# Flow and fibres experiments and simulations

FLOW
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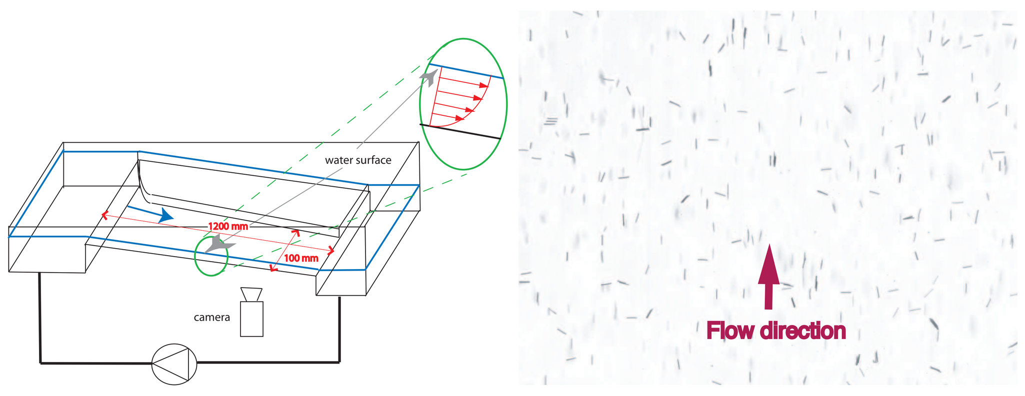
## Orientation experiment

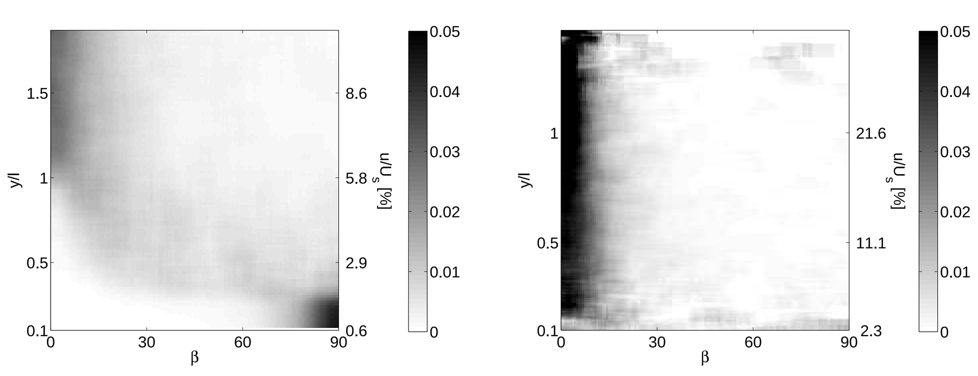
*The anisotropy of the fibre orientation in a paper determines the anisotropy of the strength properties of the paper (tear one of the sample papers in two directions for a direct demonstration!). Depending on the application, anisotropic or isotropic orientation distributions are desired. We study how fibres orient themselves in the vicinity of a solid wall. The aim is to understand and control the fibre orientation in paper produced in modern paper machines.*




The experiments are performed on a flow table shown to the left. A sheet of liquid (in these experiments a very viscous mixture of Glycerin and Poly-Ethylene-Glycol) is flowing down an inclined flat surface, driven by gravity forming a shear layer. The velocity increases from zero at the wall to some value at the free surface determined by the inclination of the plane, the viscosity of the liquid and the thickness of the sheet.
By adding fibres to the flow and filming from below, images such as the one to the right can be obtained. The black fibres are clearly seen and they are also seen to be somewhat differently oriented. Most are oriented in the flow direction, but some are seen to be oriented across the flow direction. The diameter of the fibres is 50 $\mu$m and the length is 0.5 mm in the image. The orientation of those will be compared to fibres that are 2 mm long.

