Particle Tracking Velocimetry

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Summary

Since the techniques available at our department are not applicable for slow, time varying flows, a new technique to measure velocities is necessary. The technique investigated in this work, is Particle Tracking Velocimetry (PTV), because PTV is able to measure velocities of a complex or unsteady flow in a region and at low velocities. Particle Tracking Velocimetry is also known as Low Image Density PIV (Particle Image Velocimetry). PTV determines the Lagrangian velocity of a fluid by determining the motion of particles suspended within this fluid. Therefore the particles are illuminated by a light sheet and the images of these particles are recorded. After locating the particles in the different recorded frames, the paths of the particles are reconstructed. A pair of particles is matched by predicting the position of a particle on the next frame, using its momentary velocity. Differences in size, place, shape etc. are taken into account. When the particle paths are known, the velocities can be determined \((v = \frac{\Delta x}{\Delta t})\) and the total velocity field can be calculated using spline integration. Once the velocity field is known, various quantities like vorticity, divergence, strain rate and stream function can be calculated.

A PTV setup is designed and built, using two red HeNe lasers and negative plano cylindrical lenses. Two lasers were necessary in order to avoid shadows when measuring velocities in flows around a solid body. The setup is tested on the ‘falling ball’ setup, which consists of a ball falling through a tube filled with polyisobutylene solution. The falling ball is a bench mark problem. The numerical and experimental results are compared. Because the tested flow was not axisymmetric, the accuracy of the PTV setup could not be determined. It seems however that Particle Tracking Velocimetry is applicable to polymer flows.
A PTV Setup with only one Laser
   A.1 Creating a Light Sheet ........................................ 23
   A.2 Optical Path Difference ...................................... 23
   A.3 Experimental setup ............................................. 24
   A.4 Necessary Optics ............................................... 25

B Used equipment ...................................................... 26

C Measurement Techniques ............................................. 27
   C.1 Schlieren, Schadowgraphy and Interferometry ................. 27
   C.2 Pulsed Light Velocimetry: PTV ................................. 28
Chapter 1

Introduction

This work has been done to find out whether Particle Tracking Velocimetry (PTV) is useful for measuring velocities in polymer flows. For this purpose a PTV setup has been designed, built and tested.

The experimental setup on which this technique is tested, is the so called 'falling-ball' experiment (a benchmark problem). This experiment consists of a ball falling under influence of gravity through a tube. This tube is filled with polyisobutylene (PIB) solution.

The PTV setup has to be applicable not only for the falling ball experiment, but for all kinds of experiments. For example, it should be possible to measure the velocities in the flow of a polymer melt around a cylinder.
Chapter 2

Particle Tracking Velocimetry

2.1 Flow Measurement Techniques

High accuracy in determining fluid velocity can be obtained by using Laser Doppler Anemometry (LDA). The disadvantage of LDA is, that it can only measure at a single point in the fluid at any instant. Techniques as schlieren, interferometry and shadowgraphy visualize the flow in a region, but they generally cannot be used for complex or unsteady flows [6]. A short description of these methods can be found in appendix C.

Pulsed Light Velocimetry (PLV) does not have any of these problems. It measures velocity in a small region of a flow instead of measuring it in only one point. It can also be used in complex and unsteady flows. PLV measures the motion of these regions by observing the locations of the (recorded) images of tracers at two or more times [1].

2.2 Pulsed Light Velocimetry

To the family of Pulsed Light Velocimetry belong Laser Speckle Velocimetry (LSV) and Particle Image Velocimetry (PIV). Only when the particle concentration is high enough to produce speckle, one can speak of LSV. Usually the concentration is not high enough to form speckle and therefore particle images are recorded: PIV. There are two kinds of PIV: High Image Density PIV and Low Image Density PIV.

2.3 Particle Tracking Velocimetry

Particle Tracking Velocimetry is another name for Low Image Density Particle Image Velocimetry. Characteristic for PTV are [1]:

- The number of images per unit volume to be processed is relatively small
- The probability of different particle images overlapping is small
- particles, and hence velocity measurements, are randomly located
PTV determines the (Lagrangian) velocity by measuring the displacement of particle images over a well known period of time. The velocity is computed by dividing the distance between the particle pairs by the time interval. This Lagrangian velocity of the particles is often used to represent the instantaneous Eulerian velocity. Particle Tracking Velocimetry is a fast and simple method. However, it cannot provide an accurate velocity field with a high spatial density, because the velocity information is sparse and random located [7]. More general information about PTV is given by Adrian [1] and Kuruda ea [6].

