Chapter 4

Towards Faster Flow Imaging

4.1 Introduction

Although the IMS approach can scan quickly in potential, the setup M described in section 3.2 has yet a very limited imaging speed. Increasing that would allow us to extend the exploration of the Newtonian regime, or to check the viscosity and density scaling predicted by the inertial number theory. Since particle tracking over an extended range of rotation rates would also become feasible, it would also enable us to look at the microstructure of the suspension flows. Evidently, faster imaging can give access to a vast amount of new physics.

In this chapter, we describe a new IMS setup under construction in Leiden, which can scan up to 100 times faster than the setup described in section 3.2. We will show that we can image flow speeds up to about 1 rps, and that we reduce the time to take three dimensional reconstruction scans to several seconds. In short, with this faster imaging system, we are able to image faster flows, and image flows faster.

We carried out preliminary studies of fast flows in the split-bottom geometry in this setup. We looked at the particle size dependence for 3 mm particle size suspensions. We also extended the range of flow rates imaged by a decade to $8.3 \times 10^{-1}$ rps. This new regime of flow rates opens a whole new range of unexplored suspension dynamics, in which centrifugal forces overtake gravity. We also did some preliminary three dimensional scans, and show that three dimensional images, in which clearly identifiable particle are present, can be obtained within seconds.
To distinguish it from setup M described before, we will refer to this faster IMS setup as setup L.

### 4.2 Index Matched Scanning: Setup L

![Diagram of setup L]

Figure 4.1: The setup under development in Leiden. The drawing is to scale. The aluminum frame can be closed off on all sides with opaque panels.

In order to increase the imaging rate in setup M, two main limitations had to be overcome: first of all, the imaging system used was not capable of storing...
images fast. Secondly, the camera is positioned at a large distance from the measurement cell, which reduces the influx of light. We will discuss the solutions implemented to solve these problems first, and then we will describe the setup in full detail.

4.2.1 Increasing the Imaging Rate

Imaging system -- The main speed limitation for imaging systems nowadays is storing the digital images -- there is a tradeoff between having a small amount of fast memory modules that can be accessed quickly, or having a large amount of memory that can only be accessed relatively slowly. High speed cameras capable of imaging more than 1 million frames per second are commercially available nowadays [79], but they can typically only buffer a few thousand images, which after completing the acquisition have to be transferred to a permanent storage location at a much slower rate. Slower camera systems, that use computer hard drives as storage modules, can store up to 1 million images easily, but usually at a rate of a few tens of frames per second.

This limitation in imaging systems affects the way we improve the imaging rates in setup L. There are two ways of imaging suspension flows with IMS. In one approach, the position of the sheet inside the suspension is kept at a fixed position, and a number of images is recorded. To image another cross section of the flow, the sheet is moved and another set of images is acquired again. This method was used to obtain all the flow profiles shown in chapter 3. We will refer to it as serial flow imaging. One sequence of images is typically only 1000 images large, so only a high speed memory buffer of 1000 images has to be available to store the images temporarily before writing them to slower memory modules like a computer hard drive: this can be done at an arbitrary rate in the time between two recordings at different positions in the suspension.

To increase the imaging rates for serial flow imaging, we therefore use a high speed camera (Phantom V4.2).

The other way IMS can image suspension flows is by moving the sheet continuously through the suspension, while recording images. After the complete volume is traversed by the sheet, the process is repeated. With this method the whole three dimensional flow is imaged in parallel; we will refer to it as parallel flow imaging. The maximum displacement for a particle between two consecutive volume scans should be less than a particle radius\(^1\); only then can

