Orientation of elongated particles in shear and extensional flow

by

Karl Håkansson

May 2012
Technical Reports from
Royal Institute of Technology
KTH Mechanics
SE-100 44 Stockholm, Sweden
Akademisk avhandling som med tillstånd av Kungliga Tekniska Högskolan i Stockholm framlägges till offentlig granskning för avläggande av teknologie licentiatexamen den 15 Juni 2012 kl 14.00 i seminarierummet, Brinellvägen 32, Kungliga Tekniska Högskolan, Stockholm.

©Karl Håkansson 2012
Abstract

Elongated particles in fluid flows are a big part of the world we are living in. Gaining knowledge on how particles behave in different fluid flows can potentially increase the efficiency of industrial processes and decrease the world’s energy consumption as well as improve the properties of future materials.

In this thesis, the orientation of elongated particles in two different flows are studied. The first case is a dilute fibre suspension in a turbulent flow and the second case is a semi-dilute fibril dispersion in a laminar flow. The fibres (cellulose acetate) are at least three orders of magnitude larger than the fibrils (nano-fibrillated cellulose).

The turbulent flow case is half of a full channel flow, characterised by the friction Reynolds number, and is experimentally examined. This experiment is closely related to the papermaking process. Laser Doppler velocimetry measurements are preformed without fibres in order to make sure that the flow is turbulent and fully developed. Images of the fibres in the flow are acquired using a CCD-camera, from which it is possible to detect the fibres in an image processing step and extract both the positions and orientations of the fibres. A large parameter study is carried out, where the aspect ratio of the fibres, concentration and Reynolds number are changed. Short fibres are observed to align perpendicular to the flow, while the longer fibres are found to align in the flow direction. The fibres are also seen to accumulate in streamwise streaks, believed to be caused by velocity structures in the turbulent flow.

The second flow case studied focusses on a semi-dilute dispersion in a laminar flow. It includes both experiments and numerical calculations of the fibril orientation. The aim of this study is to demonstrate that it is possible to control the fibril orientation with a fluid. In a semi-dilute dispersion, fibrils are interacting. However, no flocs or networks are formed. A flow focusing apparatus is used in order to hydrodynamically accelerate the dispersion with an outer fluid (sheath) flow. The mean orientation in the flow direction is experimentally studied by detecting the birefringence of the flowing dispersion. The orientation distribution is calculated by solving the Smoluchowski equation. The fibrils are seen to align in the flow direction both in the experiments and the calculations. Moreover, the alignment is found to increase with increasing acceleration.

Descriptors: Orientation, fibre, fibril, turbulent channel flow, particle streaks, flow focusing, nano-fibrillated cellulose, extensional flow, Smoluchowski
Preface

This licentiate thesis in fluid mechanics considers the orientation of elongated particles in two different flows; one turbulent and dilute, and the second laminar and semi-dilute. The work is experimental with the addition of a numerical comparison for the second case. The thesis is divided into two parts: Part I provides an overview and summary of the work, with chapters presenting relevant applications, summaries of the two experiments, a discussion and outlook, followed by a chapter describing the author’s contributions to the three papers. Part II consists of three papers describing the work in detail.

May 2012, Stockholm

Karl Häkansson
Part of this work has been presented by the author at:

2nd SIG43 workshop on fibre suspension flows,
9 – 10 February 2010, Stockholm, Sweden

Ekmandagarna,
25 – 26 January 2011, Stockholm, Sweden

3rd SIG43 workshop on fibre suspension flows,
6 – 8 April 2011, Udine, Italy

Svenska mekanikdagarna,
13 – 15 June 2011, Göteborg, Sweden

8th International Conference on Flow Dynamics¹,
9 – 11 November 2011, Sendai, Japan

Part of this work have been presented by coauthors at:

7th International Conference of Multiphase Flows ²,
30 May – 4 June 2010, Tampa, Florida, USA

SPCI event,
17 – 19 May 2011, Stockholm, Sweden

SIAMUF seminarium,
20 – 21 October 2011, Göteborg, Sweden

¹The presentation received a "Best poster" award
## Contents

Abstract iii

Preface iv

Chapter 1. Introduction 1
   1.1. Papermaking 1
   1.2. Composites 2
   1.3. Nano-Fibrillated Cellulose, NFC 3
   1.4. Scope of present work 4

