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Tracking droplets in a cloud-like turbulent flow

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Tracking droplets in a cloud-like turbulent flow

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Abstract

Droplets in clouds are believed to grow to raindrop size by coalescence due to collisions. Turbulent air is thought to be the main cause for these collisions. When cloud particles are small enough, they move with the turbulent air in the cloud. In this report the droplet-turbulence interactions in a fully developed homogeneous isotropic flow are examined. This is done in order to verify if turbulence enhances the downward velocity of the droplets. Also it is done to get a better understanding on atmospheric events like rain formation and cloud dynamics. Cloud conditions are replicated as good as possible in a turbulence chamber. Three-Dimensional Particle Tracking Velocimetry (3D-PTV) software is used to track the droplets in this chamber. Several analyses are applied on the 3D-PTV-data to achieve a better understanding of the droplet dynamics.

First some measurements are done in a stagnant flow case to determine if the particles reach their settling velocity in the measuring range. After that the turbulence level is increased in each following measurement. When the data is analyzed an increase can be observed in the mean downward velocity of the droplets for the weak turbulence cases ($Re \approx 140-240$). The mean downward velocity decreases again however in the strong turbulence cases ($Re \approx 310$). A few very interesting tracks of droplets passing really close by each other are seen. These could be examples of the sling effect, preferential concentration or similar movement of droplets due to some vortex.

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Nomenclature

F_D	Drag force [N]
g	Gravitational acceleration [m/s^2]
Re_p	Reynolds number of the particle
V_p	Relative particle velocity [m/s]
m_p	Mass of the particle [kg]
τ_p	Relaxation time of the particle [s]
ρ_p	Density of the droplet [kg/m^3]
d_p	Diameter of the droplet [m]
μ	Dynamic viscosity [$kg \cdot m^{-1} \cdot s^{-1}$]
V_t	Settling velocity [m/s]
η	Kolmogorov length scale [m]
λ	Taylor length scale [m]
τ_η	Kolmogorov time scale [s]
ϵ	rate of dissipation [m^2/s^3]
u	Velocity fluctuation [m/s]
ν	Kinematic viscosity of air [m^2/s]
Re_λ	Taylor-based Reynolds number
C_ϵ	Correction coefficient
l	Integral length scale [m]

Chapter 1

Introduction

Clouds arise when the sun heats the surface of the earth during daytime and water condenses into clouds. By Falkovich et al. [6] these condensed droplets are believed to grow to raindrop size by coalescence due to collisions. Turbulent air is thought to be the main cause for these collisions and therefore rain. Rain prediction requires a quantitative description of droplets in turbulence. In this report droplet-turbulence interactions are therefore examined.

3D-Particle Tracking Velocimetry (3D-PTV) is used to follow droplets in a fully developed homogeneous isotropic turbulence. Turbulence is generated in a turbulence chamber which looks like a soccer ball. The data generated by the 3D-PTV code is processed by a MATLAB code. The code calculates the path length of the droplets, the velocities of the droplets in x -, y -, z -direction, total velocity and the mean velocities. This is enough information in order to verify if turbulence enhances the downward velocity of the droplets.

Chapter 2

Theory

2.1 Particle-laden flows

Particle-laden flow refers to a class of two-phase fluid flow in which one of the phases is continuously connected (referred to as the continuous or carrier phase) and the other phase is made up of small particles or droplets (referred to as the dispersed or particle phase). Clouds are an example of a particle-laden flow. Falkovich et al. [6] claim that droplets in clouds are believed to grow to raindrop size by coalescence due to collision.

2.1.1 Particle relaxation time

Particles in a flow need a certain time to adapt to their surroundings or changes in the carrier phase velocity. This typical timescale is called the particle relaxation time (τ_p). The relaxation time follows from a force balance on a freely falling droplet. The forces acting on a droplet in still air are the drag force and gravity.

$$\mathbf{F}_D - m_p \mathbf{g} = m_p \frac{d\mathbf{V}_p}{dt} \quad (2.1)$$

For the special case of small spherical objects moving slowly through a viscous fluid, George Gabriel Stokes derived an expression for the drag constant. So under Stokes drag, it is known that $F_D = 3\pi d_p \mu V_p$. The equation for viscous resistance is appropriate for $Re_p \ll 1$. Substituting this in equation (2.1) results in

$$m_p \frac{dV_p}{dt} = 3\pi d_p \mu V_p - m_p g. \quad (2.2)$$

For a bigger Re_p following empirical relation can be used where $f_d = (1 + 0.15Re_p^{0.687})$ is a correction constant for different droplet sizes

$$F_d = 3\pi d_p \mu V_p f_d. \quad (2.3)$$

But the droplets considered in this study are not always in still air. When the air is not still, the relative velocity of the droplet with respect to the air ($u(t) - V_p$) should be accounted for. Then equation (2.2) becomes:

$$\frac{dV_p}{dt} = \frac{f_d}{\tau_p} (u(\mathbf{x}_p t) - V_p) - g, \quad (2.4)$$

where \mathbf{x}_p is the position of the particle and

$$\tau_p = \frac{\rho_p d_p^2}{18\mu} \quad (2.5)$$

is the relaxation time. Here, V_p is the relative particle velocity, ρ_d is the density of the droplet, d_p is the droplet diameter and μ is the dynamic viscosity of air [4].

For the no turbulence case, the Reynolds number of the droplet is calculated with equation (2.6)

$$Re_p = \frac{d_p u}{\nu}. \quad (2.6)$$

Settling velocity

The settling velocity or terminal velocity is the velocity reached by an object as it falls through a fluid. It depends on its size, shape, density and the difference between its specific gravity and that of the surrounding medium. A particle falling in still air will reach a terminal velocity V_t at which drag and gravity are in equilibrium. This velocity is given by

$$V_t = \frac{\tau_p g}{f_d}. \quad (2.7)$$

Gravity effects

One may believe that condensation of droplets is the most important factor for droplet growth. Actually, it is a dominant effect on droplets with diameters smaller than 10 μm . Gravity is the dominant mechanism for raindrops to fall for diameters greater than 30 μm . [10] Turbulence might be the missing link between these two regions. Gravity is also the driving force for rainfall. [2]

2.1.2 Cloud conditions

According to Falkovich et al. [6] droplets are believed to grow to raindrop size by coalescence due to collision. Because air turbulence is thought to be the main cause for collisions and therefore rain, prediction requires a quantitative description of droplet collision in turbulence. Turbulent vortices act as small centrifuges that spin heavy droplets out, creating concentration inhomogeneities. Concentration inhomogeneities increase the mean collision rate. [6]

Clouds are large scale phenomena and because of that, one can say that the local characteristics of the flow are ideal. So, a locally isotropic homogeneous turbulence with zero mean flow may define the cloud like flow condition. To replicate cloud conditions, such flows should be replicated in the turbulence chamber.

Energy cascade and Kolmogorov theory

In brief, the idea of the energy cascade is that kinetic energy enters the turbulence at the largest scales of motion. This energy is then transferred to smaller and smaller scales until, at the smallest scales, the energy is dissipated by viscous action. Kolmogorov quantified this picture. In particular, he identified the smallest scales of turbulence to be those that now

bear his name [9].

Richardson's notion of turbulence was that a turbulent flow is composed by "eddies" of different sizes. Large eddies are unstable and break up, transferring their energy to somewhat smaller eddies. These smaller eddies undergo a similar process and transfer their energy to yet smaller eddies. This process continues until the Reynolds number $Re(l) \equiv u(l)l/\nu$ is sufficiently small that the eddy motion is stable, and molecular viscosity is effective in dissipating the kinetic energy. Richardson took this very nicely into the following quote.

"Big whorls have little whorls
Which feed on their velocity
And little whorls have lesser whorls
And so on to viscosity " - Richardson (1922)

What is the size of the smallest eddies that are responsible for dissipating the energy? This question and more are answered by the Kolmogorov theory which is stated in the form of three hypotheses. [9]

- **Kolmogorov's hypothesis of local isotropy.** At sufficiently high Reynolds number, the small-scale turbulent motions ($l \ll l_0$) are statistically isotropic.
- **Kolmogorov's first similarity hypothesis.** In every turbulent flow at sufficiently high Reynolds number, the statistics of the small-scale motions have a universal form that is uniquely determined by ν and ϵ .
- **Kolmogorov's second similarity hypothesis.** In every turbulent flow at sufficiently high Reynolds number, the statistics of the motions of scale l in the range $l_0 \gg l \gg \eta$ have a universal form that is uniquely determined by ϵ , independent of ν .

2.2 Turbulence conditions

A soccer ball shaped turbulence chamber is used. The chamber is mathematically called a truncated icosahedron with 16 symmetric axes and a 5;3 symmetry. 10 axes are used to generate the turbulence. For this chamber the idea of the Göttingen group is followed [3]. In this setup less (20 instead of 32) but bigger speakers are used. The diameter of the chamber is approximately 1 meter.

2.2.1 Turbulence length and timescales

First the relevant turbulent flow parameters are determined to be able to do the necessary calculations. See equations (2.7), (2.8) and (2.9) for the Taylor length scale (λ), the Kolmogorov time scale (τ_η) and the Kolmogorov length scale (η). In these equations, ν stands for the kinematic viscosity of air. [9]

$$\lambda = \left(\frac{15\nu u^2}{\epsilon} \right)^{1/2} \quad (2.8)$$

$$\tau_\eta = \left(\frac{\nu}{\epsilon} \right)^{1/2} \quad (2.9)$$

$$\eta = \left(\frac{\nu^3}{\epsilon} \right)^{1/4} \quad (2.10)$$

The average dissipation rate of turbulence kinetic energy per unit mass with a correction coefficient C_ϵ can be defined as

$$\epsilon = C_\epsilon \frac{u^3}{l}, \quad (2.11)$$

and the integral and Kolmogorov length scales are related to the Taylor-based Reynolds number Re_λ by

$$\frac{l}{\eta} = C_\epsilon 15^{-3/4} Re_\lambda^{3/2}. \quad (2.12)$$

The integral length scale l is defined in terms of the normalized correlation function $R_{ii}(x)$ (such that $R_{ii}(0) = 1$) as

$$l = \int_0^\infty R_{ii}(x) dx. \quad (2.13)$$

In order to increase the Taylor Reynolds number, increasing the size of the turbulence chamber could be considered. The effect of magnification of the integral scale on the Kolmogorov length scale is considered in the relation of equation (2.14) as

$$\eta = \left(\frac{\nu}{u} \right)^{3/4} \left(\frac{l}{C_\epsilon} \right)^{1/4} \Rightarrow \eta \sim l^{1/4}. \quad (2.14)$$

This relation shows that the Kolmogorov length scale has a weak dependence on the integral length scale. According to Bocanegra [2] this may be an advantage, because the smallest observable η may depend on the resolution of the experiment. Hence, improvement of the Taylor Reynolds number (Re_λ) can be achieved in two ways,

- Increasing the velocities
- Increasing the size of the chamber

and the key turbulence parameters ($Re_\lambda, \eta, \tau_\eta$) are related to u and l as

$$Re_\lambda = l^{1/2} u^{1/2} 15^{1/2} \nu^{-1/2} C_\epsilon^{-1/2}, \quad (2.15)$$

$$\eta = l^{1/4} u^{-3/4} \nu^{3/4} C_\epsilon^{-1/4}, \quad (2.16)$$

$$\tau_\eta = l^{1/2} u^{-3/2} \nu^{1/2} C_\epsilon^{-1/2}. \quad (2.17)$$

Equations (2.16), (2.17) and (2.17) are giving the dependency of the main turbulent characteristics with respect to the flow parameters.

2.2.2 The sling effect

Small enough particles in a cloud move along with the turbulent air in that cloud. Falkovich *et al* [6] describe theoretically a new dynamical mechanism called the 'sling effect' by which extreme events in the turbulent air cause idealized inertial cloud particles to break free from the airflow. The sling effect causes isolated pockets in the flow wherein particle trajectories cross each other. This increases the chance of collisions that forms larger particles [1].

Chapter 3

Experimental setup

3.1 Turbulence chamber

A sketch of the turbulence chamber is seen in figure 3.1. The chamber consists of hexagons and pentagons. On the twenty hexagons are twenty speakers attached with a 30 cm diameter. In front of the speakers there are orifices to direct the flow to the middle of the chamber and to increase the jet strength. These orifices have an opening angle of 30° . The diameter of the chamber is approximately one meter. (The exact diameter varies from window to window.) The distance from the top of the chamber to the middle, where the droplets are detected, is 48 centimeter. The gray bar in figure 3.1 represents the laser beam.

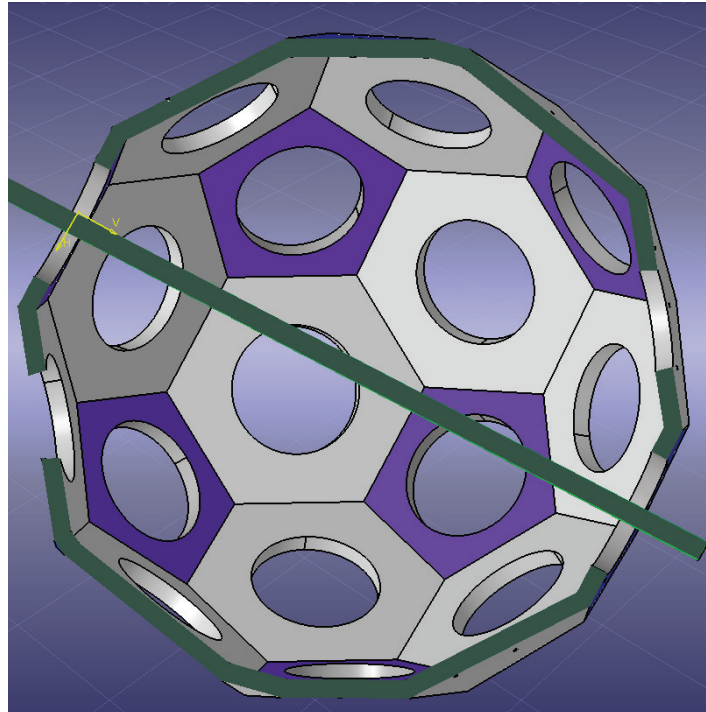


Figure 3.1: *An illustrative CAD sketch of the turbulence chamber. The bar represents the laser volume illumination.*

See figure 3.2 for a photo of the turbulence chamber equipped with the 3D-PTV system. The high speed cameras are attached on four of the pentagons of the chamber, two on the top and two on the bottom.

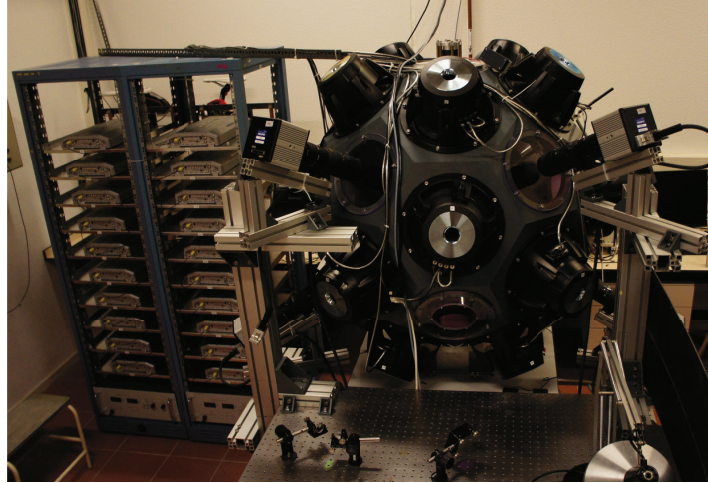


Figure 3.2: *The turbulence chamber equipped with PTV system.*

3.1.1 Rotating disk

For the droplet generation, a pressurized air-driven spindle (EST 1000K, Mannesmann-Demag, Stuttgart, Germany) and a disk with a diameter of two centimeter are used. See figure 3.3 for a sketch of the spindle with the disk. The droplet size can be varied by changing the rotation speed of the spindle. During this project a rotational speed of the spindle of approximately 2050 rad/s is used. So droplets with a diameter of approximately 25 μm are generated [2].