## Orientation close to the wall

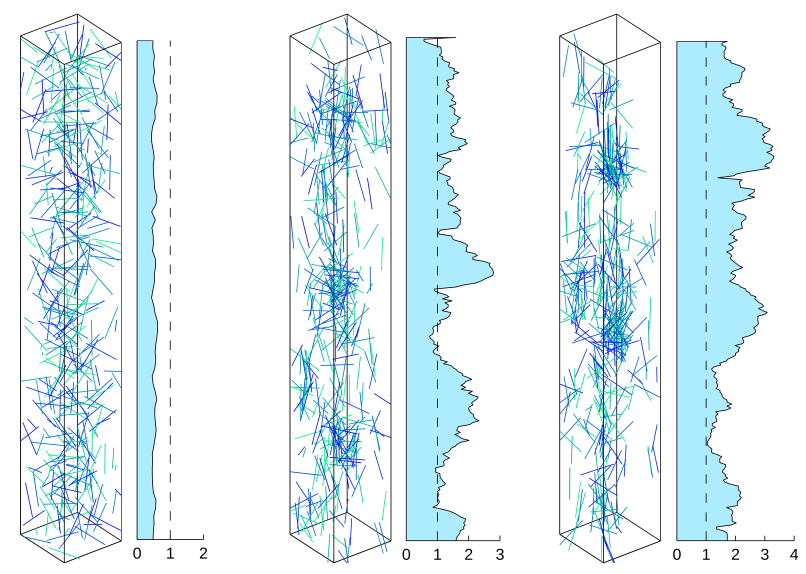
*The position and orientation of individual fibres can be determined by image analysis. From the position in consecutive images, it is also possible to determine the velocity. Since the velocity profile of the flow is known, there is a direct relationship between the velocity of a fibre and its height over the plane.*



Above, the probability density functions of the fibre orientation in planes parallell to the wall, at different distances from the wall are shown for the two fibre lengths. The distance from the wall is normalized with the fibre length and the orientation $\beta$ is defined to be 0 when the fibre is in the flow direction. The left is for short fibres and the right is for the longer fibres. Black indicate the most probable orientation at each distance from the wall.
Note that the long fibres are oriented close to the flow direction everywhere whereas the short fibres tend to be at $\beta = 90°$ close to the wall (the short fibres are seen to deviate from $\beta = 0$ already around $y = l$). Our present hypothesis is that this drastic difference is a consequence of a competition between *fluid inertia* (causing a drift towards $\beta = 0$) and *slow sedimentation combined with hydrodynamic wall-fibre interaction* (causing a drift towards $\beta = 90°$). The strength of these two effects can be estimated. The estimates indicate that the first effect should be dominant around $\beta$=0 for the long fibres whereas the second would seem to be dominant for the short fibres.
Another fascinating observation in this experiment is that the difference in orientation also gives a difference in preferred wall-normal position. The long fibres (which remain at $\beta \approx 0$) assemble at a distance of half a fibre length from the wall whereas the short ones assemble in the direct proximity of the wall.

## Sedimentation of rigid fibres

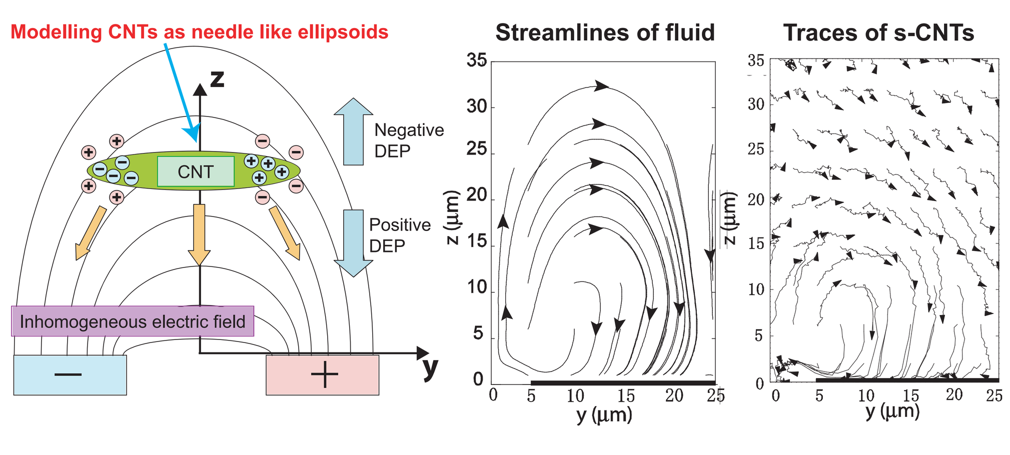
*The dynamics of rigid fibres in Stokes flow is complicated and rich of different flow phenomena. One example is sedimentation under the influence of gravity. As opposed to spheres, fibres can have motion perpendicular to gravity and the velocity depends strongly on the orientation of the fibre. Also, during sedimentation, the suspension develops clusters, often referred to as flocculation which is known to have an effect on the sedimentation velocity. We have designed a numerical method based on boundary integral methods and the slender body approximation to perform simulations of sedimenting fibres on a microscale.*



