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Abstract

Laser Doppler Anemometry (LDA) is used to measure the velocities of the flow inside a Ranque-Hilsch vortex tube. Droplet size measurements show that the droplets in the vortex tube are very small. Because of evaporation they even get smaller as they travel through the tube. LDA measurements can therefore only be done close to the entrance to the tube. When the laser alignment is good, the beam intensity is optimized and the transparent tube parts are of good quality, LDA measurements are done using the standard laser setup. This setup uses forward scattering for measurement of all three channels. A high water droplet density improves the quality of the measurement. It is necessary to use water separators to remove the film of water from the tube wall that is formed by the water. When a large flow is applied, much water can cause the formation of ice that jams the cold exit of the vortex tube.

It is possible to perform LDA measurements in the vortex tube at small mass flows with high quality.

Contents

1 Introduction

1.1 The vortex tube

The Ranque-Hilsch vortex tube was invented in 1933 by Georges J. Ranque. It is a tube that separates a high pressure airstream into a cold and a hot stream. The pressurized gas enters the vortex tube via the vortex chamber. This is a short piece of the vortex tube that has a larger diameter. The gas enters the swirl chamber tangentially. This induces a very strong swirl inside the chamber and the tube

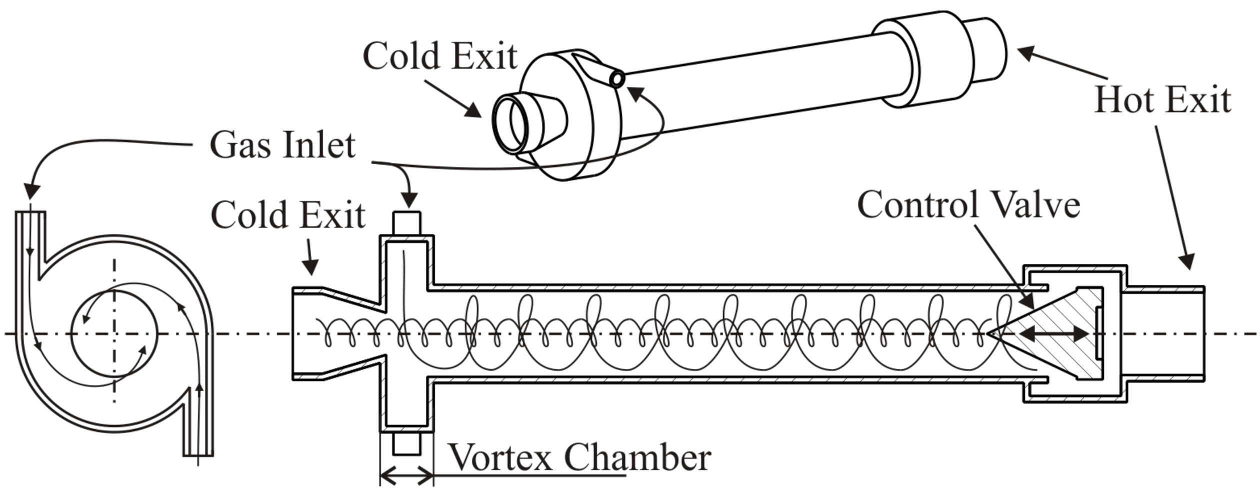

Figure 1: The Ranque-Hilsch Vortex tube.

Figure 1 shows a schematic view of a vortex tube with the vortex chamber, the tube and the exits for the hot and cold streams. The gas leaves the vortex tube at both ends. At the end of the tube a part of the gas exits at a higher temperature. The other part of the gas exits the tube via an exit in the swirl chamber at a lower temperature.

Because of the high rotational motion of the gas, there is a complicated flow inside the tube that results in the separation of energy. The gas that is transported towards the hot exit moves on the outside of the tube and is heated up on its way. The gas at the core of the tube moves flows towards the cold exit and is cooled down.

The two graphs in Figure 2 show the typical temperature separation that occurs inside the vortex tube. The temperature measurement has been performed at two different flows. The first measurement is done with a relatively small flow of 54 mn^3/h. (Because the temperature and pressure influence the density the unit normal cubic meter is used to measure the flow through the vortex tube.) The second measurement is done at a large flow of 200 mn^3/h. The temperature *Tin* is the temperature of the nitrogen entering the vortex tube. *Tc* and *Th* show the temperatures of the nitrogen exiting the vortex tube at the cold and the hot exit respectively. The cold fraction *ε,* is defined as shown in Formula 1.

$$\varepsilon = \frac{\dot{m}_c}{\dot{m}} \qquad (1)$$

The fraction of the mass flow entering the vortex tube that exits at the cold exit.

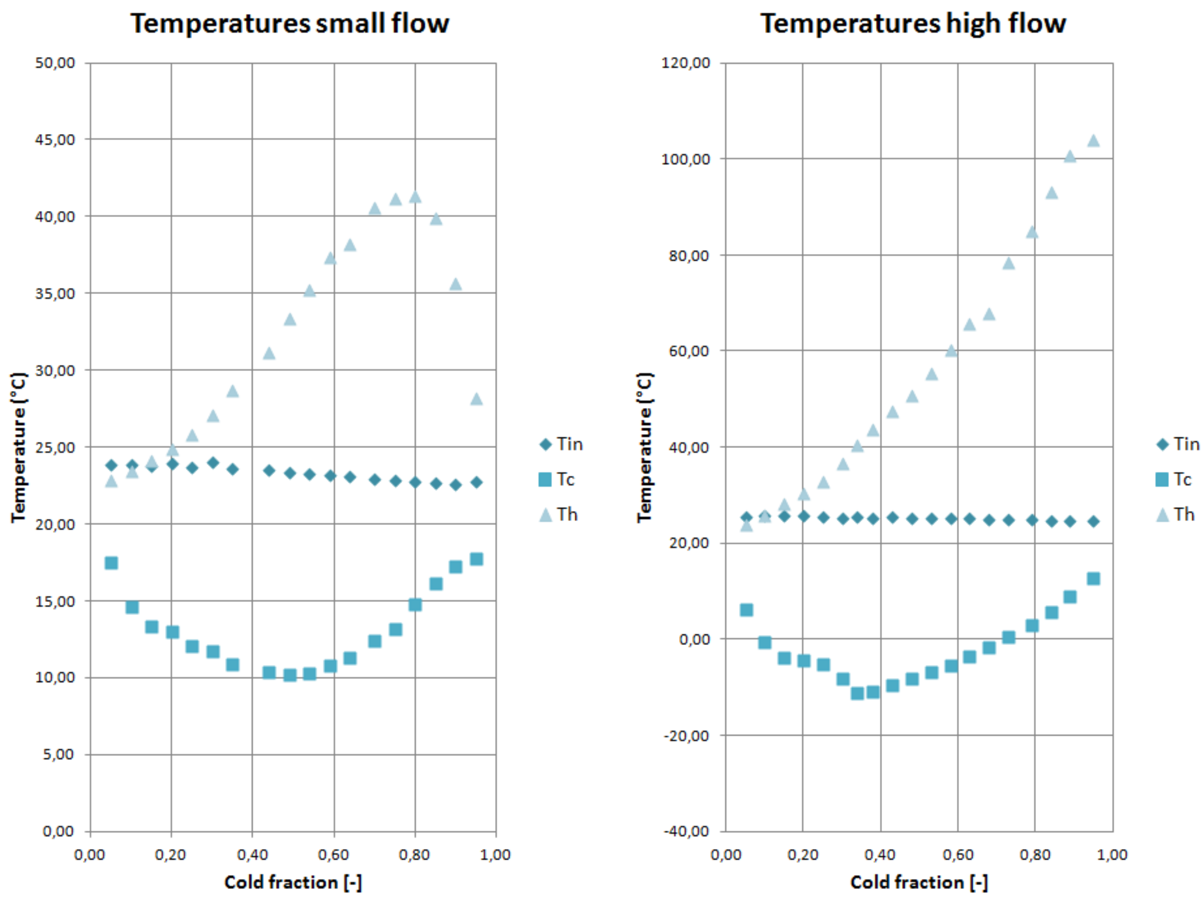

Figure 2: The graphs show the temperatures of the gas at the entrance of the vortex tube, the cold exit and the hot exit as function of the cold fraction. This measurement is done for a small flow of about 54 mn^3/h and a larger flow of 200 mn^3/h.