\(^1\)There are ways to loosen this constraint; for example using Particle Image Velocimetry (PIV) techniques first to subtract the overall mean displacement field, and then only to use particle tracking to extract the position or displacement fluctuations superimposed on the mean flow profile [80].
the particle trajectories in the three dimensional volume can be tracked, which is necessary for the study of diffusion of particles. Three dimensional imaging thus not only requires reasonably fast scanning to keep the total strain per consecutive volume low, it also requires significant amounts of memory space in the ‘buffer’ to store images acquired by the camera: A typical measurement requires 1000 three dimensional volumes of about 150 images each. Assuming that a typical image has 640x480 pixels, with a 12 bit depth, its size is \( \sim 500 \text{ kB} \) per image, and the total amount of data in this measurement is 75 GB. Most fast cameras, like the Phantom series, have only a few gigabytes of buffer memory, and will therefore not suffice for three dimensional imaging. Therefore, we use the DAS Digital Image Archiver system\(^2\). This system is capable of acquiring images from a high speed FireWire camera continuously, and storing images directly to the optimized hard drive on the workstation it is running on. The speeds at which it can acquire and save images are limited by the hard drive write speed, which is typically 50 MB per second. Assuming again a typical image size of 500 kB, this sets the acquisition of a full three dimensional stack of 150 images to 1.5 seconds. For comparison: this is comparable to the fastest confocal scanning setups nowadays available.

**Photon flux** -- To increase the frame rate with a faster imaging system, the exposure time per image has to be decreased. To keep a good contrast however, a certain photon flux has to reach the camera. To image faster, it is necessary to get more photons per unit area on the photosensitive CCD chip. In the IMS technique, the number of photons available per pixel is set by a few factors: the intensity of the laser beam, the total area of the laser sheet, the local concentration of the dye, the quantum yield\(^3\) of the dye, the distance to the fluorescent spot, the aperture of the lens, and the quantum efficiency of the CCD chip.

In setup M, the main light capturing limitation is the distance to the fluorescent dye: the distance of the camera to the measurement cell is 2 meters. We recall that this is done to avoid issues with focussing on different imaging planes. To be able to achieve higher image acquisition speeds, we therefore placed the camera closer to the flow geometry to be studied. This necessitates moving the camera together with the illuminated plane. This is to keep the images focussed for all imaging locations inside the suspension. Therefore, the camera has to be mounted on a translation stage. This however also allows us to use a fixed focal length objective, which typically have a larger aperture. This

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\(^2\)From DVC Machinevision, Breda, The Netherlands; www.machinevision.nl

\(^3\)This is the ratio of emitted over absorbed photons.
also increases the number of photons available per pixel.

A typical three dimensional scan is as deep as a typical filling height $H$ in the split-bottom cell, so a few centimeters deep. The camera has to traverse this distance within the scan time of a complete volume, which is on the order of a few seconds. This limits the total weight of the camera; we therefore use a camera/lens combination with a total weight of around 300 gr.

### 4.2.2 Setup Description

The split-bottom setup type L is shown in Fig. 4.2. Its design is inspired by setup M described in a previous chapter; however in some crucial aspects the setup is different. Below, we will discuss the components used in setup L separately, as was done for setup M.

**Laser** -- The laser used in the setup was identical to the one employed in setup M. We use the external trigger capabilities of the laser to turn it on only during the camera exposure time. This limits the effects of photobleaching -- see section 3.2.2

**Translation stages** -- We use (BAHR ELK80) translation stages for both camera and laser motion. The stages are spring-loaded to ensure they have no backlash. The stages are capable of moving quickly, up to 10 cm per second, and can carry large loads. They are driven by high torque stepper motors from Lin Engineering (4118L-01). The stepper motors are controlled by stepper motor drivers (CDR-4MPS). The maximum step size of the stages is 5 micron. The step size can be decreased by a factor 256 with the micro stepping capabilities of the stepper motor driver.

**Digital camera** -- The digital camera used to image the cross sections illuminated by the laser, is a Basler A622f FireWire camera. It is operated with the DAS Imaging Archiver software mentioned above. The QE maximum of the CMOS chip used in the camera is with 25% maximal between 550 and 650 nm. The resolution of the CMOS is 1280x1024 pixels. The exposure time can be adjusted between 80 microseconds to 0.32 seconds. The maximum frame rate at full resolution is 25 frames per second; the frame rate can be increased by using fewer pixels in the Region Of Interest (ROI). The lens used on the camera is a fixed focal length lens with an aperture of 2.8.