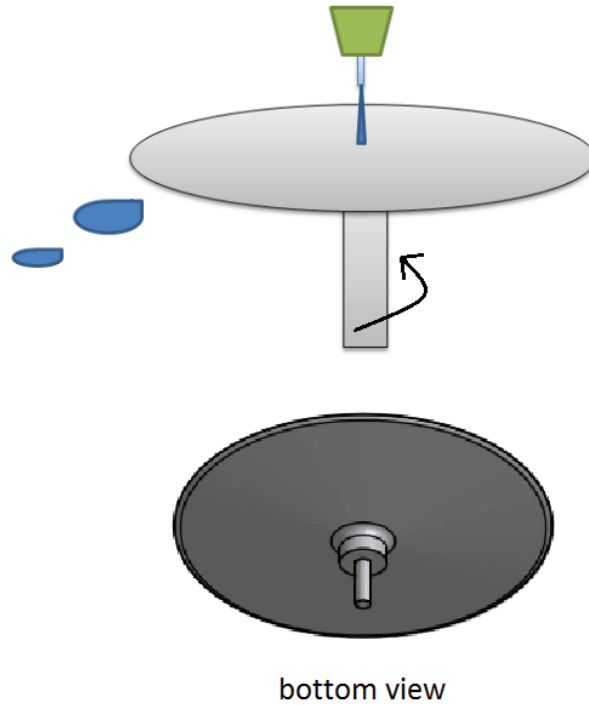


Figure 3.3: A sketch of the rotating disk used during the measurements.

Due to some facility limitations it is hard to achieve droplets bigger than $40\ \mu\text{m}$. When the rotational speed reaches around the $33,000\ \text{rev}/\text{min}$, the rotational speed remains fairly constant. The droplets size is than about $30\ \mu\text{m}$. When the rotation speed is increased, small droplets up to 10 micrometers can be created.

3.1.2 Molecular tagging with fluorescence dye Rhodamine

Rhodamine B is a fluorescent chemical compound, a dye that is used for molecular tagging. The rhodamine B has an emission wavelength of $610\ \text{nm}$ when exciting it with a laser of $527\ \text{nm}$. A mixture of rhodamine and water is used to create droplets. The fluorescent tagging helps us to well define the droplets, because of the glowing. Therefore not just the scattering light but also the emitted light is collected.

3.1.3 Speakers and signal

In this project droplets in a fully developed homogeneous isotropic turbulence are tracked. To create such a turbulence, there are 20 speakers (sub-woofers) of $30\ \text{cm}$ diameter (Alpine type-R sub-woofer model SWR-12D4) each with an independent amplifier. The jets coming from these speakers fulfill the requirement of average momentum transfer while averaging zero mass transfer. The twenty speakers are distributed in two sets of ten speakers. When the one set is pumping air into the chamber, the other set is sucking air from the chamber. The speakers are driven by an analog signal which is sent to the amplifier of the speaker. The signal that is sent to the amplifier is a sine wave. Every period of the sine, the amplitude of the signal changes and can even run negative. Before the measurement starts, the values between which the amplitude can change can be given as an input setting. An offset and a

maximum value of the amplitude between 1 and 6 V can be chosen. For example, if the offset is set at 1 V and the maximum at 3 V; the amplitude will take random values between the 1 and 3 V. The frequency remains the same through the whole measurement. Sub-woofers are suited for the lower frequencies, so frequencies between 20 and 48 Hz are used. [2]

3.2 Laser technique

3.2.1 Laser

To make the droplets visible, a high intensity laser (Empower 45, Q-Switched YLF Green Laser) is used. The laser is aligned over a table with optics until its radius is 20 mm in diameter. The beam passes through the chamber illuminating the central region of about $2 \times 2 \times 2 \text{ cm}^3$ in volume. The laser has a power of 28 mJ per pulse at 1 kHz.

3.2.2 3D-Particle Tracking Velocimetry

Three-dimensional - Particle Tracking Velocimetry (3D-PTV) is used to follow the droplets in the turbulence chamber. 3D-PTV is a distinctive experimental technique, based on multiple camera system, three-dimensional volume illumination and tracking of droplets in three dimensional space by using photogrammetric principles. Droplet positions can be followed in 3D. A typical installation of the 3D-PTV consists of three or four digital cameras, installed in an angular configuration, simultaneously recording the scattered and/or fluorescent light from the droplets seeded in the flow. The flow is illuminated by a collimated laser beam. In this project, four cameras are used in the setup. When a particle is seen by all four cameras, its position is saved for that specific time step. One of the tracking criteria is that the droplets must not travel further than their typical spacing.

The particle tracking velocimetry software performs the following tasks: calibration of the multi-camera system, image processing, particle detection, establishing correspondences, determine the 3D coordinates and finally perform the tracking from 2D images in 3D object space. The calibration of the multi-camera system consists of the determination of camera exterior and interior orientations, lens distortion and further disturbances. During the image processing high-pass filtering due to non-uniformities in the background illumination is performed. The particles are then detected in the images by a modified thresholding operator and the particles are localized with sub-pixel accuracy by a centroid operator. The stereoscopic correspondences are established, the 3D particle coordinates are determined and finally tracking is performed. [8] [5]

3.2.3 Imaging

In order to depict the droplets, four high speed cameras (Photron, 1024 PCI *Fastcam-x*) are used. The cameras provide 1000 frames per second (fps) recording at full mega pixel image resolution (1024 x 1024). These cameras are aligned on the same central volume in the turbulence chamber. The cameras are triggered by the laser pulse and are synchronised with each other. Nikkor lenses are used.

3.2.4 Calibration

Calibration is done with a calibration sheet. To have a space filling target, the calibration sheet is moved forward and backward in order to cover the center cubical volume. Because of the angle of the cameras, the calibration is done in three steps. One with the calibration sheet in the middle one with the calibration sheet turned over an angle of 45° to the left and another one with the calibration sheet turned over an angle of 45° to the right from the middle of the turbulence chamber.

Chapter 4

Results and discussion

First, droplets settling without any turbulence are investigated. Droplets are generated while the speakers are off. Then the gravitational settling velocity can be examined. When the experiment is run, the turbulence in the chamber is gradually increased in the following experiments. The results are then processed with the scripts written. Below a short description of these scripts and the results of the measurements are given.

4.1 Data processing

The photos recorded by the four high speed cameras are first processed with 3D-PTV code. This code is producing for each time step or frame a text file with the coordinates of all the droplets in that particular time step. A script reads the text files and sequences the droplets through the time steps. At the end, a matrix with all the droplets equipped with a label is produced. It is now easy to follow the droplets through time. These droplets are also provided with a time step or frame. The matrix can now easily be sorted by time step or label of the droplet. The matrix is illustrated in table 4.1.

Then, for each droplet, the velocities in that time step are calculated by subtracting the coordinates of the droplet in the following time step by the coordinates of the droplet in the current time step divided by the time between the time steps. Here v_y is the downward velocity, v_z is positive if the droplets move away from the cameras and v_x is positive if the droplets move to the left in the center cubical volume. The v_y velocity is positive if the droplet is moving up.

Table 4.1: *The idea of the matrix with droplets.*

Droplet label	time step / frame	x -coordinate	y -coordinate	z -coordinate	x -velocity	y -velocity	z -velocity	mean velocity
1	0	-1.230	7.673	0.842	...	...	...	...
2	0	1.768	7.061	8.465	...	...	...	...
3	0	3.303	-6.843	9.475	...	...	...	...
1	1	-1.130	7.546	0.770	...	...	...	...
2	1	1.751	7.060	8.404	...	...	...	...
3	1	3.317	-6.843	9.424	...	...	...	...
1	2	etc	...	...	...	...	...	...
4	2	etc	...	...	...	...	...	...

The total velocity is then calculated by

$$v_{tot} = \sqrt{v_x^2 + v_y^2 + v_z^2}. \quad (4.1)$$

To plot the track of the droplets, the droplets are first divided in three groups based on the number of frames (time steps) that the code was able to follow the droplets. There is a group between the 5 and 15 frames, a group with droplets followed between the 15 and 20 frames and a final group with droplets followed longer then 20 frames. The tracks of the last group are the most interesting to show in a figure. Also the downward velocity of individual droplets is plotted against the frames (time steps). In these figures can be seen which are the interesting parts of the measurement with a lot of droplets in the same frames. Also it can be seen if the droplets react the same (in terms of downward velocity) on the same turbulence.

4.2 Measurements

In the following sections, the results of some of the measurements are presented. First a measurement on a no flow case is done to make sure that the droplets reached their settling velocity in the measurement volume. After that some measurements are done on weak turbulence cases ($Re \approx 140$) and finally some measurements on strong turbulence cases ($Re \approx 240 - 310$). The measurements with turbulence that are done are labeled with case numbers to refer to them more easily. See table 4.2 for an overview. Turbulence is created by turning on the speakers. The offset and maximal amplitude of the specific cases are also given in the table.

The mean velocity components of all the measurements done are found in appendix A.1.

Table 4.2: *Different measurements are defined as cases.*

Case	Offset (V)	Maximal amplitude(V)	Frequency (Hz)	Reynoldsnumber	Droplet size (μm)
1	0	0.5	32	≈ 80	≈ 25
2	0.5	1	28	≈ 110	≈ 25
3	0.5	1	32	≈ 140	≈ 25
4	0.5	1	32	≈ 140	≈ 25
5	0.5	1	32	≈ 140	≈ 25
6	1	2	32	≈ 240	≈ 25
7	1	2	32	≈ 240	≈ 25
8	1	2	32	≈ 310	≈ 25
9	1	2	40	≈ 310	≈ 50

4.2.1 Measurement without turbulence

The settling velocity of the droplets given by equation (2.7) should be 0.0188 m/s. This value is calculated for a droplet size of 25 μm . See figure 4.1 for the graph of the different settling velocities corresponding with the different droplet sizes.

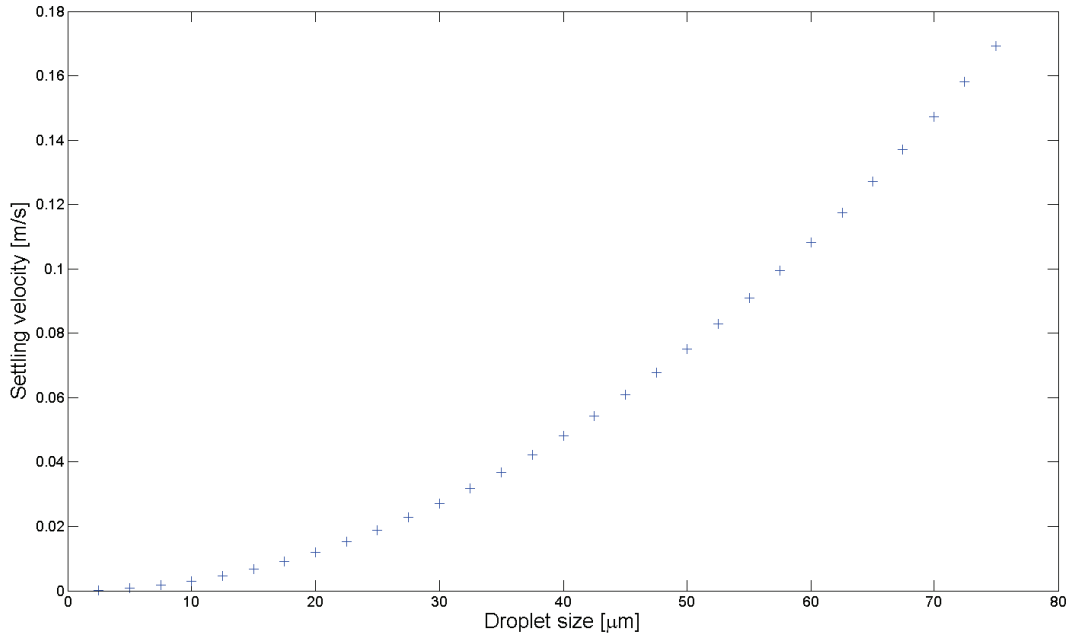


Figure 4.1: *The settling velocity of droplets with respect to the droplet size.*

This first measurement is performed to measure the settling velocity without any turbulence or mean flow. The calculated mean downward (y -) velocity is around 0.0119 m/s when all droplets that were tracked are taken into account. This velocity is still too low compared to the theoretical settling velocity. During the measurement however there were a lot of droplets that were tracked only for one or two frames. These tracks are unreliable and therefore the mean downward (y -) velocity is also calculated when only droplets that were tracked longer than 5 frames are taken into account. The mean downward velocity is then 0.0242 and therefore higher than the calculated theoretical settling velocity. When these two results are compared it can be assumed that the droplets reached their settling velocity when entering the measurement volume.

In figure 4.2 the tracks of a few droplets are plotted to get an idea of the general movement of the droplets. Droplets that were tracked longer than 20 frames are shown. The black star represents the starting position of the track of the droplet. The number represents the number of the first frame that the droplet could be seen by the 3D-PTV software. Every next star after the black star represents the droplet position in the next frame. The droplets move downward in an almost straight line as could be expected in a free fall. It is seen that there is a small deviation to the negative x -direction.

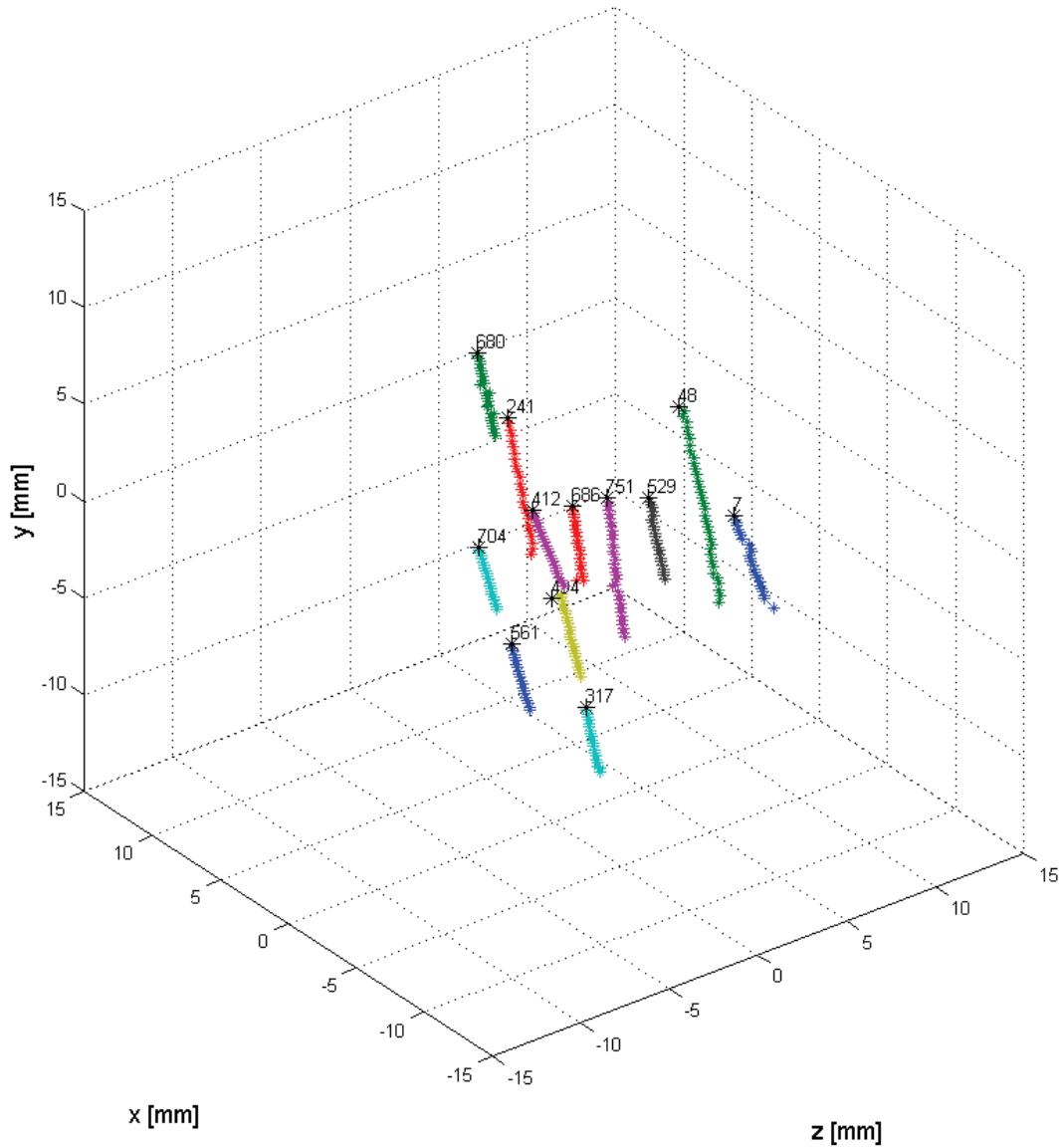


Figure 4.2: Tracks of droplets that were tracked longer than 20 frames. The black star represents the starting position and the number represents the number of the first frame that the droplet is seen.