When a large mass flow is applied it is possible to achieve temperatures that are over 100°C. The cold stream reaches -10°C. The temperature of the hot stream increases with the cold fraction. This is easy to understand using the law of conservation of energy shown in Formula 2.

$$\dot{m} \cdot T_{in} \cong c_p \cdot \varepsilon \cdot \dot{m} \cdot T_c + c_p \cdot (1 - \varepsilon) \cdot \dot{m} \cdot T_h \qquad (2)$$

1.2 Contents of this report

In this study Laser Doppler Anemometry (LDA) is used to measure the velocity in the vortex tube in order to understand its working principles. LDA is used to measure the velocity of the gas in the vortex tube and measure the size of the droplets that are used for the LDA experiment.

The goal is to measure all three velocity components of the gas inside the vortex tube. It is explained in what way the measurements are done and what the results are.

In the Theory chapter the LDA measurement technique is theoretically explained. It is shown on what theories the technique is based.

The chapter Experimental setup shows the basic setup of the experiment and the necessities to gain high quality results.

The chapter Results and discussion shows the resulting LDA measurements.

2 Theory

In this chapter the principles of Laser Doppler Anemometry (LDA) are explained [1]. Interference of laser beams is used to measure the velocity of particles in the vortex tube. This chapter shows how the velocity of the particles is calculated from the signals that are received. It also shows how droplets scatter the laser light, this is very important for the receiver configuration. The importance of positioning the measurement volume is shown in the last paragraph of this chapter.

2.1 The measurement volume

Laser Doppler Anemometry makes use of laser beams to measure the velocity of particles in a gas flow.

If two laser beams of the same frequency cross each other, they create an interference pattern. The interference pattern consists of lines of high and low intensity, called fringes. If the two laser beams have the same wavelength, the fringes are stationary. The distance between these fringes depends on the wavelength of the laser light and the angle between the laser beams. Figure 3 gives a visual interpretation of the interference of the two laser beams.

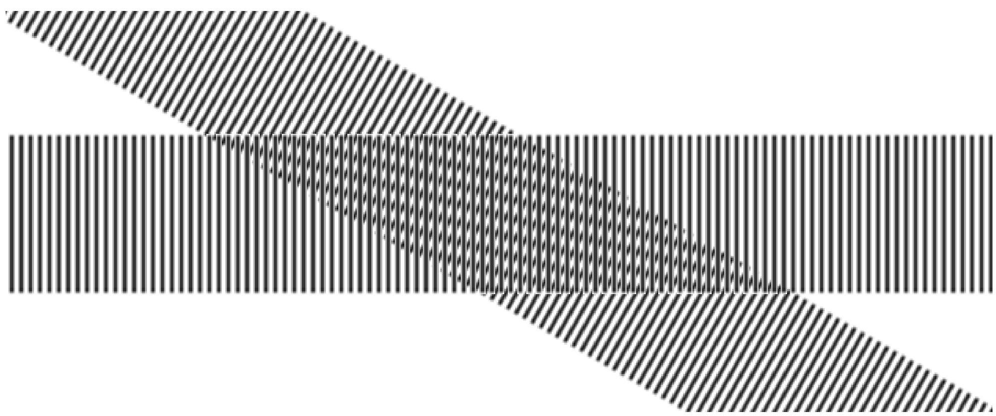

Figure 3: When two laser beams cross each other they form an interference pattern. This image shows a visual interpretation of the interference.

If a particle, a small droplet for example, moves through this interference pattern, it flashes as it goes through areas of high and low intensity. The frequency of this flashing is the Doppler frequency. It determines the velocity of the particle in the perpendicular direction to the fringes. This principle is used to measure the velocity of the droplets inside the vortex tube.

In order to measure the velocity of particles in three dimensions, three pairs of laser beams are required. Each pair uses a different wavelength so the signals are measured independently. This results in three different signals, each for one of the three velocity components.

[1] Operations Manual, Laser Doppler Velocimeter, Revision F December 2008

Because only the frequency of the passing particles is measured, the direction of the passing particle is undetermined. Only the absolute velocity component is measured. This problem is solved by adding a small frequency difference between the two laser beams of each same pair. The fringes then move at a certain velocity instead of staying at the same place. A Bragg cell is used to shift one of the laser beams of every pair down by 40 MHz. If a particle is measured with a frequency of 40 MHz the particle has no velocity in this particular direction. If the frequency drops below 40 MHz the particle moves in a negative direction.

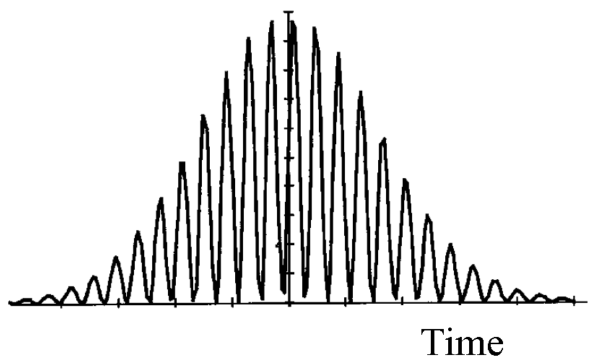

Figure 4: This image shows the typical form of a LDA signal.

When a particle moves through the measurement volume, where all six laser beams cross, the receivers pick up the signal from each pair. These signals look like the wave shown in Figure 4. The frequency of these waves is related to the velocity of the droplet in the corresponding direction. The distance between the fringes in the measurement volume is given by Formula 3.

$$\delta_f = \frac{\lambda}{\sin k} \quad (3)$$

Here *k* is half the angle between the two laser beams. When the frequency of the signal is known, the velocity is found using Formula 4.

$$u = \delta_f \cdot f_d \ (4)$$

Here, f_d is the Doppler frequency and *u* is the velocity in the direction perpendicular to the fringes.

The measurement volume is the small volume where the six laser beams of the LDA setup cross each other. The velocity and direction of the flow in this point is measured by the LDA system.

2.2 Scattering

The droplet moving through the laser beams scatters the photons in all directions. In some direction the scattering is stronger. It is important to know how light scatters when it hits a droplet in order to choose a good LDA configuration.

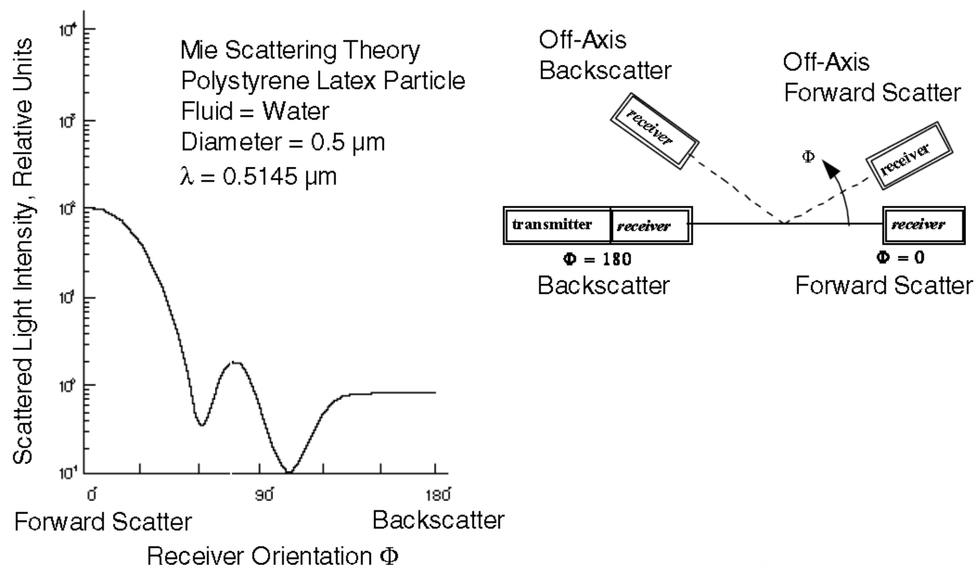

Figure 5: This image shows the typical scattering characteristics.