In order to get an image from the small particles, these are illuminated. The particles will scatter the light in all directions. To obtain the highest spatial resolution, the depth of the field which is recorded, should be small. Outside this range, the image is blurred by an amount exceeding 20% of the in-focus diameter [1]. The depth in this field is typically of the order of 1 mm. Therefore a thin light sheet is used to illuminate only those particles that are in focus. The light source is often a laser, because it can be easily manipulated by optical devices to form a thin sheet. The probability of detection decreases with the velocity component of the particle perpendicular to the sheet. Therefore sampling probability is biased towards small velocities, because the amount of particles lost due to a out of plane motion is smaller. But small velocities also lead to relative low accuracy [1].

The recording is made by a camera which axis should be parallel to the direction of the maximum light scattering. As recording media both film and video can be used. The principal difference is the spatial resolution. Film has a better resolution, and hence a better accuracy, but video provides immediate access to the information stored in the pixels. When using film the illumination has to be switched at a fixed time, which can be done for example by a rotating perforated disk [2] (see appendix C). When using video, the fixed time between two adjacent frames can be used, so the illumination does not have to be pulsed. The quality of the recording depends on the scattering power of the particles, the intensity of the sheet, the camera lens and the film sensitivity to the wavelength of the used laser light [6].

2.4 Particles

Particle Image Techniques assume that the particles will follow the flow closely. This assumption only holds when the particles are small enough and the density of the particles approaches that of the fluid. However, for recording purposes large particles are desirable. So an optimum has to be found, depending on the kind of flow. The images of the particles can only be recorded due to their scattering. Therefore, the particles must be non-adsorbing. The choice of the fluid/particle combination should be based on [8], [12]:

- Relative densities of particle material and fluid
- Direction of maximum light scattering by the fluid and high degree of light reflections
- Contamination of the system (non corrosive, non toxic)
For tracking purposes it is convenient that the displacement of the particle between two frames is more than its own diameter [6]. The amount of particles should be small enough to prevent overlap. Moreover, the distance between particles should be a few times the particle displacement between two frames (to make sure the right pairs of particles are matched). The particles should be as small as possible, at least one order of magnitude smaller than the structure of the flow under study [8]. Particle motion is discussed more detailed by Somerscales [12] and Merzkirch [8], [9].

2.5 Processing

After recording the image is made suitable for processing. When no differentiation is required, the image can be digitalized by setting each pixel whose gray level exceeds a certain threshold equal to one and zeroing all the others. Non-uniform background intensity caused by non-uniform illumination makes application of a global threshold inaccurate. In that case edge detection has to be applied. The edge of a particle gives a sharp discontinuity in intensity, which usually will not occur in the background itself [6].

Once the particles are localized, pairs of particles are matched. The basis of this searching is that the displacement of a particle cannot exceed a certain value, and (when well seeded) no other particle can be in this region. The assumption made is that the velocity of a particle will not change too much between two frames. Some tracking methods assume all the images to contain reference points and a tail to indicate the direction. Other techniques just assume the reference points (to adjust for vibrations during recording) but need no tail. These techniques add an extra displacement to the particle motion, in such way that, no matter which way the particle went, the computed velocity is always positive. Then the extra velocity is distracted and the real velocity remains.

2.6 Errors

There are three kinds of errors. The most serious error is caused by discrepancy between the velocity of the particle and the velocity of the flow. The other two kinds of errors are recording errors and processing errors [6]. Recording errors can be divided in:

- **Locating the particles.** The error can be minimized by selecting a correct threshold. Once this threshold is chosen, the error increases with the size of the particles, the image noise and the lack of image contrast.

- **Exposure time.** When using film as recording medium, the illumination has to be switched on and off instantaneously. This can be very difficult.

- **Method of digitalization and the resolution of the recording media determine the accuracy with which the displacement can be measured.**

Processing errors concern errors during particle tracking. An example is the erroneous displacement calculation due to appearance and disappearance of particles caused by the third velocity component. Further it is assumed that the Lagrangian velocity is about the same as the Eulerian instantaneous velocity vector. This could also cause errors.
As mentioned, the most serious error is caused by the difference between particle velocity and fluid velocity. In general the particle does not follow the flow, but in some cases, the difference between the particle velocity and fluid velocity is very small. A particle can never follow an abrupt change in the flow. A particle released in the fluid is subject to forces exerted by the fluid flow and by volume forces such as gravity. The following forces could play a part in determining the motion of the particle [9]: Gravitational, thermal or electrostatic forces, fluid resistance to steady or accelerated motion, fluid inertia, lift, wall effects, pressure gradients and particle interaction [13].