Chapter 2. Fibre orientation and fibre structures in wall bounded turbulent shear flow 7
   2.1. Turbulent channel flow 7
   2.2. Fibre orientation 8
   2.3. Fibre structures 9

Chapter 3. Orientation of Nano-Fibrillated Cellulose fibrils in laminar extensional flow 11
   3.1. Concentration aspects 11
   3.2. Flow apparatus 12
   3.3. Fibril orientation 13

Chapter 4. Discussion and future directions 15
   4.1. Discussion 15
   4.2. Future directions 16

Chapter 5. Papers and authors contributions 19

Acknowledgements 21

References 23
Paper 1. Measurement of width and streakiness of particle streaks in turbulent flows 30

Paper 2. Fibre orientation and fibre streaks in turbulent wall bounded flow 52

Paper 3. Orientation of nano-fibrillated cellulose in accelerated flow 74
Part I

Overview & summary
CHAPTER 1

Introduction

When two or more materials of different phases, e.g. one solid and one liquid, or two (or more) immiscible materials of the same phase are flowing the flow is said to be a multiphase flow. Such flows are present in a wide range of systems in the world, both in nature and industry. This thesis focuses on the behaviour of solid fibres/fibrils in flowing water suspensions/dispersions. The fibrils are here three orders of magnitude smaller than fibres. A dispersion is a system where the solids are small enough to have a different density than the liquid but still be in a stable state, whereas the suspension is a mixture of a liquid and solids, where the solids are too large to be in a stable state.

In this chapter, the modern papermaking process, where multiphase flows are present and important, will be described. For references considering this section, see Norman et al. (2005); Lundell et al. (2011). Thereafter, there will be a short introduction to composites. The third section is introducing a bio material with expectations to have a big impact in future composite materials. The scope of the present work will be described in the final section.

1.1. Papermaking

Making paper from wood is a very old tradition, going all the way back to 2nd century China. In those days, each sheet was made by hand. Nowadays huge paper machines produce vast amounts of paper in a continuous process.

The raw material used to make paper is wood pulp, consisting of wood fibres with diameters of about 20 µm and lengths of 0.5 – 3 mm. The wood pulp can be produced either mechanically or chemically by breaking wood chips apart. It is also possible to use a combination of both.

In a modern paper machine, the pulp, composed of ~ 1% wood fibres and ~ 99% water, is pumped into a headbox, that jets the pulp out onto a dewatering wire. The water is pressed out in a pressing stage and a fibre network is formed. Thereafter a heating (drying) step is needed in order to get the paper completely dry.

A headbox is depicted in figure 1.1, where the thickness of the headbox jet is of the order of 1 cm, the width is up to 10 m and the velocity as high as 30 m/s. The purpose of the headbox is to distribute the fibres as homogeneously as possible. The flow inside the headbox is both accelerated, to break up
1. INTRODUCTION

The strength of the paper is to a large extent determined by the fibre orientation distribution, and especially in which direction the paper is strong, see Cox (1952). The flow in the headbox influences the fibres and their orientation in different ways, acceleration in one way and the turbulence and shear in others.

One measure of paper smoothness is the formation. Examples of good and bad formation are shown in figure 1.2, where the formation is quantified by the intensity variations within each image. A piece of paper with well distributed and defloculated fibres has good formation and vice versa. The turbulence is responsible for both breaking up and forming flocs in the headbox, where the fibre size and the turbulent scales are important parameters in order to get good formation. The formation is a very important property since it determines the minimum amount of fibres needed to produce a paper with certain minimum thickness. If the formation is good, the thickness variation is low.

1.2. Composites

A composite is the product of combining two or more different and separable materials. The properties of a composite are enhanced as compared to the properties of the constituents themselves. In order to control the composite's
1.3. Nano-Fibrillated Cellulose, NFC

Figure 1.2. Examples of good and bad formation of a piece of paper, courtesy of L.D. Söderberg.

properties, it is desirable to control the structure of the constituents. A composite usually consists of a matrix material and a load bearing material, where the load bearing material most commonly consist of elongated solid particles such as a fibres. The structure properties can, for example, be the orientation of the fibres, the volume fraction or interaction between fibres.