*Stepper motors have a fixed step angle (1.8°) in this case. Microstepping drivers can reduce this fixed step angle by a certain factor.*
Enclosure -- To reduce the influence of background light, the flow-box/laser/camera assembly is mounted in a custom-built dark enclosure. The whole setup is mounted on two stacks of concrete slabs; vibration damping is achieved by sandwiching rubber mats between the concrete slabs.

Flow geometry -- The split-bottom geometry has the same design and size as type M described in the previous section. It is a square box of 15 cm sides, measuring 20 cm in height. In this setup however, the walls of the box are made of glass, to allow for the use of more aggressive index matching fluids\(^5\). The disk in this setup is driven by a stepper motor (Lin Engineering 5718L-01P), with a micro stepping driver (CDR-4MPS). The minimum step angle is 0.007°. The bottom of the box, as well as the disk, are made rough with a hexagonal (i.e.

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\(^5\)Some fluids with a high index of refraction, such as Eugenol, dissolve PMMA. See section 4.4 for an overview of index matching fluids, particles and considerations
ordered) array of conical holes, with a maximum cross section of 5 mm (similar to the setup described in section 2.2). The box can be sealed with a transparent lid, to be able to use index matching fluids that degrade when exposed to air, like Eugenol, but also to prevent evaporation of solvents in the index matching liquids, which changes its index of refraction.

Environment -- The setup is placed in a lab with only modest temperature and humidity control. Depending on the season, the relative humidity ranges from 20 to 50%, and the temperature varies between 20 and 25 °C. Both variables affect the evaporation rate of the water in the Triton-based index matching liquid, and therefore the viscosity and density of the fluid.

4.3 Preliminary Experiments

In this section we describe several preliminary experiments that demonstrate the functionality of setup L. We check whether the inertia theory scaling is indeed independent of particle size, by studying flow profiles and rheology of a PMMA/Triton suspension with 3.2 mm sized particles. Surprisingly, we find that the flow profiles, in contrast to rheology and inertial theory scaling, shows a particle size dependence.

We also look at what happens to suspension flows at rotation rates higher than reported in chapter 3 -- for example the centrifugal force at some rotation rate overtakes the gravitational force in magnitude. The onset of the influence of centrifugal forces is already apparent at rotation rates of $3.3 \times 10^{-1}$ rps, i.e. at much lower rotation rates than one would expect from the relative size of the gravitational and the centrifugal forces.

Setup L is designed with fast scanning in mind. We show that the setup delivers: one of our first tests was a three dimensional scan of an index matched suspension. The total scanning time was three seconds -- the result of the scan is discussed in section 4.3.3.

4.3.1 Triton Suspensions: Different Particle Size

The inertial number for fluid-saturated granular flows, $I_s = \frac{\sqrt{\rho_s g R_s}}{\eta}$, is independent of particle size, as we have seen in section 3.4.2. To test this, we image the flow of 3.2 mm (1/8") PMMA particles suspended in the Triton mix. We use a filling height $H/R_s = 0.5$, since for that filling height the transition from dry granular flows to the Newtonian regime is best observable in the flow profiles.
Figure 4.3: Normalized angular velocity profiles for 3.2 mm PMMA particle suspension. Different rotation rates are depicted: (a) - (f) are $\Omega = 1.6 \times 10^{-6}, 1.6 \times 10^{-5} \ldots 1.6 \times 10^{-1}$ rps. Color schema as indicated in the color bar, ranging from 0 to $\Omega$. Surface of suspension is at 23 mm.