Velocity gradients cause rotation of the particle. This causes the Magnus effect, also known as the lift-theorem of Kutta-Joukowski. The lift force moves the particle towards the region of higher velocity. Particle interaction can be caused by e.q. electrostatic forces due to the net charge, electric dipoles (permanent or induced) and magnetic dipoles of the particles. Thermal forces are caused by variation in viscosity of the fluid due to a temperature gradient. This alters the velocity profile and the drag coefficient, although the effect is usually small in fluids. At low velocities inertial effects are small enough to be neglected. Wall effects are of importance when the distance to the wall is in the order of the particles diameter. In this case the fluid flow is also disturbed by the presence of the particle. For very small particles the Brownian motion could also be of importance [12].

In absence of potential forces, the motion of the particle is described by the Bassett-Boussinesq Oseen (BBO) equation [8], [12]:

\[
\frac{du_p}{dt} = a(u_f - u_p) + b\frac{du_f}{dt} + c \int_0^t \frac{d(u_f - u_p)}{d\tau} \frac{d\tau}{(t-\tau)^{0.5}}
\]

The gravity force is \( F_g = \frac{4}{3} \pi \left( \frac{1}{2} d_p \right)^3 g (\rho_p - \rho_f) \). Because the equation is linear in the velocity of the particle, superposition can be applied. Therefore the total velocity is calculated as the sum of the velocity caused by gravity and the velocity as is calculated from the BBO equation. For low fluid velocity, the gravity may not be neglected [8], [12].
Chapter 3

Experimental Setup

3.1 Falling Ball Setup

The falling ball setup, used for testing the PTV system, consists of a perspex tube through which a ball is falling. This perspex tube is filled with PIB-C14 solution with a density of 790 kg/m³. The tube's diameter is 33.4 mm. The perspex tube is placed vertical, so the ball will fall straight down, under influence of gravity. This ball is painted black to prevent reflections. It has a diameter of 16.75 mm and its density is 797 kg/m³. The refraction index of Perspex (1.49) is almost the same as the refraction index of PIB solution (1.43). Therefore, almost no distortion will be caused at the transition from PIB-C14 to perspex. At the transition perspex - air, there is a great difference in refraction index (1.49 and 1.00 respectively). Therefore, the angle of incidence has to be very small to keep the amount of distortion small. This is obtained by surrounding the tube with a rectangular piece of perspex [12].

3.2 Choice of Illumination

In the literature different examples of PTV setups can be found [2], [6], [8]. However, all these setups use one-side illumination. When an object (for example a ball or a cylinder) is placed in the stream, there will be shadows. In these shadows, particles cannot scatter light into the camera, so the velocity in the shadows cannot be measured. When the problem is asymmetric, the velocity has to be measured in the entire plane, so shadows are not allowed. Therefore, the experiment must be illuminated from both sides. There are two ways to achieve this:

- Use one laser and split the beam using optical devices (see appendix A)
- Use two lasers

The cost of both options is about equal. The dimensions of the setup are different in both cases. When only one laser is used, there must be plenty of space available perpendicular to the light sheet. When using two lasers, the necessary space is approximately 5 cm, while the space parallel to the light sheet must be about three times larger. Because lasers can be used more universal than the optical devices needed by a setup with one laser, the second option is chosen, since it is not sure yet that the PTV setup will be satisfactory.
3.2.1 Illumination Setup

The chosen setup is one with two red HeNe lasers. Both lasers are supplied with an aluminum ring in which a negative plano cylindrical lens is mounted. These lenses provide a diverging light sheet. Because the laser beam is 0.8 \( mm \) diameter and the focus length of the lens is 6.35 \( mm \), the sheet will reach a height of 5 \( cm \) at a distance of 5.0 \( cm/0.08 \) \( mm \cdot 0.635 \) \( mm \) = 40 \( cm \) away from the lens. By setting the polarization directions of the lasers under 90 degrees, interference is prevented. The equipment used is listed in appendix B.

3.2.2 Alignment

When the ball falls exactly in the middle of the tube, the flow is axisymmetric. To get a recording of a two dimensional flow, the light sheet must be exactly through the middle of the tube. Otherwise the velocity component perpendicular to the sheet will be too large for many particles. Those particles will then appear and disappear from the light sheet and decrease the quality of the recording. To be able to get the two lasers aligned, black tape is placed on the side walls of the tube, leaving only a small slit in the middle uncovered. When the laser sheet goes through both slits, the laser is aligned well enough. The tape also prevents a possibly present second sheet (due to secondary refraction) to shine into the falling ball setup. Such a secondary sheet would decrease the quality of the recording. For the same reason, a piece of black paper is attached to the back of the tube to prevent light shining in.