The velocity component in the x -direction is of the same order as the downward (y) velocity component. An explanation for this could be that the droplets still have a radial component from the rotating disk. Or there might be some 'von Karman' flow due to the rotating disk in the turbulence chamber. In previous studies [2] is showed that when turbulence is added, the droplets are not much affected anymore by the radial flow of the spindle in the measuring range. There could be chosen to use this data from the no flow case to correct the data obtained by the measurements with turbulence. Also this data from the no flow case can be subtracted from the data with turbulence, or divide it to get dimensionless ratios. The Reynolds number of the droplets reaches almost zero as expected.

In the histograms of figure 4.3 it can be seen how the velocities are distributed. In this figure

all droplets that were tracked are taken into account. The distributions are nicely centered around the mean velocities.

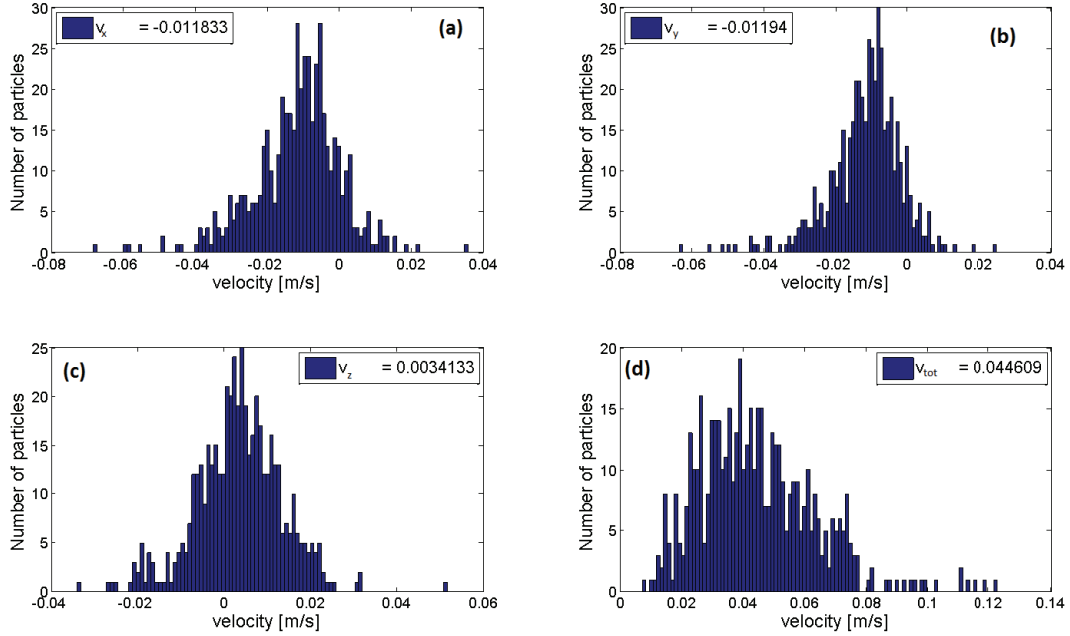


Figure 4.3: *Histograms of the velocity components of all the droplets for the no flow case. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x -direction. b. Droplets' velocity distribution in the y -direction. c. Droplets' velocity distribution in the z -direction. d. Droplets' total velocity distribution.*

During this measurement there were a lot short unreliable tracks. To see what happens if these tracks are taken out, only droplets that could be tracked longer than 5 frames are plotted in figure 4.4. During this measurement there were 378 droplets that were tracked longer than 5 frames. It are little droplets for some nice statistics but plotted anyway to get an idea of the look of the histograms.

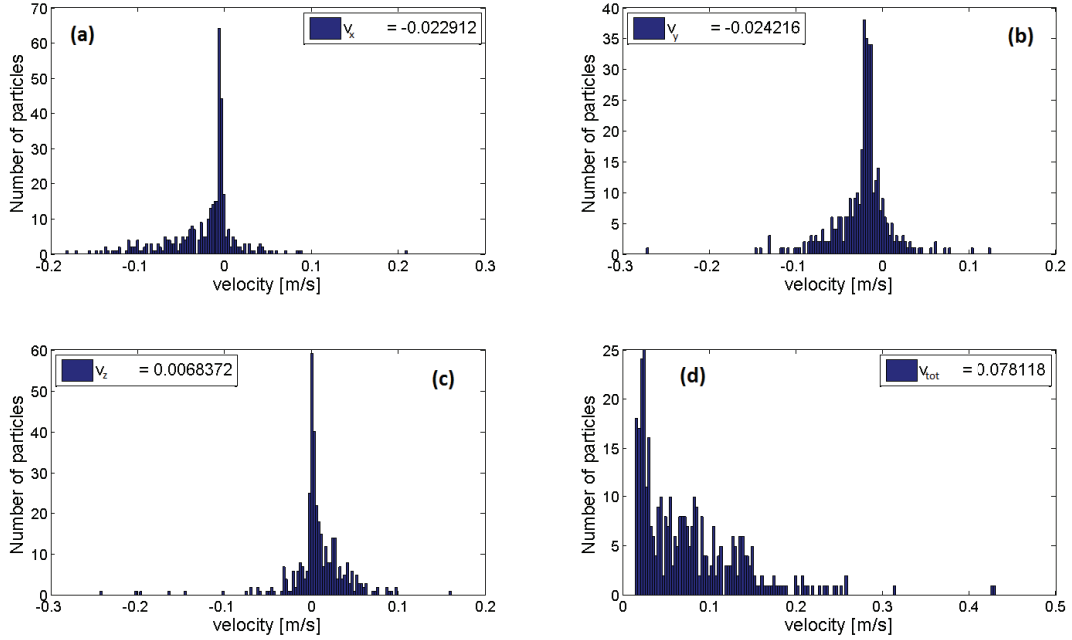


Figure 4.4: *Histograms of the velocity components of the droplets that were tracked longer than 5 frames for the no flow case. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x-direction. b. Droplets' velocity distribution in the y-direction. c. Droplets' velocity distribution in the z-direction. d. Droplets' total velocity distribution.*

The mean velocities of the long tracks are almost two times as big as the values of the mean velocities of all the droplets. As can be seen, the distribution of the droplets gets better with the longer tracks. The droplets with the short tracks can be seen as unreliable tracks and it is meaningful to take only the longer tracks into account. Therefore, for the next measurements only the histograms of the longer tracks are showed. The other histograms can be found in appendix A.2.

4.2.2 Measurements with turbulence

Below the results of some measurements with turbulence are described.

Case 1

The frequency used for this measurement is 32 Hz. Droplets are generated by a rotational speed of the spindle of 2050 rad/s. These droplets have a droplet size around 25 μm . See figure 4.5 for the mean velocities of the droplets that were tracked longer than 5 frames plotted in histograms. The histograms are nicely distributed and centered around the mean velocity. There were 2146 droplets that were tracked longer than 5 frames. The mean downward velocity increased to 0.1555 m/s from 0.0242 m/s which was the mean downward velocity for the longer tracks of the no flow case. Also the total mean velocity increased to 0.2100 m/s instead to the 0.0781 m/s for the no turbulence case. There is still some mean flow in the x-direction, maybe the turbulence is not strong enough yet to cancel out the effect of the

rotating disk.

So in contrast to the study of Bocanegra [2] there is still a component of the rotational speed of the spindle seen in the track of the droplets. Another explanation for this could be an imbalance in the signal over the speakers. For example all the speakers on the right or bottom of the turbulence chamber could be pumping air in to the chamber slightly more than than the other side. To cancel out these effects the measurement should be repeated a few times and the mean of the results has to be taken.

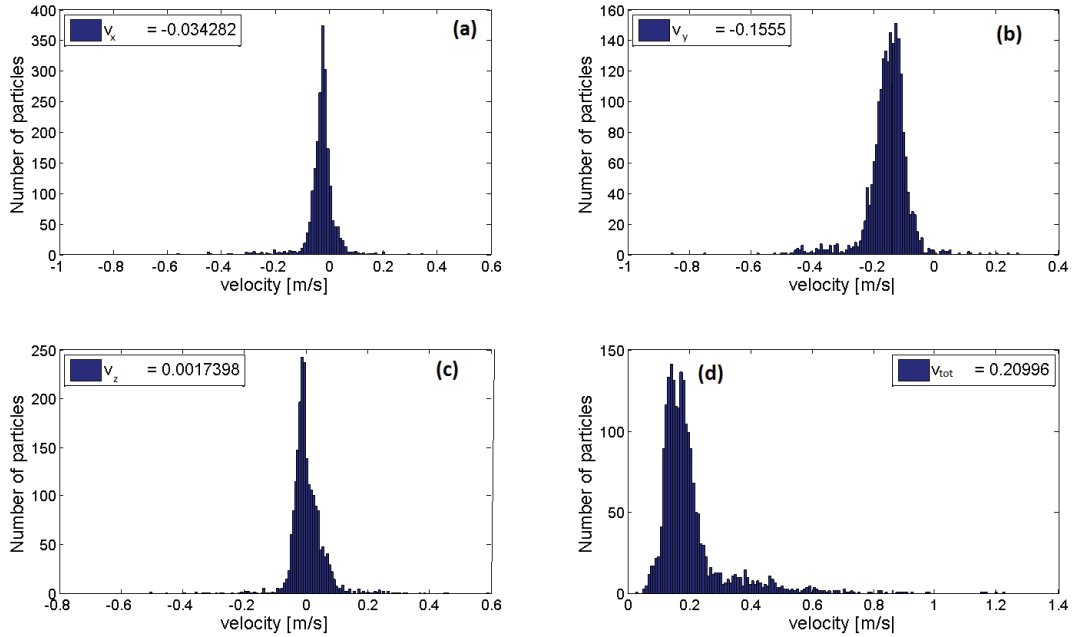


Figure 4.5: *Histograms of the velocity components of the droplets that were tracked longer than 5 frames. a. Droplets' velocity distribution in the x-direction. b. Droplets' velocity distribution in the y- direction. c. Droplets' velocity distribution in the z- direction. d. Droplets' total velocity distribution.*

See figure 4.6 to get an idea of the movement of the droplets during this measurement. The droplets are still going down in an almost straight line as could be expected in a low turbulence level case. Only slightly deflected to the negative x -direction. It can be seen that the deflection to the negative x -direction is less than the deflection in the no turbulence case. An explanation is that the droplets still encounter a force from the rotational speed of the spindle. It became less with a little turbulence but is still present.

Cases 2, 3, 4 and 5

The second series of measurements with turbulence is again done with a droplet size around $25 \mu\text{m}$. There are three measurements with a slightly different rotational speed (1900, 2050 and 2300 rad/s) and a frequency of 32 Hz. The tracks of a few droplets are plotted in figure 4.6b to get an idea of the general movement of the droplets. It looks like the droplets are passing each other, but they did not because they existed in different frames. The black star represents again the start of the track and the number gives the frame number of the start of

In figure 4.7 the histograms of the droplets that were tracked longer then 5 frames are plotted. There were 2175 droplets that could be tracked for longer frames. These results are obtained by the measurement with a rotational speed of 2050 rad/s.

For the 32 Hz, 2050 rad/s case, the downward velocity (0.0287 m/s) did not increase compared to the no turbulence case (0.0242 m/s). An explanation for this might be that there were not enough droplets (378) for the no turbulence case to calculate a meaningful settling velocity. It is also not expected that the downward velocity is less than the downward velocity for the first case. The total velocity however did increased with almost a factor 3 from 0.0781 m/s to 0.207 m/s compared to the no flow case. The data obtained by the measurements with 1900 rad/s and 2100 rad/s are consistent with the 2050 rad/s case, see table A.2. Striking is that the downward velocity of the 28 Hz, 2050 rad/s case is almost 4 times as high (0.0794 instead of 0.0287) as the downward velocity of the 32 Hz case. From this result, it looks like that this frequency has more effect on the downward velocity. However, this measurement may be done during an accidental imbalance in the speakers. To be sure, the measurements should be repeated a few times.

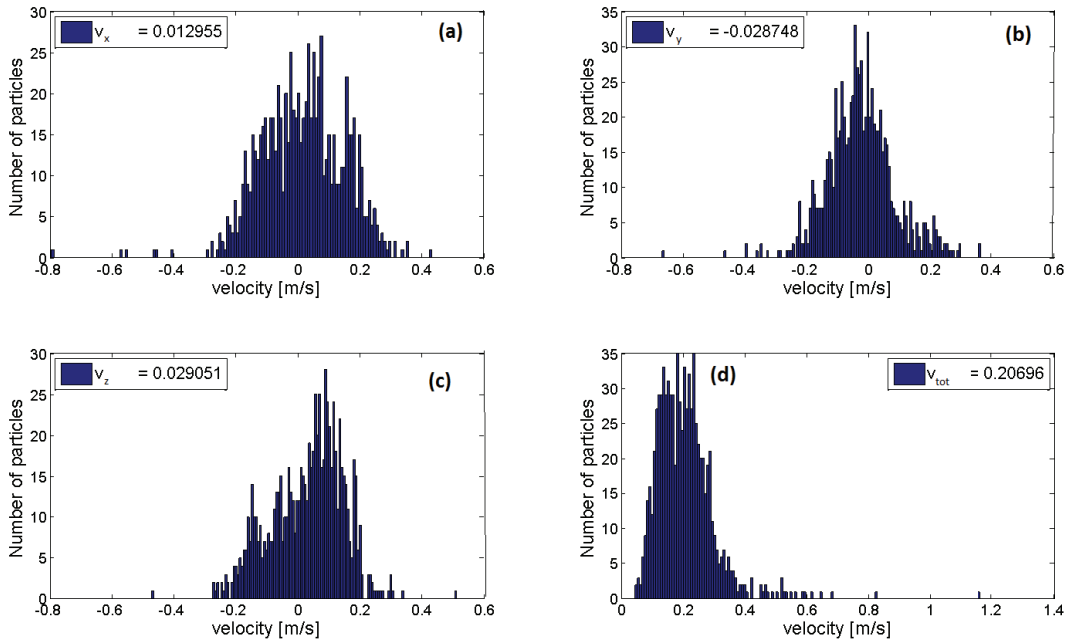


Figure 4.7: *Histograms of the velocity components of the droplets that were tracked longer than 5 frames. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x-direction. b. Droplets' velocity distribution in the y- direction. c. Droplets' velocity distribution in the z- direction. d. Droplets' total velocity distribution.*

As can be seen in the histograms there is still a component in the x -direction but it is the half of the component in the y -direction. The z -component however increased in magnitude. A possible explanation for this could be that the laser beam passes diagonally through the center cubical volume. See figure 3.1 for a sketch. Therefore, the cameras can follow the droplets longer in the z -direction, and the velocity component has a larger biased contribution. To check if this is the case, the laser should be placed at a different angle or let it reflect and

come back to cancel out the longer path distance in the z-direction. An other explanation is an accidental imbalance in the speakers. To rule out this possibility, the experiment should be redone a few times and the mean values should be taken.

