A Band Rheometer for Fibre Flow Studies

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ABSTRACT

The design of a shear flow instrument for fibre flow studies is described. The main goal was to create an as simple and homogeneous shear flow field as possible, in combination with the possibility of making observation in different directions. A fibre flow example will be discussed and, shortly, the general flow mechanisms in technical fibre suspensions. Properly scaled and modified, this design may possibly also be useful for studying flow mechanisms in other types of structural fluids.

INTRODUCTION

To state that the flow of technical fibre suspensions is complex is no exaggeration. Already at fibre contents below about 1% it consists of crowded non-coherent transient fibre flocs squeezing themselves between each other.[1-6] The floc transiency may be understood as system-thermodynamically favourable that flocs sometimes squeeze only a part of themselves between their neighbours (2nd Law, Onsager's principles of least dissipation of energy, location of all other flocs, etc.).

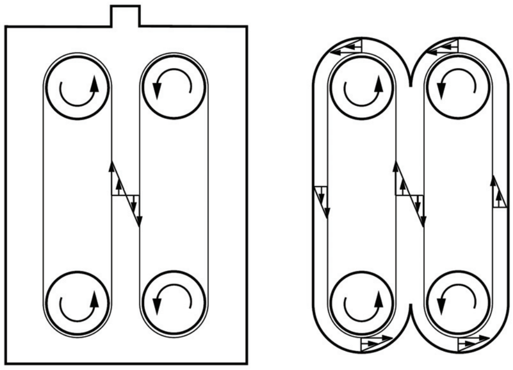
Since it is difficult to give the micro-kinematics of these systems a more exact description, a fluid dynamic theoretical treatment with its demand on well-defined initial and boundary micro-level conditions is difficult. A more symbolic than pseudo-realistic theoretical approach therefore becomes natural.[2,6] Such a theory may e.g. be based on the observation[1,2,6] that the average floc size decreases with increasing deformation rate – mainly due to a steadily ongoing floc compression (alternatively described as a squeezing-out of liquid from the floc interior without loss of fibres) interrupted by successive floc divisions. Both these processes are reversible in principle. A specific flow structures can, however, seldom be freezed into a product since the flow structure continues to develop during retardation. Freezing occurs when the internal kinetic energy becomes too small to overcome the internal potential energy barrier for floc passage.[2]

Two principally different experimental approaches can be imagined for these systems. One is to imitate the real technical fibre flows aimed at, i.e. a scaling approach.[1,2,7] The other is to idealise and homogenise the flow field to the extent that flow mechanisms start to reveal themselves as macro-manifestations.

The design of the band rheometer described here was the final attempt in the second type of approach, i.e. to try to achieve an as ideal and homogeneous shear flow as possible.

DESIGN CONSIDERATION

The first band instrument known to the author was built by Taylor in the 1930's for studying the deformation and break up of individual drops in water, Fig. 1a.[8] Here the endless bands were made of 35 mm



(a) (b)

Figure 1. a) Taylor's parallel band instruments, b) The present design.

filmstrips. With gears and pinned rollers a shear flow field was created between the two vertically counter-running bands. The bands were 1.36 cm apart, and the highest shear rate not more than 0.5 s^{-1}.

The band instrument described in this work, Fig. 1b, may at a first glance look similar, but has a different purpose that requires special design considerations. Technical fibre suspensions (fungal in fermentations, extruded polymeric, botanical in papers, nano-fibres in composites, etc.) are to begin with processed at much higher deformation rates and also at such high fibre concentrations that individual fibre flow (or even individual fibre floc flow) does not occur. The present instrument was therefore designed for nominal shear rates from 0 to 6000 s^{-1}. Positioning of the bands was also allowed for to permit fibre network deformation studies.

Another factor that cannot be ignored in connection with technical fibre flow is the thixotropy. That is, that it takes some time (or rather a certain amount of strain, or mechanistically a number of floc passages) for a new flow/floc structure to establish. If the deformation rate varies in the instrument, the system will establish some kind of Lagrangian average micro-flow/floc structure, with a corresponding average stress, which complicates the analysis. The design therefore aims at as homogeneous