We image the velocity profiles for over a large range of rotation rates: $\Omega = 1.6 \times 10^{-6} \ldots 1.6 \times 10^{-1}$ rps. For $\Omega$ below $5 \times 10^{-5}$ rps, the interframe time is always larger than 40 seconds, which is enough time to image the slices at the five different heights (4.5, 8.5, 12.5, 16.5, 20.5 mm) we use to measure the flow profile. This means that for these slow runs, we image in parallel mode. The interframe time decreases from 300 seconds at the lowest rotation rate measured, to 150 milliseconds at the fastest driving rates. For the slowest two rotation rates measured, the total strain is about half a rotation of the disk, which
may not be enough to set up a steady state flow throughout the whole cell, as was observed in [37], Fig. 5. Note that in this experiment, we used a Foculus FO 432b camera, instead of the Basler camera mentioned earlier.

For the slowest runs, that take a few days to complete, we prepare the index matching fluid slightly differently; see section 3.2.2. Instead of using the recipe with a substantial amount of water and zinc chloride, as was used for the measurements at higher rotation rates, for the low rotation rates of $\Omega = 1.6 \times 10^{-6}$ rps, we now add only enough water and zinc chloride to make the dye have the proper absorption and emission spectrum. The reduced amount of zinc chloride used reduces its precipitation, so that the fluid is usable for several days, which increases the total useful measurement time.

![Normalized angular velocity profiles and dry granular flow equations](image)

Figure 4.4: A comparison between the normalized angular velocity profiles and the dry granular flow equations. Again, different rotation rates are depicted: (a) - (f) are $\Omega = 1.6 \times 10^{-6}, 1.6 \times 10^{-5} \ldots 1.6 \times 10^{-1}$ rps.

**Slow flow limit** -- The results of the experiments are shown in Fig. 4.3. Note that we imaged more rotation rates than shown in that figure (11 in total); we
leave half the data out for clarity. From the contour plots, it is again obvious that at lower rotation rates the flow profiles are very similar to dry granular flows. This is shown in more detail in Fig. 4.4; the point-by-point comparison with the dry granular flow model is quite good at the lower rotation rates. The comparison for $\Omega = 1.6 \times 10^{-6}$ rps seems slightly worse; in that experiment the limited amount of strain may impede the matching to the dry flow profiles.

Figure 4.5: The comparison of the normalized angular velocity profile data from the 3mm PMMA suspension to the Stokes flow solution. The suspension was driven at $\Omega = 1.6 \times 10^{-1}$ rps.

Fast flow limit -- We compare the velocity profile measured at $1.6 \times 10^{-1}$ rps with the Newtonian profile in Fig. 4.5. We see again that the flow profiles for the suspension tends towards Newtonian behavior, although the suspension with the 4.6 mm particles was already almost fully Newtonian at half that rotation rate. This suggests that the rate dependence of the flow behavior for these 3.2 mm suspensions is different from the 4.6 mm suspensions.

To see how strong the particle size dependence is we compute for each rotation rate the average mean squared difference $\sum (\omega_S(r,z) - \omega_D(r,z))^2/N$ between the measured velocity profiles and the dry granular flow equations. Here $N$ is the total number of datapoints for which the normalized angular velocity $\omega(r,z)$ is available. The onset of rate dependence should then be visible as an increase of this quantity with increasing $\Omega$ -- indeed we see this quantity rise earlier for the 4.6 mm suspension than for the 3 mm suspension; see Fig. 4.6a.
Mismatch in rate dependence -- What can explain this large mismatch observed in the moment of the onset of rate dependence in the velocity profiles for the two different suspensions? From the scaling arguments, it is unlikely that this is due to the particle size. Moreover, the rheological data of the 4.6 and 3.2 mm suspensions (reproduced from section 5.4.2 in Fig. 4.6b), are virtually indistinguishable from each other, although a small particle size cannot be ruled out.

One difference between the two experiments is the temperature of the fluid: Setup M, in which the 4.6 mm particles were imaged, was located in a laboratory with temperature control, and room temperature there was never higher than 22 °C. Setup L does not have temperature control. Moreover, the stepper motor used to drive the disk was directly coupled to the bottom of the flow cell, and warmed up substantially when in use. This heated the fluid to a temperature of about 27 °C. In appendix 5.7.2 it was shown that Triton has modest temperature dependence in its viscosity between 22 and 27 degrees; its viscosity changes by almost a factor 2 in that range. The 3.2 mm particle suspension experiments were therefore most likely carried out with an index matching fluid that had a lower viscosity, which would shift the onset of rate dependence to higher rotation rates, consistent with the trend observed in the data.