In figure 4.8 the downward velocities of all the individual droplets are given. This figure can be a bit confusing but is good to get insight in the downward velocity fluctuations of the whole measurement with respect to the mean downward velocity of the measurement. The mean is represented by the black line. Each droplet has a different color in the plot, and when parts of the plot are magnified, the droplet downward velocity with respect to the mean can be examined. The part between the 3000 and 3400 frames is magnified in figure 4.9. Due to figure 4.9 some issues with the 3D-PTV code can be addressed. The big light blue spike for example probably is some software malfunction. When tracks of droplets are plotted some sharp ‘jumps’ or spikes are seen in the plotted tracks. These sharp spikes result in big velocity spikes seen in figure 4.9. A suggestion for future research would be to apply some smoothing or polynomial fitting to these data to get better results without the spikes. Also can be seen that droplets act similar during certain time frames. For example the two red and dark red/purple tracks at the end of the graph have the similar upward trend during a few frames. The spikes in the bottom track again might disappear after some smoothing or polynomial fitting.

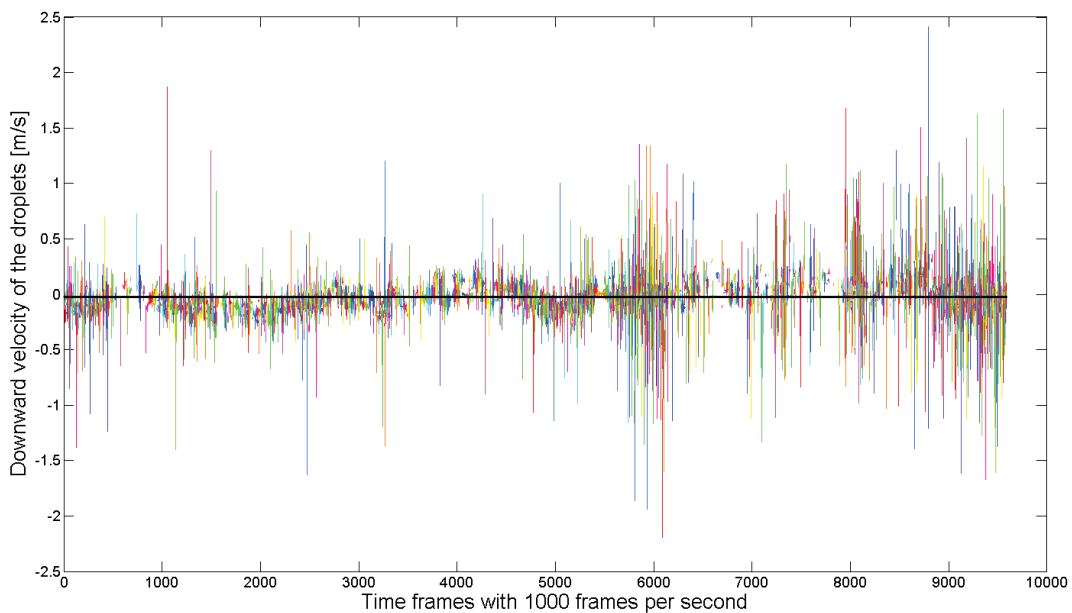


Figure 4.8: *Downward (y-) velocity [m/s] of the individual droplets during time. Droplets seen through the whole measurement are plotted. The black line stands for the mean downward velocity.*

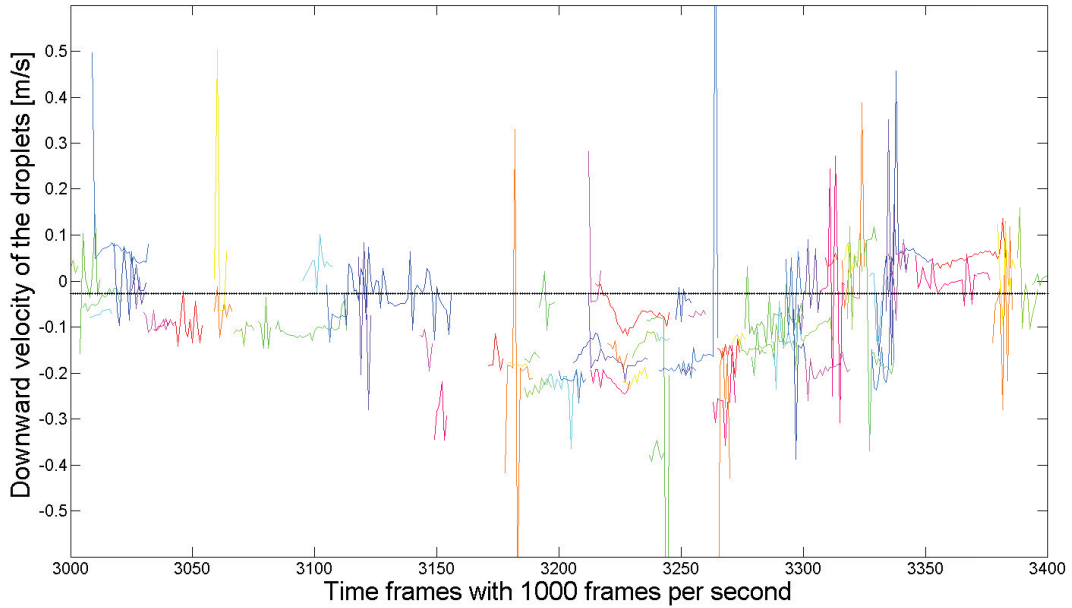


Figure 4.9: Downward (y -) velocity [m/s] of the individual droplets during time. Droplets seen between frame 3000 and 3400 are plotted. The black line stands for the mean downward velocity.

Some of these figures are also made for the other cases and are almost identical. Therefore they can be found in appendix A.2.

Cases 6 and 7

For the next measurements the turbulence is increased further. The amplitude now varies between the 1 and 2 V. One measurement is done with a rotational speed of 2050 rad/s, the other measurement is done with a rotational speed of 2300 rad/s. The droplet size stays around the 25 μm . The histograms corresponding with the measurement done with a rotational speed of 2050 rad/s can be seen in figure 4.10. Again only the tracks of the droplets that were tracked longer than 5 frames are plotted. For this strong turbulence case it was a lot harder to track droplets in a higher turbulence case. There were only 1274 droplets that could be tracked longer than 5 frames.

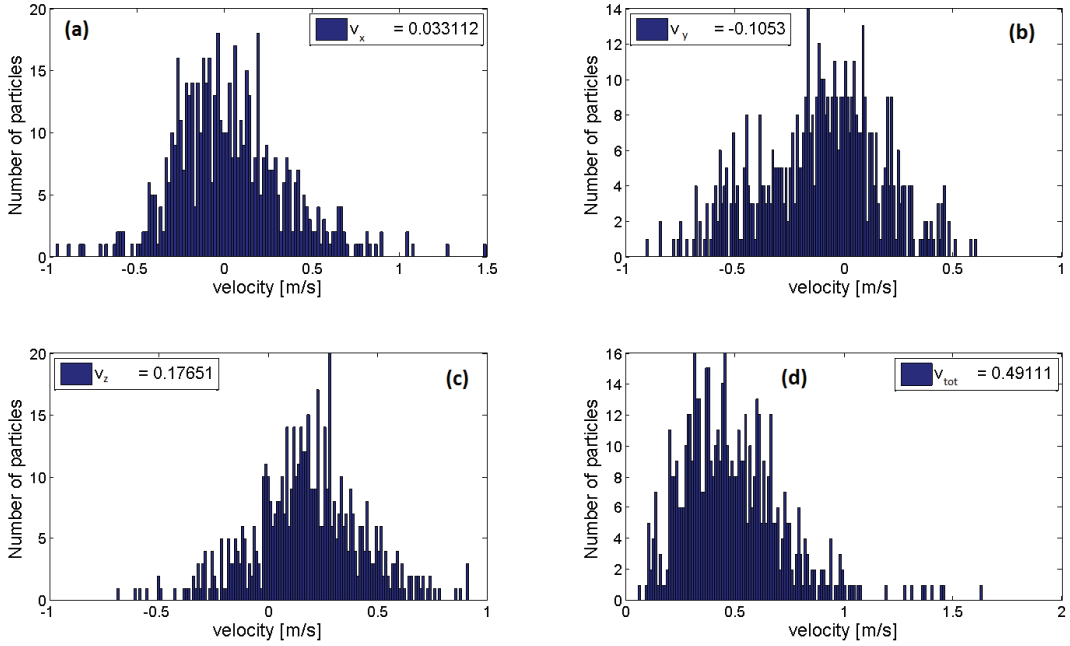
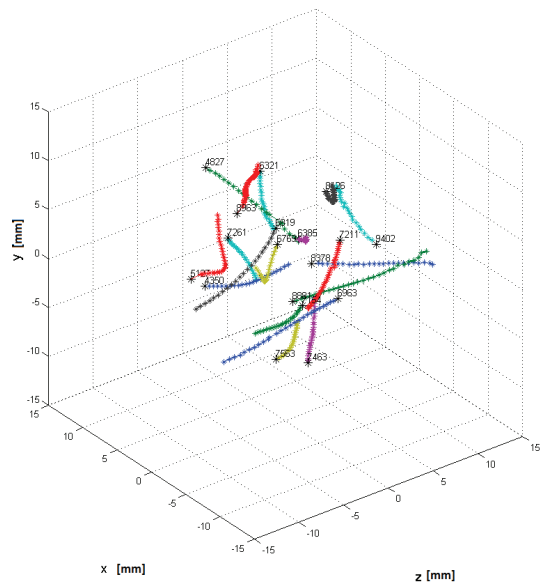


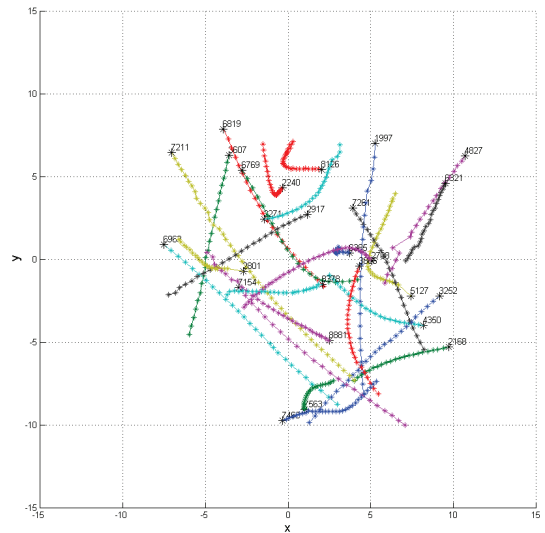
Figure 4.10: *Histograms of the velocity components of the droplets that were tracked longer than 5 frames. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x -direction. b. Droplets' velocity distribution in the y -direction. c. Droplets' velocity distribution in the z -direction. d. Droplets' total velocity distribution.*

The mean velocity increased with more than a factor two with respect to the lower turbulence cases. This is what could be expected. The downward velocity also increased a bit more with respect to the previous cases and increased even with a factor ten with respect to the no turbulence case. It can be said that there is indeed an effect on the downward velocity by adding turbulence to the system. But there is also a clear effect seen on the total velocity and the x - and z - velocities. Especially the z -component has the same magnitude as the y -component. This could partially be explained by the angle of the laser beam and partially maybe by an accidental imbalance in the speakers. There has to be done more measurements to set up nice statistics and to say something meaningful about it.

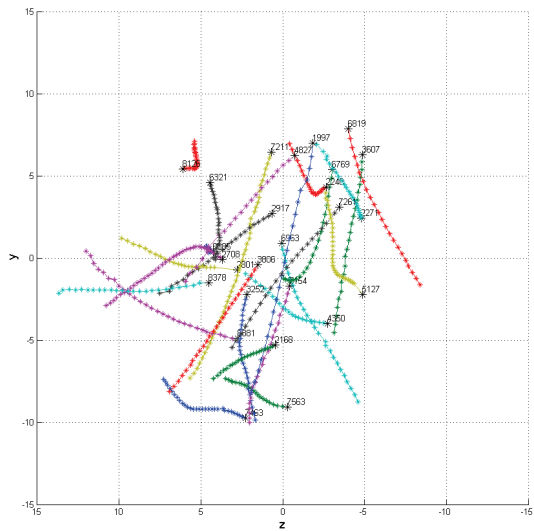
In figure 4.11 the tracks of some droplets that were followed longer than 20 frames are plotted. There is immediately a difference between this graph and the same graph for the lower turbulence cases described above. The droplets now even move upwards. That is possibly why the increase in downward velocity is not that spectacular. The total velocity on the other hand, increases with a factor two with respect to the less turbulent cases. In the figure, the iso-view and some side-views are given to give better insight in the droplet movements during this measurement.



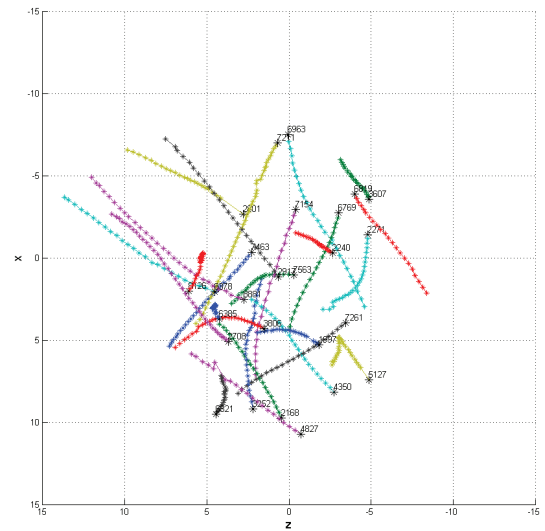
(a) Tracks of droplets that were followed longer than 20 frames in iso-view



(b) Tracks of droplets that were followed longer than 20 frames in side view.



(c) Tracks of droplets that were followed longer than 20 frames in side view.



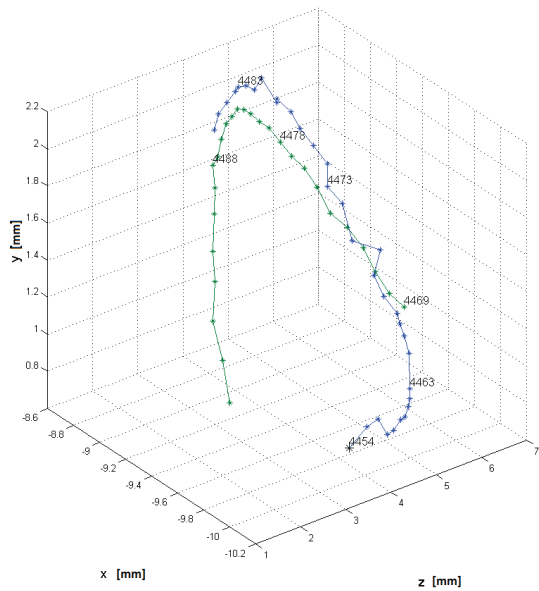
(d) Tracks of droplets that were followed longer than 20 frames in top view.