To predict the scattered light intensity the Mie Scattering Theory is used. Figure 5 shows the typical scattering characteristic of small particles. The angle Φ is the receiver orientation. If the angle is zero the receiver is directly in line with the laser transmitter. If the angle between the laser beam and the receiver is small the scattered light is called forward scattering. The figure shows that the intensity of scattered light is high for forward scattering. If the angle is larger than 90° the receiver uses backscatter.

Preferably forward scatter is used because of the high intensity. If it is not possible to measure forward scatter, due to limitations in the receiver configuration for example, backscatter is usually used instead.

2.3 Position of the measurement volume

Figure 6 shows a cross section of the vortex tube. The red line in the figure shows the area where the measurements take place. The measurement volume is moved along this line to measure at different radii.

In order to get good results it is necessary that the measurement volume is in the correct position relative to the tube.

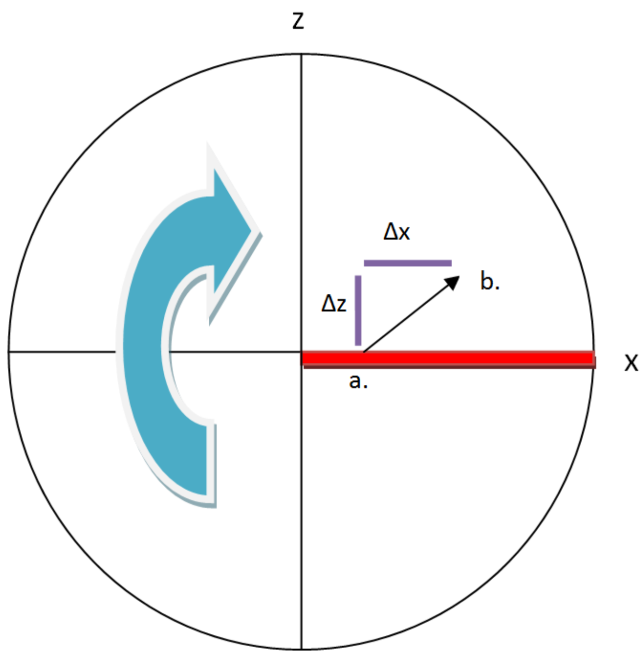

Figure 6: The measurement volume of the LDA moves along the red line. The blue arrow shows the tangential velocity of the flow.

If the measurement volume is not in the right position, on the x-axis of the tube, the measured radial and tangential velocities are erroneous. Imagine that a LDA measurement is supposed to be done in point a but the actual measurement position is point b. This is shown in Figure 6, *Δx* and *Δz* are the differences between the point *a* and the actual position *b*.

U_t is the tangential velocity as function of the radius and U_r is the radial velocity. These are the values that should result from a good measurement. The actual radius *r* in point *b* is shown in Formula 5

$$r = \sqrt{(x + \Delta x)^2 + \Delta z^2} \quad (5)$$

$$v_\theta(x + \Delta x, \Delta z) = -\frac{x + \Delta x}{r} \cdot U_\theta(r) - \frac{\Delta z}{r} \cdot U_r(r) \quad (6)$$

Formula 6 shows the tangential velocity that is actually measured. This velocity is measured in the *x* direction. Formula 7 shows the radial velocity. The values for the velocity that are measured (v_ϑ, v_r) are different from the velocities at point a that should be measured.

$$v_r(x + \Delta x, \Delta z) = \frac{x + \Delta x}{r} \cdot U_r(r\,) - \frac{\Delta z}{r} \cdot U_\theta(r) \quad (7)$$

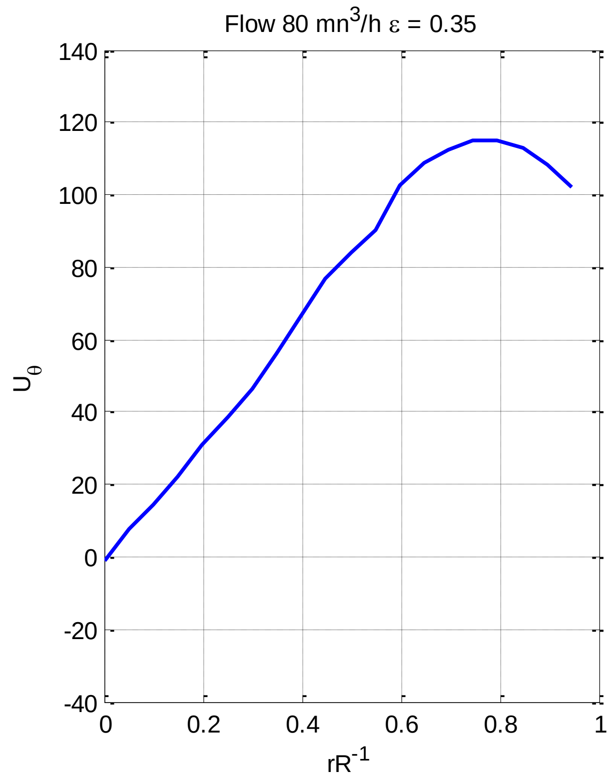

Figure 7: This is a result of a typical measurement of the tangential velocity when a flow of 80 mn^3/h is applied. The cold fraction is 0,35. The result shows that the core of the flow has a solid body rotation.

Figure 7 shows the tangential velocity in the vortex tube. The velocity near the core increases linear. This means that the rotation behaves like a solid body.

Because the angular velocity near the core is constant, $U_\vartheta(r)$ is equal to:

$$U_\theta(r) = r \cdot \omega \qquad (8)$$

Where ω is a constant.

The radial and tangential velocities then become:

$$v_\theta(x + \Delta x, \Delta z) = -(x + \Delta x) \cdot \omega - \frac{\Delta z}{r} \cdot U_r(r) \quad (9)$$

$$v_r(x + \Delta x, \Delta z) = \frac{x + \Delta x}{r} \cdot U_r(r) - \Delta z \cdot \omega \quad (10)$$

The angular velocity in the case of the measurement shown in Figure 7 is about 8000 rad/s. The radial velocity has an order of magnitude of 10 m/s. This means that the relative influence of Δz on v_Θ is much smaller than the influence of Δz on v_r. It is therefore very important to minimize Δz.

The error in the x direction Δx influences the measured radial velocity only slightly and only shifts the results of the radial velocity. The correct position along the x-axis is done by finding the minimum of the radial velocity, this is at x=0.

Finding the correct z component is harder and more important because the radial velocity is strongly influenced by the tangential velocity if the height is incorrect. A mathematical way is found to find Δz to be able to correct the velocities.

At the core of the vortex tube, the radial velocity should be zero because of the symmetry. So, if there is a radial velocity at $x=0$, there is a non zero Δz. A measurement of the tangential speed at a radius of 2 or 3 millimeters is chosen (x^*) to determine the angular velocity (ω).

$$\omega = -\frac{v_\theta(x^*)}{x^*} \qquad (11)$$

At the core (where the radial velocity is zero) Formula 10 becomes:

$$v_r(0, \Delta z) = -\Delta z \cdot \omega \qquad (12)$$

This means that Δz is:

$$\Delta z = -\frac{v_r(0, \Delta z)}{\omega} = \frac{x \cdot v_r(0, \Delta z)}{v_\theta(x)} \qquad (13)$$

This way, the position of the measurement volume is corrected. But it is also possible to correct previous measurements that have been performed with an erroneous alignment along the z axis. Because it is possible to find ω and v_r, Δz are calculated and (using Formula 10) all values of the radial velocity can be compensated for the error.