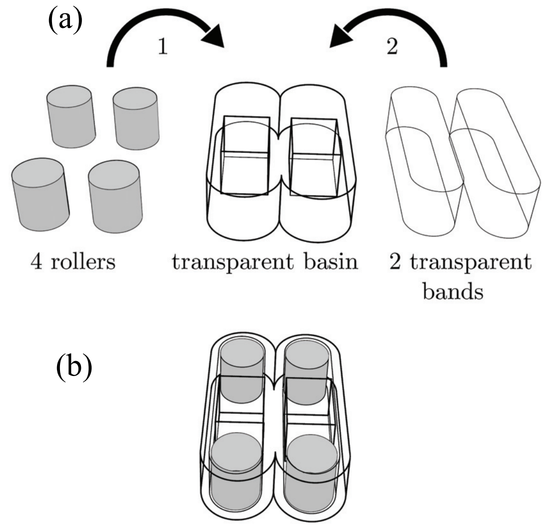


Figure 2. The band rheometer, principally. a) The main components consist of a transparent basin with two observation shafts, four rollers and two transparent bands, b) The assembled band instrument.

shear rate conditions as possible. This can theoretically be achieved by counter-running the bands att equal speeds and making the distance between two bands twice that between one band and a wall, Fig. 1b.

THE BAND RHEOMETER

The design principle is shown in Fig. 2. A transparent open basin with four lobes and two shafts was constructed. Four vertical rollers, with the same diameters and heights as the shaft widths and height were centred in the lobes.

Two endless bands made of OH-film were stretched over the rollers so that they slid against the flow-parallel shaft walls made of 2 mm thick glass. The rollers were mounted directly on the axes of four electric engines, which in turn were bolted into the basin bottom. One engine in each pair is slave-driven by the other. The speed of the bands (2 cm apart) can be varied independently, either manually or by following a program. Normally the bands were driven at equal speeds in counter-rotating mode to achieve shear homogeneity and also make the motion in the central channel as slow as possible relative to the observer, which facilitates visual observation.

MATERIALS

Basin

Bottom; Transparent Perspex plate, thickness 20 mm, Side walls; Transparent Perspex plate, thickness 20 mm, Gables; CNC-milled aluminium, Shafts: Perpendicular to flow transparent Perspex 10 mm thick, parallel flow float glass 2 mm thick.

Engines

4 asynchronic electric engines, Dietz Electronic (Germany), Vectordrive DSM1-14, 2.2 kW. Speed 0-12000 rpm, pair-wise synchronous drift, positioning possibilities. Manual steering or by a written program.

Electronics

4 Frequency converters, Dietz Electronic (Germany), Vectordrive DSV5444-6/400.

Rollers

4 aluminium rollers, diameter 10 cm and height 10 cm.

Bands

Cut and glued together OH-film, length ca. 143 cm. Normally full height 10 cm used, but sometimes also narrower.

Stress evaluation

A number shear stress evaluation methods was considered, although not fully realised. It was thus assumed that for more concentrated fibre suspensions and at higher speeds, the increase in engine power could be used to calculate the stress. For lower speeds torque measurement of a roller axis was planned. Another idea was to use shear sensitive films (of strain gauge type) glued to in the inside of the basin and flush-mounted in the wall surface.

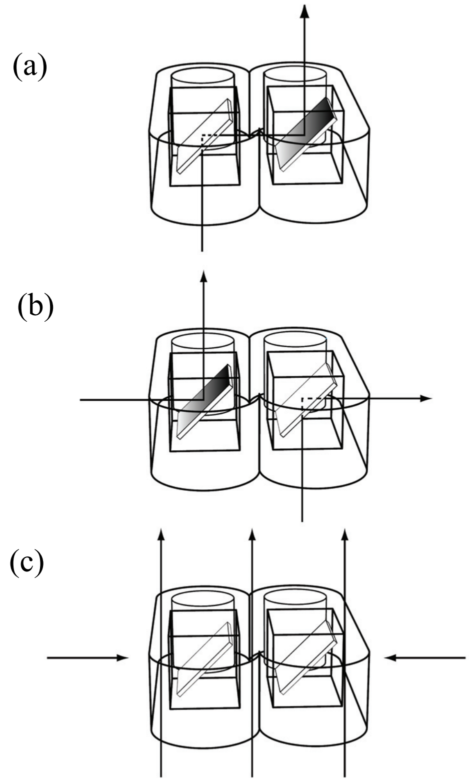


Figure 3. Observation and illumination directions. a) In shear direction central region. b) In the shear direction, outer region, and c) In the indifferent direction.

OBSERVATION & LIGHTENING

Insertion of double-sided mirrors in the shaft, angled 45°, allows different and observation directions, Fig. 3. The shafts also serve as ducts for blowing cooling air to protect the instrument from heat from the intensive lighting that sometimes is needed to visualise the faint streaks between the close-packed fibre flocs.