3.3 Seeding

The used seeding is 'Optimage'. The density of this commercial seeding is a little bit higher than the density of water and its size is larger than 25 micrometers. The advantage of this seeding is that the particles are spherical. The density of the seeding is too large, but in this kind of flow (taken into account the viscosity and the velocity of the fluid) this is not important.

3.4 Recording

The recordings are made using a VHS camera and Video Cassette Recorder (VCR). The camera is placed perpendicular to the light sheet, so the focal plane coincides with the light sheet. The falling ball was recorded when it was halfway the tube, where it is falling stationary. It is important to make a recording in which both the world coordinates (§3.4.2) and the reference points (§3.4.1) are visible every time the position of the camera is changed. The world coordinates do not have to remain inside the view, but the reference points must be visible at all times. Furthermore, it is important to start the recording at least ten seconds before the experiment starts, otherwise the digital image processing system will not be able to control the VCR.
3.4.1 Reference Points

The reference points are necessary to adjust for vibrations of the setup and/or the camera. About six reference points should be used. For the falling ball setup, three reference points at each side of the tube have been used. These reference points are made of white paint on a piece of black tape which is placed on the perspex tube.

3.4.2 World Coordinates

World coordinates are necessary to determine the magnitude of the velocity. When no world coordinates are known, the velocities can only be calculated in pixels per second. World points, whose coordinates are exactly known, are used to relate the pixel system to the real world coordinates of the imaged process. World coordinates are also used to adjust for the influence of distortion (from setup or camera lens). For this goal, a (maximal) third order polynomial is fitted. For this reason it is recommended to use some world points in the middle and some at the side of the image. Those points may not be all on the same line.

World points can be all the recognizable points on the recording. For the falling ball, a plate of black painted perspex is used, which fits exactly in the tube. It has 6×8 holes at 5±0.005 mm distance. This plate is illuminated from the back side by an ordinary lamp. The recording shows small light sources at regular distances, as can be seen in figure 3.4.2. Some of these (one at each corner and four in the middle) are registered.
Chapter 4

Data Processing

For the processing of data, the image processing system * DigImage * can be used, available in the divisions Energy Technology (WOC/WET, W) and Fluid Dynamics Laboratory (FT, N). * DigImage * is a menu driven system. A short manual for DigImage is written by Gert van der Plas [10]. The post processing is done with the programs * prtplot * and * DGP * (in the /usr11/DGP directory of the WFW network). Figures can be made with the programs * matlab, gnuplot * and * coplot * . This section will show the sequence in which the data is processed. For more details about * DigImage *, see the DigImage Manual [3].

4.1 DigImage

* DigImage * needs some way to control the VCR. Because the VCR sometimes skips frames when reversing mode, * DigImage * not only drives the VCR, but also checks it. This is done by using an audio signal, which has to be put on the tape first.

The next thing * DigImage * should do, is to grab an image in which both reference points and world coordinates are visible. These points have to be registered.

After that, another image is grabbed, this time showing the experiment. When using VHS instead of Super VHS (SVHS), interlacing will probably cause problems. Therefore the image has to be manipulated, for instance by duplicating the odd lines. This however reduces the amount of information on the grabbed image, therefore it is better to use SVHS. The particles can be tracked after adjusting the tracking parameters such that about all the particles are located, but no pollution is considered as a particle. * DigImage * can track up to 4096 particles.

To track the particles, * DigImage * takes control of the VCR to grab all the frames it needs. Therefore the VCR should be stopped at the place where the image is grabbed, before particle tracking is started. Tracking is accomplished by finding the matching images of the particles on each two frames. This is done by computing the expected location on the next image, which is the velocity $ \times $ time interval added to the momentary location. For every deviation of this location, particle dimension, particle image intensity, or other possible errors, some costs are added [10]. These costs are minimized by finding the correct pairs. Once these pairs are found, the velocity is computed (distance divided by time) and the next pair of frames is compared. During tracking, * DigImage * will show the particle paths. After tracking, the positions and velocities of the particles are known over the specified period.
4.2 Trk2dVel

The post processing program Trk2dVel is available on the DigImage system. This program can be used for a qualitative look at the data. It is possible to calculate and view particle paths, velocity fields, stream function, vorticity, divergence and more. By allowing only particle paths which are more than e.g. five times the sample spacing, erroneous data is not used for the computing of these quantities. Trk2dVel can also write a .pv-file, in which the positions and velocities of the particles at a specified time are written. This file can easily be read by plot-programs such as Matlab. This program can then be used to calculate the necessary quantities.