The figure above shows results from a simulation with 400 fibres sedimenting in a periodic box under the influence of gravity. The fibre configuration is shown at the initial time and at two later times. The distribution of fibres is initially uniform and randomly arranged. As time proceeds, clusters are formed with fibres continuously entering and leaving the clusters. The plot to the right of each box shows the average sedimentation velocity of the fibres as a function of the vertical position in the box. The dashed black line indicates the velocity of one isolated vertical fibre. The clustering of fibres and their increased vertical alignment is clearly seen to increase their sedimentation speed.

## Sorting carbon nano-tubes

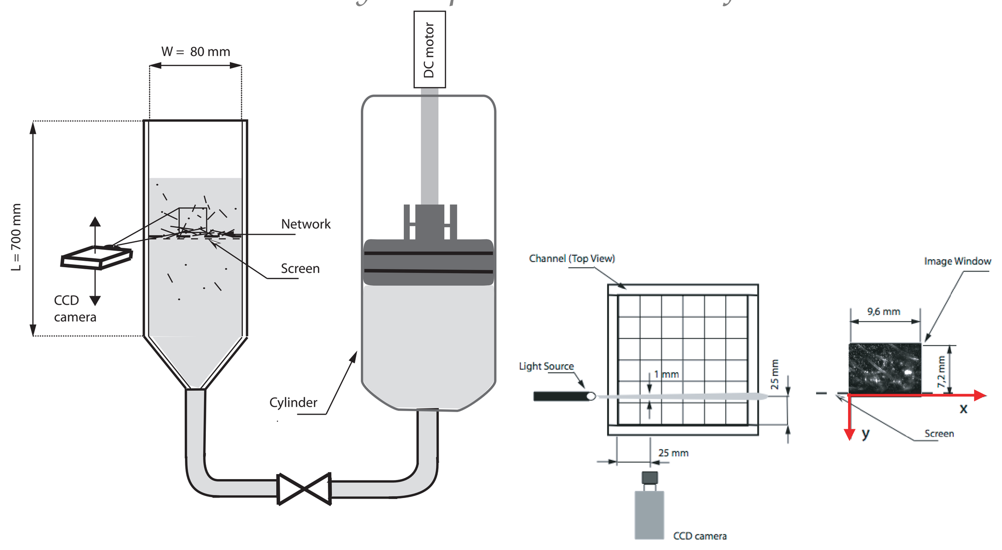
*It is difficult to control e.g. the electrical properties of carbon nano-tubes (CNTs) while they are created. It is therefore necessary to sort them afterwards. This can be done with dielectrophoresis (DEP), a method that utilizes an oscillating inhomogeneous electric field. The resulting polarization is also inhomogeneous. If the permittivity of the particle is different to that of the surrounding fluid, a the particle will be subjected to a force. The magnitude and direction of this force depends on the geometry and electrical properties of the particles and thus, the force can be used to sort them.*




Above, a typical DEP configuration is shown and next to it, calculated flow streamlines and CNT trajectories are shown. The trajectories are integrated taking the DEP-force, the flow drag and brownian motion into account. Furthermore, Joule heating is taken into account. Since the material properties vary with temperature and particle concentration, the electric field as well as the flow field are determined at each time step. For these fields, the velocities of the CNTs are given by assuming the net force on them to be zero (they are assumed to be inertiafree). The CNTs are modelled as prolate spheroids. For this geometry, there exists analytical expressions for the hydrodynamic and electrical forces which are used in this work.