Figure 4.11: Tracks of droplets that were followed longer than 20 frames.

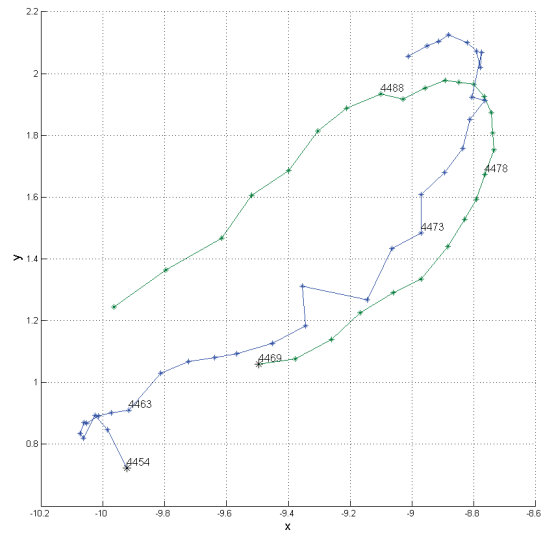
Cases 8 and 9

There are also two measurements performed with a frequency of 40 Hz. The first measurement is done with a rotational speed of 2050 rad/s and the second with a rotational speed of the spindle of 1200 rad/s. The results of these measurements are found in the tables A.2 and A.3. Accompanying graphs can be found in appendix A.2. As can be seen, the total velocity increased a lot with respect to the lower turbulence cases. Especially when only looking at the droplets that could be followed longer than 5 frames. It should be mentioned that the y -velocity does not have a clear increase and might even decrease with respect to previous cases. This kind of turbulence therefore let the drops move very intense and that does not benefit the downward velocity.

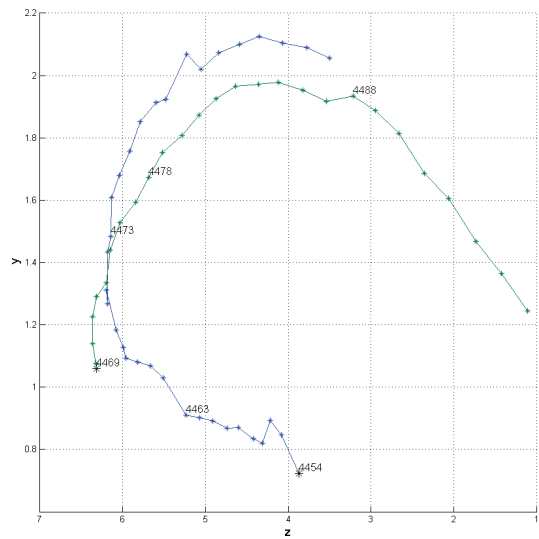
For the second measurement (1200 rad/s) the droplet size lays around the 50 μm . There is one big difference in the results between this measurement and the measurement done with the 25 μm droplets. The downward velocity of the measurement with the bigger droplets increased with a factor two with respect to the measurement with the smaller droplets. The x - and z - velocity components remain almost the same. The total velocity decreases a bit, an explanation for this might be that larger droplets are less taken by the turbulence. In this measurement the tracks of two droplets are interesting. They passed really close by each other in almost the same time frames. The tracks of these two droplets are plotted in figure 4.12, an iso-view and some side views are given to give better insight. The numbers represent the frame of the droplet in that specific point. These measurements need to be validated, but there are a couple of tracks that are probable clustering, coalescence or the sling effect [1]. These preferential concentrations are some evidence that can elucidate some atmospheric phenomena.



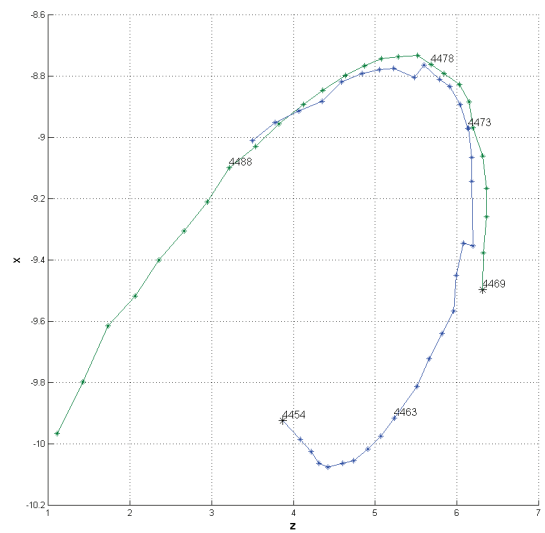
(a) Tracks of droplets that were followed longer than 20 frames in iso-view



(b) Tracks of droplets that were followed longer than 20 frames in side view.



(c) Tracks of droplets that were followed longer than 20 frames in side view.



(d) Tracks of droplets that were followed longer than 20 frames in top view.

Figure 4.12: Tracks of droplets that were followed longer than 20 frames.

When the photos made by the high speed cameras are scrutinized, it is very hard to define which droplets the software was able to follow. However it can be said that this event was not some software malfunction or a cluster of droplets seen as two separate droplets. So these droplets move almost along the same path. An explanation for this could be that there was a vortex at that point and the droplets were small enough to move along that vortex or the sling effect. On the closest points, between time frame 4483 and 4487 the droplets move along each other with a mutual distance of approximately 0.14 mm.

The tables with all the results can be found in appendix A.1. As can be seen from the tables, the first measurement does not agree well with the other measurements. It would be wise to repeat that measurement (case 1). See figure 4.13 for the mean downward velocity of a few cases plotted against the Reynolds number. As can be seen, a higher Reynolds number increases the mean downward velocity until a certain point. After that the turbulence gets to intense and the droplets are moving very chaotic, which results in a lower mean downward velocity. All the blue stars represent a droplet size of $25\ \mu\text{m}$ and the black plus represent a droplet size of $50\ \mu\text{m}$. The mean downward velocity for the $50\ \mu\text{m}$ droplets is twice as high as the mean downward velocity of the $25\ \mu\text{m}$ droplets. An explanation could be that the heavier droplets are less taken by the turbulence.

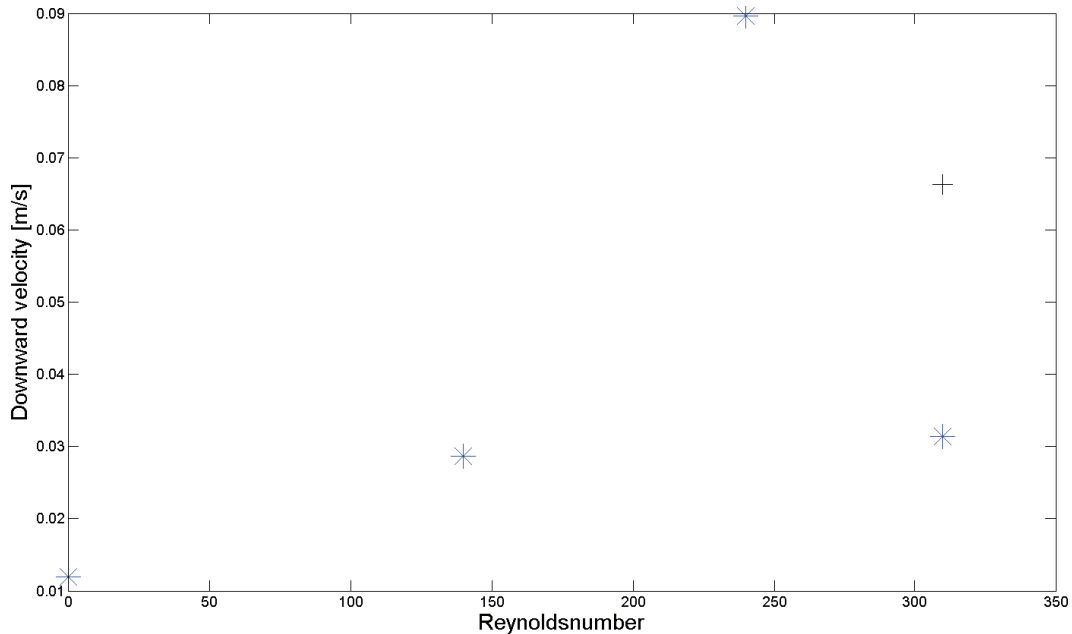


Figure 4.13: *The mean downward velocity plotted against the Reynolds number. The blue stars represent a droplet size of $25\ \mu\text{m}$ and the black plus represent a droplet size of $50\ \mu\text{m}$.*

In general can be concluded that turning up the frequency of the speakers results in a greater turbulence increase than turning up the amplitude. When the turbulence level is increased, the droplets are becoming hard to follow.

4.2.3 Decomposing the signal

To make sure if the signal over the speakers is completely random and there is no time dependency in the signal, a Fourier plot is performed. Luckily there is no frequency dependency found in the signal. A Fourier plot can be found in figure 4.14 to get an idea.

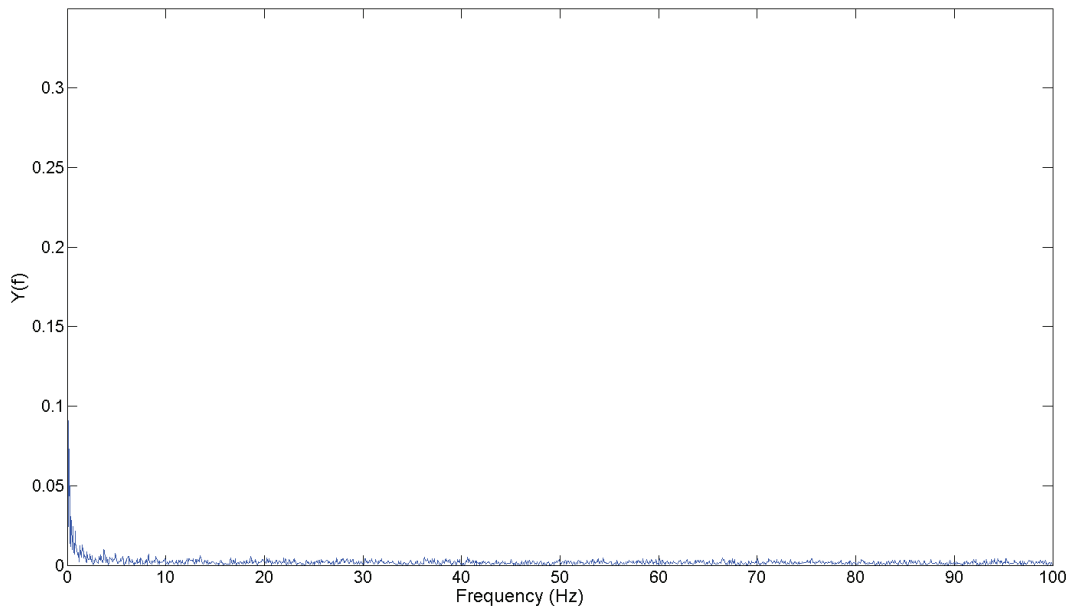


Figure 4.14: *Fast Fourier Transform of the mean velocity of the droplets at each time step*

Chapter 5

Conclusion

So does turbulence enhances the downward velocity of the droplets? From the measurements it can be concluded that the downward velocity of the droplets indeed increases when turbulence is added to the system. An increase in the downward velocity however is only seen up to a certain turbulence level. For a strong turbulence ($Re \approx 310$) there is a decrease in the downward velocity. The movement of the droplets then becomes chaotic. The measurements done are not enough to state that turbulence unconditionally enhances the downward velocity of the droplets.

During the measurements a few interesting tracks are seen of droplets passing close by each other. The question remains if these tracks are explained by preferential concentration, clustering of droplets, the sling effect or that the droplets were just small enough to be affected by vortices.

To improve this experiment and be able to make better conclusions, it is necessary to take a look at the angle of the laser when it passes through the measurement volume. A further suggestion would be to improve the results with turbulence by applying some smoothing or polynomial fitting to the data. It is also recommended to repeat the measurements to set up some better statistics.

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Appendix A

Appendix

A.1 Tables corresponding with the measurements

Table A.1: *Mean velocity components and Reynolds number of the droplet without any flow.*

Measurement	mean x -velocity [m/s]	mean y -velocity [m/s]	mean z -velocity [m/s]	mean velocity [m/s]	Reynolds number of the droplet
No Turbulence, all droplets	-0.0118	-0.0119	0.0034	0.0446	0.0704
No Turbulence, long tracks	-0.0229	-0.0242	0.00684	0.0781	

Table A.2: *The mean velocities of the different measurements. The mean is taken only over all the droplets that were tracked.*

Case	Measurement	mean x -velocity [m/s]	mean y -velocity [m/s]	mean z -velocity [m/s]	mean velocity [m/s]
1	0.05V 32Hz 2050 rad/s	-0.033	-0.0857	0.0046	0.1326
2	1.05V 28Hz 2050 rad/s	0.0359	-0.0794	-0.0212	0.1416
3	1.05V 32Hz 1900 rad/s	0.0229	-0.0219	-0.0389	0.1535
4	1.05V 32Hz 2050 rad/s	0.0078	-0.0203	0.0277	0.1407
5	1.05V 32Hz 2100 rad/s	-0.0365	-0.0327	0.0664	0.1499
6	2.1V 32Hz 2050 rad/s	0.0049	-0.1076	0.122	0.3204
7	2.1V 32Hz 2300 rad/s	-0.0223	-0.0611	0.133	0.2908
8	2.1V 40Hz 2050 rad/s	0.1133	-0.0151	0.0613	0.3701
9	2.1V 40Hz 1200 rad/s	0.0381	-0.0544	0.0825	0.3606

Table A.3: *The mean velocities of the different measurements. The mean is taken only over the droplets that were tracked longer than 5 frames.*

Case	mean x -velocity [m/s]	mean y -velocity [m/s]	mean z -velocity [m/s]	mean velocity [m/s]
1	-0.0343	-0.1555	0.0017	0.2100
2	0.0846	-0.1382	-0.0447	0.2255
3	0.0419	-0.0274	-0.0634	0.2590
4	0.0130	-0.0287	0.0291	0.207
5	-0.0674	-0.0655	0.1269	0.2686
6	0.0252	-0.0803	0.1639	0.4375
7	-0.0203	-0.0896	0.1955	0.4636
8	0.2096	-0.0314	0.1434	0.6998
9	0.0774	-0.0663	0.1515	0.5819

Table A.4: *The Reynolds number of all cases and η and τ_η of a few cases.*

Case	Re_λ (approximately)	η	τ_η
1	80	...	...
2	110	...	...
3	140	...	...
4	140	...	...
5	140	...	...
6	240	0.000189	0.0024
7	240	0.000189	0.0024
8	310	0.000126	0.00105
9	310	0.000126	0.00105

A.2 Results of measurements with turbulence

A.2.1 0V_0.5V 32Hz 2050 rad/s

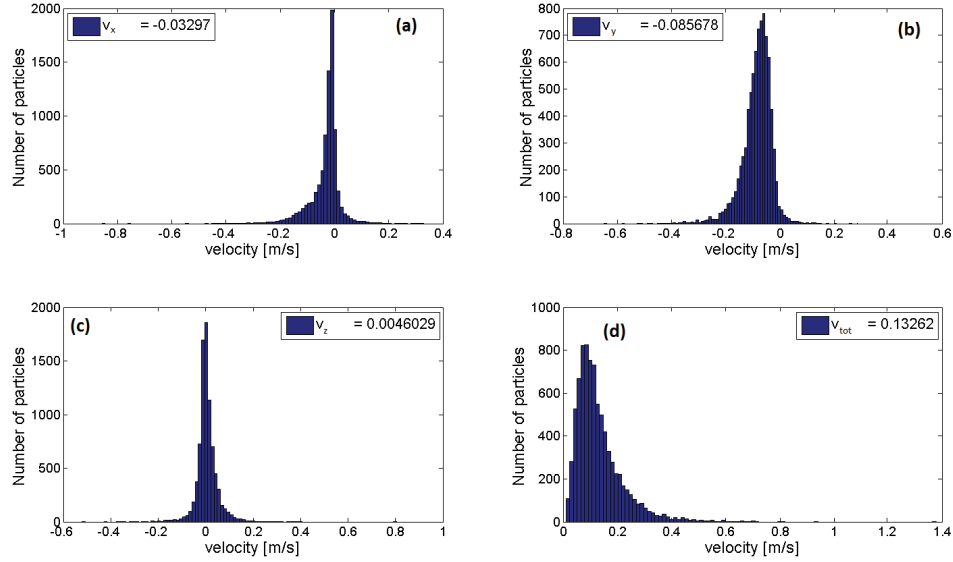


Figure A.1: Histograms of the velocity components of all the droplets. The mean velocities are mentioned in the legends. **a.** Droplets' velocity distribution in the x -direction. **b.** Droplets' velocity distribution in the y -direction. **c.** Droplets' velocity distribution in the z -direction. **d.** Droplets' total velocity distribution.