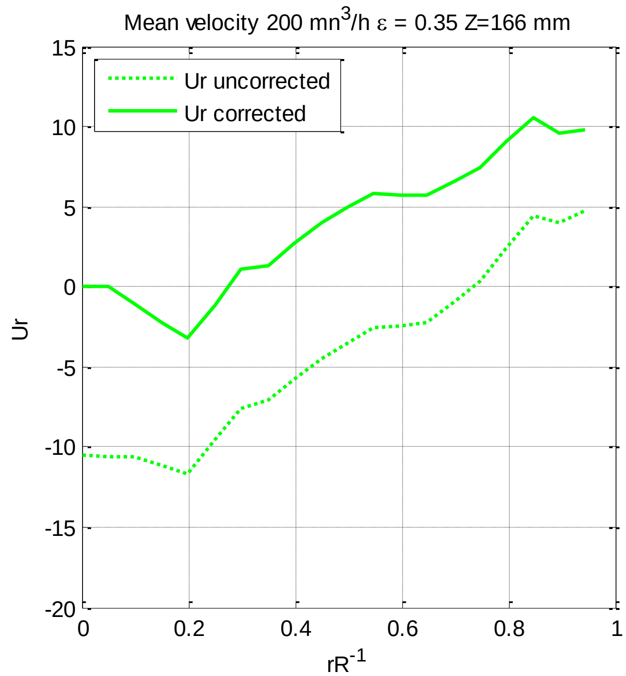

Figure 8: Radial velocity measured with LDA as function of the radius. The measurement is performed at an incorrect height. The uncorrected curve shows that the radial velocity is not measured zero at the core of the tube. When the correction is applied the velocity is zero at the core. The result of the correction is shown in the corrected curve.

Figure 8 illustrates the result of a correction applied to a real measurement at an erroneous height.

All results shown in this report have been corrected using this technique.

3 Experimental setup

This chapter explains the experimental setup used to perform LDA measurements. The first part of this chapter is about the way the gas flow through the tube is regulated and how it can be influenced and measured. It describes how the droplets are inserted in the nitrogen as well. The second part explains how the LDA measures the speed of the droplets and thereby the flow of the gas in the vortex tube. In the end of the chapter it is explained how particle sizing works.

3.1 The Vortex tube

The vortex tube used has a diameter of 40 mm. The length of the vortex tube is adjustable. The swirl chamber, with a diameter of 80 mm, is fitted to one side of the tube and a spider at the other end. A high pressure nitrogen flow is used as working fluid. Small droplets are inserted into the flow to allow LDA measurements to be made.

Some parts of the vortex tube are transparent in order to do the optical measurements. These tube parts are constructed out of PMMA. If the material is too thick the laser beams are refracted too much and they don't cross each other at the same place.

3.2 Flow and droplets

The flow of nitrogen through the vortex tube, the humidity of the nitrogen and the droplets in the stream influence the measurement. This paragraph shows how the flow and the droplets in the flow are adjusted and how they affect the results.

The cold fraction is an important variable to describe the flow inside the vortex tube. By adjusting the valves, the amount of gas exiting at the cold and hot exits is regulated. The mass flow into the vortex tube and the hot flow are measured using two mass flow meters. An automatic system uses the data from these meters and controls the valves to keep the cold fraction and flow constant during measurements. The pressure at which the nitrogen enters the tube is also adjustable. Measurements are performed with a constant mass flow and constant cold fraction.

LDA only works when there are droplets in the flow. If the droplets are too small, they easily evaporate into the nitrogen and the LDA cannot measure them properly. But if the droplets are too large, they don't follow the nitrogen flow and go towards the walls of the tube by means of the centrifugal force. This gives erroneous results. When the large droplets reach the walls of the tube they can form a thin layer of liquid on the windows. This causes the laser beams to diffract, and LDA is not possible.

3.2.1 Nozzles

Because droplets of water evaporate quickly in dry nitrogen, the gas is first humidified. This is done in a large pressure vessel. The dry nitrogen is inserted at the bottom of the vessel. Inside the vessel there are nozzles that spray water into the nitrogen flow. Because the vessel is relatively wide, the velocity of nitrogen is low and there is enough time for the water to evaporate. The humidified nitrogen exits the vessel at the top and is led to the entrance of the vortex tube. If the nitrogen is very humid it is possible that water condensates in the vortex tube when the temperature changes.

The water is pressurized by a pump, the pressure determines the amount of water sprayed into the vessel. If the nozzles spray enough water into the vessel, some droplets might enter the vortex tube where they are detected. It is unknown whether these droplets have been transported to the vortex tube from the pressure vessel or they have been formed by condensation. These droplets are used to do the LDA measurement.

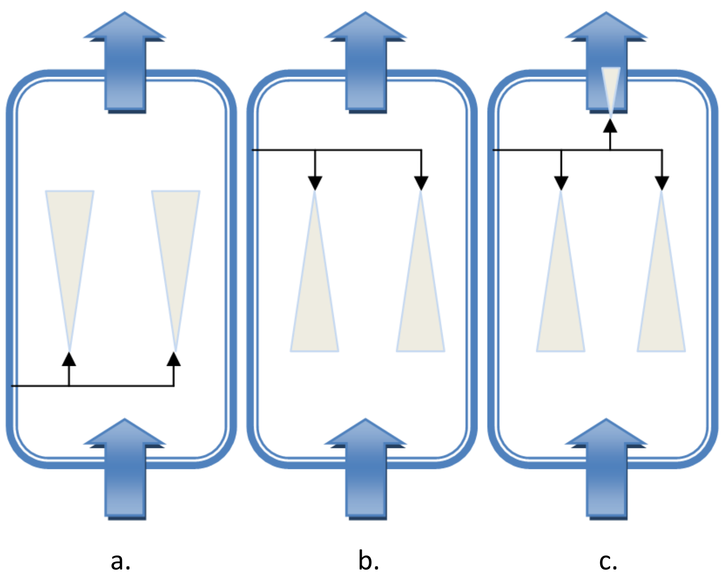

Figure 9: Different nozzle setups inside the pressure vessel.

Three different setups are tried for the nozzles inside the pressure vessel, shown in Figure 9. Experiments show that the setup shown in Figure 9 c. works best because a lot of water enters the vortex tube.

3.2.2 Water separation

When the nozzle setup shown in Figure 9 c. is applied, a lot of water enters the vortex tube. This water causes a film of water on the transparent tube parts. This makes it impossible to perform a measurement. A separation ring is created to extract water from the vortex tube. The separation ring has a small slit around the inside of the vortex tube. The centrifugal force, created by the strong swirl inside the vortex tube, forces the water into the slit. From the slit, small tubes carry the water away. A picture of a water separator is shown in Figure 10.

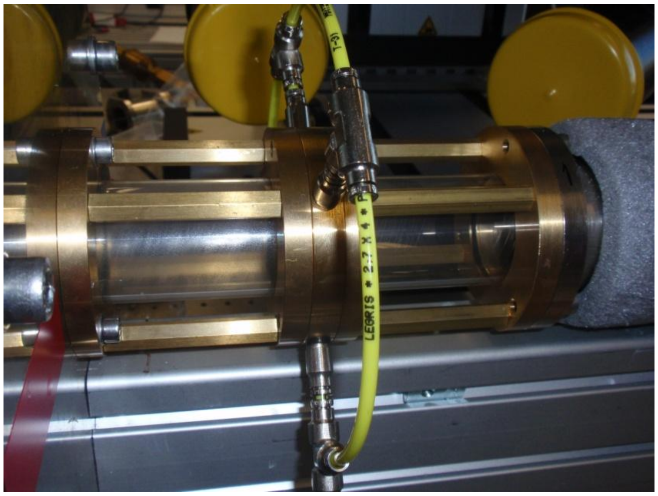

Figure 10: Water separator. The water separator removes the film of water from the tube.