1.3. Nano-Fibrillated Cellulose, NFC

Cellulose is one of the most abundant polymers in the world, and is found in wood, plants and bacteria, in different sizes and quantities. Here the focus is on wood. Wood is built up by fibres typically composed of one third of cellulose, one third of lignin and one third of hemicelluloses, see e.g. Norman et al. (2005) and references therein. The strength of the wood fibres is correlated to the long straight cellulose chains, where the lignin act as the matrix and the hemicelluloses interconnects the cellulose with itself and lignin. Cellulose polymer chains do not appear one by one in the cell wall, but rather as bundles of polymer chains, called fibrils. The fibre cell wall is built up by different layers in which the cellulose fibrils have different preferred orientation, with respect to the fibre direction. The outermost layer has a random fibril-orientation distribution, the second close to 90°, the third a smaller angle 10° – 30° and the last layer close to 90° again. These different orientations makes it possible for the tree to withstand both compression and bending. Tuning the orientation
of the fibrils in man-made materials could potentially give rise to a wide range of different properties.

If the cellulose fibrils withhold their size and structure while extracted and separated from the wood, the outcome is called Nano-Fibrillated Cellulose, NFC, see Eichhorn et al. (2010). The typical length of a fibril is $1 - 3 \, \mu m$ and the diameter is $20 - 40 \, nm$. One single crystalline cellulose polymer has experimentally been found to have an elastic modulus of 140 GPa, see Sakurada et al. (1962) compared to $\sim 20 \, GPa$ for plant fibres, see Morton & Hearle (1975). The fibrils are expected to have properties very close to the crystalline cellulose polymer, since a fibril consists of approximate $15 - 20$ polymers.

The energy consumption of the extraction process has recently been greatly improved due to an enzymatic pre-treatment of the pulp, see Pääkkö et al. (2007). This allows for a more expensive post treatment of the NFC, without the sacrifice of a more expensive end product.

1.4. Scope of present work

There are many ways to study the interactions between fluid flows and elongated particles, both of macroscopic- and nano-scale size. Observing the orientation distributions in well defined flows provides insight to the dynamics of the systems and the interactions between particles and the fluid, as well as the interactions between two or more particles with each other.

The scope of this work is to experimentally observe and analyse the orientation distributions of elongated particles in two different flows, one laminar and one turbulent. In order to enable this, experimental techniques and data analysis methods are developed. A dilute suspension was used in the turbulent experiment, and a semi-dilute dispersion in the laminar. Moreover, the fibre distributions were investigated numerically for the semi-dilute and laminar case.

The first experimental setup can be related to the headbox of a papermachine, where fibre-wall interactions frequently occur. The second setup was used to study the behavior of the NFC fibrils in a well defined flow, in order to control the fibril orientation in a future composite.

The aim of the laminar and semi-dilute experiment is not to study the process in details, but rather to test if it is possible to aligning fibrils with a fluid flow in an efficient manner.

A full literature review on every aspect touched upon in this thesis would result in a twice as thick thesis and is therefore not included. The goal is to combine information from many different areas and not to focus on one specific detail.

The first experiment was a close collaboration with Mr. Kvick, and the authors’ contributions are described in chapter 5.
1.4. SCOPE OF PRESENT WORK

Chapter 2 describes and summarises the turbulent and dilute experiment, while chapter 3 is dedicated to the laminar and semi-dilute study. The discussion and future directions are found in chapter 4.
1. INTRODUCTION
Fibre orientation and fibre structures in wall bounded turbulent shear flow

In the headbox of a paper machine, the pulp flow is both accelerated and turbulent. Fibre flocs are formed and broken up and the orientation of the wood fibres in the dried paper is partly determined here. The fibre orientation is a key parameter in any composite, and correlated to the strength of the final product, see Cox (1952).