The other difference between the two suspensions is the preparation of the index matching fluid. Small variations in the amount of water mixed into Triton can change its viscosity substantially. Combined with the temperature dependence of the fluid, we can most likely account for the shift on the logarithmic scale in Fig. 4.6, between the data sets for the different suspensions.

We conclude that the mismatch in the rate dependence for the suspensions with different particle sizes is therefore most likely due to experimental issues.

4.3.2 Fast Flows

The role of centrifugal forces -- In the limit of very high rotation rates, the centrifugal force on the particles starts to dominate over the gravitational force. We have already seen this in chapter 2. There, we estimated, on the basis of the balance of centrifugal force and gravitationally induced frictional forces that the centrifugal forces come into play at rotation rates of 1 rps and higher. However, as shown in the appendix 3.6 of chapter 3, the centrifugal force also sets up a counterclockwise (as seen looking into the direction of the rotational flow) secondary flow in Newtonian fluids, driven in the split-bottom geometry. We know from the previous two chapters that above 0.1 rps the suspension starts to behave as a Newtonian fluid. So at the rotation estimated above, the secondary flow in the fluid has already developed substantially, and is probably
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Figure 4.6: (a) The average mean squared difference (MSD) as a function of $\Omega$. For small $\Omega$, the MSD is small since the flow resembles dry granular flows. Symbols: $\bigcirc = 3$ mm PMMA particles, $\times = 4.6$ mm PMMA particles. (b) $T(\Omega)$ of the two different suspensions. Symbols are the same as in (a).

the dominant driving mechanism of all radial particle motion.

Radial flow measurements -- To clarify whether centrifugal force alone, or the secondary flow itself is dominating the particle motion in the suspension flow, we image a vertical cross section of the flow in the split-bottom setup, while rotating the disk at 0.016 to 0.8 rps. We use a filling height $H/R_s$ of 0.5. To image the fast flows, we use a Phantom V4.2 B/W camera (512x512 pixels, 8 bit) with an exposure time of 10 ms. See Fig. 4.7 for a schematic drawing of the setup.

In Fig. 4.7b-e, snapshots of the surface structure are shown. The overall shape of these structures is stable in time. At 0.016 rps the surface of the suspension is flat, except for the heaps at the edges, which are present even without rotation and can be removed by more careful leveling of the surface. We see that at 0.16 rps, a small dip is developing in the center of the suspension. The dip becomes more pronounced at 0.4 rps, and at 0.8 rps, the whole center is empty of particles. This rotation rate is well below the estimate based on the balancing of frictional and centrifugal forces on an individual particle. Most likely, the secondary flow that develops in the fluid/particle mixture, that is essentially Newtonian around 0.1 rps, drives the particles outward. Note that the flat surface of the suspension restores itself almost completely after switching of the driving disk.
4.3.3 Three Dimensional Scanning

A very early test in which a full three dimensional reconstruction scan was taken with setup L is shown in Fig. 4.8. Each reconstruction scan consists of 125 scans, acquired in less than 3 seconds. The number of slices per cm is 30. Only histogram equalization (see appendix 8.1) was applied to improve the contrast; no band pass filtering [81] or smoothing was used. The reconstruction scans have enough contrast for particle tracking methods [82]. The streaks visible at the surface are due to a slight index mismatch between particles and fluid. This also reduced the resolving power at greater horizontal depths -- in the second half of the box laser scatter makes distinguishing particles by eye impossible.

4.4 Improvements

Setup L is still under continuous development and offers many directions in which its functionality can be improved rather easily and fruitfully. In what
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Figure 4.8: A three-dimensional reconstruction scan acquired in setup L. Particles and direction of the laser light are indicated.

follows, we give a list of possibilities. We discuss how different suspensions can give access to different regimes of suspension flows, or even allow one to combine rheology and imaging. We also discuss several different ways to improve the imaging methods we use now, and mention some other simple modifications that have been made since the experiments, mentioned in this chapter, were carried out.