Different designs for the slit are manufactured. When two of these slits are applied to the vortex tube, it is possible to improve the measurement quality and quantity.

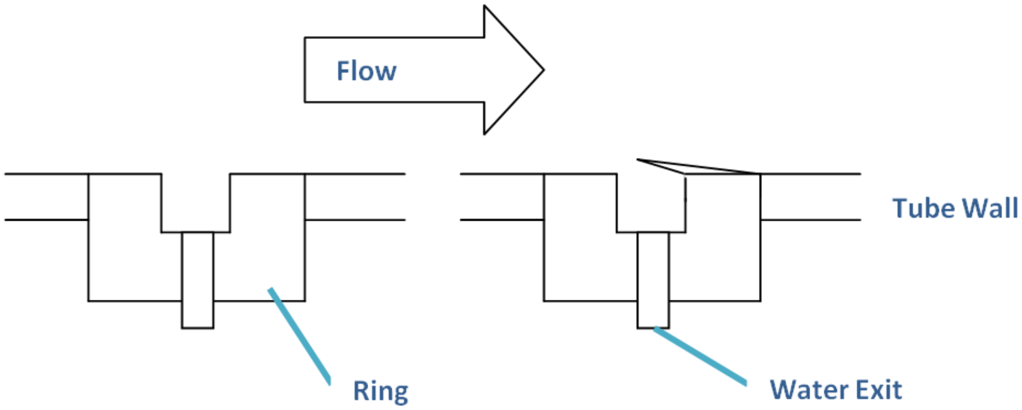

Figure 11: The water separator schematically.

Figure 11 shows some designs for the slit of the separation ring. In general, the slits with the smallest openings work best, they extract more water and less nitrogen flows away through them.

3.2.3 Ice

When a large flow is applied to the vortex tube, the temperature at the cold exit of the tube drops below the freezing point of water. This creates a problem. When there is a lot of water in the nitrogen flow and the local temperature inside the vortex tube is below 0°C it forms ice. When a lot of ice is formed it blocks the cold exit and the flow inside the vortex tube changes entirely. Care must therefore be taken that the cold exit of the vortex tube doesn't get filled with ice. This means keeping the flow, or the amount of water low enough.

3.2.4 Temperature

The temperature of the nitrogen and the temperature of the surroundings influence the measurement. Measurements that are repeated with exactly the same settings on a different day can have very different results. A different temperature of the gas means that the density of the gas is different, this influences the flow. When the nitrogen is cold ice can also form more easily in the vortex tube.

3.3 LDA measurement

The laser beams used to do LDA measurements are emitted by probes. These probes aim the beams at a certain point in the vortex tube. Droplets scatter the light from the lasers. This scattering is received back by the probes and sent to optical sensors. The signals are then processed by photon multiplier tubes and band pass filters. If the remaining signal is strong enough to pass the Burst threshold it is passed to a computer. The PC analyses the signals and calculates the velocity of a particle in three dimensions.

3.3.1 LDA setup

The three different wavelengths of the laser beams used in this LDA setup are created by an argon ion laser. An argon laser emits at 13 different wavelengths. The wavelengths used are 476 nm (dark blue), 488 nm (light blue) and 514 nm (green).

Optical fibers are used to transport the laser beams from the laser to the probes that are placed near the vortex tube.

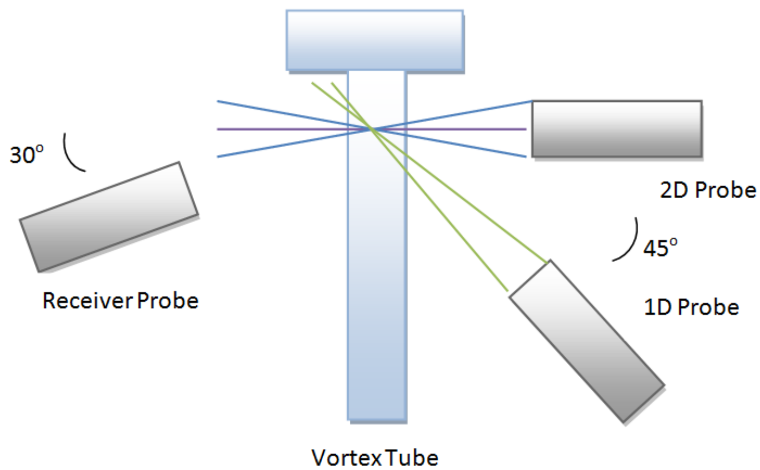

Figure 12: The vortex tube. The 1D and 2D probe emit the laser beams. All three probes can be used to measure the signals.

The laser beams are emitted from two laser probes. The probe that is lined up perpendicular to the vortex tube emits two pairs of laser beams, the other one emits one pair of laser beams. The first probe is therefore called the 2D-probe, one pair of laser beams is emitted vertically and the other one horizontally. The other probe is called the 1D-probe. This setup is shown in Figure 12.

The laser light that is refracted by a droplet in the vortex tube is received by the laser probes or by the special receiver probe. The signal from the green laser is referred to as channel 1, the signal from the light blue laser channel 2 and the dark blue channel 3.

The received signals are transported to the optical sensors via optical fibers and a light bar. There are two different light bars available. The light bar is effectively the entrance to the optical sensors. It has filters that split the signals. The first light bar is called the PDPA light bar, it has one combined entrance for the signals from channel 2 and 3. It uses three signals from the receiver probe to measure channel 1. This is used to measure the size of the droplets. With the LDA light bar, the second light bar, it is impossible to measure the size of the droplets. The LDA light bar has one entrance for the channel 3 signal and one combined entrance for channel 1 and 2. It is needed to use the same probe for channel 1 and 2 while channel 3 has to be measured from another probe. The design of these two light bars strictly limits the possibilities of the LDA setup.

3.3.2 Signal Processing

As a droplet moves through the measurement volume, it scatters light with a certain frequency. The scattered light is collected by the probes and transmitted via optical fibers to the Photon Multiplier Tubes. PMT's convert the optical signal into an electrical signal. A PMT voltage is applied to every PMT and is set for every channel. Increasing the PMT voltage increases the gain of the PMT. Not only the gain of the signal but also the gain of the noise is increased however. Every channel has its own PMT.

The output of the PMT is then high-pass filtered to remove low frequency portions of the input. This high-pass filter is adjustable separately for every channel.

In order to remove most of the other noise in the signals, they are passed through a selectable band pass filter. The different band pass filters have different widths. To make sure the signals from the scattered light fit through the band pass filter and aren't cut off, the frequency of the signal are mixed down. The down mix frequency is adjustable, and so is the band width of the filter, for every channel.

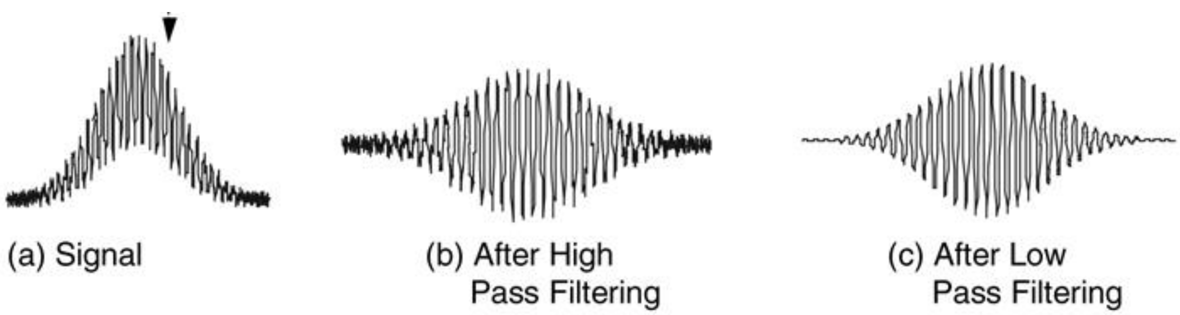

Figure 13: Signal processing.