In the paper by Kvick et al. (2012), experiments with a dilute fibre suspension in a wall bounded turbulent shear flow were conducted. The low concentration made it possible to study the fluid flow interaction with particles without particle-particle interactions. A full description of the setup and the parameters are found in Kvick et al. (2012). The main purpose was to analyse the position- and orientation distributions of the fibres in the flow. And in order to do so, the fibres were dyed black and a camera was used to capture images of the fibres in the flow. An example image in the flow-vorticity plane \((x-z)\) is displayed in figure 2.1. A large parameter study was carried out and the fibre orientation distribution and fibre position distribution was found for each experiment with the use of a steerable filter, evaluated in Carlsson et al. (2011). Selected results will be presented and discussed in this chapter.

2.1. Turbulent channel flow

A channel flow is defined as the flow between two plates, i.e. a rectangular geometry with high aspect ratio. Turbulent channel flow can be characterized by the friction Reynolds number, \(Re_\tau\):

\[
Re_\tau = \frac{hu_\tau}{\nu},
\]

where \(h\) is the half height of the channel, \(\nu\) is the kinematic viscosity, \(u_\tau = \sqrt{\tau_w/\rho}\) is the friction velocity and, \(\tau_w\) and \(\rho\) are the wall shear stress and fluid density, respectively.

The experimental setup used in Håkansson et al. (2012a) and Kvick et al. (2012) consists of an open channel with water flowing down on a glass plate. The density and viscosity differences between the water and air makes it possible to approximate this experimental setup with half of a full channel. The
surface velocity of the half channel is hence the same as the centreline velocity of the full channel. The flow velocities and fluctuations were experimentally measured by laser Doppler velocimetry, and the flow was concluded to be turbulent and fully developed at the image capturing location.

In channel flow as well as in boundary layers, high and low velocity streaks are present in the near wall region due to counter-rotating vortices, see Kim et al. (1987); Jeong et al. (1997); Matsubara & Alfredsson (2001); Lagraa et al. (2004). The velocity structures have been analysed by e.g. Zacksenhouse et al. (2001), reporting that the low speed streaks have a mean width of $\sim 50l_\tau^+$, where $l_\tau^+ = \nu/u_\tau$ is the viscous length scale.

### 2.2. Fibre orientation

In the experiment, the length of the sedimenting rigid cellulose acetate fibres ($\rho = 1300$ kg/m$^3$) was varied. Three different fibre lengths, $l = 0.5, 1$ and 2 mm having the same diameter, $d = 70$ µm, corresponding to aspect ratios, $r_p = l/d = 7, 14$ and 28 respectively, were used separately. The different aspect ratios are found to affect the orientation distribution heavily, as is displayed in figure 2.2. The short fibres, $r_p = 7$, are oriented perpendicular to the flow, $90^\circ$, while the long fibres, $r_p = 28$, are oriented in the flow direction, $0^\circ$, and the fibres with aspect ratio, $r_p = 14$, are oriented more isotropically. These three experiments were performed at about the same friction Reynolds number based on a half channel height, $Re_\tau \approx 125$. However, the same behaviour was
2.3. Fibre Structures

The fibres form fibre streaks for certain Reynolds numbers. These streaks are observed in figure 2.1. In order to understand how the fibres are affected by the fluid, quantitative measures are needed.

A quantification method for particle streaks was developed within the scope of this thesis. The method is described and evaluated in Håkansson et al. (2012a), where the two quantities provided are a streakiness measure, $\Xi$, and $\tau$.

seen for most Reynolds number investigated, Re$_r = 50 - 210$. The orientation distributions for fibres with $r_p = 7$ and 14 became more isotropic for Re$_r > 200$. In the studies by Carlsson et al. (2007) and Carlsson (2009) on fibre orientation in laminar flow a similar behaviour as in the present study was observed. It was concluded that the competing effects were the sedimentation and the wall contact versus fluid inertia. The sedimentation and direct wall contacts drives the fibre orientation towards the spanwise direction and the fluid inertia drives the orientation towards the flow direction.

As seen in figure 2.1, most of the fibres have a rather small out of plane angle, if any at all. This is in agreement with particles performing Jeffery orbits in laminar shear flow, Jeffery (1922). When particles perform Jeffery orbits, they remain in the $x$-$z$-plane most of the time, and periodically flip out of this plane. The rotation out of the $x$-$z$-plane may also be hindered by the fact that most fibres have sedimented and are very close to the glass plate.