4.4.1 Other Suspensions Types

The physics of suspensions depends on the relative densities of particles and fluids and the viscosity of the fluid. In particular, the inertial number for suspensions introduced in section 3.4.2 depends directly on the viscosity, and the granular pressure, which is set by $\Delta \rho$, the density difference between the fluid and the particles used. Here, we list a few different fluids and particle types that can be used for index matching. We have not used them extensively, so the list of their advantages and disadvantages is not exhaustive. Naturally, to verify scalings in rheological experiments, the restrictions on particle properties are much less severe.

Other particles -- Besides PMMA, there is another material which is used to produce spherical particles, and which has a low index of refraction: borosilicate glass. Sigmund Lindner for example sells borosilicate glass spheres (type P), with an optical index $n_D$ of 1.47. The glass beads do not absorb any fluids, and therefore are not susceptible to index changes or cracking, as the PMMA
particles are. They can also be washed and reused in different index matching liquids. The bulk density $\rho_p$ of the particles is $2.4 \times 10^3$ kg/m$^3$. This makes them heavier than PMMA, and they can therefore not be density matched with Triton. Note that Mo-Sci also sells borosilicate glass spheres with the same low index of refraction, but they seem to display surface defects that scatter light and hence render them unusable for the scanning techniques.

**Dimethyl Sulfoxide** -- Dimethylsulfoxide (DMSO) has an optical index $n_D$ of 1.479, and can therefore be used to index match both PMMA and borosilicate glass spheres (the latter treated below). It has a viscosity of 2 mPa·s, and a density of $1.1 \times 10^3$ kg/m$^3$. DMSO mixes very well with water, so its index can be tuned simply by adding water. Adding NaI$^7$ to the solution can increase the density of the fluid, to match the density of PMMA.

The amount of water one needs to reduce the index of DMSO to that of the borosilicate glass spheres is not enough to use Nile Blue 690 perchlorate -- with such a small amount of water its spectrum will not be tuned to the wavelength of the laser. In DMSO, we use Atto 633, a rhodamine based dye that is not very expensive and made to absorb light at 633-635 nm. The dye dissolves very well in both DMSO and water.

**Eugenol** -- Eugenol is a relatively safe and cheap liquid with very high index of refraction ($n_D = 1.541$). Its index can be tuned with ethanol with which it mixes very well. It has a low viscosity of 2 mPa·s, comparable to that of DMSO. Its disadvantages are that it degrades over time when exposed to oxygen, and it has a very strong clove-like odor. It also dissolves PMMA, so it cannot be used with PMMA particles. The density of eugenol is $1.06 \times 10^3$ kg/m$^3$; it is compatible to Nile Blue 690.

**Sodium Polytungstate** -- Sodium PolyTungstate (SPT) can be used if a high density liquid is necessary. It is a salt that mixes well with water, and it can therefore be used to make a solution whose density can be tuned between 1 and $2.8 \times 10^3$ kg/m$^3$. The index of the solution changes with its density from 1.33 to values larger than 1.6. Note that its viscosity also increases with its density. We verified that it is compatible with Nile Blue; Nile Blue 690 added to an SPT solution remained blue for a timespan of several days, after which we stopped observations.

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$^6$Many thanks to Kinga Lorincz for sharing this recipe with us.

$^7$Mixing NaI with water and DMSO will result in a yellow liquid. Adding a small amount of sodium thiosulfate removes this coloring.
The high density of SPT combined with its index matching capabilities can be used to do rheology and flow imaging simultaneously in the following way.

Figure 4.9: An hypothetical 'inverted' flow cell, capable of simultaneous imaging and rheology. The particles in the suspension are pushed upwards due to buoyancy.