The signal frequencies that are left are measured by the signal processor. Another variable in the signal processing is the Burst threshold. It is the voltage level that signals must reach before they are processed. If the burst threshold is very high only very strong signals are measured. The signals are then valuated by the signal-to-noise-ratio (SNR). If the SNR is set to *high* only the best quality bursts are passed on. This decreases the burst efficiency, the relative amount of bursts that make it through the SNR. If the burst efficiency is very low, there are a lot of low quality signals being picked up by the probes. The SNR has several settings from *very low* to *high*.

One pair of laser beams is used to measure one velocity component of the droplets in the nitrogen stream. By using six lasers, it is possible to measure all three components. This way the average velocities in the three directions are determined. But if the turbulence statistics of the droplets in the stream are needed, the averages are not enough. To determine the turbulence statistics, the three velocity components are needed from the same droplet. In order to achieve this, a computer combines signals from the three channels that are from the same droplet. This is called hardware coincidence. The signals are combined to calculate the droplets velocity. The coincidence data rate shows how many coincident signals are measured per second. It is also possible to save all the data and let the software combine the coincident data later. This however very quickly uses all the available space on the computers' memory.

In order to make a good LDA measurement, the high-pass filter, band-pass filter, down mix frequency, burst threshold and the Signal-to-noise-ratio have to be chosen correctly so the burst efficiency and the (coincidence) data rate are high.

3.3.3 LDA configuration

In the theory chapter the characteristic of scattering are shown. It shows that the light intensity of the scattered light depends on the angle between the laser beam and the receiver probe. Especially forward scattering is shown to work best because of its high scatter intensity. It is needed to take the scattering of the light into account when choosing the configuration.

The documentation of the laser suggests that low burst efficiency gains high quality measurements because a low burst efficiency means that only the best few signals are used. In practice however, a good measurement has a high data rate and a high burst efficiency.

The standard setup for the laser and receivers are as follows. The lasers for channel 1 and 2 are emitted from the 2D probe, the green laser (CH1) is used to measure the tangential velocity. The laser for CH3 is emitted from the 1D probe. All signals are measured from the receiver probe.

The best combination of the transmitter and receiver probes differs from measurement to measurement and depends on the conditions.

3.3.3.1 Best configuration

Experiments have shown that the original configuration of the transmitters and receivers works best. Several other configurations have been tried and they occasionally work better under specific circumstances.

The beam generator that splits the beam from the laser into the six different laser beams can be adjusted. By careful tuning the beam intensity improves.

When the laser beams are aligned properly and the beam intensity is optimized the results with the original setup are very good. The influence of the alignment and the beam intensity is very large. Because the combination of the standard setup and the inbuilt filters and light bars is best, this configuration is used in the experiments.

The transparent tube parts that are used to do the LDA measurement also influence the quality of the measurement. When a newer tube part with less imperfections is used, the data rate and burst efficiency increase dramatically. The measurements shown in this chapter are done with tube parts of high quality.

3.3.3.2 Characterization of the airflow in vortex tube

The movement of the flow inside the vortex tube at each point is characterized by three velocity components: The axial velocity u_z, the radial velocity u_r and the tangential velocity u_Θ. The configuration of the laser probes determines which components of the actual flow are measured. To convert the measured velocity components in the cylindrical coordinates, a transformation matrix is used. This is shown in formula 11. This matrix is different for every transmitter configuration.

$$\begin{bmatrix} u_r \\ u_\theta \\ u_z \end{bmatrix} = [A] \cdot \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (14)$$

Here V_1, V_2 and V_3 are the components measured by the LDA system. The transformation matrix A is used to calculate the direction and velocity of the particle in the vortex tube.

When the configuration of the laser probes is complicated it is not always easy to determine the transformation matrix. The matrix is therefore determined using the inverted matrix.

Usually it is much easier to determine the inverse of the transformation matrix. It shows how the components that are measured are composed using the coordinates in the vortex tube.

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = [B] \cdot \begin{bmatrix} u_r \\ u_\theta \\ u_z \end{bmatrix} \quad (15)$$

When the matrix B is constructed, the transformation matrix A is its inverse.

$$[A] = [B]^{-1} \quad (16)$$

To illustrate a transformation matrix, the matrix for the standard laser configuration is shown below.

$$\begin{bmatrix} u_r \\ u_\theta \\ u_z \end{bmatrix} = \begin{bmatrix} 0 & 1 & \sqrt{2} \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (17)$$

3.3.4 Particle Sizing

The laser setup can also be used to measure the size of the droplets. This is called 'Phase Doppler Particle Analysis' or PDPA. The receiver probe is used to do particle sizing. The receiver probe has four different receivers. One of them is used to detect signals from channel 2 and channel 3. There are three detectors that receive signals from channel one. These three channels are used to determine the size of the droplets.

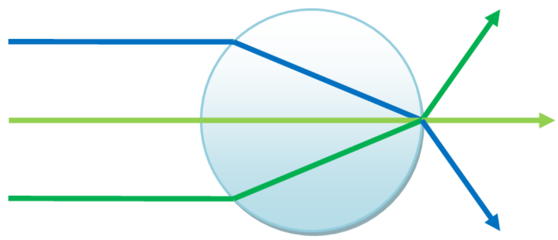

Figure 14: Laser beams refract when they hit a droplet. The direction of refraction depends on where it hits the droplet.

When a laser beam hits a droplet it is refracted. This is shown in the image in Figure 14. The laser beam is refracted in a direction that changes very quickly when the droplet passes. The direction of the refracted beam changes fast when the droplet is small or has a high velocity. The three receivers inside the receiver probe look at the droplet each from a slightly different angle. They all pick up the signal that is created by the interference pattern of the lasers, but because of this refraction, there is a small phase difference between the signals that are measured. This phase difference is combined with the velocity of the droplet, determined by the frequency of the signal, to calculate the droplet size.

The surface of a spherical droplet increases with the square of the diameter. This means that a larger droplet scatters more light when it passes the measurement volume. The intensity of a signal has to be proportional to the square of its diameter. This fact is used to discard bad measurements. When a signal from a droplet is in proportion far too weak or too strong to its measured size it is discarded.

4 Results and discussion

4.1 LDA results

All the results shown below are achieved using the standard LDA setup. In the measurements the burst efficiency has been optimized. This is done by choosing the right PMT voltages, burst thresholds, band pass filters and down mix frequencies. The cold fraction is always 0,35.

4.1.1 Small mass Flow

The measurement at 100 mn^3/h is performed with the water nozzle configuration shown in Figure 9 c. Two separation rings to extract the water film from the vortex tube.