**Figure 2.2.** Orientation distributions for three cases corresponding to aspect ratios, $r_p = 7, 14$ and 28, where $0^\circ$ is in the flow direction.
2. FIBRE ORIENTATION- AND STRUCTURES IN TURB. SHEAR FLOW

Figure 2.3. The streak width, $SW$, is shown in (a) and the streakiness, $\Xi$, in (b), versus $Re_\tau$. The full and the dashed line in (a) corresponds to $50l^+$ and $70l^+$, respectively. The symbols, (■, ▼, •), are experimental measurements where corresponding to $r_p = 7$, 14, 28, respectively, in both (a) and (b)

In each experiment, 150 images were captured, and with each image containing 150 – 1500 fibres, a total of 22,500 – 225,000 fibres were detected in each experiment. This large amount of fibres was seen to be enough for the fibre orientation data to converge. There are more measurement points in figure 2.3a than in figure 2.3b. The reason for this is that after the analysis method was developed, the streakiness did not converge for a few experiments, and those experiments are not included in the presented results.
CHAPTER 3

Orientation of Nano-Fibrillated Cellulose fibrils in laminar extensional flow

Nano-fibrillated cellulose, (NFC), is a new material with high potential in strength and stiffness, see Sakurada et al. (1962); Moon et al. (2011). With the decrease of newsprint there is an opportunity for one or several new high value forest-based products to enter the market. Studying the properties and behaviour of NFC is crucial in order to design the best possible application. In this section, the behaviour of a semi-dilute water/NFC dispersion in an extensional flow will be studied.

First, the concentration of elongated particles will be discussed, secondly the hydrodynamic focusing setup will be described and finally results of how small, light and elongated NFC particles behave in the accelerated flow will be presented.

3.1. Concentration aspects

Interactions between the different phases in a multiphase system of solids and liquids can be divided into different parts. The liquid will exert a force on the solid, and the solid will exert a force on the liquid. Furthermore, the solids can interact with each other either through hydrodynamic or mechanical forces. In a flowing suspension or dispersion the concentration of elongated particles is a key parameter when the dynamics of the flow are of interest. For low concentrations, the interactions between particles can be neglected and there are only fluid-particle interactions. The crowding number, \( N \), defined as;

\[
N = \frac{2}{3} C_v \left( \frac{l}{d} \right)^2,
\]

is used to quantify the number of mechanical interactions in a suspension containing elongated particles, reviewed by Kerekes (2006). The length of the particle is \( l \), the diameter is \( d \) and the volume concentration is denoted \( C_v \). Instead of considering the actual volume concentration, \( C_v \), of all particles, the crowding number, \( N \), relates the volume of the sphere that encloses the particle when swept over all angles to the total volume available. The crowding number, \( N \), is the magnitude of the overlapping of these spheres, and hence the number of interactions between the particles when allowed to rotate freely.
From the definition of $N$ in equation 3.1, it should be noted that the aspect ratio, $l/d$ is affecting $N$ to the power of two, i.e. if the aspect ratio is large, particle-particle interactions can occur even at low volume concentrations.

There are three concentration regimes, (i) dilute $N << 1$, (ii) semi-dilute $1 < N < 60$ and (iii) concentrated $60 < N$, see Kerekes (2006). In the dilute regime, mechanical interactions between the particles seldom occur. However, even at low concentrations, hydrodynamic interactions may be of importance. In the semi-dilute regime, mechanical particle-particle interactions become substantial and when the suspension is concentrated, the particles movement are very restricted and a network is formed. Another commonly used quantity to define the concentration is $n l^3$, where $n$ is the number of particles per volume. The crowding number is related to $n l^3$ as: $N = n l^3 \pi/6$.

The most complex regime is the semi-dilute regime, where, depending on the size and shape of the particles, different behaviour are observed, Trevelyan & Mason (1951); Teraoka et al. (1985); Koch (1995). A comparison between experiments and computations in the semi-dilute regime are presented in the paper by Håkansson et al. (2012b).