A.2.2 0.5V_1V 28Hz 2050 rad/s

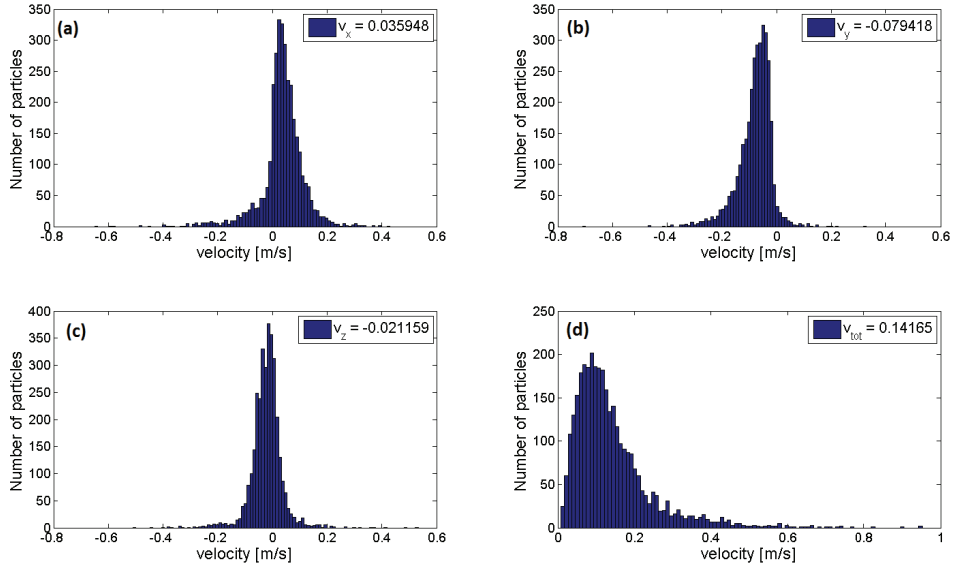


Figure A.2: *Histograms of the velocity components of all the droplets. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x-direction. b. Droplets' velocity distribution in the y- direction. c. Droplets' velocity distribution in the z- direction. d. Droplets' total velocity distribution.*

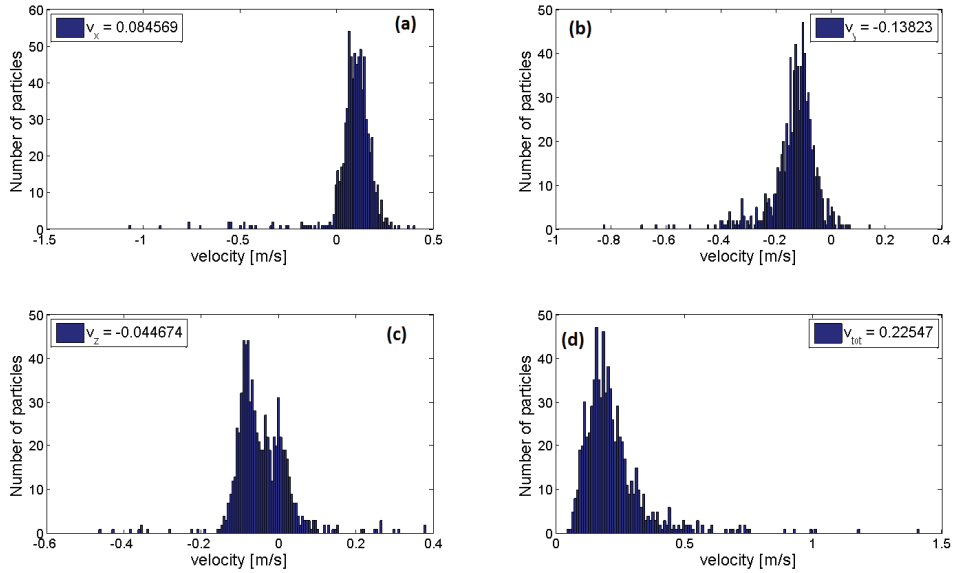


Figure A.3: *Histograms of the velocity components of all the droplets that were tracked longer than 5 frames. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x-direction. b. Droplets' velocity distribution in the y- direction. c. Droplets' velocity distribution in the z- direction. d. Droplets' total velocity distribution.*

A.2.3 0.5V_1V 32Hz 1900 rad/s

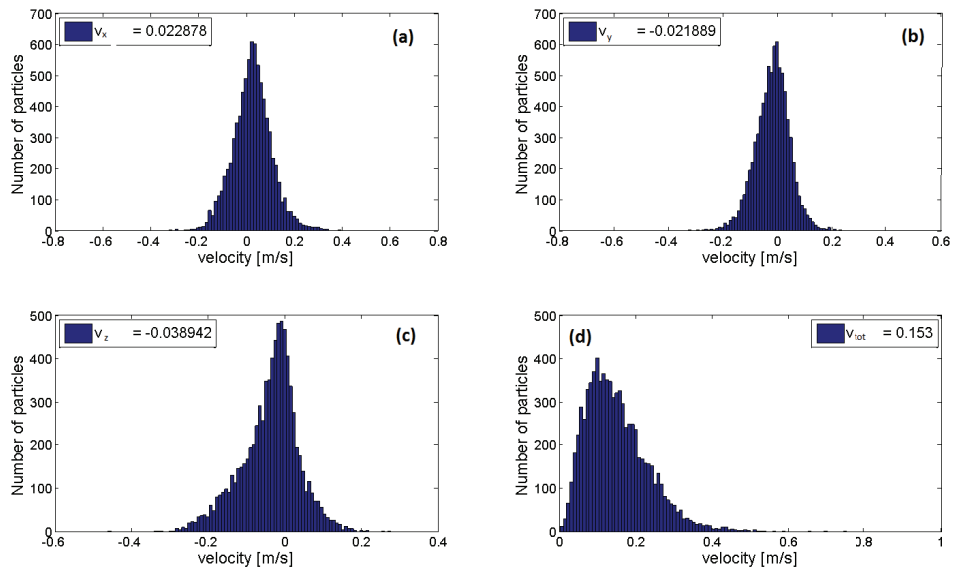


Figure A.4: Histograms of the velocity components of all the droplets. The mean velocities are mentioned in the legends. **a.** Droplets' velocity distribution in the x -direction. **b.** Droplets' velocity distribution in the y - direction. **c.** Droplets' velocity distribution in the z - direction. **d.** Droplets' total velocity distribution.

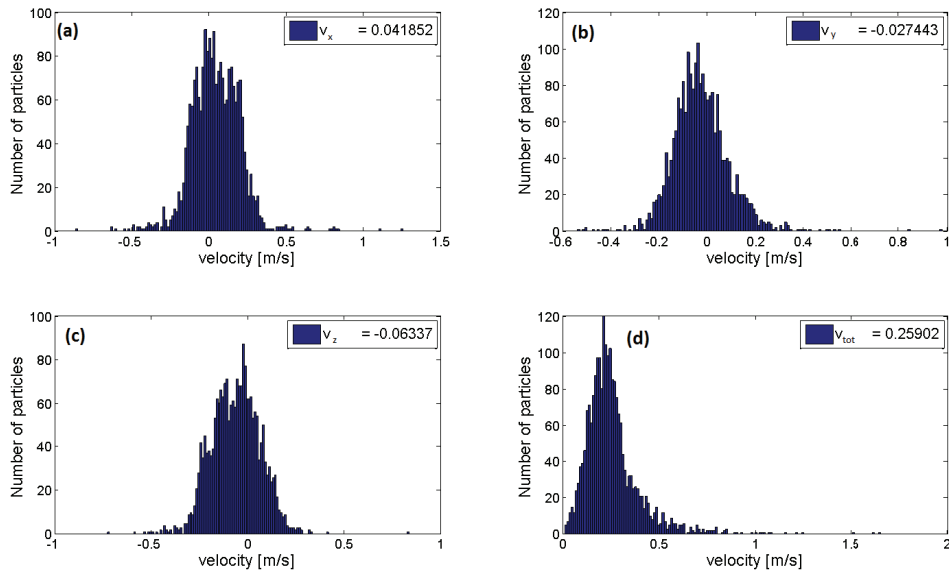


Figure A.5: *Histograms of the velocity components of all the droplets that were tracked longer than 5 frames. The mean velocities are mentioned in the legends. **a.** Droplets' velocity distribution in the x-direction. **b.** Droplets' velocity distribution in the y- direction. **c.** Droplets' velocity distribution in the z- direction. **d.** Droplets' total velocity distribution.*

A.2.4 0.5V_1V 32Hz 2050 rad/s

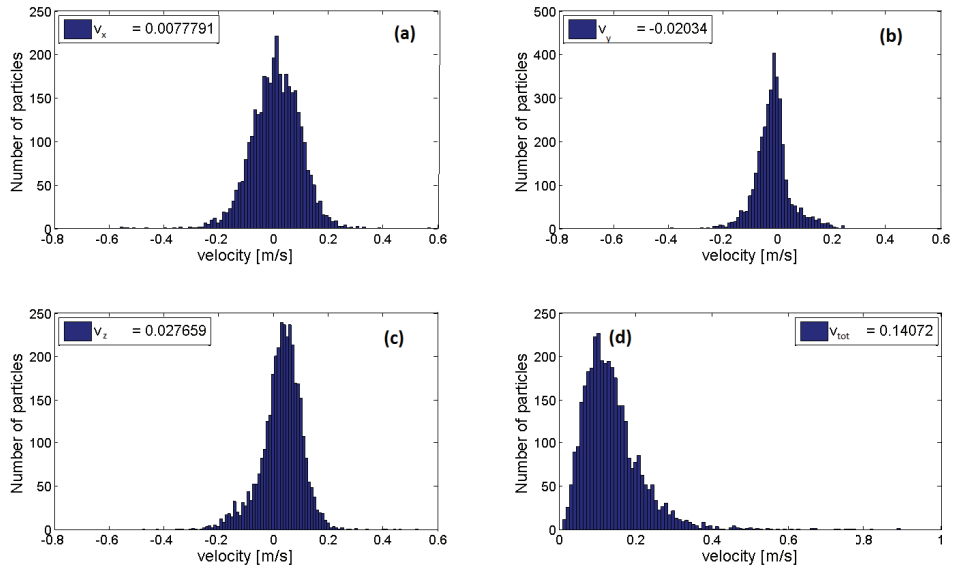


Figure A.6: Histograms of the velocity components of all the droplets. The mean velocities are mentioned in the legends. **a.** Droplets' velocity distribution in the x -direction. **b.** Droplets' velocity distribution in the y -direction. **c.** Droplets' velocity distribution in the z -direction. **d.** Droplets' total velocity distribution.

A.2.5 0.5V_1V 32Hz 2100 rad/s

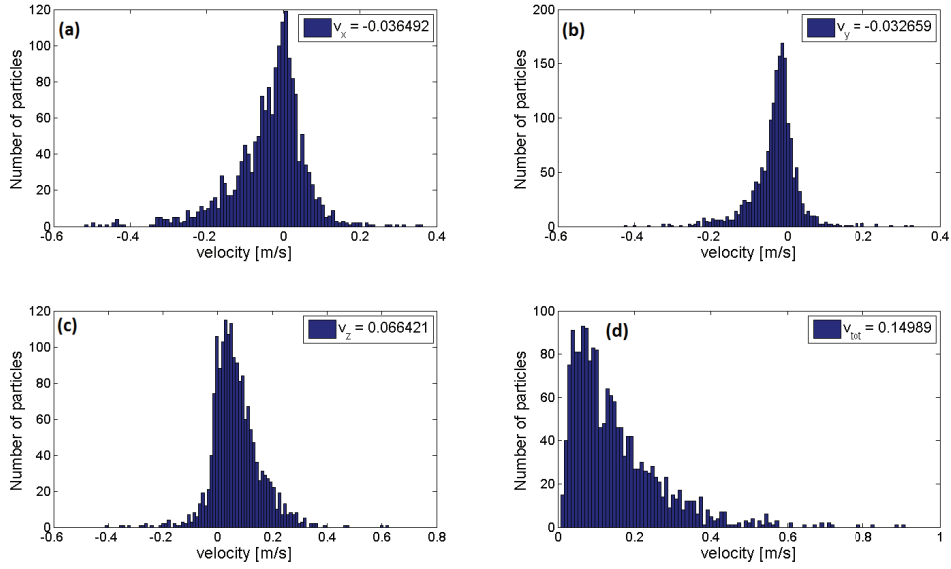


Figure A.7: *Histograms of the velocity components of all the droplets. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x-direction. b. Droplets' velocity distribution in the y- direction. c. Droplets' velocity distribution in the z- direction. d. Droplets' total velocity distribution.*

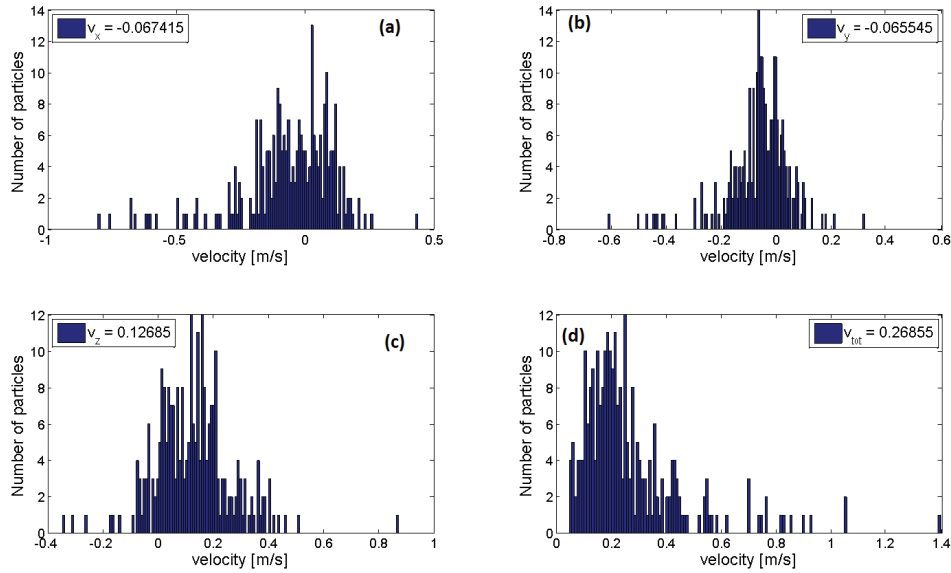


Figure A.8: *Histograms of the velocity components of all the droplets that were tracked longer than 5 frames. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x-direction. b. Droplets' velocity distribution in the y- direction. c. Droplets' velocity distribution in the z- direction. d. Droplets' total velocity distribution.*

