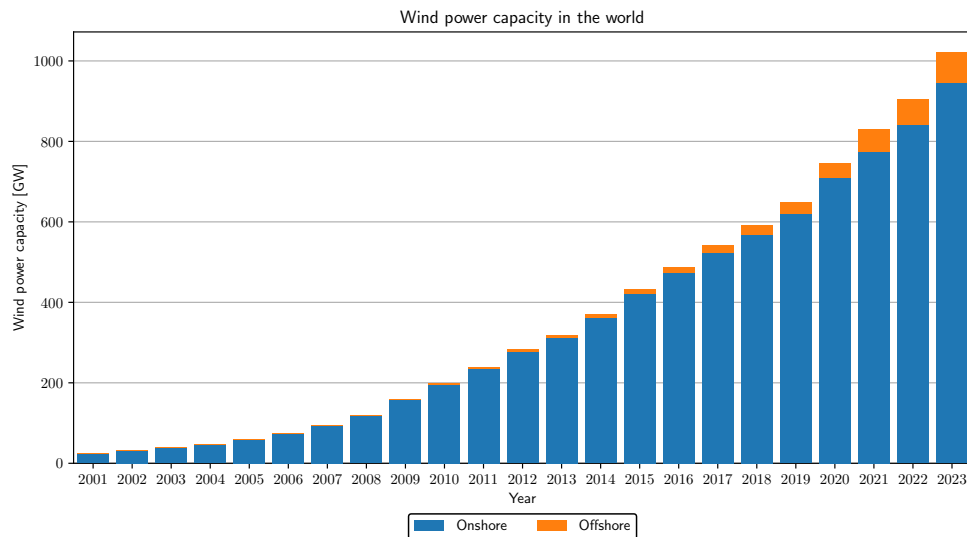


Figure 1.1: Evolution of the wind power capacity in the world from 2001 to 2023.

Moreover, the energy production capacity of each single wind turbine has also been increasing through the years. This can be seen in Figure 1.2 from the last global wind report of the Global Wind Energy Council (GWEC) [1]. Getting a better energy density for a single wind turbine is done by increasing the size of its blades.

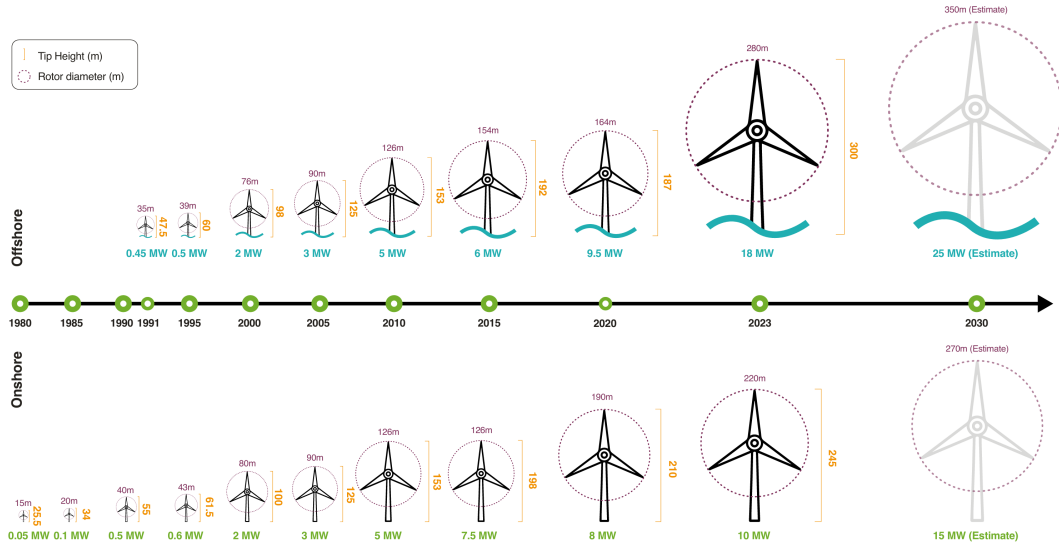


Figure 1.2: Trend of onshore and offshore turbine size, 1980-2030.

As wind turbines get larger, the velocity difference over the height of the rotor increases. This can be negligible for small installations. But a better understanding of this wind shear is crucial for the development of larger and more efficient wind turbines. Indeed, if this velocity difference is not taken into account, internal stresses in the turbine can be higher than expected, leading to a shorter lifespan of the installation. It is also important to make studies with velocity gradients, as it leads to a different wake behavior, leading to a potential loss in wind farm efficiency if not taken into account.

The velocity profile in the atmosphere is not linear. The atmospheric boundary layer is characterized by a logarithmic wind profile. However, in some cases, a linear wind shear can be a good approximation over the height of a wind turbine.

Large-eddy simulation (LES) investigations on the effects of a linear wind shear on a wind turbine have been done in the past by Parinam et al [2]. However, the physical validity of the results is limited as the inflow is laminar.

In order to better understand how a turbulent wind velocity gradient impacts a wind turbine, we first need to go back to fundamentals and analyze the effects of a turbulent linear wind shear on itself. This is the goal of this work.

1.2 Objectives and outline

This Master thesis aims at studying the behavior of a turbulent linear wind shear in a large-eddy simulation. First a validation of the numerical method will be done by recreating a case from existing literature. The physical validity of the simulated flow will be investigated. Then, the effects of different parameters such as the turbulence intensity and the velocity gradient will be studied.

Chapter 2 introduces the methodology used for the numerical simulations in this Master thesis. First defining the useful parameters of a turbulent and linear wind shear. Then presenting the in-house LES code BigFlow, the subgrid scales modeling and the Mann algorithm needed to generate turbulence boxes used for the inflow. Finally giving the framework used for our numerical simulations.

Chapter 3 presents a comparison between existing experimental results and a numerical sim-

ulation of the same flow. This comparison will allow to validate the numerical method used in this thesis. Additional analyses are performed to better understand the effects of the subgrid scale model and to locate the zone for physical validity.

Chapter 4 discusses additional case studies of turbulent wind shear. Allowing to better characterize the effects of different parameters of the flow on the results and the validity of the simulation.

Chapter 2

Methodology

2.1 Turbulent linear wind shear

In the following, we study an airflow moving in the x direction, with a linear velocity gradient in the y direction (vertical). As the flow is turbulent, we use the Reynolds decomposition: $\bar{u}$ is the time averaged velocity and u' the fluctuations. A linear wind shear is defined by a wind velocity profile described by a linear function of the form:

$$\bar{u}(y) = U_c + \frac{d\bar{u}}{dy}y \quad (2.1.1)$$

Where $\bar{u}(y)$ is the x -direction time-averaged velocity at height y , U_c is the wind speed at the center of the domain ($y = 0$ and $z = 0$) and $\frac{d\bar{u}}{dy}$ is the constant velocity gradient. Note that $\bar{u}$ is not a function of x (the streamwise direction) and z (the spanwise direction). Also note that $\bar{v}$ and $\bar{w}$, the y and z -directions time-averaged velocities, are zero.

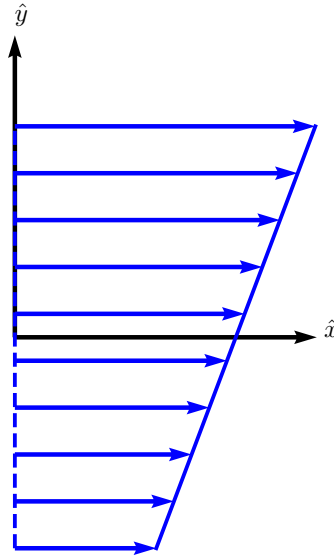


Figure 2.1: Representation of the time-averaged velocity profile $\bar{u}(y)$.

In order to generalize the following analyses, we will use the dimensionless shear parameter α defined as:

$$\alpha = \frac{d\bar{u}}{dy} \frac{H}{U_c} \quad (2.1.2)$$

Where H is the height and width of the domain. This nondimensional velocity gradient allows to compare our simulations done in large domains with past experiments done in smaller wind tunnels. For simplicity, we also define the dimensional shear parameter.

$$S = \frac{d\bar{u}}{dy} \quad (2.1.3)$$

The turbulent fluctuations of the flow will be superimposed on this mean linear shear at the inlet of the domain. In order to quantify the scale of these fluctuations, we will use the turbulence intensity in the center of the height of the computational domain:

$$TI = \frac{\sqrt{\frac{2}{3}\bar{k}}}{U_c} \quad (2.1.4)$$

With $\bar{k} = \frac{1}{2}(\overline{u'u'} + \overline{v'v'} + \overline{w'w'})$ the turbulent kinetic energy (TKE). The evolution of the TKE is given by:

$$\frac{d\bar{k}}{dt} = P - \bar{\varepsilon} \quad (2.1.5)$$

with P the production of TKE and $\bar{\varepsilon}$ its dissipation. The production term is given by:

$$P = -\overline{u'_i u'_j} \frac{d\bar{u}_i}{dx_j} \quad (2.1.6)$$

Which, in our case, simplifies to:

$$P = -\overline{u'v'} \frac{d\bar{u}}{dy} \quad (2.1.7)$$

Using Equation 2.1.5 and Equation 2.1.7, we can compute the dissipation term as:

$$\bar{\varepsilon} = P - \frac{d\bar{k}}{dt} \quad (2.1.8)$$

$$= -\overline{u'v'} \frac{d\bar{u}}{dy} - U_c \frac{d\bar{k}}{dx} \quad (2.1.9)$$

2.2 Bigflow

The flows simulated in this Master thesis are computed using the in-house LES code BigFlow developed by Georges [3], further developed by Britceux [4], then rewritten by Duponcheel [5] as part of their PhD theses. The code has since undergone improvements and new features implementations through different Master and PhD theses. It is a 4th order finite difference code solving the incompressible Navier-Stokes equations in 3 dimensions with an added subgrid-scale model.

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla P + \nabla \cdot (\tau + \tau^{sgs}) + \mathbf{f} \quad (2.2.1)$$

$$\nabla \cdot \mathbf{v} = 0 \quad (2.2.2)$$

With:

- $P = p/\rho$, the pressure divided by the density,
- $\tau = 2\nu S$ the viscous stress tensor, where S is the strain rate tensor: $S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$,
- τ^{sgs} the subgrid-scale stress tensor used to model the effect of the unresolved scales on the resolved scales,
- $\mathbf{f}$ the volumetric forces.

We can compute the subgrid-scales (SGS) dissipation effects using different models. In this thesis, we use a regularized variational multiscale (RVM) model [6, 7]. This type of modeling acts on the small-scale part of the LES field. Thus the SGS stress is computed using

$$\tau_{ij}^{sgs} = 2\nu^{sgs} S_{ij}^s \quad (2.2.3)$$

With S_{ij}^s the strain rate of the small resolved scales. ν^{sgs} is the SGS viscosity, applied to the small scales. It is computed with

$$\nu^{sgs} = C_{R_s}^{(n)} \Delta^2 (2S_{ij}^s S_{ij}^s)^{1/2} \quad (2.2.4)$$

Δ is the geometric mean of the grid spacing in the three directions: $\Delta = (\Delta_x \Delta_y \Delta_z)^{1/3}$. $C_{R_s}^{(n)}$ is a coefficient depending on n , the number of iterations of a second order discrete filter. A higher value of n leads to a higher order (order $2n$) filter. This work will focus on the $n = 1$ RVM model. The loss in accuracy compared to $n = 3$ is sufficiently small and the computational cost is lower. The values of different models' constants were calibrated using several mesh resolutions and compared to direct numerical simulations (DNS) of homogeneous isotropic turbulence by Cocle et al in [8]. The value of $C_{R_s}^{(1)}$ was found to be 0.066 in that article.

The computations are done on a staggered mesh [9], with the pressure and the velocity fields being stored on different grid points.

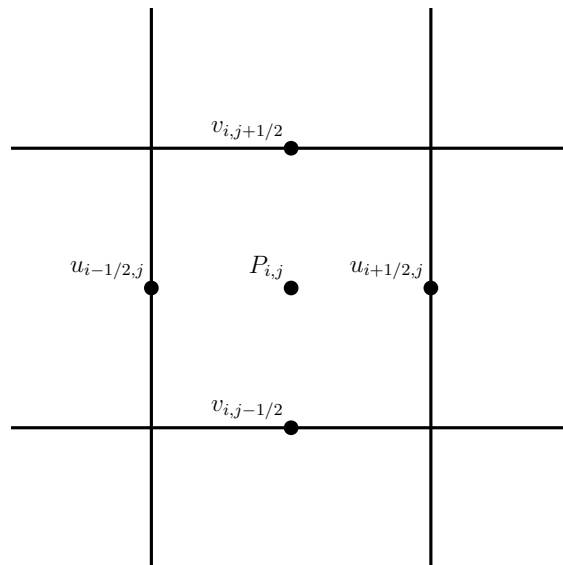


Figure 2.2: Example of 2D staggered grid. The pressure is stored in the center of the cells, the velocity components are stored on the faces of the cells.