3.2. Flow apparatus

The flow apparatus used in the paper by Håkansson et al. (2012b) is depicted in figure 3.1. There are three inlets and one outlet, where one liquid, with mass flow rate, $Q_1$, is focused by an outer sheath flow, with mass flow rate, $Q_2$, see figure 3.1. At the focusing point, where the four channels intersect, the inner core flow is accelerated and the flow is said to be extensional. This particular design was chosen partly due to its growing popularity in flow studies, see e.g. Knight et al. (1998); Anna et al. (2003); Cubaud & Mason (2006), but also because of its property of reducing the shear on the inner fluid. A generic setup is in this case wanted in order to validate the first results. Moreover, in this study the addition of particles in the flow are examined, which has not been
studied previously. The channel used here is one or two orders of magnitude greater in physical size compared to previous studies, making it possible to reach different parameter ranges.

The NFC dispersion shows a birefringent behaviour when the particles orientation distribution is anything but random. A solid or liquid is birefringent if it has different indices of refraction, depending on the incoming polarisation of the light. This property is utilized in order to measure the relative orientation in the flowing dispersion. The birefringence is observed as different light intensities when put between two crossed polarisers. The birefringent sample can rotate the polarisation of the light going through the first polariser and in this manner, light can pass through the second polariser, even though the polarisers are crossed. The magnitude of the rotation of the polarisation is dependent on the birefringence and the thickness of the sample. Moreover, the outgoing light intensity is periodic with respect to the rotation.

The sample is in this experiment the core flow, and since the intensity is periodically dependent on the thickness of the sample, a small sample is used to be sure that not more than half of a period is covered. This is one reason to why the same setup as in the previous chapter was not used. Another benefit with this setup is that the total sample volume is small, less than 10 ml of 0.3% NFC dispersion was used in this experiment compared to 120 l that is needed for the previous experiment.

### 3.3. Fibril orientation

In the paper by Håkansson *et al.* (2012b), both computations and experiments are performed in order to demonstrate that NFC fibrils align in the direction of the acceleration of an extensional flow. The size of the fibrils, with diameters

---

**Figure 3.2.** The relative order parameter $S/S_{ref}$ versus downstream position, from the experiment (a) and the computation (b). The legend corresponds to $Q_2/Q_1$. 
60 nm and lengths of a few µm making them invisible to the human eye, and a birefringence based method was used to get a quantitative measure of the relative alignment. The NFC dispersion is fed into the core and accelerated by water from the sides, see figure 3.1. The acceleration, $Q_2/Q_1$, was varied and the orientation was observed; upstream of, during and downstream of the acceleration.

The Smoluchowski equation, Doi & Edwards (1986), was solved numerically for the orientation distribution at the centreline of the channel. A Brownian diffusion term and a flow acceleration term was included in the equation. The boundary conditions for the computations, i.e. the accelerations, were found through the experimental images, where the width of the NFC-dispersion thread at different positions could be detected. The thread was assumed to have a square cross section.

A relative order parameter, $S/S_{ref}$, was introduced and could be extracted from both the computations and experiments. The order parameter is a measure of how strong the alignment in a given direction is, here the flow direction is of interest (Håkansson et al. 2012b; van Gurp 1995). The case $Q_2/Q_1 = 1.15$ (closest to $Q_2/Q_1 = 1$) was used as reference, and in figure 3.2, the relative order parameter, $S/S_{ref}$, versus downstream position are shown. The fibrils are found to be more oriented for higher acceleration both in the experiments and in the computations. The computations show a much greater alignment during the acceleration, but both methods are of the same order in relative alignment further downstream.
4.1. Discussion

Non-spherical particles are a key ingredient in many kinds of materials, such as fibres in paper and polymers or fibrils in nano-scale materials. In the manufacturing processes of these materials, the design of the flow geometries are crucial and by introducing new designs, improved products can be made. In order to design better processes, the knowledge of the behaviour of non-spherical particles in different flow situations must be increased.