## Network formation experiment

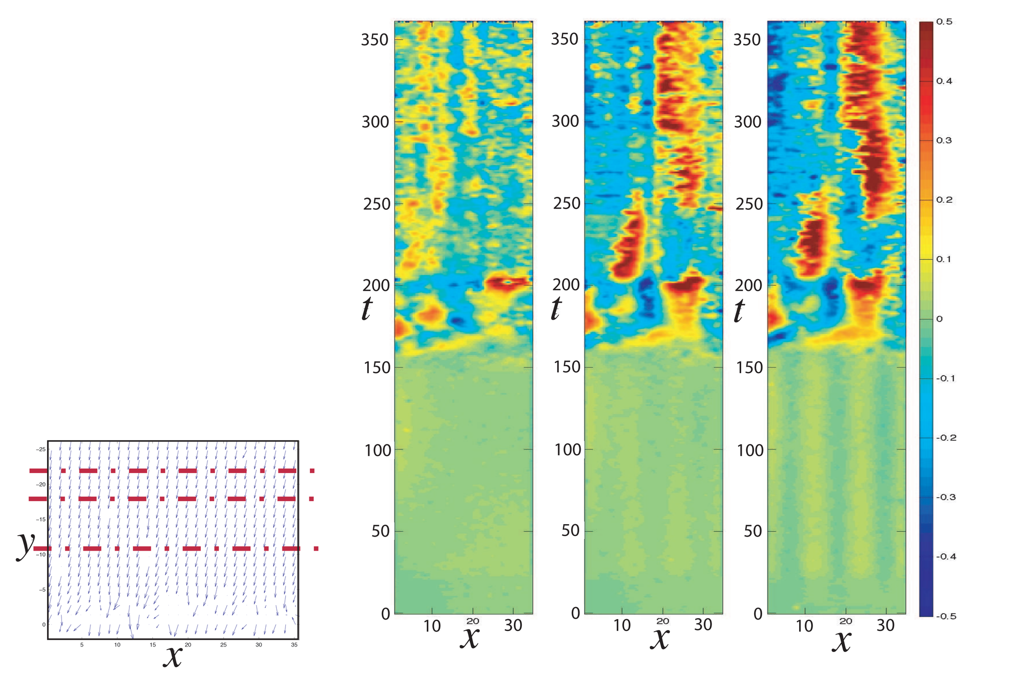
*A paper is a network of cellulose fibres. This network is formed by draining a fibre suspension of approximately 0.5-1% fibre concentration through a permeable wire. As the water is removed, the fibre concentration increases and a network is formed on the wire. An experiment in which this process can be studied have been built. The experiment has been scaled up a factor of ten in size and viscosity compared to cellulose fibres in water.*



To the left, the flow apparatus is seen. It consists of a test section (left) and a driving unit (right). The driving unit consists of a piston which displaces the fluid in the test section. In the test section, fibres are suspended in the liquid above a screen. As the test section is emptied by moving the piston upwards, a fibre network is formed on the screen.
The optical index-of-refraction of the fibres is matched to that of the liquid. Thus, the fibres are transparent and the flow inside the network can be studied by adding tracer particles. Specially developed digital image improvement followed by standard PIV-analysis of the movements of the tracer particles provide the flow velocity in a vertical plane inside the network.

## Velocities in the fibre network

*Typically, one wants to study how the network and flow interacts. To some part, the development of the network can be deduced by regions of high (open network) and low (more dense network) velocities.*



The variation of the vertical velocity is shown in three $xt$-planes (i.e. along three horizontal line as a function of time). Red is high and blue is low velocity. The lengths are scaled with the fibre diameter and the time is scaled so that the fluid moves one fibre diameter per time unit. Three $xt$-planes are shown. The vertical positions of the planes are indicated by the red lines in the figure to the left. At $t \approx 150$, the fibre network is formed. Before this, there are only small, periodical, variations (most accentuated in the right $xt$-plane, which is closest to the screen) due to the periodical openings of the screen. After the formation of the network, larger variations are seen and the open and more dense regions are clearly visible. At $t \approx 200$ and 250, there are restructurings of the network and the flow changes its path.