With such mesh, the code needs to use ghost points to compute values and their necessary derivatives at the boundaries. In order to keep the 4th order accuracy of the code, the boundary conditions are applied using 3 layers of ghost points.

2.3 Mann boxes

In order to generate the turbulence used in our studies, we use Mann's algorithm [10, 11]. This method is often used in the wind energy community to generate inflow turbulence for wind

turbine simulations. It uses a Kaimal spectrum [12, 13] to generate statistical perturbations in the 3 directions of the velocity field. The output of the algorithm is a 3D box with a collocated mesh that can be superimposed to the mean velocity field of the flow at the inlet boundary of the BigFlow simulation. The turbulence box is then convected by the mean flow through the simulation domain. The turbulence intensity, the size of the box and the number of grid points in each direction can be adjusted to fit the desired turbulence characteristics and periodicity through a Python script preprocessing the values before calling `windsimu.exe` [14]. Simulation are ran over a integer number of Mann boxes through-flows to ensure that all the properties of the box are conserved. For the same reason, the following results are also investigated on a whole number of Mann boxes through-flows, after allowing the flow to develop.

2.4 Numerical setup

The following numerical simulations are performed in a domain of size $12H \times H \times H$. The domain is discretized with a mesh of 128 points per H . The total grid consists thus of $1536 \times 128 \times 128$ points. The grid is uniform in the three directions with a spacing $h = H/128$. The origin of the domain is located at the center of the y-z plane of the inlet boundary, so the x-coordinate goes from 0 to $12H$ and the y and z-coordinates go from $-0.5H$ to $0.5H$. The domain is represented in Figure 2.3.

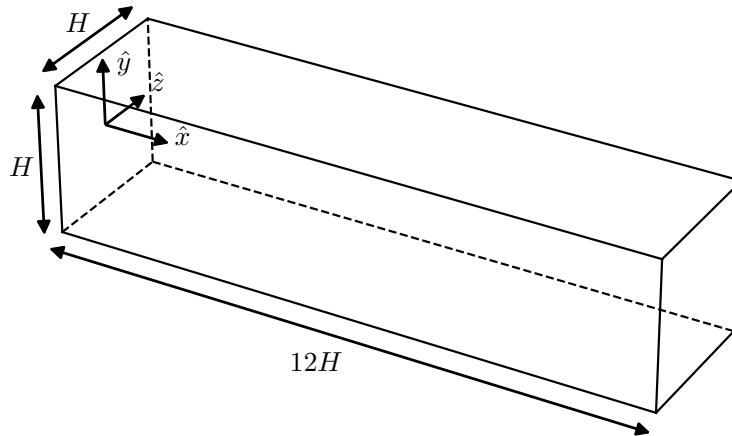


Figure 2.3: Representation of the domain used in the simulations.

The inflow boundary condition is located at $x = 0$, the outflow boundary condition is located at $x = 12H$. Both spanwise boundary conditions are periodic and the top and bottom boundaries are slip conditions. The slip boundary condition impose that $v = 0$ at the top and bottom of the domain. In order to mitigate the effects of the slip conditions on u , the analyses will not be performed on the whole height of the domain, but on a slice from $y = -0.25H$ to $y = 0.25H$. The mean velocity profile at the inlet is defined using the desired dimensionless shear parameter α and $U_c = 10m/s$.

The turbulence used in the simulations is generated using a Mann box as described in Section 2.3. It has a dimension $12H \times H \times H$. It is initially created with $2048 \times 128 \times 128$ points, then interpolated to $1536 \times 128 \times 128$ points to fit the grid of the BigFlow simulation. The turbulence intensity is set to the desired value using in the Python preprocessing script. The box is convected by the mean flow through the domain. The flow is allowed to develop for a full through-flow of the Mann box. It is then studied over the second through-flow of the Mann box.

We define the convective time as the time it takes for the flow at the center of the domain to travel a distance H :

$$t^* = \frac{tU_c}{H} \tag{2.4.1}$$

The flow is thus studied from $t^* = 12$ to $t^* = 24$.

Throughout this work, the only parameters that vary between the different LES are the dimensionless shear parameter α and the turbulence intensity (TI).

Chapter 3

Comparison between experimental results and large-eddy simulation

3.1 Introduction

The first investigation consist in a comparison with an experiment. We study the same case as the one made in a wind tunnel by Tavoularis and Corrsin in [15] and also presented in chapter 5.4.5 *Homogeneous shear flow* of *Turbulent flows* by Pope [16]. In their experiment, the velocity profile is induced by a shear-flow generator composed of ten parallel channels and various mesh screens placed upstream. This setup is represented in Figure 3.1, taken from the article.

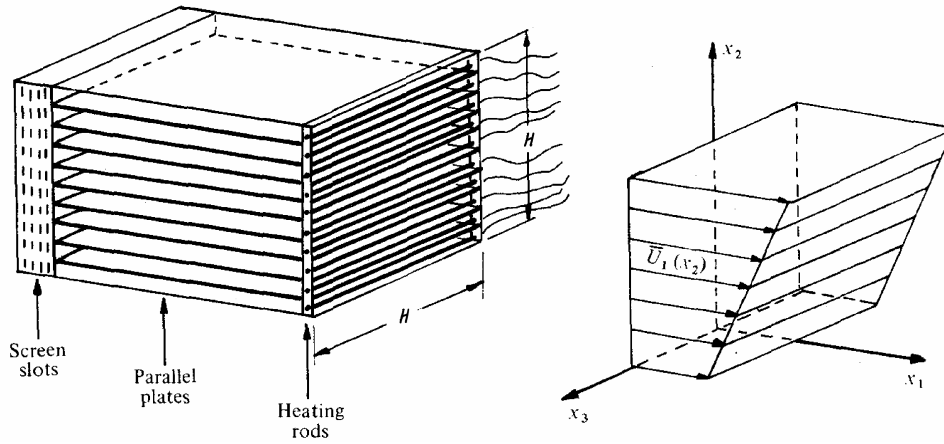


Figure 3.1: Representation of the experimental shear generator.

As shown, the study is done in a wind tunnel with a height and width H . This length is used for the nondimensionalization of the experimental results. In the same way, the results of the simulations presented in this work are made dimensionless using the height and width of the domain, H . The shear parameter of the flow is given as:

$$\alpha = \frac{d\bar{u}}{dy} \frac{H}{U_c} = 1.17 \quad (3.1.1)$$

The results of this experiment show an increase in turbulent energy with the distance from the inlet. Figure 3.2 presents that increase for the three normal Reynolds stresses.

Reynolds stresses are a measure of the turbulent energy in a flow. They are defined as the covariance of the velocity fluctuations in two directions ($\overline{u'_i u'_j}$). The turbulent kinetic energy is

half the sum of the normal stresses, given for $i = j$.

$$\bar{k} = \frac{1}{2} \overline{u'_i u'_i} \quad (3.1.2)$$

Non-diagonal components of the Reynolds stress tensor are shear stresses. Put in other words, normal Reynolds stresses represent the amount of TKE present in the flow in each of the three directions. Studying the evolution of the Reynolds stresses allows to better understand the changes in the velocity fluctuations in the flow, as well as the variations of its turbulent energy. Thus giving us a first insight into the relative value of the production and dissipation of TKE.

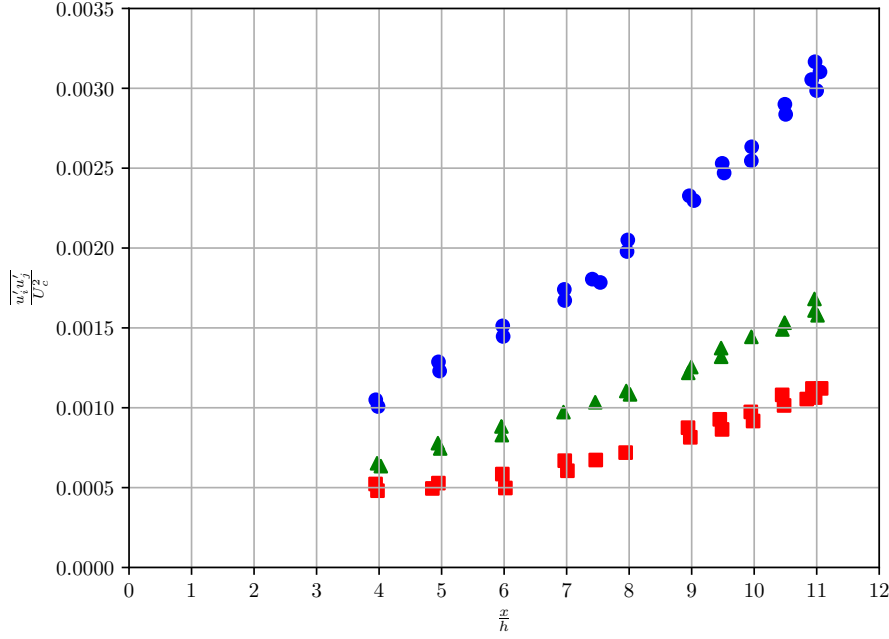


Figure 3.2: Reynolds stresses against axial distance in the experiment of Tavoularis and Corrsin [15]. $\frac{u'u'}{U_c^2}$ (●) ; $\frac{v'v'}{U_c^2}$ (■) ; $\frac{w'w'}{U_c^2}$ (▲).

Note that the represented measurements start at $\frac{x}{H} = 4$, due to constraints in the placement of the anemometers. Using these results, we are able to compute the turbulence intensity (TI) at the start of the analysis using Equation 2.1.4. Computing the TI of this flow is necessary to recreate the same inlet conditions in the LES study performed in the following section.

$$TI = \sqrt{\frac{2}{3} \frac{1}{2} \left(\frac{\overline{u'u'}}{U_c^2} + \frac{\overline{v'v'}}{U_c^2} + \frac{\overline{w'w'}}{U_c^2} \right)} \quad (3.1.3)$$

$$= 2.5\% \quad (3.1.4)$$

After a certain development distance, as presented by Pope in [16], this type of flow becomes self-similar and some statistics of the flow become constant in time and thus also in the x-direction. Those metrics are:

- $\frac{\overline{u'u'}}{\bar{k}}$, $\frac{\overline{v'v'}}{\bar{k}}$ and $\frac{\overline{w'w'}}{\bar{k}}$, the normal stress to TKE ratios,
- $-\frac{\overline{u'v'}}{\bar{k}}$, the shear stress ratio,
- $\rho_{uv} = \frac{\overline{u'v'}}{\sqrt{\overline{u'u'} \overline{v'v'}}}$, the correlation coefficient between u and v,

- $\frac{S\bar{k}}{\bar{\varepsilon}}$, the dimensionless turbulent timescale $\left(\frac{\bar{k}}{\bar{\varepsilon}}\right)$,
- $\frac{P}{\bar{\varepsilon}}$, the ratio of the production to the dissipation.

Their values are given in Table 3.1.

	$x/H = 7.5$	$x/H = 11$
$\frac{\overline{u'u'}}{\bar{k}}$	1.04	1.07
$\frac{\overline{v'v'}}{\bar{k}}$	0.37	0.37
$\frac{\overline{w'w'}}{\bar{k}}$	0.58	0.56
$-\frac{\overline{u'v'}}{\bar{k}}$	0.28	0.28
$-\rho_{uv}$	0.45	0.45
$\frac{S\bar{k}}{\bar{\varepsilon}}$	6.5	6.1
$\frac{P}{\bar{\varepsilon}}$	1.8	1.7

Table 3.1: Values of the self-similarity statistics in the experiment of Tavoularis and Corrsin [15].

In the next section, the same statistics are used to determine when the simulated sheared flow starts to become self-similar.

3.2 Numerical simulation results

The experiment of Tavoularis and Corrsin [15] is thus reproduced numerically in BigFlow in a domain of $12H \times H \times H$ and using the setup as described in Section 2.4 with an inflow velocity $U_c = 10m/s$, a shear parameter $\alpha = 1.17$ and a Mann box with a TI of 2.5% as determined in Equations 3.1.1 and 3.1.4.

Figures 3.3 and 3.4 are instantaneous representation of the flow during the simulation.