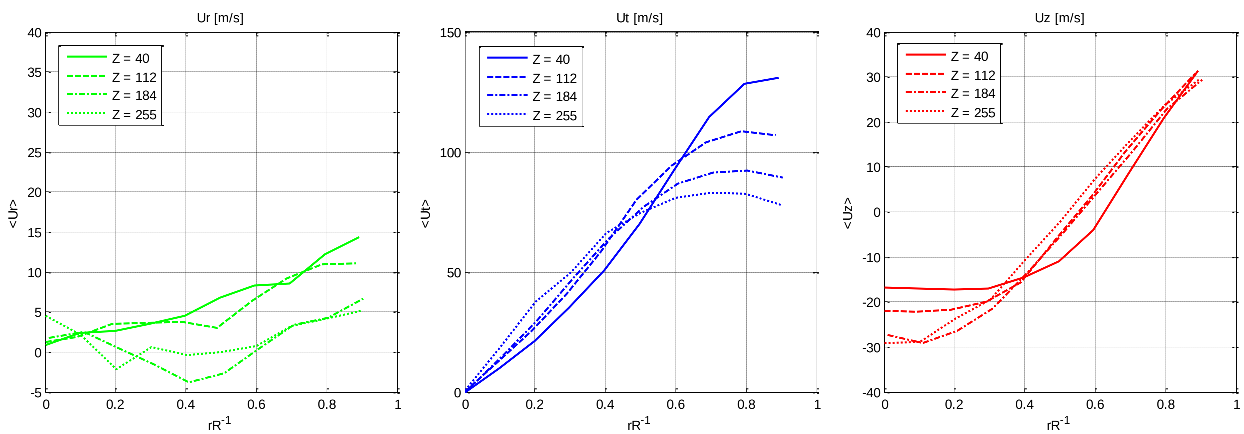

Figure 15: Results of the LDA measurement with a flow of 100 mn^3/h as function of the radius.

The measurement is performed at 40, 112, 184 and 255 mm from the vortex chamber. The results are shown in Figure 15.This measurement was very successful. The quality of the data is very high. This result shows that it is possible to do very good measurements with LDA when a mass flow of 100 mn^3/h is applied.

The results show how the flow inside the vortex tube behaves. The tangential velocity shows to be a lot larger than the other velocities. The tangential velocity near the edge decreases with the distance to the vortex chamber. The graph of the axial velocity shows the backflow near the core of the tube. This is where the colder nitrogen is transported back to the vortex chamber.

4.1.2 Large mass Flow

The measurement at 200 mn^3/h is with the nozzle configuration shown in Figure 9 b. The large flow causes the temperature at the cold exit to drop below the freezing temperature of water. When the third water nozzle is applied, the exit gets filled with ice and the flow is influenced by it. By removing the third nozzle, a decent measurement is still possible.

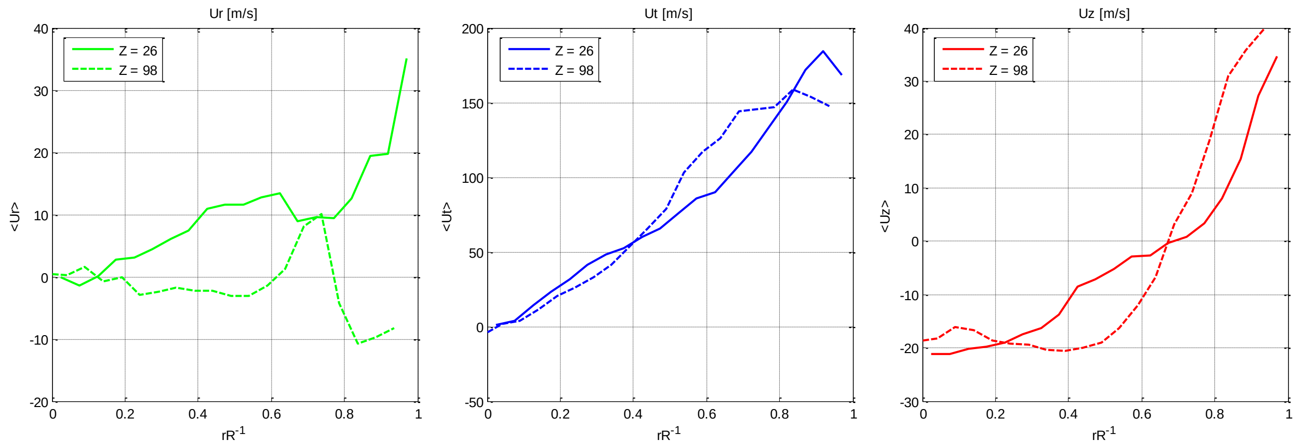

Figure 16: Results of the LDA measurement at a flow of 200 mn^3/h as function of the radius.

The measurement at large mass flow is done at 26 and 98 mm distance from the vortex chamber. The result of the measurement is shown in Figure 16. The quality of this result is lower than the result from the measurement at 100mn^3/h. It turns out that it is harder to measure the droplets when the flow is larger. There are fewer droplets in the flow because the third nozzle is not applied and because more droplets evaporate in the higher flow. Measurement at a larger distance from the vortex chamber is very difficult. There are few droplets left because of evaporation and most of the droplets are very small.

4.2 PDPA results

A PDPA measurement is used to measure the droplet size at a flow of 100 mn^3/h. Only one pair of lasers is needed for this measurement. Because the green laser is the brightest and usually produces very good data rates, channel 1 is used for this. The droplet size and tangential velocity are measured. The results of this experiment are shown in Figure 17. The receiver probe has to be used to make PDPA measurements. The results are very good because the receiver probe measures the green lasers' forward scattering.

At a flow of 100mn^3/h no ice forms inside the vortex tube. The nozzle setup shown in Figure 9 c is used in the pressure vessel. Two water separation rings are used to remove the water film from the glass. Because there is no coincidence and the green laser is very bright there is a very high data rate. Also the burst efficiency is very high.

The plot of the tangential velocity in Figure 17 is very smooth en shows how the tangential velocity changes as a function the location in the vortex tube. The velocity is highest near the edge of the tube and decreases with the distance to the entrance. This measurement of the tangential velocity is of better quality than earlier results of 3D measurements.

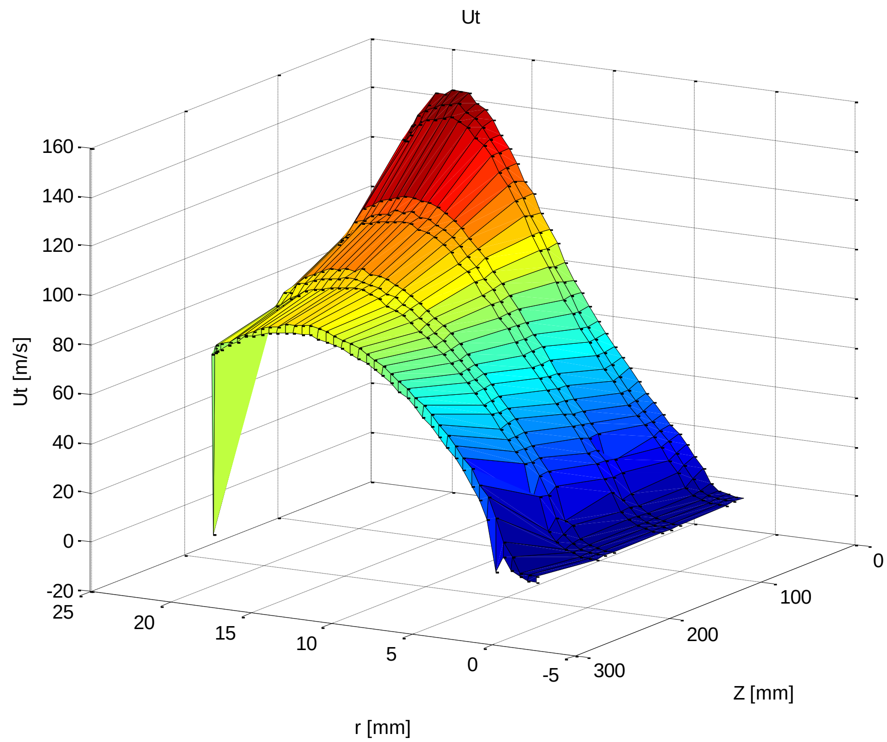

Figure 17: Results of the PDPA experiment. This graph shows the tangential velocity as function of the distance from the vortex chamber and the radius.