4.3 Prtplot

With the program prtplot a .prt-file made by DigImage can be converted in a .pv-file. Prtplot can also make a postscript file which shows the (averaged) velocity or particle paths during a specified period of time or on a specific moment. The postscript files will have the extension .out.

To use this program not only the .prt-file is necessary, but also a .dat-file. This file must contain the size of the tracking window, the sample spacing, the unit, and the scale factor:

\[ \text{xmin} \quad \text{xmax} \quad \text{ymin} \quad \text{ymax} \quad \text{sample\_spacing} \quad \text{unit} \quad \text{scale\_factor} \]

For the falling ball the .dat file looks like:

\[ -16.972 \quad 17.2299 \quad -22.7085 \quad 20.0506 \quad 0.04 \quad \text{mm} \quad 10 \]

This .dat-file must have the same base name as the .prt-file.

4.4 DGP

The program DGP, Digitalisation Photographs, determines vorticity, strain rate, stream function, Jacobian and divergence from a given two dimensional velocity field, as written in a .pv-file. Using the velocities at the particle locations, a fit is made for the total velocity field. This is done using a spline interpolation. The interpolated velocity in x-direction is given by:

\[ u = Sv(N + 1) \cdot x + Sv(N + 2) \cdot y + Sv(N + 3) + \sum_{i=1}^{N} Sv(i) \cdot d_2(i) \cdot \ln d_x(i) \]  

Here \( d_x(i) \) is \((x - x_i)^2 + (y - y_i)^2\). The interpolation function for the velocity in y-direction is the same. The first three coefficients correspond to a linear least squares fit for each velocity component. The spline coefficients \( Sv(i) \) are calculated by solving the Nth order system of equations by applying equation 4.1 to the N measurement points. This interpolation function is of a very high order compared to the number of points on which it is fitted.

The output of DGP is written in a .asc-file. This file can be read by programs such as matlab, gnuplot and coplot. Then these programs can be used to make (two- or three dimensional) plots.
Chapter 5

Results

5.1 Results of the Experiment

After trying several times and using diverse equipment, it is clear that it is not possible to let the ball fall exactly in the middle of the tube. Therefore the flow is not axisymmetric and many particles appear and disappear during recording. The results shown here are obtained using a recording which shows an almost two dimensional flow. This image can be seen at the front page of this report. Since the ball did not fall the same way twice, the repeatability is not determined.

The used record contains a few bubbles. These can be recognized as the very large 'particles'. Because bubbles do not follow the flow, the large particles are neglected. This is obtained by setting the tracking parameters [10]. About five hundred particles are localized by DigImage in the grabbed image. Because many particles appear and disappear, only two hundred fifty could be tracked over more than five frames. The tracked paths of those can be seen in figure 5.2. With the program prtplot a picture of the velocity is made, picture 5.2.

![Figure 5.1: Velocity on centerline](image)

Figure 5.1: Velocity on centerline
5.2 Comparison of Experimental and Numerical Results

The velocity field is also obtained by a numerical experiment with Seprun. For this numerical experiment special elements were used and a main program written by ir S. Selen. The velocity field calculated is given in picture 5.3.

When comparing figures 5.2 and 5.3 it can be seen that the velocity field is qualitative the same. (The arrows in the top right of figure 5.2 give the scale. One arrow length equals 1 cm/s in figure 5.2 and 3 cm/s in figure 5.3.) However the problem of PTV is seen very clearly here: the velocity field does not have a high spatial density. It can just give the velocity at the points where particles happened to be.

For quantitative comparisons figure 5.1 can be used. The dotted line shows the velocity at the centerline as determined using the velocity-fit made by DGP, the other shows the velocity calculated by Sepran. The slopes in the right picture are not identical. This is probably due to an inaccurate fit. This velocity field fit is made using a spline interpolation. As figure 5.1 shows, the fit curves back at the image edge (at about 20 mm from the center of the ball). A lack of particles in this region or inaccurate velocity determination of these points (caused by the small displacement) can be the cause. The inaccuracy of the fit is also visible at the edge of the ball (at 8.375 mm from the center).
The assumption that the difference between the slopes is due to an inaccurate fit instead of being caused by erroneous results from the numerical experiment, is justified in the left part of figure 5.1: the slopes are almost the same. There is however a small displacement between the two lines. This can be caused by an inaccurate placement of the ball, since this is done manually.