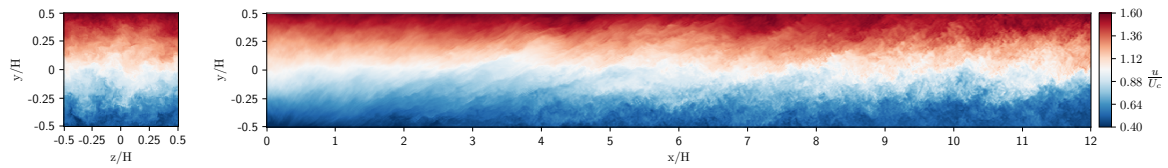


Figure 3.3: Instantaneous velocity field u at $x/H = 6$ (left) and $z/H = 0$ (right).

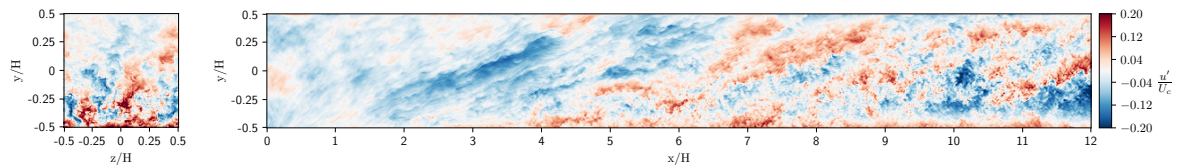


Figure 3.4: Instantaneous velocity fluctuations field $u' = u - \bar{u}\left(\frac{y}{H}\right)$ normalized by the velocity at the center U_c , at $x/H = 6$ (left) and $z/H = 0$ (right).

From these figures, we see the evolution of the velocity in y due to the linear shear we impose at the inlet. We also already observe that the flow evolves in x . There is a change in the turbulence patterns around $x/H = 6$.

3.2.1 Velocity profile

The first step of this analysis is to check whether the velocity profile stays constant through the domain. For this, we plot the time-averaged and spanwise-averaged velocity profile at different distances from the inlet.

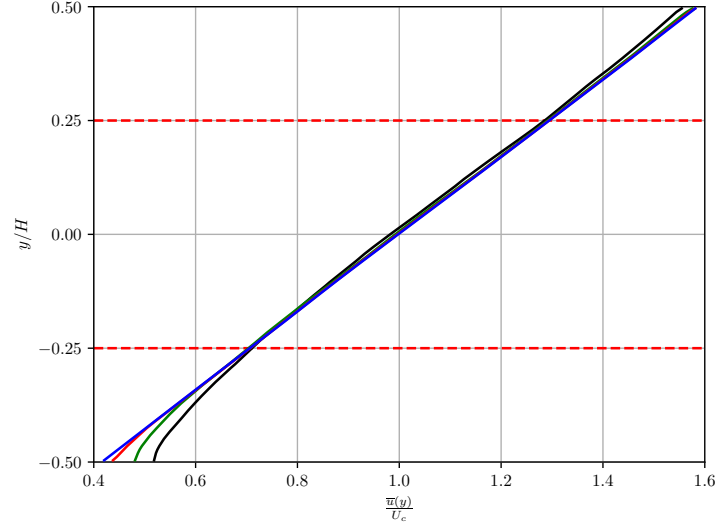


Figure 3.5: Time-averaged velocity profile at different distances from the inlet. $x/H = 0$ (—) ; $x/H = 3$ (—) ; $x/H = 6$ (—) ; $x/H = 11$ (—) ; limits of the studied domain (---).

Within the studied region, from $y/H = -0.25$ to $y/H = 0.25$, the velocity profile stays close to the expected linear profile imposed at $x/H = 0$. This shows that we can analyze the following results knowing that the flow has a constant shear parameter. Outside of the study region, we see the effects of the slip boundary conditions slowly affecting the flow by decreasing the slope of the velocity profile.

We also notice that the profile seems to decay faster at the bottom of the domain than at the top. At the bottom boundary, the slope of the velocity profile seems to tend to infinity, which is not the case at the top. The reason for this has not been found in this thesis. It would thus be interesting to further study the effects of the slip boundary conditions on the velocity profile by looking at the top and the bottom of the domain separately.

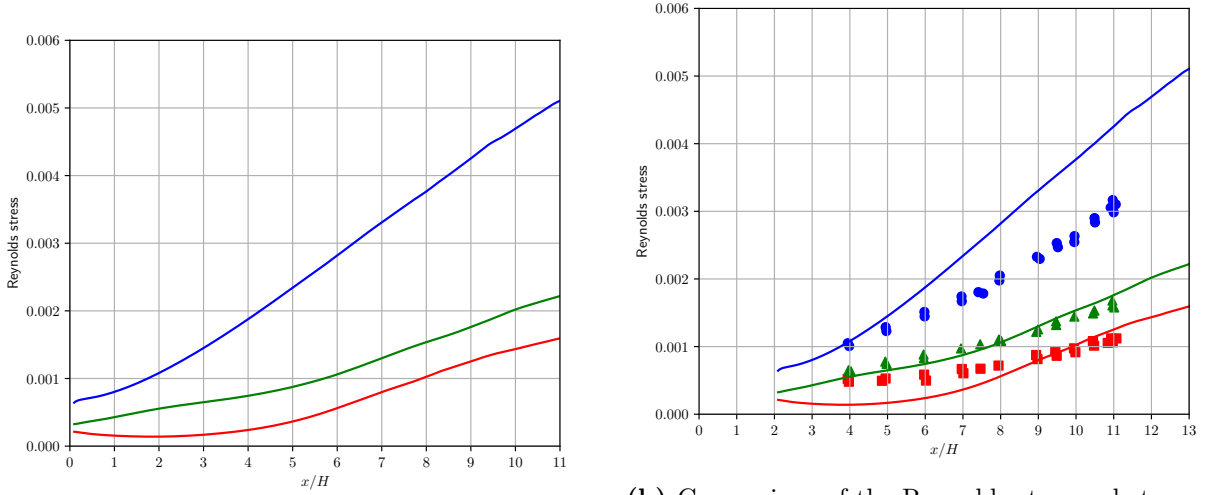
3.2.2 Reynolds stresses

We now look at the evolution of the normal Reynolds stresses with the distance from the inlet and compare the numerical results with the experimental ones presented in Figure 3.2. The Reynolds stresses are computed with a time-average over the second Mann box through-flow and a space-average over the planes defined from $y/H = -0.25$ to $y/H = 0.25$ and from $z/H = -0.5$ to $z/H = 0.5$.

For readability reasons and in order to mitigate the impacts of the inflow and outflow boundary conditions, we plot the results from $x/H = 0.1$ to $x/H = 11$. Also, for lack of better information on the experimental setup, we do not know the exact position of the beginning of the linear sheared flow. We do not know if the $x = 0$ position is before or after the shear generator. As

we do not have an exact spatial reference point, we will shift the numerical results by 2 in x/H to compare them with the experimental points. This value of the shift is taken in order to get a better fit of our results over the data, it has no physical meaning or reason.

We see from Figure 3.6 that our results are close to those of Tavoularis and Corrsin [15]. The shapes of all three curves are close to what is expected, and always growing. When directly comparing both sets of results, with the shift in x , we observe that the numerical results tend to begin with lower values than the experimental measurements. But towards the end of the domain, the numerical results have a higher value than the experimental ones. This is especially noticeable for $\frac{\overline{u'u'}}{U_c^2}$. One thus observes a greater production term in the numerical simulation than the experiment.



(a) Reynolds stresses against axial distance in the simulation.

(b) Comparison of the Reynolds stresses between the simulation and the experiment with a shift of 2 in x/H .

Figure 3.6: Numerical results: $\frac{\overline{u'u'}}{U_c^2}$ (—); $\frac{\overline{v'v'}}{U_c^2}$ (—); $\frac{\overline{w'w'}}{U_c^2}$ (—). Values from Tavoularis and Corrsin [15]: $\frac{\overline{u'u'}}{U_c^2}$ (●); $\frac{\overline{v'v'}}{U_c^2}$ (■); $\frac{\overline{w'w'}}{U_c^2}$ (▲).

The differences between both results are probably due to the incertitude in the experimental setup, the LES model we used or the numerical turbulence that is generated using Mann's algorithm and the TI may not be exactly the same. Altogether, these results are close and in satisfying agreement. They show the expected evolution of the flow's energy. The following studies will now go further into the effects of the RVM model on the flow dissipation, the effects of the linear shear on the turbulence production and thus the values of the self-similarity statistics of Table 3.1.

3.2.3 Energy spectrum

To better understand the dissipation of the turbulent energy, and the range of frequencies impacted by the RVM model, we analyze the variations in the energy spectrum of the flow in the Mann box and at different distances from the inlet.

We will thus compute:

$$E(k^*) = \frac{1}{2} \left(\widehat{u'u'}^* + \widehat{v'v'}^* + \widehat{w'w'}^* \right) \quad (3.2.1)$$

With

- k^* a dimensionless wave number: $k^* = k \frac{U_c}{\frac{du}{dy}} = \frac{2\pi f}{\frac{du}{dy}}$, f is a frequency,

- $\widehat{u'}$ the Fourier transform of the velocity fluctuations in the x-direction,
- $\widehat{u'}^*$ the complex conjugate of $\widehat{u'}$.

The Fourier transforms are computed using the Fast Fourier Transform (FFT) algorithm applied to the velocity fluctuations saved at a sufficient number of time steps. The FFT were computed for different fixed x positions, at $y=0$ and all 128 z positions. The plots hereunder represent the average of those 128 spectra. The resulting spectra are cut at $k_{max}^* = \frac{\pi}{h} \frac{U_c}{\frac{d\bar{u}}{dy}}$, the maximum wave number that can be resolved by the grid with points spaced by a distance h. Further, spectral information would not be pertinent. Inside the turbulence box, the sampling is done in x and not in time. Both are equivalent inside the box as $t = x/U_c$.

First, we look at the change in the energy spectrum from initially in the Mann box to the inlet of the BigFlow domain. In Figure 3.7, we rapidly see that both spectra are exactly equal up to a certain cut-off wave number close to $k_{max}/2$. The initially created spectrum is close to linear in the log-log graph. But after interpolating the velocity field at the inlet to transition from a collocated grid inside the box to a staggered grid in BigFlow, the spectrum indicates that the higher wave numbers are already dissipated.

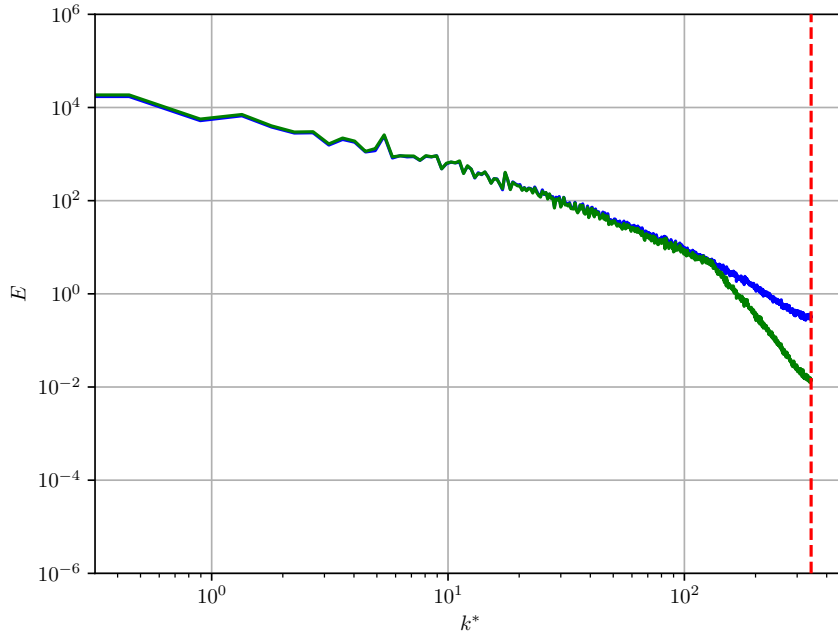


Figure 3.7: Energy spectrum before and after entering the computational domain. Inside the mann box (—) ; $x/H = 0$ (—) ; k_{max} (---).

The evolution of the energy spectrum in x is given in Figure 3.8.

The large wave numbers fastly dissipate after the inlet. At just $x/H = 0.1$, the angular point already present in the inlet spectrum is even more pronounced, the slope of the spectrum after that point greatly increases, reaching a maximum of dissipation. Moreover, close to the inlet, the concavity of the curves after that point is not as expected.