In Fig. 3a the observation direction is across the central shear flow region in the shearing direction. In (b) the views are across the outer shear flow region in the shearing direction. In (c) they are also in the indifferent direction. Observations can be made bye eye, with camera or cinematically.

THE PHYSICAL INSTRUMENT

The physical instrument is shown in Fig. 4, where the hither gable has been removed.

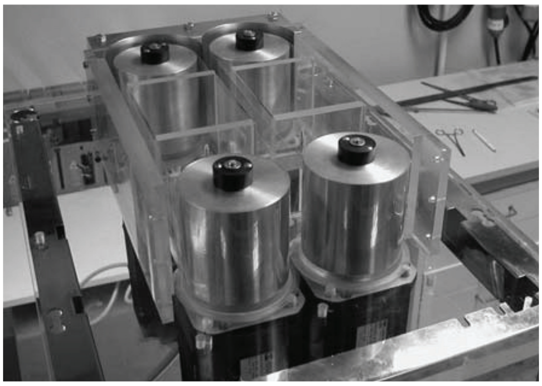


Figure 4. The parallel band instrument with the hither gable removed.

The plastic bands can be faintly being seen between the rollers and the shafts. A switch from metal gables to distortion-free transparent gables was planned as indicated in Figs. 1 and 2 but never realised.

Fig. 5 shows the entire set up, with the engines below the basin bottom, and the four converters in the cabinet on the wall. The computer on the table serves as interface. Two bands can be seen on the desk.

Figure 5. The parallel band instrument, with electronics and computer system in the background.

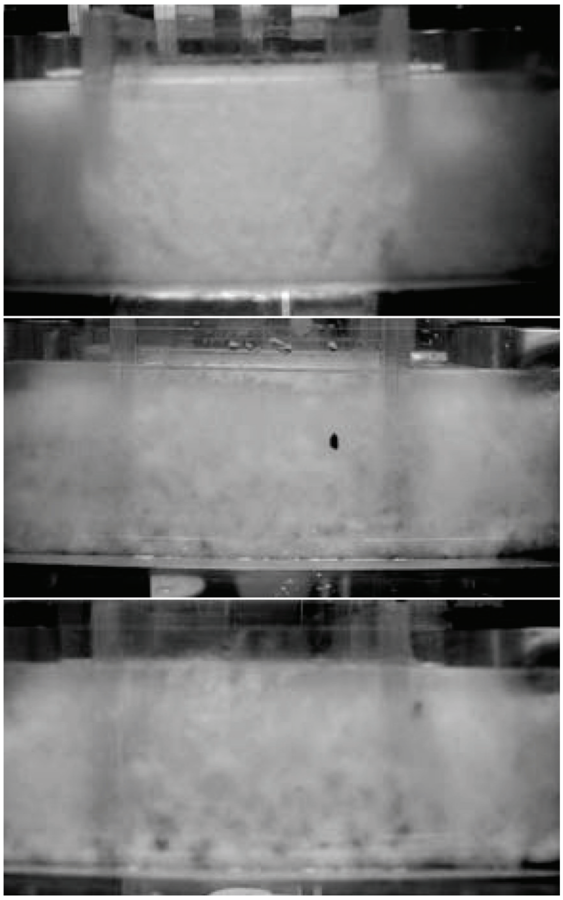


Figure 6. Three examples. Chemical spruce fibre suspension. Fibre concentration below 1%. Band motion to the right. Vertical bars are shaft cross walls.

AN EXAMPLE

The three photographs in Fig. 6 show the development of the flow structures with increasing band speed, for some test runs with the band instrument.

More subtle details that can be easily observed by eye before the instrument and in the original digital photographs often get lost in print. The principal details will therefore be pointed out. The first photograph shows a fibre network plug flow. Like technical fibre networks normally are, this is built up of sintered-together fibre flocs, which can possibly be observed. The floc-free streaks that slope downwards with about 45° in the floc direction should be noticed. Closer inspection reveals that such streaks are always located between compressive stress chains composed of compressed flocs. The streaks form when liquid is squeezed out laterally when the floc chains are compressed lengthwise due to the overall deformation. It should also be noted that these chains seem to tip over towards the end of the shaft region and then break up.

In the second photograph flocculated flow has commenced. The floc flow units are larger that the primary flocs in the network. In the third photograph these large flocs have started to resolve into smaller flocs, typically reduced in size by a length factor of about two.