After calculating the velocities, written in the .pv-file, the position of the ball had to be determined. This is done graphically, which can cause an error of maximal 0.5 mm. This position is used to add some velocity vectors to the .pv-file at the position of the ball. Some velocity vectors are also added at the position of the side walls. These extra velocities are necessary to get a better fit, in which solid bodies have an uniform velocity distribution.

5.3 Vorticity, Divergence, Strain rates and Stream functions

In the next figures, the ball has no motion and the walls have a velocity of 6.87 mm/s. This is accomplished by adding 6.87 to all the velocities in y-direction in the .pv-file.

5.3.1 Vorticity

The vorticity is showed in figure 5.5. Vorticity is defined as $\frac{dv}{dx} - \frac{du}{dy}$. As can be seen from figure 5.3, the component $\frac{dv}{dx}$ is at the right side positive near the ball and negative near the wall. This can also be found in figure 5.5. There are four places with vorticity. At both sides of the ball, and at both sides next to the wall. The vorticity at the left side near the wall and at the right side from the ball are positive, the others negative. These results are physically correct. The vorticity is smaller near the walls, where the component $\frac{dv}{dy}$ is almost zero.
5.3.2 Divergence

The divergence is defined as \( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \). For a two dimensional flow, the divergence is zero. In figure 5.7 it can be seen that the recorded flow is not entirely two dimensional. The global amount of divergence is 2 s\(^{-1}\) instead of zero. The divergence is very large to the right of the ball. In figure 5.2 it can be seen that at this specific place, one particle is tracked erroneously. Probably this 'particle' is not a real particle, but a small bubble, which didn't exceed the maximum dimension given as tracking parameter. This would explain why it is moving up, instead of down.
5.3.3 Strain rates

The strain rates $\frac{du}{dx}$ and $\frac{dv}{dy}$ can be seen in the figures 5.8 and 5.9. These figures show that the strain rates are small, except for the peak in $\frac{dv}{dy}$ which can be explained by the bubble, as mentioned in the previous section. The strain rate $\frac{du}{dx}$ should be of order $V/\Delta r = 0.0069 \text{ms}^{-1}/0.0084 \text{m} = o(0.82^{-1})$. The strain rate calculated by DGP is of this order.

![Figure 5.8: Strain rate $\frac{du}{dx}$](image1)

![Figure 5.9: Strain rate $\frac{dv}{dy}$](image2)

5.3.4 Stream function

The stream function $\psi$ is determined by the equations $u = \frac{\partial \psi}{\partial y}$ and $v = \frac{\partial \psi}{\partial x}$. DGP can calculate the stream functions using three different methods. The method using an analytical integration of the spline coefficients is discouraged, since its routine may contain an error. The method using the Poisson equation gives more reliable results. When the vorticity is calculated using spline coordinates, the Poisson equation is solved iteratively. As boundary condition the stream function is given at the boundaries. This stream function is automatically determined by DGP. If the boundary integral over the boundary does not equal zero, its error is spread over the entire boundary. This is acceptable for small values. After solving the Poisson equation, the stream function is known, except for an additional constant, in all the grid points.

The last method directly integrates the velocity field. Since the derivative of the velocity is not determined, the error made by this routine is smaller than the error made by the routine using the Poisson equation. The error is in the order of one percent.

If necessary, these stream functions could be compared with stream functions generated by Sepron. In figure 5.13 the streamlines go neatly around the ball, but in figure 5.15 they go straight through the ball. Only the first figure is physically right. This is the figure made with the routine using a direct integration of the velocity fields.
Figure 5.10: Stream function using Poisson equation
Figure 5.11: Stream function using velocity field

Figure 5.12: Figure made with matlab
Figure 5.14: Figure made with matlab

Figure 5.13: Figure made with coplot
Stream lines using Poisson equation.
Figure 5.15: Figure made with coplot
Stream lines using velocity field.
Chapter 6

Conclusions and recommendations

It seems that Particle Tracking Velocimetry is useful for measuring the velocity of polymer flows. However, the accuracy could not yet be determined, because it was not possible to create an axisymmetric flow. This accuracy should be determined by testing the PTV setup on a real two dimensional flow, for example a polymer melt flow around a cylinder, before purchasing other equipment.