As we look further downstream, the amount of dissipation of the high wave numbers decreases, and seems to converge around $x/H = 9$. The production of turbulent energy affects all wave numbers. The intensity of the spectrum increases for all wave numbers as we observe higher

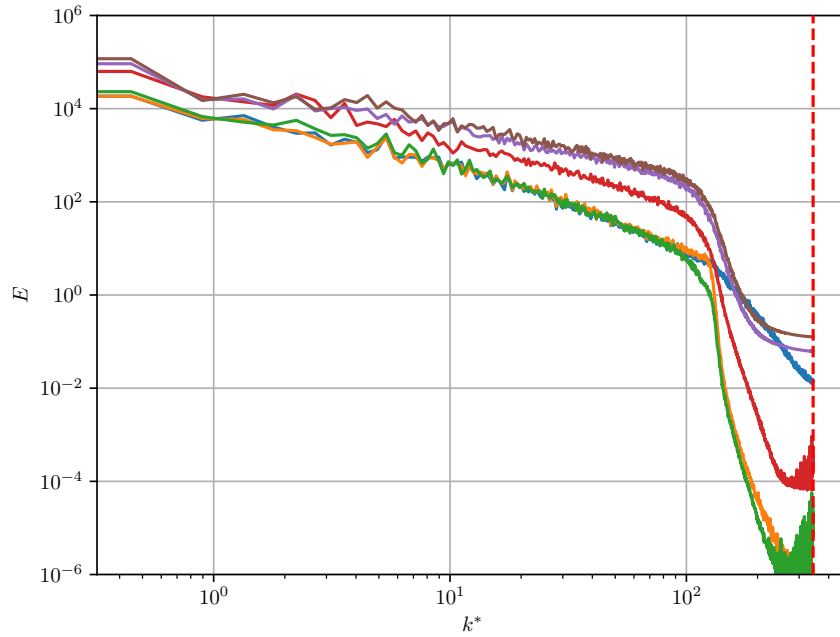


Figure 3.8: Energy spectrum at different distances from the inlet. $x/H = 0$ (—); $x/H = 0.1$ (—); $x/H = 1$ (—); $x/H = 6$ (—); $x/H = 9$ (—); $x/H = 11$ (—).

values of x/H . The further we look, the more the slope of the curve before the cut-off decreases. As said, this also seems to converge around $x/H = 9$.

3.2.4 Dissipation and production

Before looking at the values of the self-similarity statistics, we present the evolution of the dissipation and production terms of the turbulent energy (Equation 2.1.5). Looking at those dimensional values will help us understand the trends in the parameters of Table 3.1 before self-similarity. The production term is computed using Equation 2.1.7. The dissipation can either be computed using Equation 2.1.9, or it can be measured directly in BigFlow. In this section we show the results of both methods.

For the same reason as in Section 3.2.2, we plot the curves from $x/H = 0.5$ to $x/H = 11$. Also in the same way as in Section 3.2.2, the curves plotted are the average of the value over the planes defined from $y/H = -0.25$ to $y/H = 0.25$ and from $z/H = -0.5$ to $z/H = 0.5$ and over time.

In Figure 3.9, one sees that the computed and measured values of the dissipation are close to one another, as expected. Secondly, we notice that the dissipation term stays at zero, or close to zero at the beginning of the domain. This seems surprising as the RVM model should start dissipating the subgrid scales right from the start. This means that the numerical solution requires a distance of approximately $3H$ before representing a real turbulent flow with dissipation. Finally, it appears that, as hinted by figure 3.6a, the production is always higher than the dissipation leading to an increase in the turbulent energy throughout the domain. It is interesting to note that $P - \bar{\epsilon}$ is close to constant and even decreases a little at the end of the computational domain. Thus if both quantities continue to increase linearly after the end of the domain as they seem to be doing, $\frac{P}{\bar{\epsilon}}$ would tend to 1.

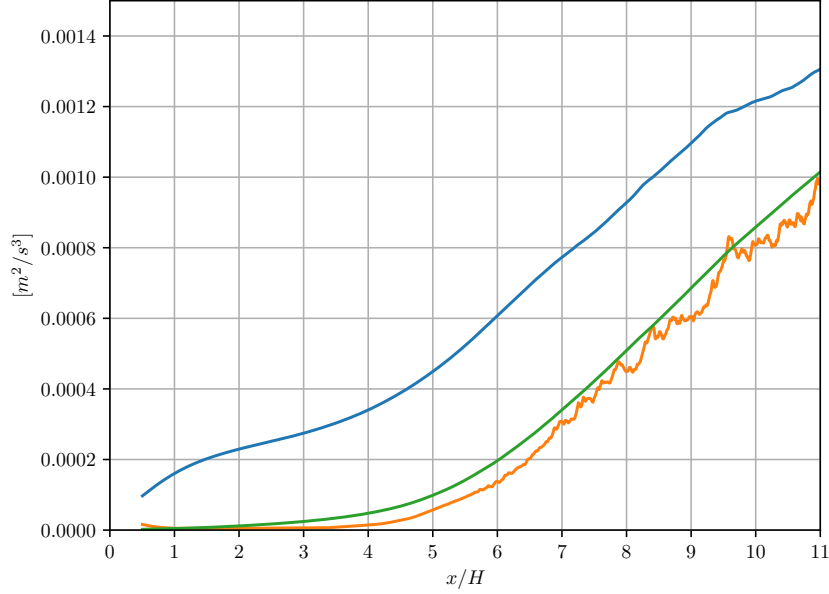


Figure 3.9: Production and dissipation terms against axial distance. P (—) ; computed $\bar{\varepsilon}$ (—) ; measured $\bar{\varepsilon}$ (—).

3.2.5 Self-similarity statistics

Finally, we look at the values of the self-similarity statistics of Table 3.1. In order to give the values at more x positions than just the two of the reference paper, we will plot the curves of each statistic with respect to the distance from the inlet. Again, the curves are the average of the value over the planes defined from $y/H = -0.25$ to $y/H = 0.25$ and from $z/H = -0.5$ to $z/H = 0.5$ and over time. They are presented in Figure 3.10.

All the statistics tend to a constant value. Some slower than others, especially $\frac{S\bar{k}}{\bar{\varepsilon}}$ which reaches its constant value at the very end of the domain. Otherwise, quantities in Figures 3.10a to 3.10d reach almost their self similarity value from $x/H = 9$. We also see that both the turbulent timescale, $\frac{\bar{k}}{\bar{\varepsilon}}$, and the ratio of the production to the dissipation go to infinity close to the inlet. This is due to the fact that the dissipation is close to zero as seen in Figure 3.9. These graphs have been cut to a maximum y -axis value of 10 and 20 to better show the evolution of the statistics near self similarity.

To compare the values obtained through the numerical method with the experimental ones, we will add the values measured at $x/H = 11$ to those of Table 3.1 and those of the DNS study of Rogers and Moin [17] also presented by Pope in [16]. Note that Rogers and Moin's study did not perform a spacial analysis but a time analysis. Their nondimensional parameter is thus St . With, as above, S the shear parameter and t the time. As $t = x/U_c$, we can use $\frac{x}{H} = \frac{St}{\alpha}$ to get the equivalent position. The values of the statistics are presented in Table 3.2.

We see that the statistics of this numerical study have values in good agreement with those of the experiment and the DNS. Generally, the relative difference between the experimental values and those obtained by LES, is kept under 30%. The largest difference with the experiment is for $P/\bar{\varepsilon}$ with a 26.3% relative difference. Altogether, these results show that the numerical tools we are using are able to recreate the flow of a turbulent wind shear after a certain distance to achieve self-similarity as the relative error on the different quantities are close to those of the DNS.

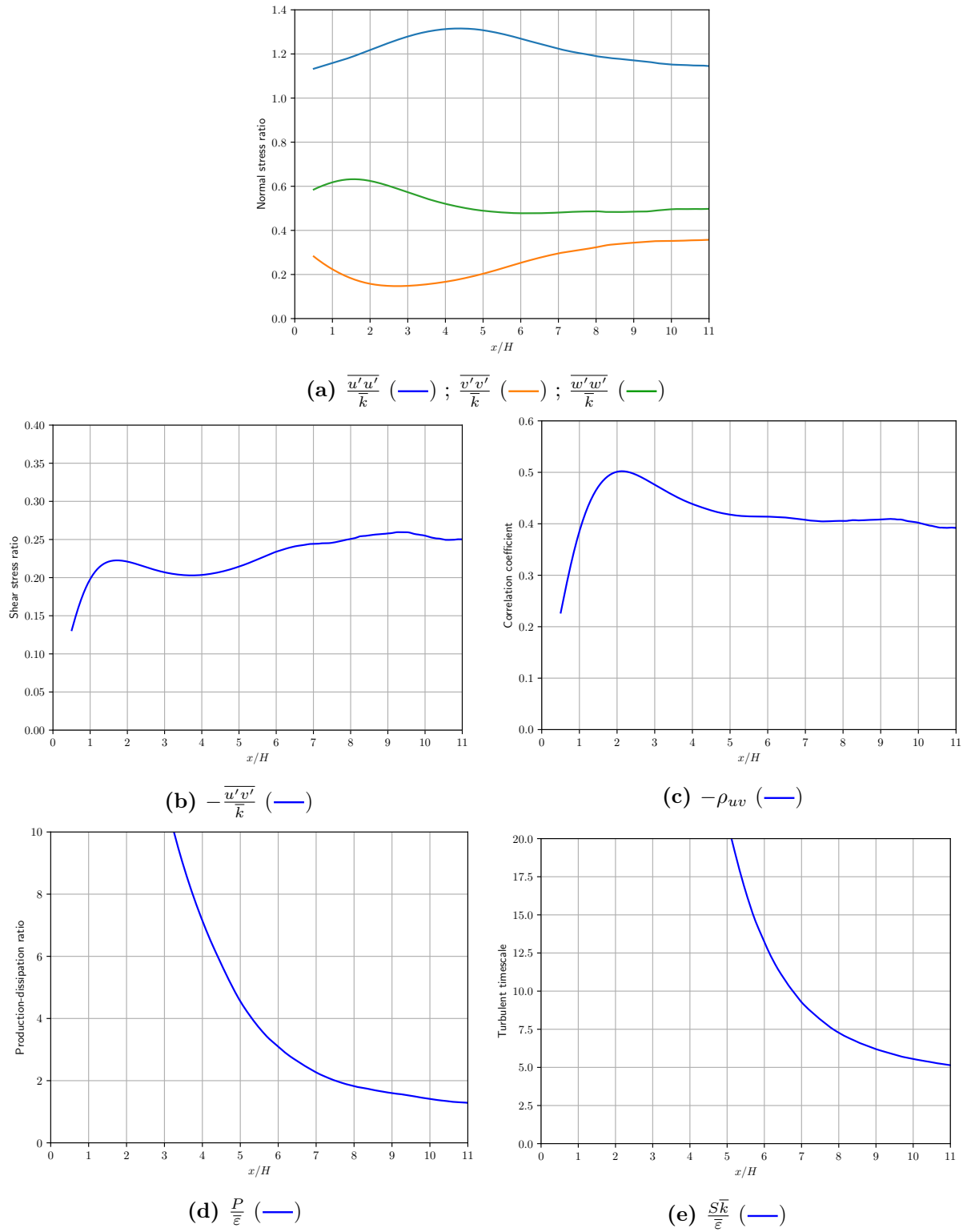


Figure 3.10: Self-similarity statistics of the studied LES.

	Tavoularis and Corrsin		Rogers and Moin	LES
	$x/H = 7.5$	$x/H = 11$	$St = 8$ ($x/H = 6.8$)	$x/H = 11$
$\frac{\overline{u'u'}}{k}$	1.04	1.07	1.06 (0.5%)	1.14 (8.1%)
$\frac{\overline{v'v'}}{k}$	0.37	0.37	0.32 (13.5%)	0.36 (2.7%)
$\frac{\overline{w'w'}}{k}$	0.58	0.56	0.62 (8.8%)	0.50 (12.3%)
$-\frac{\overline{u'v'}}{k}$	0.28	0.28	0.33 (17.9%)	0.25 (10.7%)
$-\rho_{uv}$	0.45	0.45	0.57 (26.7%)	0.39 (13.3%)
$\frac{\overline{Sk}}{\varepsilon}$	6.5	6.1	4.3 (31.7%)	5.14 (18.4%)
$\frac{P}{\varepsilon}$	1.8	1.7	1.4 (20.0%)	1.29 (26.3%)

Table 3.2: Statistics from the experiment of Tavoularis and Corrsin [15], the DNS of Rogers and Moin [17] and the LES of this thesis. In parentheses, the absolute value of the relative error with respect to the average of both experimental values.

3.3 Conclusion

In this chapter, we reproduced the experiment of Tavoularis and Corrsin [15] using a LES code in order to compare the results between both. The experiment consists in an homogeneous shear flow. The different studied quantities are considered between $-0.25H$ and $0.25H$, where the velocity profile is stable and not affected by the top and bottom boundary conditions.