A.2.6 1V_2V 32Hz 2050 rad/s

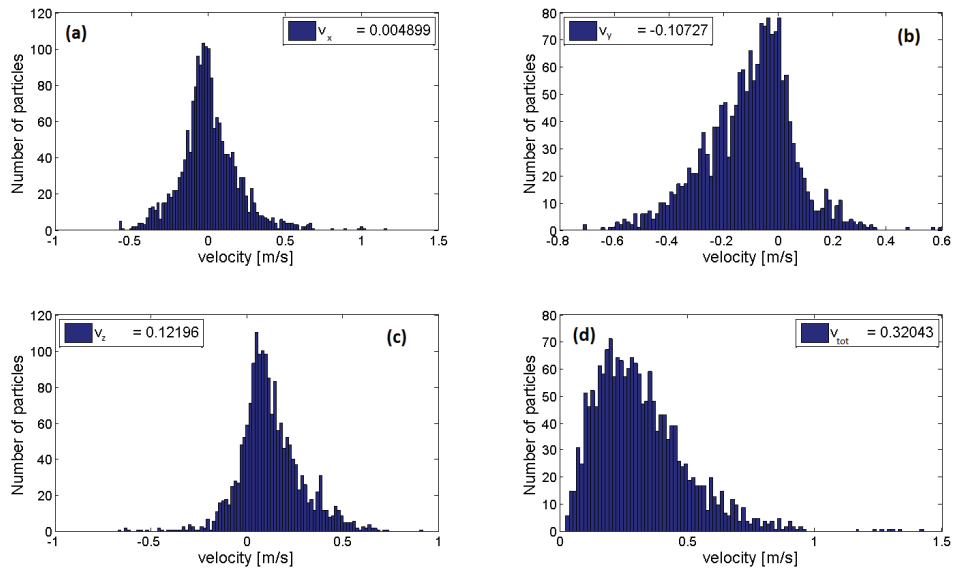


Figure A.9: *Histograms of the velocity components of all the droplets. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x-direction. b. Droplets' velocity distribution in the y- direction. c. Droplets' velocity distribution in the z- direction. d. Droplets' total velocity distribution.*

A.2.7 1V_2V 32Hz 2300 rad/s

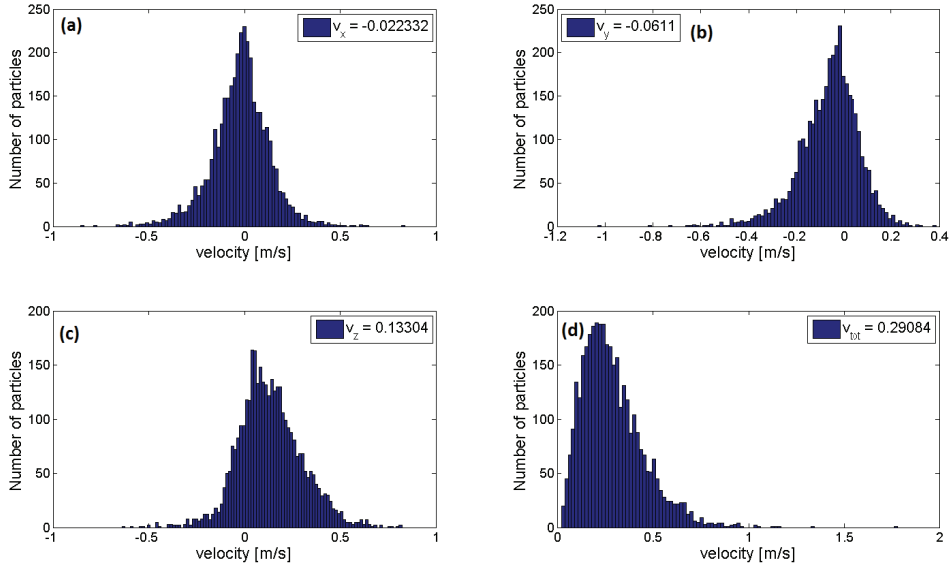


Figure A.10: *Histograms of the velocity components of all the droplets. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x-direction. b. Droplets' velocity distribution in the y- direction. c. Droplets' velocity distribution in the z- direction. d. Droplets' total velocity distribution.*

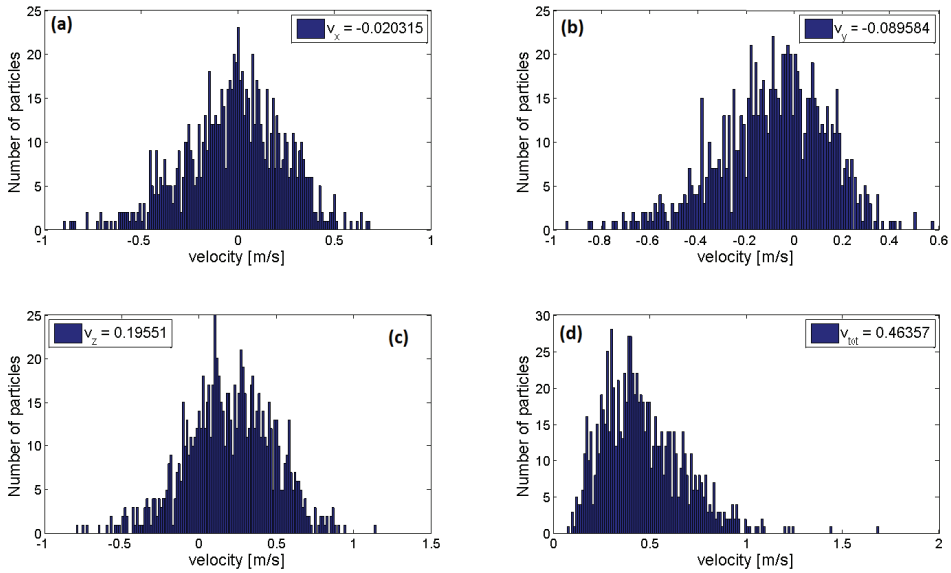


Figure A.11: *Histograms of the velocity components of all the droplets that were tracked longer than 5 frames. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x-direction. b. Droplets' velocity distribution in the y- direction. c. Droplets' velocity distribution in the z- direction. d. Droplets' total velocity distribution.*

A.2.8 1V_2V 40Hz 2050 rad/s

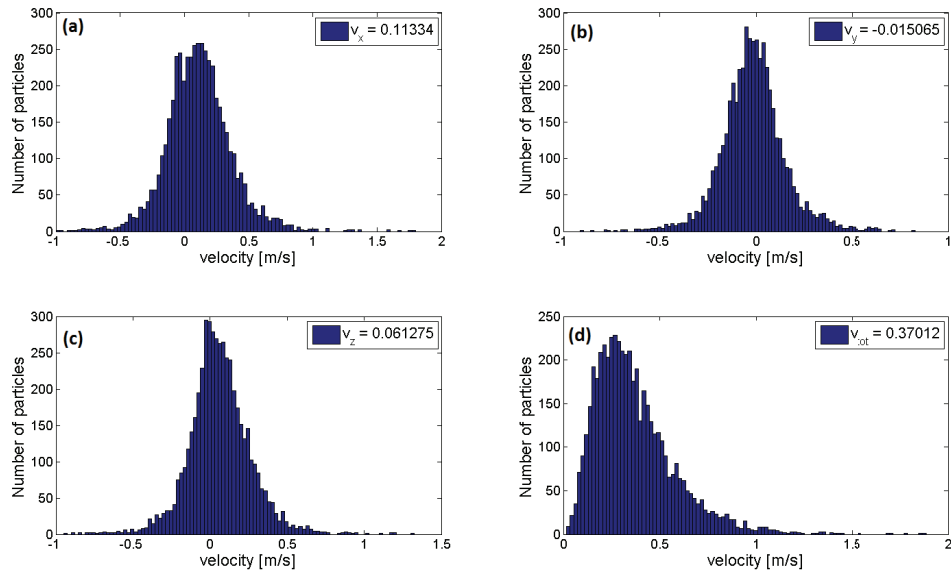


Figure A.12: *Histograms of the velocity components of all the droplets. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x-direction. b. Droplets' velocity distribution in the y- direction. c. Droplets' velocity distribution in the z- direction. d. Droplets' total velocity distribution.*

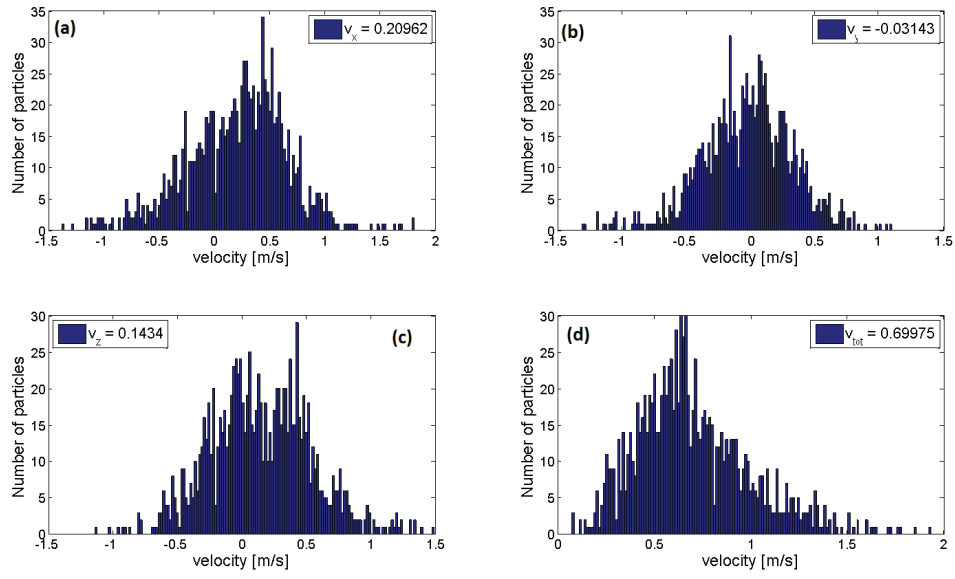


Figure A.13: Histograms of the velocity components of all the droplets that were tracked longer than 5 frames. The mean velocities are mentioned in the legends. **a.** Droplets' velocity distribution in the x -direction. **b.** Droplets' velocity distribution in the y -direction. **c.** Droplets' velocity distribution in the z -direction. **d.** Droplets' total velocity distribution.

A.2.9 1V_2V 40Hz 1200 rad/s

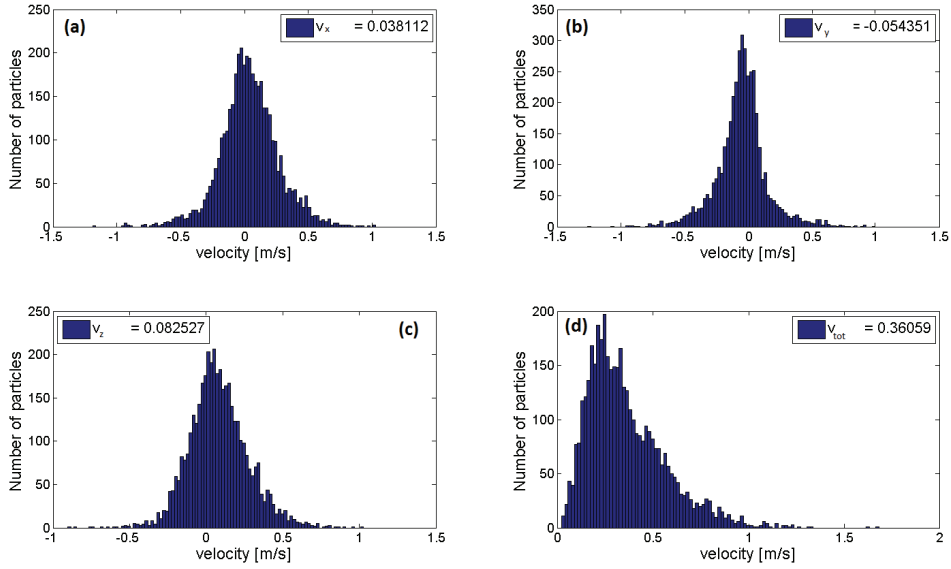


Figure A.14: *Histograms of the velocity components of all the droplets. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x-direction. b. Droplets' velocity distribution in the y- direction. c. Droplets' velocity distribution in the z- direction. d. Droplets' total velocity distribution.*

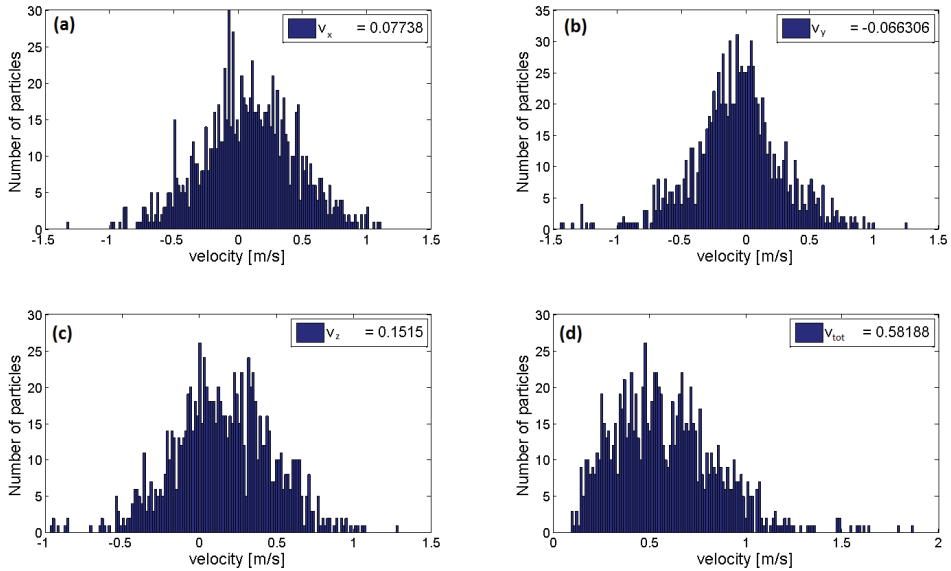


Figure A.15: *Histograms of the velocity components of all the droplets that were tracked longer than 5 frames. The mean velocities are mentioned in the legends. a. Droplets' velocity distribution in the x-direction. b. Droplets' velocity distribution in the y- direction. c. Droplets' velocity distribution in the z- direction. d. Droplets' total velocity distribution.*