Cellulose based materials have been around for thousands of years and are here to stay. Cellulose is the world’s most abundant polymer and is both biodegradable and renewable. Replacing oil-based materials with cellulose would be beneficial for the environment in many ways. Furthermore, the society would take a step towards a more sustainable future. These are a few reasons to why cellulose is the object of study in this thesis.

Two experiments were performed, where the first was a dilute suspension in a complex flow. The interactions between the flow and the particles were studied by observing the fibre orientation and position distributions. The orientation distribution of sedimenting fibres towards a wall in a turbulent shear flow is far from simple to predict. The fibres are affected by many competing forces, such as sedimentation, wall interactions, turbulence, shear, inertia. In this study, it was concluded that sedimentation, wall interactions and the fluid inertia where the dominant forces in the parameter region studied. Through the analysis of the position distributions of the fibres, it was found that the fluid structures forced the fibres to agglomerate in fibre streaks. As the fluid structures became smaller, so did the tendency for the fibres to agglomerate in streaks.

The knowledge gained through the first experiments can not only be of interest to the papermaking process, it can also be used to validate numerical simulations. The distinct difference between the orientations distribution of the short fibres and the long fibres is a challenging validation case for simulations.

It was shown in the second experiment, where a semi-dilute NFC dispersion was accelerated by a sheath flow, that the small elongated particles aligned and stayed aligned, in the flow direction. A numerical computation was performed
with confirming results. These results are very interesting when designing new processes where the alignment and structure of the material is important. The alignment of the particles is expected, but the speed of randomisation due to Brownian diffusion is difficult to predict. The particle-particle interactions are believed to help the fibrils stay aligned, and this system should therefore be highly concentration dependent. A much higher concentration on the other hand, may not align at all, due to the formation of networks at the inlet.

Contractions and extensional flows are widely used in order to align elongated particles. But in a confined converging geometry, the flow is not only extensional, shear forces are strong close to the walls and the shear is affecting the final orientation distribution. In the present setup, the sheath flow acts as a lubricant, and hence minimises the shear on the core flow. The shear is believed to make the orientation distribution more random compared to a pure extensional flow, and as seen in the first experiment, shear can give rise to unwanted flow structures.

4.2. Future directions

In order to design or improve a process, the physics behind the process needs to be known. The turbulent channel experiment showed that elongated particles gathered in streamwise structures, and the reason is suggested to be related to the flow structures. Therefore one way of achieving a more homogeneous distribution would be to remove the flow structures. Future work on this experiment could be focused on determining where in the wall normal direction the fibres are located, and perform combined flow and particle velocity measurements. However, these experiments will not be pursued by the author.

The future work will be carried out in order to obtain a better understanding as well as improving the flow focusing setup. Achieving a higher degree of alignment, and measuring how long the alignment lasts, is one direction. This could be achieved with an increased speed, that in turn would eventually lead to hydrodynamic instabilities. The geometry can also be changed in order to achieve a higher degree of alignment. The numerical calculations could also be used to predict the behaviour in a different geometry and in a dispersion of higher concentration. The numerical model will be improved by including a more realistic velocity profile.

Another direction is to include chemistry in the channels. Diffusing particles or polymers through the interfaces would be of interest in a possible composite process.

A third future direction is aiming on orienting fibrils in a sheet instead of in a thread. A 2-dimensional system will of course be more complex, and the design of the setup is at this point not clear. However, orienting particles with a sheath flow in a similar manner should be possible, and would be of great interest.
Finding a quantitative comparison between a pure extensional flow and an extensional flow with shear is an intriguing project. An experiment would be preferred, but the manufacturing of such a 3-dimensional channel is not trivial.
CHAPTER 5

Papers and authors contributions

Paper 1

Measurement of width and streakiness of particle streaks in turbulent flows
K. Håkansson (KH), M. Kvick (MK), F. Lundell (FL), L. Prahl Wittberg (LPW) & L. D. Söderberg (DS). To be submitted

A new method for quantification of particle streaks is developed. KH and MK developed the method and performed the analysis under supervision of FL, LPW and DS. KH investigated and accounted for the dependence of concentration, image size, artificial particle size and streak width in the method. MK incorporated the Voronoi method into the analysis. KH, MK, FL and LPW wrote the paper jointly with input from DS.