In the present setups, the disk used to drive the flow is located at the bottom, and the flow is imaged from the top. The motor cannot be used to do rheological experiments -- ideally, one would like to drive the disk with a rheometer that can record the applied torques while driving the flow. However (stress driven) rheometers typically drive a system from above, and in the current setup the imaging devices is already located there. Another drawback of driving the suspension from above with a rheometer, is that it requires the presence of a suspension-penetrating rod, connecting the driving disk and the rheometer, which blocks parts of the laser sheet.

With an SPT solution, index matched to borosilicate glass spheres, these problems can be solved: SPT at this index of refraction has a density higher than that of the glass spheres, so the buoyancy force on the submersed particles then pushes them up, which makes driving the system from above necessary. The system can this be driven from the top with a rheometer, and imaged from below. See Fig. 4.9 for a schematic drawing of this setup.
4.4.2 Imaging Improvements

Small fan angle laser sheet -- It is possible to increase the photon yield substantially by using a line generator with a smaller fan angle. This can be used if one is only interested in a small subsection of the flow -- the same output power of the laser is then distributed over a smaller area. This can be used both for two dimensional cross section studies of very rapid flows, but also for rapid three dimensional scanning of small volumes. We used a 5° fan angle to achieve an increase in fluorescence of more than a factor 10.

Wavelength filter -- Particle Tracking Velocimetry (PTV) methods applied on the three dimensional reconstruction scans obtained by parallel imaging are sensitive to image noise. One source of image noise is (Rayleigh) scattering of the laser light on objects in the flow cell. The scattered photons will show patterns and spots in the scanned images: see for example Fig. 3.2. In these images, the disk at the bottom is clearly visible, while only a cross section of the fluid far away from the disk is illuminated.

To reduce the influence of Rayleigh scattered photons on experimental images, a filter is used, that blocks all light that does not come from fluorescence. Since the emission peaks of the fluorescent dyes are tens of nanometers in width, and since all the fluoresced light can be used to enhance contrast, we use a longpass filter, that filters out the light below a threshold wavelength. Nile Blue 690 perchlorate fluoresces at wavelengths > 690nm, so with this dye we use a cutoff wavelength of 665 nm. The dye Atto 633, necessary in combination with DMSO, has a much smaller Stokes shift, i.e. its emission peak at 657 nm is very close to that of the excitation laser wavelength of 633 nm. Therefore a longpass filter with a steep edge around 640-650 nm is required.

Larger aperture lens -- Fixed focal length optics with an aperture of 0.95 are available from Schneider. The large aperture in these lenses increases the amount of light by a factor 2 to 4 with respect to the current lenses used. This translates into more contrast, or allows for faster scanning. The Schneider lenses have the drawback that they can only be used with the Atto 633 dye, since they are designed for wavelengths $\lambda$ between 400 and 700 nm, and the light emitted by Nile Blue 690 perchlorate has $\lambda > 700$ nm.

4.4.3 Miscellaneous

Different Bottom Roughnesses -- The hexagonal pattern of holes drilled in the bottom plate tends to induce crystallization for the 4.6 mm PMMA spheres
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We have used. For 4.6 mm spheres, we will therefore use a bottom plate with a different roughness: the bottom plate will have holes of

**Temperature control** -- The viscosity, index of refraction and density of the fluids and particles all depend on temperature. It is therefore important to keep the temperature as constant as possible. To ensure temperature stability in the system, we mounted a heat-exchanger to the bottom of the disk. The heat exchanger, connected to a heat circulator (Haake EZ Cool 80) keeps the temperature of the measurement cell constant to within 0.1 °C in the range of -20 to 80 °C. Note that this temperature control was not implemented when doing the experiments described in section 4.3.1.

4.5 Conclusions

In this chapter, we have described the development and some testing of a new fast IMS setup. We have shown that we improved the scanning time with respect to setup M by more than an order of magnitude. We have demonstrated that setup L is capable of carrying out the same experiments as were done in setup M.

We have shown that being able to image suspension flows faster gives access to new types of flow. Furthermore, we have shown that there is still a substantial amount of simple improvements to be made, that can extend the applicability of the fast scanning setup even more.