A.3 Scripts

A.3.1 Loadandsequencedroplets.m

```
clear all;
clc

n = 1000000;
T = 1;
N = 9600;
M = [];
l = [];
S = [];
y = [];
nrows = [];
b = 1;
s = 1;
p = 1;
r = 1;

for i = 1:N;
    filename = ['../res/added.', num2str(i+n)];
    fid = fopen(filename);
    A = textscan(fid, '%f_%f_%f_%f_%f_%f');
    m = [A{1,1},A{1,2},A{1,3},A{1,4},A{1,5}];
    nrows(i,1) = i-1;
    nrows(i,2) = m(1,1);
    s = sum(nrows(1:i-2,2));
    m = m(2:end,:);
    m(:,6) = i-1;
    for j = 1:nrows(i,2);
        if m(j,1) == -1
            m(j,7) = b;
            b = b+1;
        else
            m(j,7) = M(m(j,1)+s+1,7);
        end
        B(j,1) = b;
        B(j,2) = m(j,2);
    end
    M = [M;m];
    fclose(fid);
end
```

```

varname = strcat('M');
filename = strcat('I:../work/matlab/',varname);
save (filename ,varname);

%sort op particle number, remove sequence information and put particle
%number in first column
M(:,1) = M(:,7);
M(:,2) = M(:,6);
M(:,6:7)=[];
SP = sortrows(M,1);

for q = 1 : length(SP)-1
    if SP(q,1) == p && SP(q+1,1) == p
        r = r+1;
        for k = 3:5
            SP(q,k+3) = (SP(q+1,k)-SP(q,k))/T;
        end
        SP(q,9) = sqrt(SP(q,6)^2+SP(q,7)^2+SP(q,8)^2);
    elseif SP(q,1) == p
        l(p,1) = p;
        l(p,2) = r;
        if r > 2;
            S = sum(SP((q-r+1):(q-1),:));
            for k = 3:6
                SP(q,k+3) = S(1,k+3)/(r-1);
                l(p,k) = SP(q,k+3);
            end
        end
        p = p+1;
        r = 1;
    end
end

%%
MT = sortrows(SP,2);
p = 0;
r = 1;
for w = 1 : length(MT)-1
    if MT(w,2) == p && MT(w+1,2) == p
        r = r+1;
    elseif MT(w,2) == p

```

```

        if r > 2;
        ST = sum(MT((w-r+1):w,:));
        y(w,1) = MT(w-1,2);
        y(w,2) = ST(:,6)/r;
        y(w,3) = ST(:,7)/r;
        y(w,4) = ST(:,8)/r;
        y(w,5) = ST(:,9)/r;
        end
        p = p+1;
        r = 1;
    end
end
y(y(:,2) == 0,:) = [];

%%
varname = strcat('y');
filename = strcat('I:../work/matlab/velcotiestimestep',varname);
save (filename,varname);

varname = strcat('SP');
filename = strcat('I:../work/matlab/particlensort',varname);
save (filename,varname);

varname = strcat('MT');
filename = strcat('I:../work/matlab/timestepsort',varname);
save (filename,varname);

varname = strcat('l');
filename = strcat('I:../work/matlab/length',varname);
save (filename,varname);

```

A.3.2 Plotscript.m

```

clear all;
close all;
clc;
cd('...')
varname = strcat('y');
filename = strcat('I:../work/matlab/velcotiestimestep',varname);
load (filename,varname);

varname = strcat('SP');
filename = strcat('I:../work/matlab/particlensort',varname);

```

```

load (filename ,varname);

varname = strcat('MT');
filename = strcat('I:../work/matlab/timestepstest',varname);
load (filename ,varname);

varname = strcat('l');
filename = strcat('I:../work/matlab/length',varname);
load (filename ,varname);

N = SP(size(SP,1),2);
s = [];
S = [];
P = [];
e = [];
h = 1;
c = 1;
w = 1;

%constants to calculate the dimensionless quantities and settling time
a = 9*power(10,-2); %integral length scale [m]
nu = 1.9*power(10,-5); %kinematic viscosity of air
C_e = 0.03; %correction constant
k = 1; %turbulent kinetic energy
r_d = 999.972; %density of the droplet [kg/m^3]
d_p = 30*power(10,-6); %droplet diameter [m]
mu = 2; %dynamic viscosity of the droplet
g = 9.81; %acceleration gravity [m/s^2]

for i = 1:l(size(l,1),1)
    if l(i,2) < 5
        l(i,2) = -1;
    end
end
lc = l;
lc(lc(:,2)== -1,:) = [];

for i = 1:size(lc,1)
    if lc(i,2) > 20
        e(3,h) = lc(i,1);
        h = h+1;
    elseif 5 < lc(i,2) && lc(i,2) < 15

```

```

        e(1,c) = lc(i,1);
        c = c+1;
    elseif 15 < lc(i,2) && lc(i,2) < 20
        e(2,w) = lc(i,1);
        w = w+1;
    end
end
end

for i = 1:3
for x = e(i,:)
    s = SP;
    s(s(:,1)~=x,:) = [];
    P = [P;s];
end
end

%%
PP = sortrows(P,1);
p = 1;
r = 1;
o = [];
for w = 1 : length(PP)-1
    if PP(w,1) == p && PP(w+1,1) == p
        r = r+1;
    elseif PP(w,1) == p
        if r > 2;
            ST = sum(PP((w-r+1):w,:));
            o(w,1) = PP(w-1,1);
            o(w,2) = ST(:,6)/r;
            o(w,3) = ST(:,7)/r;
            o(w,4) = ST(:,8)/r;
            o(w,5) = ST(:,9)/r;
        end
        p = p+1;
        r = 1;
    else
        for i = 1:500
            if p ~= PP(w+1,1)
                p = p+1;
            end
        end
    end
end
end

```

```

end
o(o(:,1) == 0,:) = [];

%%
S = sum(o);
disp('The mean velocity of the particles in the x-direction is:')
v_x_long = S(:,2)/length(o)

disp('The mean velocity of the particles in the y-direction is:')
v_y_long = S(:,3)/length(o)

disp('The mean velocity of the particles in the z-direction is:')
v_z_long = S(:,4)/length(o)

disp('The mean velocity of the particles:')
v_mean_long = S(:,5)/length(o)

%% figure1
% Here the mean velocity of the particles in each direction are given for
% each time step. (The x-, y-, z- and mean velocities of all the particles
% in time.)
figure(1)
subplot(4,1,1), plot(y(:,1), y(:,2), 'b+') %s(size(s,1),10)
hold on
title('mean velocity of the particles in the x-direction', 'FontSize',13)
ylabel('mean velocity in m/s', 'FontSize',13)
% axis([0 N 0 0.15])
subplot(4,1,2), plot(y(:,1), y(:,3), 'r+')
hold on
title('mean velocity of the particles in the y-direction', 'FontSize',13)
ylabel('mean velocity in m/s', 'FontSize',13)
% axis([0 N 0 0.15])
subplot(4,1,3), plot(y(:,1), y(:,4), 'b+')
hold on
title('Mean velocity of the particles in the z-direction', 'FontSize',13)
ylabel('mean velocity in m/s', 'FontSize',13)
% axis([0 N 0 0.15])
subplot(4,1,4), plot(y(:,1), y(:,5), 'r+')
hold on
title('Mean velocity of the particles', 'FontSize',13)
xlabel('time step', 'FontSize', 13)
ylabel('mean velocity in m/s', 'FontSize',13)

```

```
% axis ([0 N 0 0.15])
```

```
%% figure2
```

```
figure (2)
```

```
for x = e(1,1:50)
```

```
    s = SP;
```

```
    s(s(:,1)~= x,:) = [];
```

```
    strValue = strtrim(cellstr(num2str(s(1,2), '%d')));
```

```
    plot3(s(:,5), s(:,3), s(:,4), '-*')
```

```
    text(s(1,5), s(1,3)-70, s(1,4)-60, strValue, 'VerticalAlignment', 'bottom');
```

```
    title('Paths_of_particles_who_are_followed_between_0,01_and_0,015_seconds', 'FontS
```

```
    xlabel('z_[mm]', 'FontSize', 13)
```

```
    ylabel('x_[mm]', 'FontSize', 13)
```

```
    zlabel('y_[mm]', 'FontSize', 13)
```

```
    hold all
```

```
    plot3(s(1,5), s(1,3)-70, s(1,4)-60, '*k', 'markersize', 10)
```

```
    grid on
```

```
    axis square
```

```
end
```

```
hold off
```

```
%% figure3
```

```
figure (3)
```

```
for x = e(2,1:50)
```

```
    s = SP;
```

```
    s(s(:,1)~= x,:) = [];
```

```
    strValue = strtrim(cellstr(num2str(s(1,2), '%d')));
```

```
    plot3(s(:,5), s(:,3), s(:,4), '-*')
```

```
    text(s(1,5), s(1,3)-70, s(1,4)-60, strValue, 'VerticalAlignment', 'bottom');
```

```
    title('Paths_of_particles_who_are_followed_between_0,015_and_0,02_seconds', 'FontS
```

```
    xlabel('z_[mm]', 'FontSize', 13)
```

```
    ylabel('x_[mm]', 'FontSize', 13)
```

```
    zlabel('y_[mm]', 'FontSize', 13)
```

```
    hold all
```

```
    plot3(s(1,5), s(1,3)-70, s(1,4)-60, '*k', 'markersize', 10)
```

```
    grid on
```

```
    axis square
```

```
end
```

```
hold off
```

```
%% figure4
```

```
figure (4)
```



```

for x = e(3,1:50)
    s = SP;
    s(s(:,1)~= x,:) = [];
    strValue = strtrim(cellstr(num2str(s(1,2), '%d')));
    plot3(s(:,5),s(:,3),s(:,4), '-*')
    text(s(1,5),s(1,3)-70,s(1,4)-60,strValue, 'VerticalAlignment', 'bottom');
%     title('Track of a droplet that is followed more than 0,02 seconds.', 'FontSize',
    xlabel('z_ [mm]', 'FontSize', 13)
    ylabel('x_ [mm]', 'FontSize', 13)
    zlabel('y_ [mm]', 'FontSize', 13)
    hold all
    plot3(s(1,5),s(1,3)-70,s(1,4)-60, '*k', 'markersize', 10)
    grid on
    axis square
end
hold off
% figure5 Here the velocities of the particle with respect to the time are plotted.
figure(5)
cc=hsv(12);
z=1;
for x = e(3,:)
    s = SP;
    s(s(:,1)~= x,:) = [];
    subplot(4,1,1), plot(s(:,2),s(:,6), 'color', cc(z,:))
    hold on
    subplot(4,1,2), plot(s(:,2),s(:,7), 'color', cc(z,:))
    hold on
    subplot(4,1,3), plot(s(:,2),s(:,8), 'color', cc(z,:))
    hold on
    subplot(4,1,4), plot(s(:,2),s(:,9), 'color', cc(z,:))
    hold on
    if z < 12
        z = z+1;
    else
        z = 1;
    end
end
hold off

% figure(6)
z = 1;

```

```

for x = o(:,1)
    s = SP;
    s(s(:,1)~=x,:) = [];
    plot(s(:,2),s(:,7), 'color',cc(z,:))
%     title('Downward (y-) velocity of different droplets during the time', 'FontSize'
xlabel('Time_frames_with_1000_frames_per_second', 'FontSize',20)
ylabel('Downward_velocity_of_the_droplets_[m/s]', 'FontSize',20)
    hold on
    if z < 12
        z = z+1;
    else
        z = 1;
    end
end
plot(1:N, v_y_long, '-*k', 'MarkerSize',2)
hold off

%% fftplot
Fs = 1000;
T = 1/Fs;
L = N;
t = (0:L-1)*T;
%plot(Fs*t(1:length(y)), y(:,5));
%%
NFFT = 2nextpow2(L);
f = Fs/2*linspace(0,1,NFFT/2+1);
Y = fft(y(:,5),NFFT)/L;

figure(7)
semilogx(f,2*abs(Y(1:NFFT/2+1)))
title('FFT_of_the_mean_velocity_of_the_droplets_at_each_time_step', 'FontSize',13)
xlabel('Frequency_(Hz)_log_scale', 'FontSize',13)
ylabel('Y(f)', 'FontSize', 13)

%%
S = sum(y);
disp('The_mean_velocity_of_the_particles_in_the_x-direction_is:')
v_x_st = S(:,2)/length(y)

disp('The_mean_velocity_of_the_particles_in_the_y-direction_is:')
v_y_st = S(:,3)/length(y)

```

```

disp ('The mean velocity of the particles in the z-direction is:')
v_z_st = S(:,4)/length(y)

```

```

disp ('The mean velocity of the particles:')
v_mean_st = S(:,5)/length(y)

```

```

%%

```

```

figure (8)
nbins = 100;
subplot (2,2,1); hist (y(:,2), nbins)
hold on
%title('x-velocity of the droplets', 'FontSize', 13)
xlabel ('velocity in [m/s]', 'FontSize', 18)
ylabel ('Number of particles', 'FontSize', 18)
hleg1 = legend ([ 'v_{mean}=', num2str(v_x_st) ]);
set (hleg1, 'FontSize', 16);
subplot (2,2,2); hist (y(:,3), nbins)
hold on
%title('y-velocity of the droplets', 'FontSize', 13)
xlabel ('velocity in [m/s]', 'FontSize', 18)
ylabel ('Number of particles', 'FontSize', 18)
hleg1 = legend ([ 'v_{mean}=', num2str(v_y_st) ]);
set (hleg1, 'FontSize', 16);
subplot (2,2,3); hist (y(:,4), nbins)
hold on
%title('z-velocity of the droplets', 'FontSize', 13)
xlabel ('velocity in [m/s]', 'FontSize', 18)
ylabel ('Number of particles', 'FontSize', 18)
hleg1 = legend ([ 'v_{mean}=', num2str(v_z_st) ]);
set (hleg1, 'FontSize', 16);
subplot (2,2,4); hist (y(:,5), nbins)
%title('Mean velocity of the droplets', 'FontSize', 13)
xlabel ('velocity in [m/s]', 'FontSize', 18)
ylabel ('Number of particles', 'FontSize', 18)
hleg1 = legend ([ 'v_{mean}=', num2str(v_mean_st) ]);
set (hleg1, 'FontSize', 16);

```

```

%%

```

```

figure (9)
nbins = 150;
subplot (2,2,1); hist (o(:,2), nbins)
hold on

```

```

% title ('x-velocity of the droplets', 'FontSize', 13)
xlabel('velocity_in[m/s]', 'FontSize', 18)
ylabel('Number_of_particles', 'FontSize', 18)
hleg1 = legend(['v_{mean}_= ', num2str(v_x_long)]);
set(hleg1, 'FontSize', 16);
subplot(2,2,2); hist(o(:,3), nbins)
hold on
% title ('y-velocity of the droplets', 'FontSize', 13)
xlabel('velocity_in[m/s]', 'FontSize', 18)
ylabel('Number_of_particles', 'FontSize', 18)
hleg1 = legend(['v_{mean}_= ', num2str(v_y_long)]);
set(hleg1, 'FontSize', 16);
subplot(2,2,3); hist(o(:,4), nbins)
hold on
% title ('z-velocity of the droplets', 'FontSize', 13)
xlabel('velocity_in[m/s]', 'FontSize', 18)
ylabel('Number_of_particles', 'FontSize', 18)
hleg1 = legend(['v_{mean}_= ', num2str(v_z_long)]);
set(hleg1, 'FontSize', 16);
subplot(2,2,4); hist(o(:,5), nbins)
% title ('Mean velocity of the droplets', 'FontSize', 13)
xlabel('velocity_in[m/s]', 'FontSize', 18)
ylabel('Number_of_particles', 'FontSize', 18)
hleg1 = legend(['v_{mean}_= ', num2str(v_mean_long)]);
set(hleg1, 'FontSize', 16);

%% turbulent scales
eps = C_e*(v_mean_st^3/a);
lambda = ((15*nu*v_mean_st^2)/eps)^(1/2);
tau_etaa = (nu/eps)^(1/2);
etaa = (nu^3/eps)^(1/4);

% key turbulence parameters, Reynolds number, eta en tau_eta
%la == lambda
Re_la = power(a,0.5)*power(v_mean_st,0.5)*power(15,0.5)*power(nu,-0.5)*power(C_e,-0.5)
eta = power(a,0.25)*power(v_mean_st,-0.75)*power(nu,0.75)*power(C_e,-0.25)
tau_eta = power(a,0.5)*power(v_mean_st,-1.5)*power(nu,0.5)*power(C_e,-0.5)

%relaxation time of the droplet
tau_d = (r_d*(d_p)^2)/(18*mu);
% Stokes number
St = tau_d/tau_eta;

```

```
%settling velocity  
V_t = tau_d*g;
```