Figure 7. Streak formation between lengthwise compressed floc/stress chains in a shearable cube instrument. Nylon fibre suspension.[1,9,10]

DISCUSSION

The results in Fig. 6, in a comprehensive way demonstrate the simple rules that have been found in all types of technical fibre suspensions that the author has studied. The downward sloping streaks in the first picture e.g. correspond to the pattern in the shearable cube instrument in Fig. 7. These in turn fit into the general scheme in Fig. 8, which summarises experiments with many types of technical fibre suspensions (microbial, polymeric and botanical) in many types flow instruments (shear; straight and contractive tube flow, straight contractive and expansive channel flow; Couette flows; torsional flow; cone-and-plate flow; headboxes with straight and curve walls, the band instrument in this work, etc).

Most phenomena observed in technical fibre flow systems get natural and intuitively understandable explanations if the actual flow structures are taken into account. Thus although e.g. up to 20 flocs can be counted in stress chains like in Fig. 6 and continuum

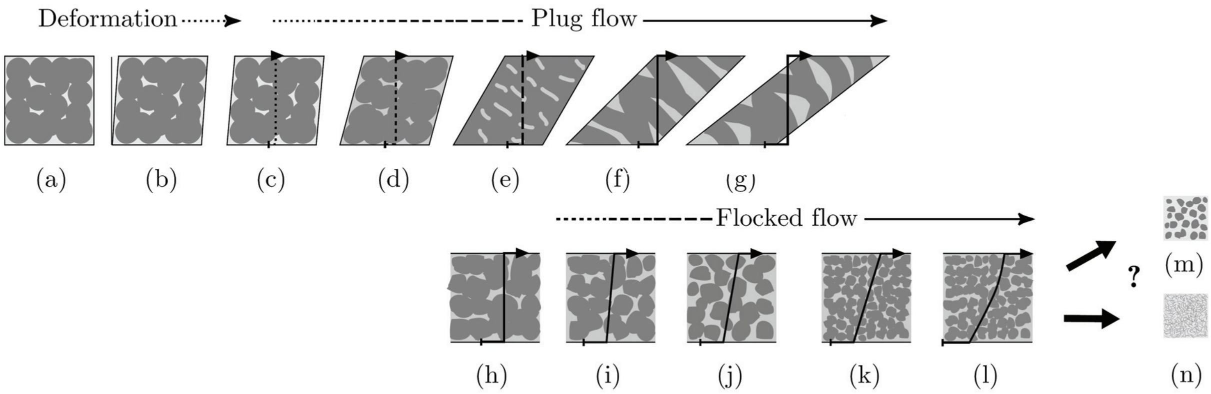


Figure 8. A standard fibre flow scenario.[6] a) Undeformed network, b) Elastically deformed network, c) Plastically deformed network, d) Development of compressive stress/floc chains in largest compression direction, e) Lateral squeezing out of liquid from floc chains, f) Continued lengthwise compression of floc chains, g) Buckling of floc chains, h) Separation of floc chains into flocs, i) Flocked flow, j) Floc compression, k) Floc splitting, l) Inertial effects, and finally (if fibre milling is excluded) depending on the circumstances m) Asymptotically compressed flocs, and n) Fully dispersed flocs, i.e. individual fibre flow.

theory therefore ought to apply for regions if this magnitude it apparently does not since such phenomena falls outside this theory. Much micro-hydrodynamic and micro-rheological (i.e. with non-linear constitutive phase models) modelling, just due to the their nature becomes fibre-based instead of on floc-based. A common theoretical misconception (and that has also spilled over to practical/experimental thinking), with roots in wrong analogies with colloid systems, is that the flocs in technical fibre suspension are the result of a flocculation process (ortho- and/or perikinetic). Flocs can, however form also through the break up of a network. The flocs in still-standing technical fibre networks should be viewed as frozen-developed dissipative flow structures. Even when in some few cases when the initial fibre flocs actually formed through a flocculation process (as e.g. in a fungal process starting with the inoculation spores), the memory of this is soon wiped out and irrelevant for the final result. That is, the result would have been about the same if one instead had started with inoculating with mycelium (normally not practiced for strain propagation reasons).

CONCLUSION

Preliminary tests of the band instrument thus indicated that it worked as intended. It was built in 2003 but was then, because of lack of time and money never developed further. It became a torso that still lacks both arms and legs, and would certainly also have benefited from a head. The presented design ideas may in spite of this perhaps be useful.

ACKNOWLEDGEMENTS

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