Once the accuracy has proved to be well enough, the following items should be considered.

- The red HeNe lasers should be changed for green lasers, because cameras are more sensible to green light than they are to red light. Or use another kind of illumination, for example a slide projector.

- A Super VHS camera and VCR should be used. The spatial resolution is higher, because the interlacing causes less problems. Therefore more information can be obtained.

- Contamination should be prevented, because it can cause erroneous particle tracking results. A bubble, for example, can disturb calculations of divergence and strain rates.
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Appendix A

PTV Setup with only one Laser

It is possible to make a PTV setup with only one laser. In this case the laser beam is split using optical devices. In this appendix, this setup will be explained.

A.1 Creating a Light Sheet

The light sheet is obtained by using a plano cylindrical lens. This lens causes the laser beam to divergence in only one direction. When no divergence of the final light sheet is allowed, you can use a second lens to convergence the beam so that the exiting light sheet is parallel. The maximum height that can be obtained in that case is 3.6 cm. Therefore, two lenses are used. One negative plano cylindrical lens with a focal length of 6.35 mm and one positive plano cylindrical lens with a focal length of 300 mm. Calculation of maximum height: \( y = \frac{1}{2} \frac{D^2}{f_1} = \frac{1}{2} \cdot 0.8 \text{ cm} \cdot \frac{300}{6.35} = 3.6 \text{ cm} \). If divergence is not a problem, the second lens is not needed.

To make sure only a thin sheet of light enters the experimental setup, you should use two splits just behind each other. The first to catch all the light and to let only a small amount pass. The second to catch the light which was refracted at the side of the first one. This way, only a neat thin sheet will pass.

A.2 Optical Path Difference

To prevent interference, the optical path difference should be more then the coherence length, given by \( \Delta x_c = c \Delta t_c = \frac{c}{\Delta \nu_D} \) [5]. \( \Delta \nu_D \) is 1400 MHz, therefore \( \Delta x \) is 21 cm [4]. This leads to the dimensions as given in the figure on page 24. The experimental setup which is used here, is the 'melted polymer flow around a cylinder' setup, because the dimensions for this setup are larger then those of the 'falling ball' setup. However, for the 'melted polymer flow' setup, the height of the sheet need not be 5 cm, because the cylinders diameter is only 2.5 mm.
A.3 Experimental setup

The setup is as follows: A negative plano cylindrical lens is placed as close to the laser head as possible. A 50/50 beam splitter is placed at 90 cm from the laser head. About 40.5 % of the laser light is transmitted and 45 % is refracted. After 210 mm (this is 300 mm from the first lens) the refracted beam passes a positive plano cylindrical lens. By then the height of the sheet is 3.6 cm and will not vary anymore. When this lens is not used, the sheet will continue to diverge and part of the light will not enter the experimental setup.

After two mirrors the refracted beam has lost 17.2 % of its intensity \( (1 - (0.91)^2 = 1 - 0.828 = 17.2\% ) \) when it reaches the experimental setup. The transmitted beam loses only 9 % of its intensity, because it reflects on only one mirror. Because the beam splitter does not actually split the beam 50/50, the final intensities are 33.5 % for the refracted beam and 36.9 % for the transmitted beam.

The exact distances between the different optical components are not important. However, it is important to keep the distance between the negative lens and the laser as small as possible and the distance between both lenses about 30 cm. The optical path difference varies between 210 and 310 mm (in the experimental setup).
A.4 Necessary Optics

The necessary optics for this setup are: (all to be supplied by Melles Griot)

- Negative Plano-cylindrical Glass Lens, \( f = -6.35 \), \( x = 25.0 \), \( y = 7.0 \) [mm], 01LCN000 @ f 179,-
- Positive Plano-Cylindrical Glass Lens, \( f = 300 \), \( x = 60 \), \( y = 50 \) [mm], 01LCP019 @ f 169,-
- 50/50 Plate Beam splitter, 50 mm diameter, 03BTF023 @ f 106,-
- 3 mirrors: crown glass with protected aluminum, 50 mm diameter, 01MFG027 @ f 85,- a piece.