We have compared the Reynolds stresses of the LES with the experimental results and found that they are close to one another with differences caused by uncertainties in the experimental setup or the numerical generation and handling of the turbulence. Looking at the energy spectrum, and the graphs of the dissipation and production terms, we have seen the effects of the RVM model on the flow SGS and dissipation through the domain. Finally, we have computed the self-similarity statistics of the flow and found that the starting position of the self-similar flow is around $x/H = 9$. Comparing those statistics to those presented by Pope in [16], we have observed that those statistics are in good agreement between the experiment, the DNS of Rogers and Moin [17] and the LES investigation.

The different results we have obtained show that the numerical tools we are using can successfully simulate such a flow. However, the physical validity of this flow only starts after a certain distance from the inlet, as it needs to be self-similar. This distance would need to be taken into account in any further study of linear shear flows. Especially in the case of wind turbines simulations. The wind turbines should be placed in the self-similar region of the flow, and not before it, in order to have a correct representation of the turbulent wind shear.

For further studies on this case, we could look into different SGS models, such as RVM with 3 filter iterations or the Smagorinsky model [18], which applies the SGS viscosity to all scales. We could study the different behaviors obtained for the energy spectrum, the dissipation and thus the energy and statistics. We remind that this thesis only uses the RVM model with one iteration of the filter. It would also be interesting to recreate this simulation in an even longer domain to analyze the evolution of P and $\bar{\varepsilon}$ after the end of the domain. As already mentioned in section

3.2.4, the ratio of the production to the dissipation could tend to 1 after a longer distance or the curves could reach a plateau.

Chapter 4

Parametric study

4.1 Introduction

After successfully recreating and studying the homogeneous shear flow of Tavoularis and Corrsin [15], we now aim to study the effects of two key parameters on such a flow: the turbulence intensity and the shear parameter. Making those parameters vary allows to better understand the production and dissipation behavior of the flow, as well as the effects on the self-similarity of the flow.

To the knowledge of the writer, such study has not been performed before. The results of this chapter are however critical for future studies on the effects of a linear wind shear on a wind turbine. Indeed, the flow around the turbine needs to be self-similar to be physically valid. By understanding the effects of the parameters of the flow on the self-similarity, one can simulate more reliable flows and wind turbine wakes.

As mentioned in section 2.4 the TI is set when generating the turbulence box and the velocity gradient is set in BigFlow. Five different simulations are run, each with a different combination of TI and α . The velocity in the center of the domain is kept at $U_c = 10m/s$. The dimensions of the computational domains and Mann turbulence boxes are also kept the same as in the previous chapter, $12H \times H \times H$. The values of the parameters of the different cases are presented in Table 4.1. In the same way as in the previous chapter, when applicable, the presented curves are the average of the results over the planes defines from $y/H = -0.25$ to $y/H = 0.25$ and from $z/H = -0.5$ to $z/H = 0.5$ and time-averaged over the second through-flow of the Mann turbulence.

Case	TI [%]	α
1	2.5	1.17
2	2.5	0.75
3	6.0	1.17
4	6.0	0.75
5	10.0	0.75

Table 4.1: Parameters of the different cases studied.

Case 1 is the case of Tavoularis and Corrsin [15] already presented in details in Chapter 3. The values of $TI = 6\%$ and $\alpha = 0.75$ of case 3 are chosen to be closer to atmospheric conditions for large wind turbines. Cases 2 and 4 are created by interchanging the values of TI and α of cases 1 and 3. This allows to study the effects of each parameter independently while looking at atmospheric and wind tunnel values of the parameters. Finally, case 5 is chosen to study the effects of a high TI on the flow while still working with realistic atmospheric values.

4.2 Results

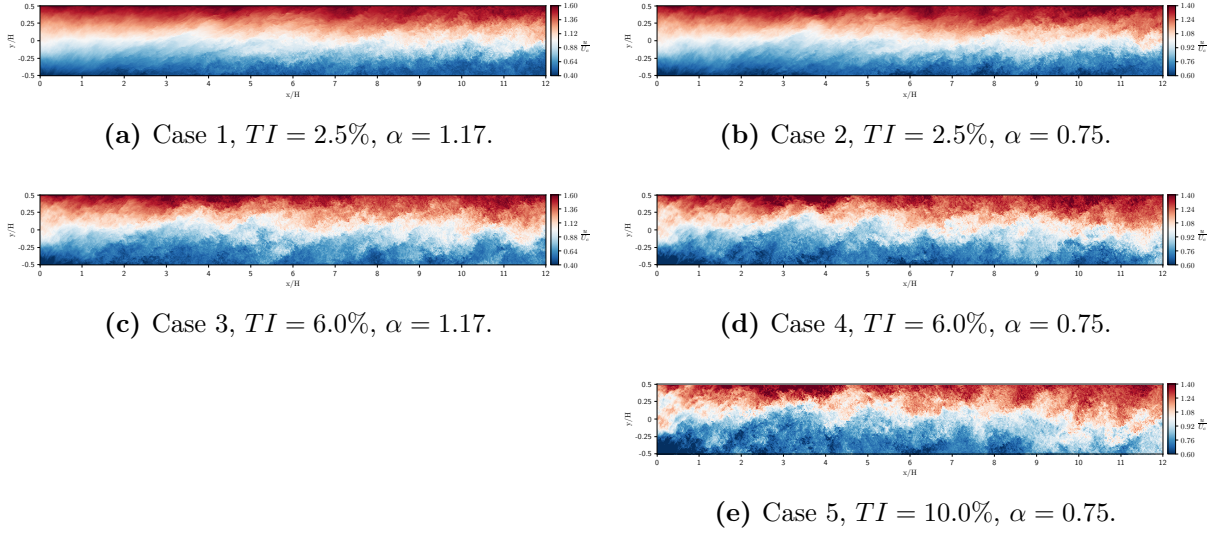


Figure 4.1: Slice at $z/H = 0$ of the instantaneous velocity field u . Color scales are the same for cases with the same shear.

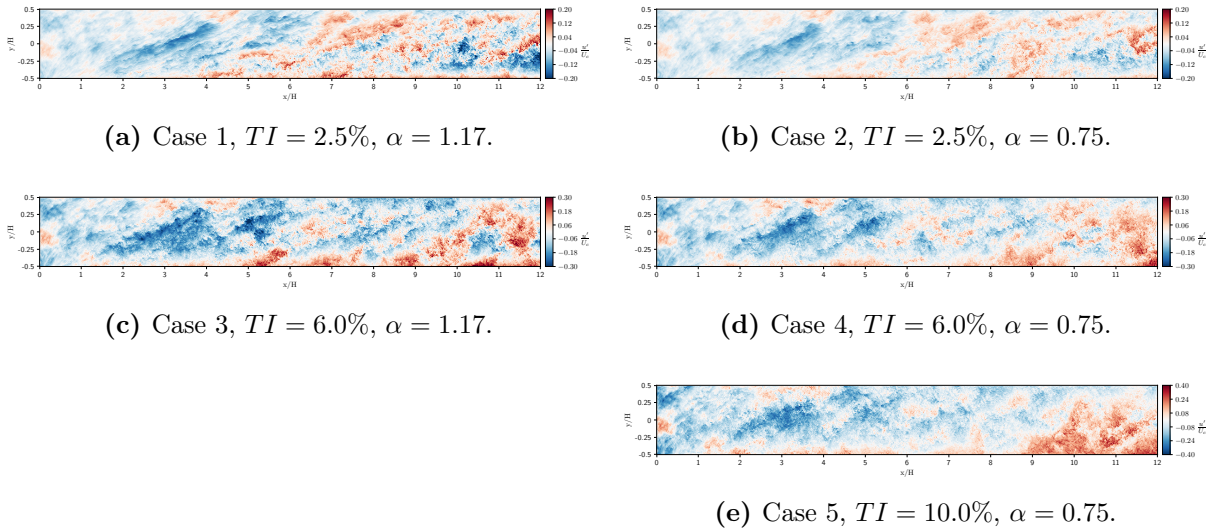


Figure 4.2: Slice at $z/H = 0$ of the instantaneous velocity fluctuations field $u' = u - \bar{u}(\frac{y}{H})$ normalized by the velocity at the center U_c . Color scales are the same for cases with the same TI .

One observes in Figures 4.1 and 4.2 the increase in turbulence patterns and fluctuation intensity between the cases with increasing TI . As the color scales are equivalent for cases with the same

TI in Figure 4.2, one also sees that for a lower velocity gradient, the production of turbulence is lower as well.

4.2.1 Velocity profile

Again, the time-averaged velocity profiles are studied at different distances from the inlet. Now, we analyze the impact of the shear and the turbulence on the boundary effects. The profiles are presented in Figure 4.3.

We observe by comparing the left and the right column, cases with the same TI but different velocity gradients, that the velocity profile decays faster for a higher shear parameter. The amplitude of the change in velocity at the walls between the inlet and $x/H = 11$ is lower on the right.

In the same way, by comparing the different rows (cases with the same shear but with a different TI), we see that the velocity profile gets more impacted by the slip boundary conditions for higher TI. The TI seems to have more impact on the decay than the gradient. We notice that for cases 1 and 2, the velocity profile is close to linear for all x inside the studied region. Cases 3 and 4 show that the top and bottom boundaries have affected all the way to the middle of the domain but these effects still remain small between $y/H = -0.25$ to $y/H = 0.25$ and the flow keeps a close to linear profile. In case 5, this observation is even more pronounced. For $x/H = 11$, the profile is not linear anymore throughout the height of the domain. Using only the top and bottom velocities, we find a shear parameter that is closer to $\alpha = 0.45$.

For future simulations, if the turbulence is significant, the top and bottom boundaries should be placed even further apart. For such cases, the effects of the slip conditions is felt rapidly through the height of the computational domain, which changes the shape of the velocity profile and thus the type of flow studied.

4.2.2 Reynolds stresses

In this section, we study the effects of the turbulence intensity and the shear parameter on the energy evolution of the flow. The Reynolds stresses are presented in Figure 4.4. Note that all the scales of the graphs are different. They are chosen to better analyze the shape and behavior of the stresses.

With these figures, one notices that the value of the velocity gradient has close to no impact on the shape of the evolution of the Reynolds stresses. However, it has a clear effect on the amplitude of the stresses. While Figure 4.4a and 4.4b look very similar in shape, the values of the stresses in Figure 4.4b are close to half those of Figure 4.4a. The same observation can be made for Figures 4.4c and 4.4d.

The turbulence intensity, on the other hand, has a clear impact on the shape of the stresses. By definition, the TI also changes the amplitude of the stresses at the inlet of the domain. On top of that, the lower the TI, the more the energy of the flow grows in x . The stresses of cases with $TI = 2.5\%$ keep growing with no sign of inflection point after $x/H = 11$. For $TI = 6.0\%$, the stresses seem to reach a plateau. In those cases, after a certain distance at a constant value, the stresses start to increase again, particularly $\frac{u'u'}{U_c^2}$. In the scenario with $TI = 10.0\%$, the stresses grow only for a short distance before decreasing slightly until the end of the domain.

It is also interesting to note that, when looking at the values of each Reynolds stress, they are always in the same order. There is always more energy in the streamwise direction than in the spanwise direction, and more in the spanwise direction than in the y -direction.