Paper 2

Fibre orientation and fibre streaks in turbulent wall bounded flow
M. Kvick (MK), K. Håkansson (KH), F. Lundell (FL), L. Prahl Wittberg (LPW) & L. D. Söderberg (DS). To be submitted

The orientation and spatial distribution of fibres in a turbulent wall bounded flow is studied experimentally. MK and KH performed a majority of the experiments and analysis in close collaboration under supervision of FL, LPW and DS. In addition, KH performed the LDV measurements and MK implemented the anisotropy as an analysis method. MK, KH, FL and LPW wrote the paper jointly with input from DS. Parts of these results have been published in:

Streak Formation and Fibre Orientation in Near Wall Turbulent Fibre Suspension Flow
M. Kvick, K. Håkansson, F. Lundell, L. D. Söderberg & L. Prahl Wittberg
ERCOFTAC bulletin, 2010, Vol. 84
Fibre Streaks in Wall Bounded Turbulent Flow
M. Kvick, K. Håkansson, F. Lundell, L. D. Söderberg & L. Prahl Wittberg
7th Int. Conf. on Multiphase Flow
May 30 – June 4 2010, Tampa, FL, USA

Paper 3
Orientation of nano-fibrillated cellulose in accelerated flow

This work is a combination of experiments and simulations, were the experiments were conducted by KH. The numerical code was written by FL and KH, while the simulations were performed by KH. The data analysis was performed by KH with input from FL and the writing was performed by KH with input from FL, LPW, LW and DS. The original idea for the work was suggested by FL, LW and DS.
Acknowledgements

The Knut and Alice Wallenberg Foundation is greatly acknowledged for funding the Wallenberg Wood Science Center, in which this work has been carried out.

A big thank you goes to my three supervisors, first of all Daniel Söderberg for accepting me as a PhD student and for all the great ideas and deeper questions, second of all Fredrik Lundell for the every day guidance, motivation and support at all times. Last but not least Lisa Prahl Wittberg for the large amounts of proof reading and the discussions, enhancing my understanding of the underlying concepts.

I would also like to give a special thanks to Mathias, with whom I spent many long days in the basement. It would have taken more than twice as long to do everything without you and it would not have been half as fun.

Thank you Andreas Fall, for introducing me to colloidal chemistry (more than once), the thoughtful discussions and also for providing clean NFC samples.

I am very happy to a part of the paper group, where Outi has taught me lots about stability, Allan helped with tips and insights regarding the water table, and Gabri always had good ideas on more general experimental and multiphase problems. Tomas, Michail, Afshin, Ramin, Charlotte, Gustav, Roland and Yu who are or have been a part of the group since I started, are thanked for the pleasant working environment.

Kim and Göran in the workshop is greatly thanked for always helping out and being in a good mood. Christian Aulin, Tom Lindström and Invenit AB are greatly acknowledged for providing the NFC. I would like to thank Lars Wågberg for all great insights, ideas and proposals. Thanks to Dr. Mihai Mihaescu for reviewing this thesis.

The people at the fluid physics laboratory deserves a mentioning for the nice work place atmosphere and the fikas. Thank you Olle, Alexander, Ramis, Antonio, Sissy, Shintaro, Markus, Julie, Alexandre, Renzo, Sohrab, Niklas, Robert, Martin, Johan, Emma, Ylva, Shahab, Bengt, Fredrik, Malte and Thomas. I
acknowledgements

would also like to thank the people at OB18, especially: Peter, Marit, Johan, Florian, Enrico, Andreas, Qiang, Daniel, Stevin and Feng.

Everyone in the WWSC both from KTH and Chalmers, are greatly acknowledged for the good times at the workshops and during the doctoral courses.

Karl Hakansson
References


REFERENCES


Kvick, M., HÅKANSSON, K., LUNDELL, F., PRAHL WITTBERG, L. & SÖDERBERG, L. D. 2012 Fibre orientation and fibre streaks in turbulent half channel flow. To be submitted.


ZACKSENHOUSE, M., ABRAMOVICH, G. & HETSRONI, G. 2001 Automatic spatial

Part II
Papers