This optics have to be placed, so holders are needed. Necessary holders:

- Holder negative lens: 25 x 25, 07LHC001 @ f 242,-
- Holder positive lens: 60 x 60, 07LHC003 @ f 211,-
- Holder beam splitter, with screw, 0.22", 50.8 mm diameter, 07MSS001 @ f 765,-
- Holder mirrors: various possibilities, price varying between f 278,- and f 339,-

Total costs at least f 2761,- (without laser). Unless some of this equipment is already available, this is a very expensive solution.
Appendix B

Used equipment

The equipment used for the Two Laser Particle Tracking Velocimetry setup is:

- 2 Negative Plano Cylindrical Glass Lenses,
  \( f = -6.35\, \text{mm}, \quad x = 25.0\, \text{mm}, \quad y = 7.0\, \text{mm} \)
  Melles Griot 01LCN000

- 2 Cylindrical Laser Holder,
  Melles Griot 07HLH002

- 1 Optical Rail,
  Melles Griot 07ORN009

- 2 Rail Carriers,
  Melles Griot 07OCN501

- 2 HeNe laser model 1125P, 5 mW,
  Applied Laser Technology SN 1150951, 1164570

- 2 Power supply model 1202-2 for the 1125P head,
  Applied Laser Technology SN 4L7323, 461234.

Addresses of the suppliers:

- Melles Griot,
  Hengelder 23,
  P.O. Box 272,
  6900 AG Zevenaar,
  Tel.: 0316 333041,
  Fax.: 0316 528187.

- Applied Laser Technology,
  De dintel 2,
  5684 PS Best,
  Tel.: 04998 75375,
  Fax.: 04998 75373.
Appendix C

Measurement Techniques

C.1 Schlieren, Schadowgraphy and Interferometry

A medium is termed optically heterogeneous when its refractive index is not the same everywhere, due to a chemical (mixture of different materials) and/or physical (temperature of pressure distribution) nature. Optical visualization methods as schlieren, schadowgraphy and interferometry visualize the light ray deviations due to these refractive index differences. To become visible, these deviations or wavefront deformations must involve changes in illumination or color on an observation screen [14]. Diffraction of light by the particles causes deflection of some of the light [11]. This gives the same effect as refractive index heterogeneities.

Schadowgraphy shows dark lines and bands. Without the heterogeneous medium, the observation screen is uniformly illuminated. With the medium, a light ray SM (C.1), which normally follows path MA, is deflected by the refractive index heterogeneities near M, to path MA'. If the screen is less illuminated in A and more illuminated in A' than without the heterogeneous medium, there are illumination changes on the screen.

Schlieren can make a constant refractive index visible, this in contrast to the schadowgraphy method. By schlieren, so called schlieren diaphragms are placed in the focal planes of the field lenses (C, L1, L2). This could, for example, be a square hole as entrance diaphragm D1 and a knife edge as exit diaphragm D2.

![Figure C.1: Schadowgraphy principle](image-url)
The light source must be large enough to fill the square as uniform as possible. The knife edge aligned parallel to the $y$-axis will either cut off or admit more of the deflected light, causing a change in the intensity of the light reaching the camera (O,E). For small deflections, the change in contrast illumination $\Delta E$ is proportional to $\int \frac{\partial \beta}{\partial z} dx$. If $\frac{\partial \beta}{\partial z}$ is independent of $x$, the derivative may be evaluated [11].

Propagating through a heterogeneous transparent medium deforms the light wavefront, as a change in the refractive index causes a corresponding change in light velocity and hence transit time. Interferometry is a technique for comparing the shape of a wavefront to that of a reference wavefront. It shows the difference in wavefront shapes by means of dark and bright lines, the interference fringes. These fringes occur every time the optical path difference is an integer number of light wavelengths. In fluid dynamics research holographic interferometry is used almost exclusively, because it is much easier to use and cheaper to build than the classical interference setups. It has become possible to let wavefronts, traveling the same path at different times, interfere. The use of a single path, which is done by holographic interferometry, has the advantage of self compensating for optical component defects as they act likewise on both interfering wavefronts.

### C.2 Pulsed Light Velocimetry: PTV

The method of PTV which is used here, uses a camera and VCR. The used light is not pulsed, although PTV is a Pulsed Light Velocimetry technique. However, PTV can also be performed using film and pulsed light. This is the way PTV is done originally. The pulsed light can be made e.q. by a rotating perforated disk [2]. Usually the beginning of the particle path is indicated by a little point, caused by a short light pulse. After that, the light is turned on for a longer period. This gives a continuous line on the photo, indicating the particle motion. The end of the path is also indicated by a little point. Therefore the illumination has to be switched on and off in a specific order. It is important that the light is on or off instantaneously to give a sharp corner. Only particle paths which have a beginning point and an end point are used. This is done, because particle paths which do not have both these points are caused by a particle which suddenly appeared in or disappeared from the illuminated plane.