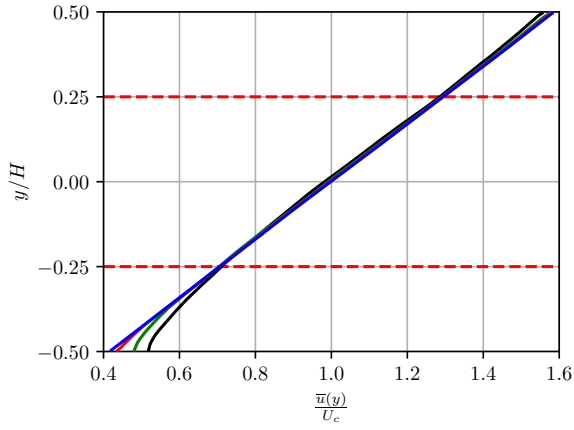
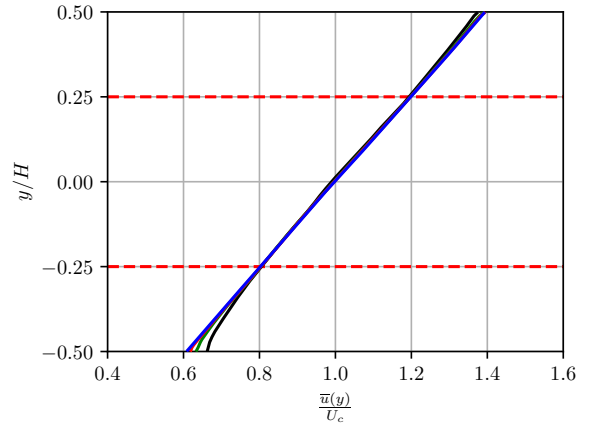
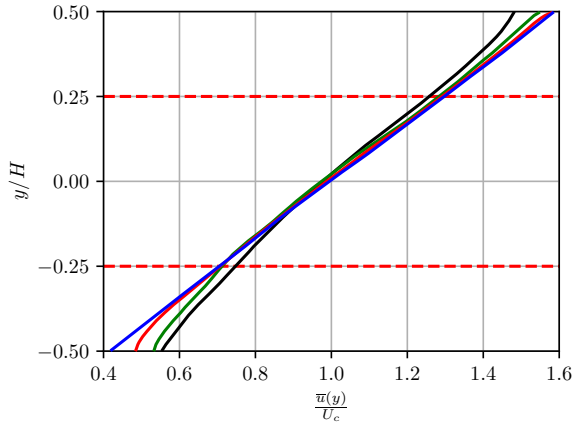
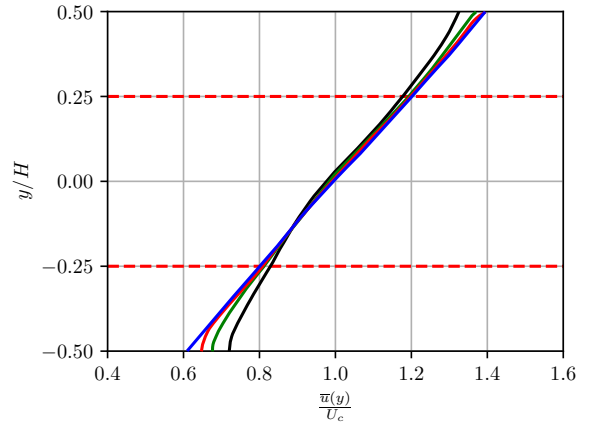
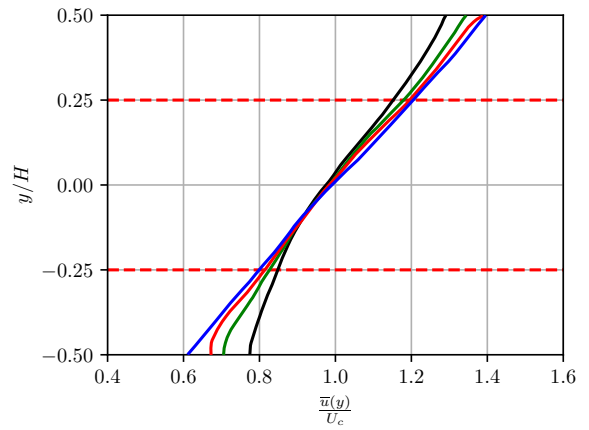
(a) Case 1, $TI = 2.5\%$, $\alpha = 1.17$.(b) Case 2, $TI = 2.5\%$, $\alpha = 0.75$.(c) Case 3, $TI = 6.0\%$, $\alpha = 1.17$.(d) Case 4, $TI = 6.0\%$, $\alpha = 0.75$.(e) Case 5, $TI = 10.0\%$, $\alpha = 0.75$.

Figure 4.3: Comparison of the time-averaged velocity profiles at different distances from the inlet. $x/H = 0$ (— blue —); $x/H = 3$ (— red —); $x/H = 6$ (— green —); $x/H = 11$ (— black —); limits of the studied domain (--- red ---).

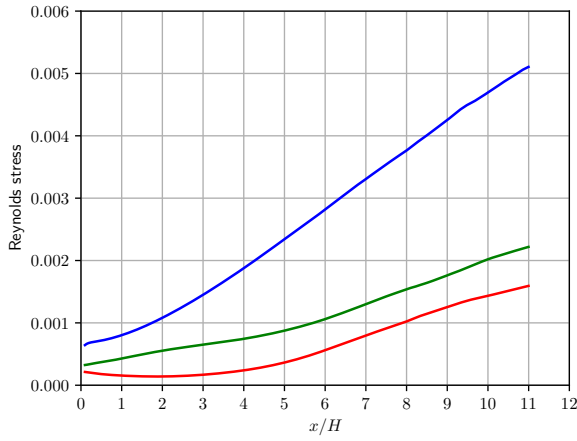
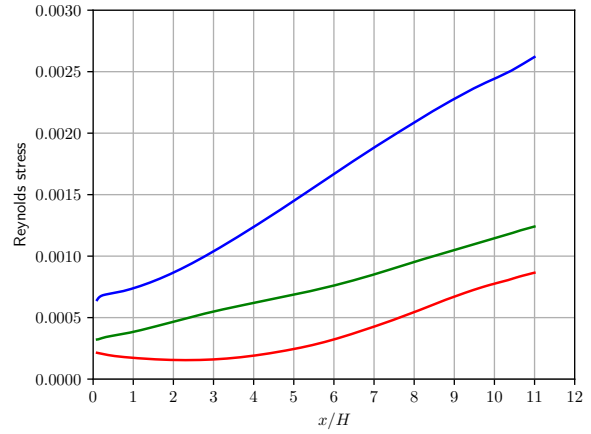
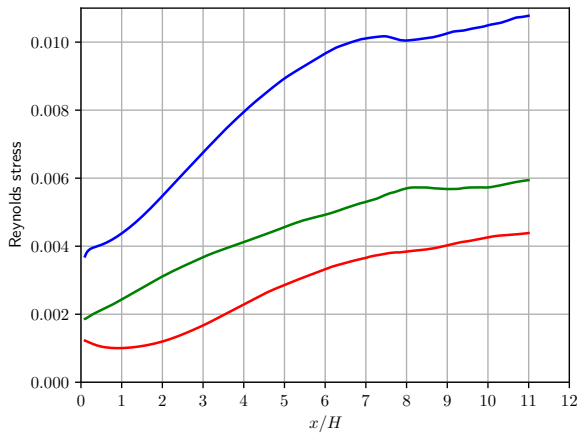
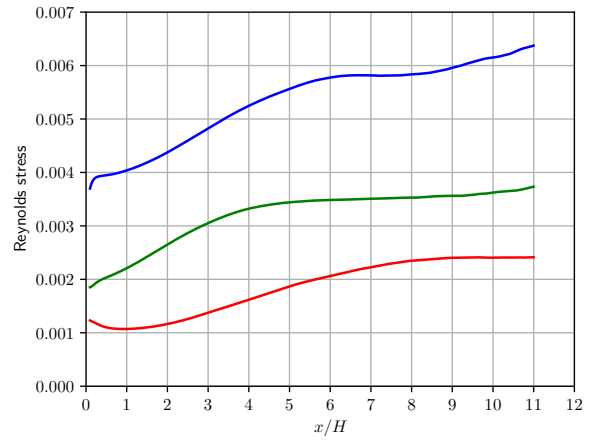
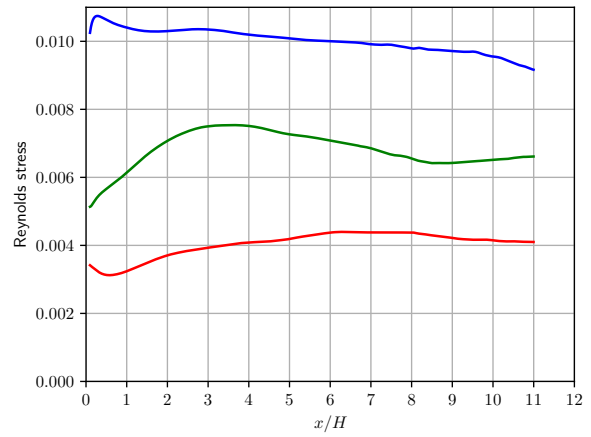
(a) Case 1, $TI = 2.5\%$, $\alpha = 1.17$.(b) Case 2, $TI = 2.5\%$, $\alpha = 0.75$.(c) Case 3, $TI = 6.0\%$, $\alpha = 1.17$.(d) Case 4, $TI = 6.0\%$, $\alpha = 0.75$.(e) Case 5, $TI = 10.0\%$, $\alpha = 0.75$.

Figure 4.4: Comparison of the Reynolds stresses against axial distance in the simulations. $\frac{\overline{u'u'}}{U_c^2}$ (—); $\frac{\overline{v'v'}}{U_c^2}$ (—); $\frac{\overline{w'w'}}{U_c^2}$ (—).

4.2.3 Energy spectrum

We have seen in Section 3.2.3 that for a certain distance after the inlet, the energy spectrum of the flow has a concavity that is not expected. We also noticed that much of the large wave number dissipation is made in that region. Now, we study whether the turbulence intensity and the wind shear have an impact on the evolution of the spectrum. The evolution of the energy spectrum with the distance from the inlet for all cases are presented in Figure 4.5.

The figures show that all the studied cases have a certain distance with great dissipation in the large wave numbers. Increasing the TI seems to reduce the unexpected concavity at the beginning of the domain. This can be seen clearly for cases 1 and 2, slightly for cases 3 and 4 and it is nearly not there for $TI = 10\%$. A greater TI also leads to a faster convergence of the spectrum. The spectrum of case 1 is converged after $x/H = 9$ while the spectrum of case 5 is already converged at $x/H = 6$. Moreover, we observe that the change in the slope of the spectrum is less pronounced for higher TI. This could be linked to the energy tendency we showed in Figure 4.4. For lower TI, the amount of TKE in the flow keeps increasing, leading to a more pronounced change in the slope of the spectrum. Whereas for case with decreasing Reynolds stresses, the slope of the spectrum is more constant in x . By looking at the starting value of the spectrum of each case, for the smaller wave number, we see that the higher the TI, the higher the level of the spectrum. Just as for the Reynolds stresses, flows with greater TI have more energy. This is logical as the TI and the TKE are directly linked by Equation 2.1.4.

The effect of the shear parameter is less visible but still present. By comparing both columns of Figure 4.5, one notices that a higher velocity gradient has the same effect as a higher TI for the convergence of the spectrum. We see this effect by looking at the curve for $x/H = 6$ that is closer to the curve for $x/H = 9$ for cases with a higher shear. Unlike the TI however, it seems that the change in the slope of the spectrum is more pronounced for higher α . We see a larger area between the curves for $x/H = 1$ and $x/H = 11$ in Figure 4.5c than in Figure 4.5d. It is probably due to the fact that a higher shear leads to more energy in the flow, as presented in Section 4.2.2. It is thus apparent that more flow energy leads to a larger difference between the slope of the spectrum at the beginning and the end of the domain.

As said in Section 3.2.3, it would be interesting to use other subgrid scales models to see if the convergence and the slope of the spectrum remain the same for each case.

4.2.4 Dissipation and production

Now, we study the variations in the dissipation and production terms of TKE between the different cases. The evolutions of the production and dissipation terms with respect to the distance are presented in Figure 4.6. As explained in Section 3.2.4, looking at the tendencies of P and $\bar{\epsilon}$ can give us further information on the energy evolution of the flow. It also gives more insight on the effects of the TI and shear parameter on the self-similarity statistics presented in the next section. Once again, note that the scales are different for each graph.