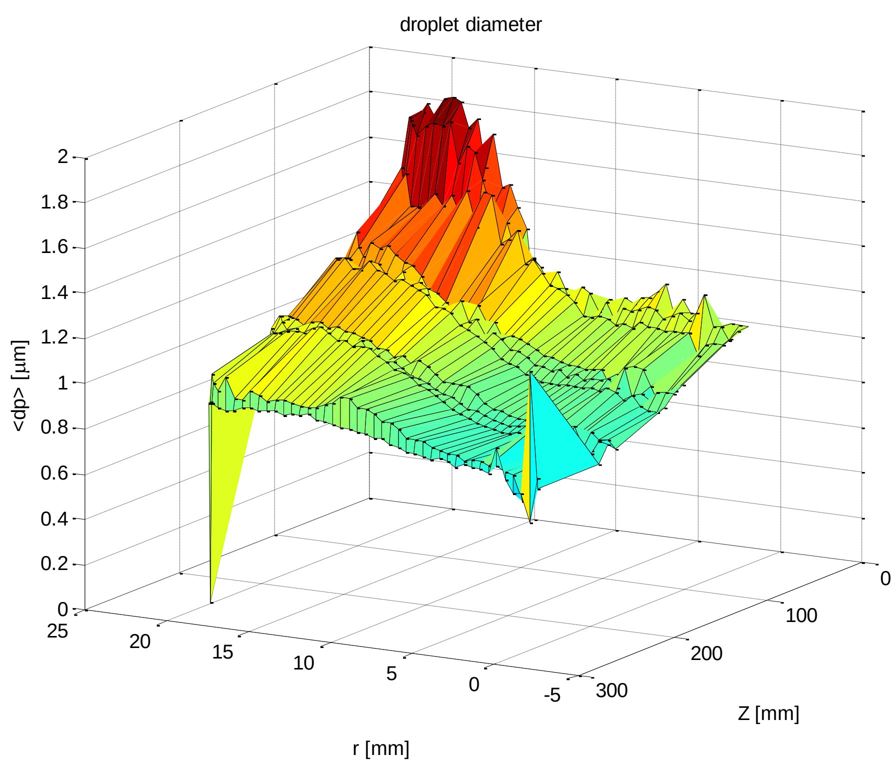

Figure 18: The average droplet diameter as function of the distance from the vortex chamber and the radius.

Figure 18 shows the average droplet size measured in different locations in the vortex tube. The PDPA setup only measures diameters that are larger than 0,5 µm. The droplets in the vortex tube are often smaller than this. The figure above therefore only shows the average of the droplets with diameters over 0,5 µm.

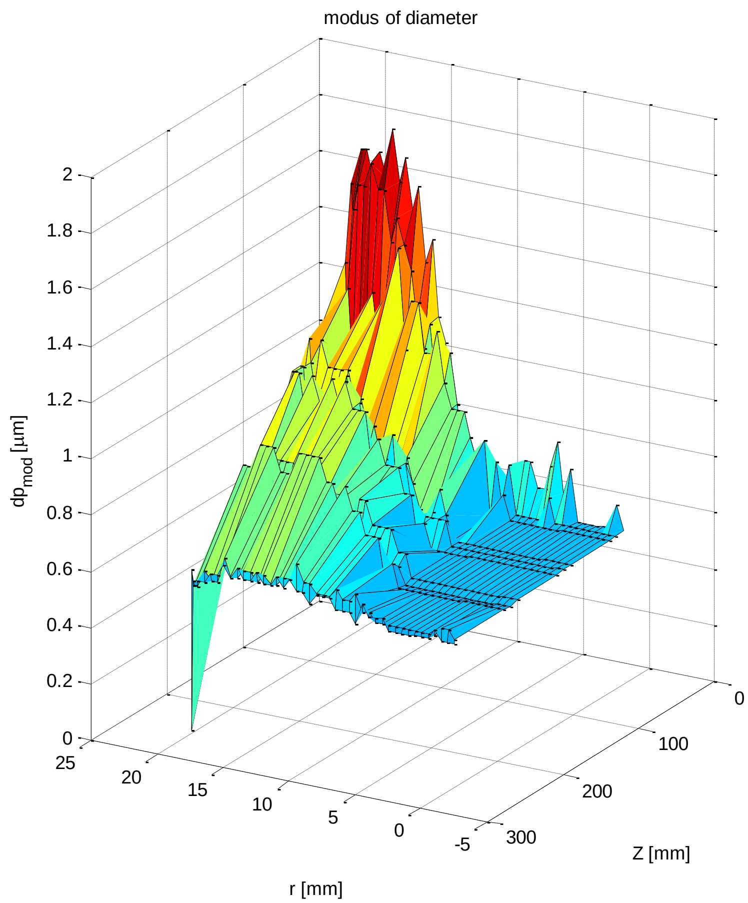

Figure 19: This graph shows the modus of the droplet diameter as function of the distance from the vortex chamber and the radius.

The graph in Figure 19 shows the modus of the diameter. The modus shows the diameter that is measured most. This graph shows that the modus is often 0,5 µm near the core. The actual average droplet size is probably below the 0,5 µm in these places. The average droplet sizes shown in Figure 18 are actually the average diameters of the droplets that have a diameter larger than 0,5 µm. The actual averages are therefore lower.

The diameter measurements show that the droplets that are used in the LDA measurements are very small. At some places in the vortex tube a lot of them are too small to be measured. The droplets are larger near the edge of the tube and the diameter decreases further in the tube due to evaporation. This explains why it becomes harder to measure the velocities at larger axial distances.

5 Conclusions

The following conclusions are made from the performed research.

- Droplet size measurements show that the droplets inside the vortex tube are very small. Small droplets are harder to detect. The largest droplets are found near the edge of the tube and near the vortex chamber. In the core and at larger distance from the entrance of the tube, the droplets get smaller. This is why it is hard to perform LDA measurements at large distances from the vortex chamber.

- For a good LDA measurement it is important to align the lasers properly. The results drastically improve if the alignment is even slightly improved.

- The quality of transparent tube parts is important for the quality of the measurement. Replacing the transparent parts with newer or cleaner parts improves the results strongly.

- The beam intensity is optimized by tuning the beam generator. A high beam intensity is very important to improve the quality of the measurement.

- It is very important to make sure the measurement volume (the area where the laser beams cross each other) is aligned properly with the tube. When the measurement volume is too low or too high the results are influenced strongly because of the strong swirly motion of the gas in the tube. A method to calculate the error in the height of the measurement volume is shown in Formula 13.

- The standard configuration for the LDA measurement works best. Other setups occasionally work better but usually not for the entire range of the measurements. The original setup uses forward scattering for all three channels. If the lasers are aligned properly, the transparent tube parts are of good quality and the beam intensity is optimized the original laser and receiver setup is capable of doing all LDA measurements in the vortex tube.

- The flow in the vortex tube is strongly influenced by the temperatures of the nitrogen and the surroundings. This might be caused by the difference in the density of the gas.

- Certain combinations of the flow and the cold fraction causes ice to form at the cold exit of the vortex tube. This ice jams the cold exit when a lot of it is formed. This influence the flow in the tube. A high flow, high water density or low temperature of the nitrogen increases the chance of ice forming in the vortex tube.

- In general, more water density in the nitrogen stream improves the quality of the measurement. It is needed to apply the vortex tube with water separators to remove the film of water that otherwise forms on the inside of the transparent tube parts.

5.1 Recommendation

- It is observed that the velocities inside the vortex tube are strongly affected by the temperature of the gas entering the tube. Velocity measurements performed at different temperatures demonstrate the effect the temperature has on the velocities.

- The velocities and the size of the droplets are measured using PDPA. It is expected that larger droplets behave differently compared to the smaller ones. The measured velocity data can be selected by the size of the droplet when both are measured simultaneously. This can show how the velocities of the droplets depend on their size.