As in section 4.2.2, one observes that cases with the same value of turbulence intensity have similar shapes for the evolution of the production and dissipation. However, again, the amplitude of the terms in the cases with lower shear are close to half of the amplitude of the terms for $\alpha = 1.17$. Similarly, it appears in the figures that increasing the TI also increases the amount of TKE production and dissipation. One also notices that the measured dissipation and the computed one are in good agreement for all cases except for case 5, with $TI = 10.0\%$. In that case, the two curves take different paths after $x/H = 6$. This is probably due to the high deformation in the velocity profile starting at that distance as shown in Section 4.2.1. The equation, based on the assumption of a linear profile, is probably not valid anymore. In the following section, as in last chapter, we compute the self-similarity statistics using the measured

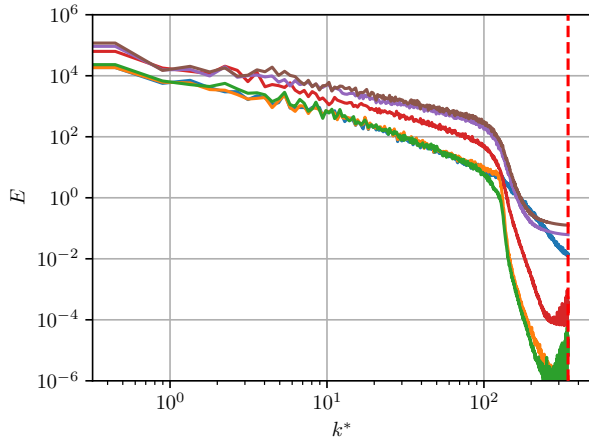
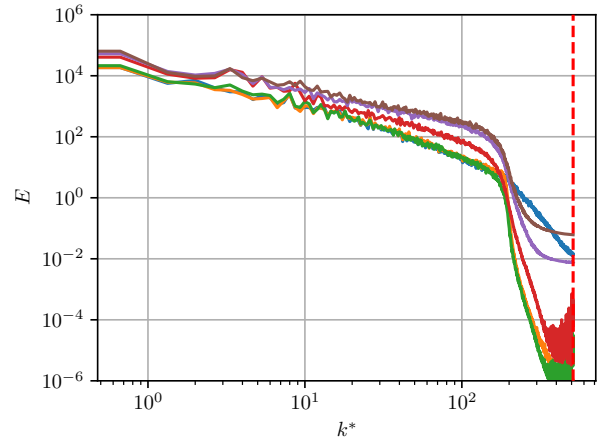
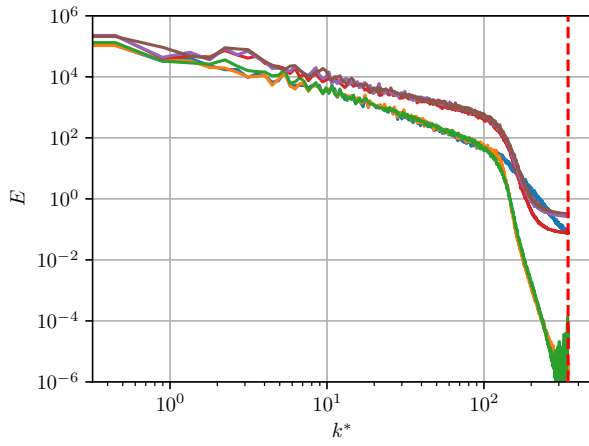
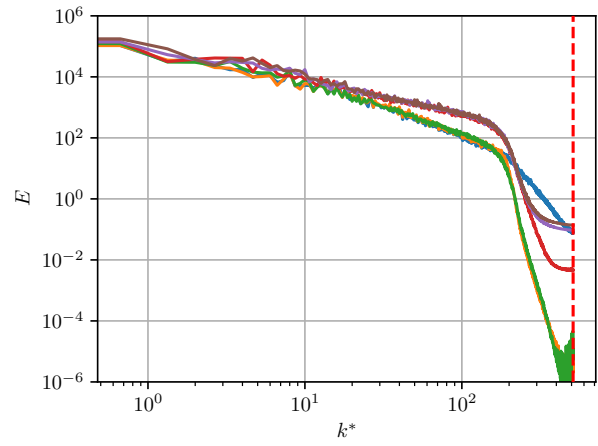
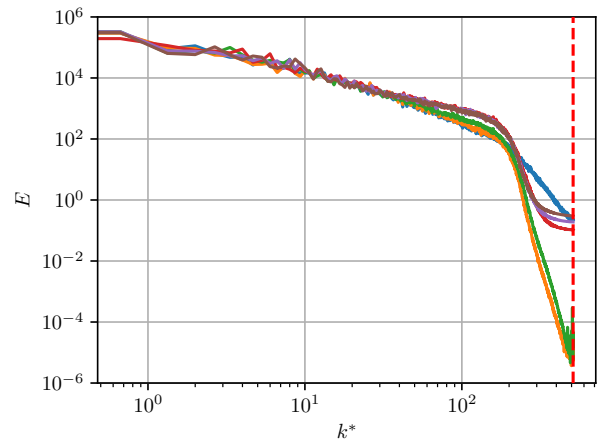
(a) Case 1, $TI = 2.5\%$, $\alpha = 1.17$.(b) Case 2, $TI = 2.5\%$, $\alpha = 0.75$.(c) Case 3, $TI = 6.0\%$, $\alpha = 1.17$.(d) Case 4, $TI = 6.0\%$, $\alpha = 0.75$.(e) Case 5, $TI = 10.0\%$, $\alpha = 0.75$.

Figure 4.5: Energy spectrum at different distances from the inlet, for the five cases of Table 4.1. $x/H = 0$ (—); $x/H = 0.1$ (—); $x/H = 1$ (—); $x/H = 6$ (—); $x/H = 9$ (—); $x/H = 11$ (—).

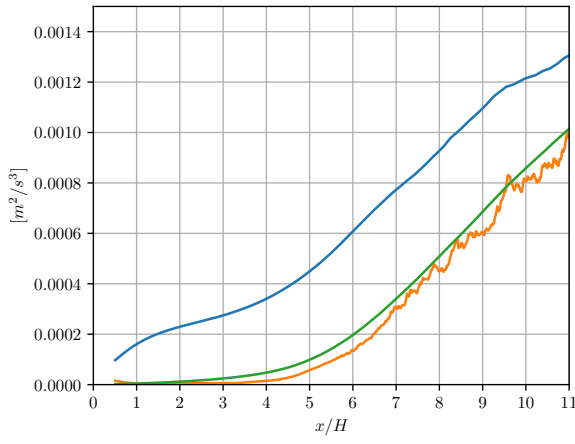
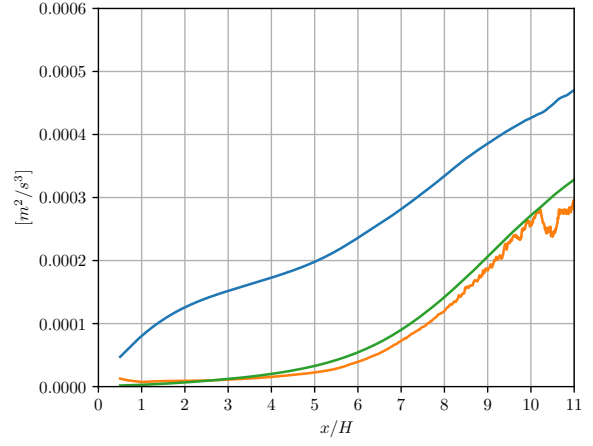
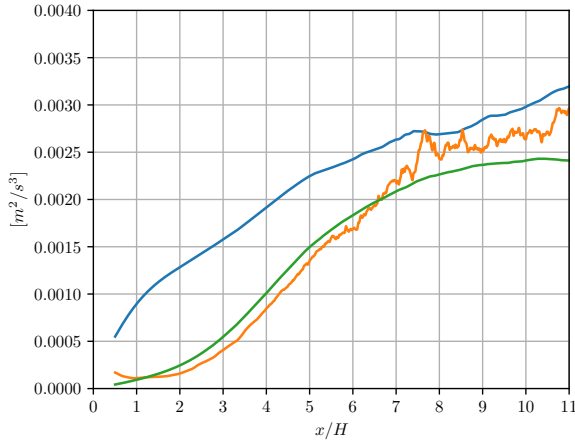
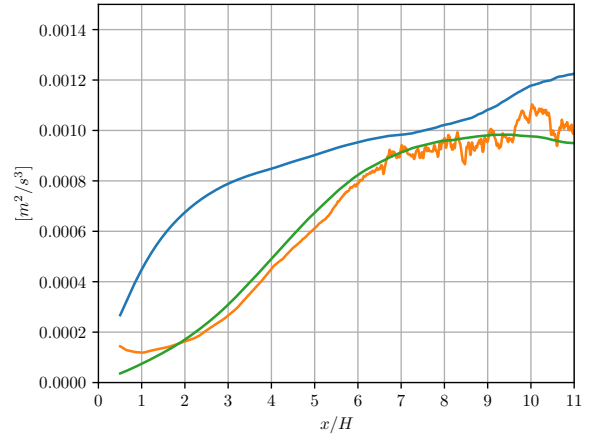
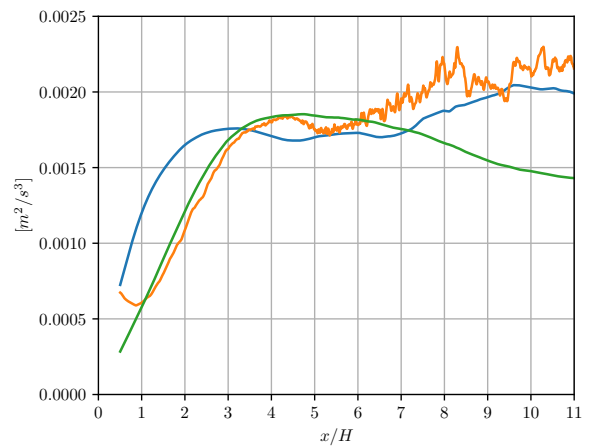
(a) Case 1, $TI = 2.5\%$, $\alpha = 1.17$.(b) Case 2, $TI = 2.5\%$, $\alpha = 0.75$.(c) Case 3, $TI = 6.0\%$, $\alpha = 1.17$.(d) Case 4, $TI = 6.0\%$, $\alpha = 0.75$.(e) Case 5, $TI = 10.0\%$, $\alpha = 0.75$.

Figure 4.6: Comparison of the production and dissipation terms against axial distance. P (—) ; computed $\bar{\varepsilon}$ (—) ; measured $\bar{\varepsilon}$ (—).

dissipation as it is more reliable and does not depend on assumptions.

In Figures 4.6a and 4.6b, we see, as noticed in Section 3.2.4, that the dissipation term stays at a value close to zero for the first part of the domain. This surprising behavior is not present in the other cases. It is thus probable that the RVM SGS model works better when the flow is more turbulent. In cases 1 and 2, that level of turbulence is reached after $6H$ while for cases 3, 4 and 5, the flow is already sufficiently turbulent at the inlet. With $TI = 2.5\%$, the dissipation and production seem to be growing to infinity. The simulations made with a higher TI show that the dissipation and production terms reach a plateau after a certain distance. And, in the case of $TI = 10\%$, the dissipation term even decreases at the end of the domain. Seeing this behavior in the high TI cases, it seems probable that, had we used a longer domain, the dissipation and production terms in the first two graphs would have reached a plateau as well.

4.2.5 Self-similarity statistics

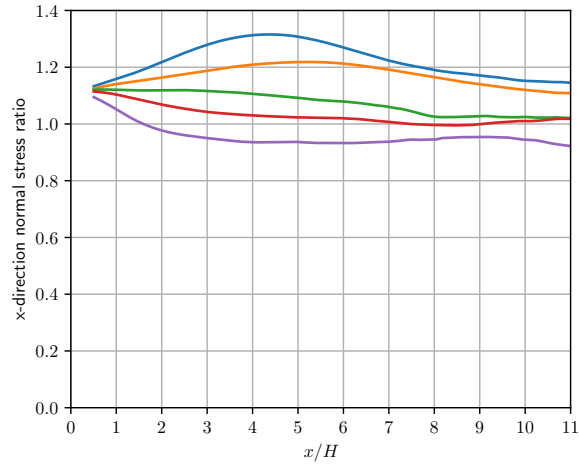
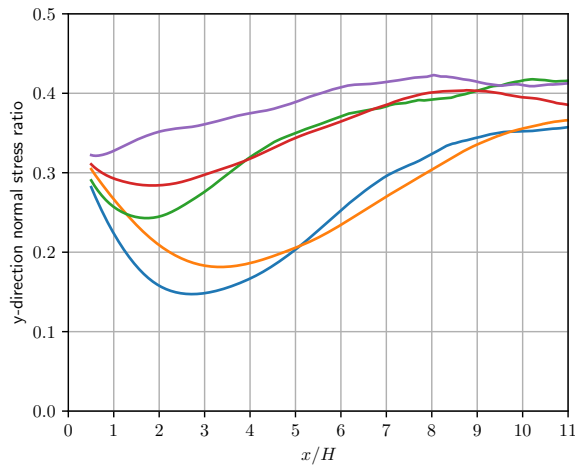
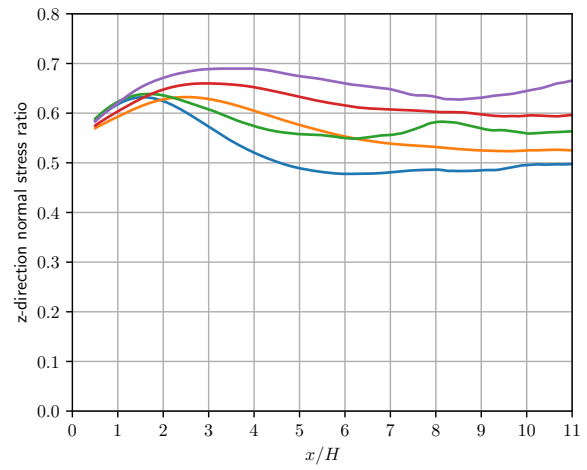
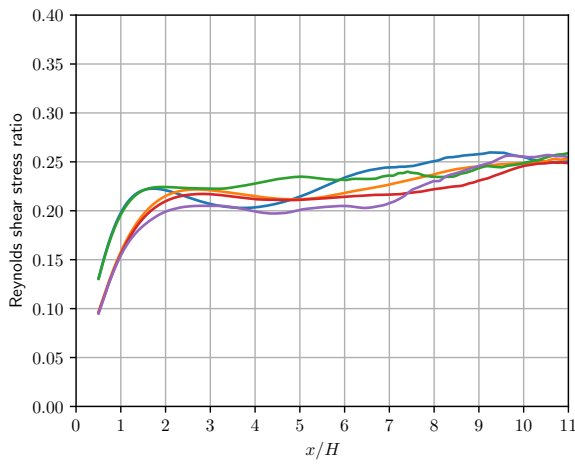
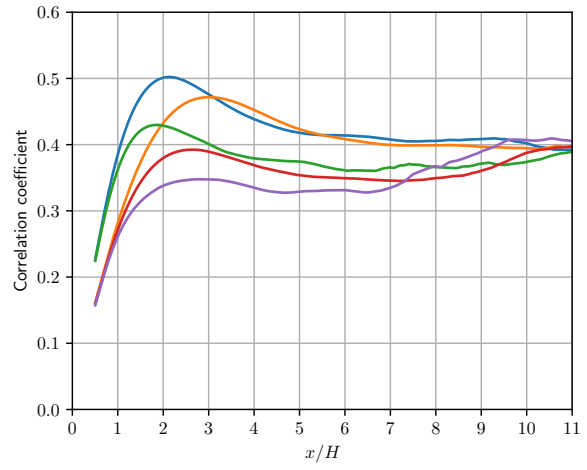
Finally, we compute the self-similarity statistics of Table 3.1 for the different cases to see if they converge in all scenarios and to what value. The evolution of each statistic with the distance from the inlet is presented in Figure 4.7. For clarity and to better compare the different values of the statistics during self-similarity, the results at $x/H = 11$ are presented in Table 4.2.

With some rare exceptions in Figures 4.7a to 4.7c, all the statistics of all the cases converge to a constant value. Except for the normal stress ratios, the values of the statistics in each case are very close to each other at the end of the domain. The normal stress ratios are the only statistics that do not converge to a constant value throughout the scenarios. For $\frac{\overline{u'u'}}{k}$, the final value decreases when the TI increases or when the shear parameter decreases. In reaction to that, as $\frac{\overline{u'u'}}{k} + \frac{\overline{v'v'}}{k} + \frac{\overline{w'w'}}{k} = 2$, by definition of the TKE, the values of $\frac{\overline{v'v'}}{k}$ and $\frac{\overline{w'w'}}{k}$ increase in these conditions. This is easier to observe in Table 4.2.

In Figures 4.7f and 4.7g, one can see the effects of the TI on the convergence of the turbulent timescale and the ratio of production to dissipation. The higher the TI, the faster the convergence. As already seen in previous results, one again notices that the higher the TI, the faster the flow reaches self-similarity. In Section 4.2.4, we have seen that the dimensional values of P and $\bar{\epsilon}$ are greater for flows with more TI or with a larger shear. It is interesting to see that, even though the values are different in all cases, their ratio, in Figure 4.7g, all converge to the same value at self-similarity. The shear parameter has a less pronounced effect on the convergence of these statistics. But, as for the energy spectrum, a more energetic flow, with a higher shear or TI, converges faster to its equilibrium.

Looking at all the figures, sometimes not taking into account outlier curves that do not go to a constant value, we have found the distance to wait before each scenario reaches self-similarity.

Cases 1 and 2 reach self-similarity at $x/H = 9$, cases 3 and 4 at $x/H = 7$ and case 5 at $x/H = 5$. This is in agreement with the previous statements. The higher the flow energy, the faster the flow reaches self-similarity. This means that for future simulations, the domain could be shortened for cases with a higher TI or shear parameter, saving computational resources.

(a) $\frac{\overline{u'u'}}{U_c^2}$ (b) $\frac{\overline{v'v'}}{U_c^2}$ (c) $\frac{\overline{w'w'}}{U_c^2}$ (d) $-\frac{\overline{u'v'}}{U_c^2}$ (e) $\rho_{uv} = \frac{\overline{u'v'}}{\sqrt{\overline{u'u'} \overline{v'v'}}$

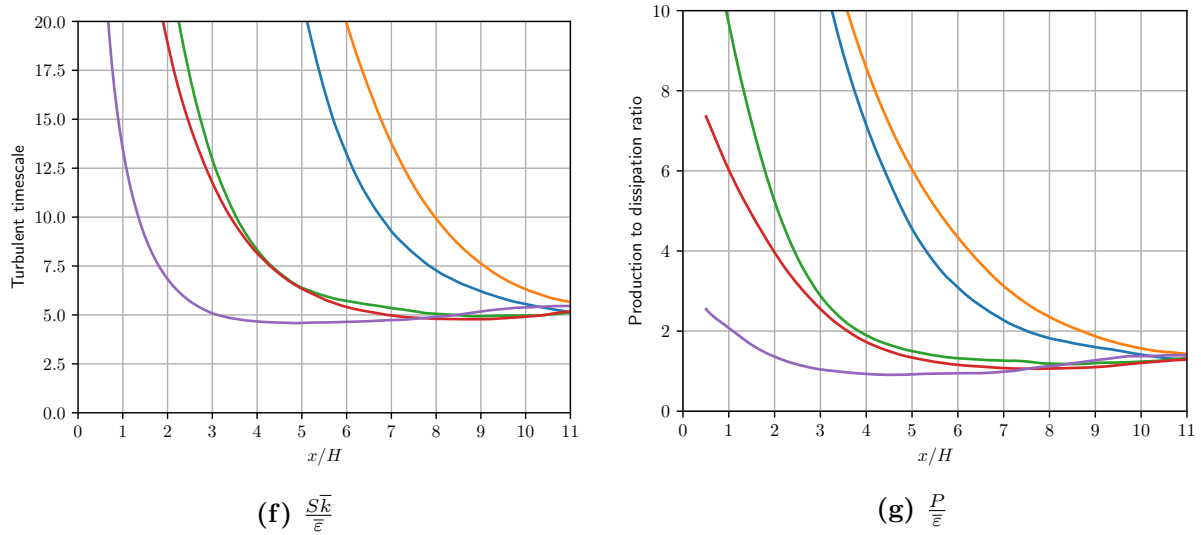


Figure 4.7: Evolution of the self-similarity statistics with the distance from the inlet for the five scenarios of Table 4.1. Case 1 (—); Case 2 (—); Case 3 (—); Case 4 (—); Case 5 (—).

	Case 1	Case 2	Case 3	Case 4	Case 5
$\frac{\overline{u'u'}}{\overline{k}}$	1.14	1.11	1.02	1.02	0.92
$\frac{\overline{v'v'}}{\overline{k}}$	0.36	0.37	0.42	0.39	0.41
$\frac{\overline{w'w'}}{\overline{k}}$	0.50	0.53	0.56	0.60	0.66
$-\frac{\overline{u'v'}}{\overline{k}}$	0.25	0.25	0.26	0.25	0.25
$-\rho_{uv}$	0.39	0.40	0.40	0.40	0.41
$\frac{S_k}{\epsilon}$	5.14	5.66	5.12	5.18	5.46
$\frac{P}{\epsilon}$	1.29	1.43	1.32	1.29	1.39

Table 4.2: Value of the self-similarity statistics for the different LES cases presented in this work.

4.3 Conclusion

In this chapter, we built on the results of the previous chapter to study the effects of two parameters on the turbulence of the flow. To do so, we have created five different cases with different values of the turbulence intensity and the shear parameter, by interchanging the values of the parameters of the case of Tavoularis and Corrsin [15] and arbitrary values taken close to atmospheric conditions. To keep the variability between the cases to a minimum, we have used the same domain, the same region of interest (between $y/H = -0.25$ and $y/H = 0.25$) and the same boundary conditions for all the simulations.

We have presented the evolution of the velocity profile, noticing that for flows with high energy, the top and bottom slip boundary condition fastly affect the flow. In the case with the most TI,

after a certain distance, the profile stops being linear. Looking at the Reynolds stresses, each TI level led to a different evolution of the energy. The lower the TI, the more the energy grows in x . It even decreases for a sufficiently high TI. The shear parameter has more of an effect on the amplitude of the stresses. For the lower shear, the values are close to half those of the cases with higher shear and same TI. Studying the energy spectrum, and the curves of production and dissipation, we have seen that the higher the TI or the velocity gradient, the faster the flow starts dissipating as expected. Cases with higher TI do not have a zero dissipation term at the beginning of the domain, and their energy spectrum converges faster. Finally, we have computed the self-similarity statistics of Table 3.1. Showing that the higher the energy of the flow, the faster it reaches self-similarity. Except for the ratio of normal stresses, all the statistics converge to a same constant for all cases. In the case of the normal stress ratios, the higher the TI, the lower the value of $\frac{\overline{u'u'}}{k}$ and the higher the values of $\frac{\overline{v'v'}}{k}$ and $\frac{\overline{w'w'}}{k}$.

Further studies could elongate even more the domain to see if the Reynolds stresses reach a plateau at a much further distance. In this work, we have seen that for low TI, the energy of the flow keeps growing after starting lower. For medium TI, it reaches a plateau. And for high TI, it decreases after starting higher than the other cases. It would be interesting to see if all TI cases reach the same value after a much longer distance, reaching an energy equilibrium dependent only on the shear parameter. As in the previous chapter, it would also be interesting to use other subgrid scales models to see if changing the dissipation changes the convergence rate of the statistics, or see how it changes the energy spectrum of the flows. Increasing the height of the domain to much larger values could also be done in the future. This would allow making sure that the flow in the studied region is not affected by the top and bottom boundaries, which have impacts on the velocity profile and thus the total energy of the flow. Note that increasing the height of the domain seems necessary for future analyses in longer domains as the impact of the boundaries spread through the height of the domain with x .

Chapter 5

Conclusion and perspectives

This thesis was undertaken to provide a deeper knowledge of the behavior of a turbulent linear wind shear in a large-eddy simulation (LES) with turbulence generated through Mann’s algorithm. In this work, we have studied linear shear flows. Evaluating the physical validity of the simulated flow and studied the effects of the different parameters.

Chapter 1 presented the motivations and objectives of this work. The goal is to simulate and investigate a turbulent linear wind shear in a LES to understand better its behavior for future wind turbines simulations.

In Chapter 2, we reminded the different notions required to study a turbulent linear wind shear. We then swept through the different numerical tools used in this work. Starting with BigFlow, the in-house LES code that solves the incompressible Navier-Stokes equations with an added subgrid scale model, RVM. We then presented the Mann algorithm used to generate the turbulence superimposed to the mean flow at the inlet of the numerical domain. A Mann box is a 3D box filled with statistical perturbations created with a Kaimal spectrum. This chapter finishes with the framework used for the numerical simulations. The size of the domain, the mesh, the boundary conditions, and the spatial and temporal regions of interest are described.

Chapter 3 gave the first numerical results of this thesis. We recreated the experiment of Tavoularis and Corrsin [15] presented in *Turbulent flows* of Pope [16]. Comparing the results of the LES with the experimental data, we have shown that the numerical method of this work is valid and can create a flow that is in good agreement with real-world data. It was also discovered that the flow is not physically valid in the first part of the domain. The flow needs a certain distance before being self-similar. The value of this distance was found and is important as it is the minimum distance from the inlet at which future studies should place a wind turbine to have the most realistic results.

In Chapter 4, the effects on the different results of the turbulence intensity and the velocity gradient were studied. Five different cases were simulated with different values of these parameters. We showed that increasing the shear parameter or the TI increase the amount of energy in the flow. This amount of energy seems to have a maximum value, as high TI flows have Reynolds stresses that decrease with the distance from the inlet. Whereas low TI flows have Reynolds stresses that increase greatly with the distance from the inlet. Generally, the more energetic flows converge faster to their self-similar state than others. However, we have also shown that those flow are more impacted by the boundary conditions, changing the shape and slope of the velocity profile.

To investigate deeper the behavior of a turbulent linear wind shear, one could compare the effects of different subgrid scale models on the evolution of the dissipation and the convergence

to self-similarity. Furthermore, it would bring more insight to simulate these flows in larger domains. A greater height would allow to dismiss completely the effects of the boundaries inside a centered study region. A longer domain would permit to study the evolution of the flow over a longer distance. Seeing if the energy of all case ever reach one single and equal equilibrium only dependant on the shear parameter of the flow. With better knowledge of the flow, one could now study the effects of this flow on a wind turbine and on its wake. The behavior of the TKE or the velocity profile could be investigated in that new case.

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