The non-Newtonian Fluid Mechanics of Technical Fibre Suspensions: Compressive Flows

Ulf Björkman

Department of Fibre and Polymer Technology, Royal Institute of Technology (KTH),
100 44 Stockholm, Sweden

* Email: ulf@kth.se
Fax: x46.8.7908101

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Abstract:

The flow of non-Newtonian technical fibre suspensions (paper pulps) through a number of contractions is analysed and compared. Traditionally technical fibre flows are modelled as flow of fibres in a suspending medium. Here they are treated as crowded flows of fibre flocs from which the liquid may be squeezed in and out from. Compressive flows are common in the fibre-based process industry. They can e.g. be found in the headbox of a paper machine, in extruder nozzles in polymer technology, in the stirrer zone of mixers, etc. Traditionally such flows are analysed in elongational flow terms. Here it will be demonstrated that elongational and compressive flows for technical fibres suspensions differ qualitatively. The nature of technical fibre flocs is also discussed. For historic reasons they have come to be regarded as the outcome of a flocculation process of electrostatic-colloidal and/or mechanical-entanglement type. It will be shown that such a process is unnecessary for technical fibre suspensions and that these flocs are qualitatively different, viz. frozen-developed dissipative structures of the flocky fibre flow from which they originate. It will also be demonstrated that technical fibre flocs, in contrast with flocs of the chemically flocked type, are basically non-coherent, i.e. not kept together by themselves. It is this non-coherence that makes a compressive approach fruitful, for these economically important flows. An attempt to explain the reasons behind the present state of fibre flow theory is presented. The ambition is to stop to the present inproductive tradition in technical fibre flow.

Zusammenfassung:

Das Fließverhalten von nicht-Newtonschen Suspensionen von technischen Fasern (Pulpe) in unterschiedlichen Kontraktionsströmungen wird analysiert und verglichen. Bisher wurde das Fließverhalten von suspendierten technischen Fasern durch das Fließverhalten von Fasern in einem suspendierenden Medium modelliert. Dabei wurden sie als Strömungen von konzentrierten Faser-Flocken modelliert, in die die Flüssigkeit hinein- bzw. hinausgedrückt wird. Kompressionsströmungen treten in vielen industriellen faserbasierten Prozessen auf. Beispielsweise findet man sie im Stoffeinlaufkasten von Papiermaschinen, in Extruderdüsen bei der Kunststoffverarbeitung, in der Rührzone von Mischern, etc. Traditionell werden solche Strömungen mit den Begriffen der Dehnströmungen untersucht. In dieser Arbeit wird gezeigt, dass sich Dehn- und Kompressionsströmungen für Suspensionen von technischen Fasern wesentlich unterscheiden. Die Natur der Flocken aus technischen Fasern wird ebenfalls diskutiert. Aus historischen Gründen werden sie als Produkt des Flokkulationsprozesses von elektrostatisch-kolloidalen und/oder mechanischen Verschlaufungstypen betrachtet. Es wird gezeigt, dass dieser Prozess für Suspensionen technischer Fasern unnötig ist und dass sich diese Fasern qualitativ unterscheiden, vgl. die eingefrorenen dissipativen Strukturen der Strömungen von flockigen Fasern, aus denen sie hervorgehen. Es wird ebenfalls gezeigt, dass die Flocken von technischen Fasern, im Gegensatz zu den Flocken chemischer Natur, grundsätzlich nicht kohärent sind, d. h. sie werden nicht durch sich selbst zusammengehalten. Es ist diese Nichtkohärenz für diese ökonomisch bedeutenden Strömungen, die diesen Kompressionsansatz aussichtsreich macht. In dieser Arbeit wird versucht, die Gründe zu erklären mit dem Ziel, die gegenwärtig ergebnislose Tradition bzgl. des Fließverhaltens technischer Fasern zu stoppen.

Résumé:

L'écoulement des suspensions de fibre technique non-Newtoniennes (pulpes de papier) à travers un nombre de contractions est analysé et comparé. Traditionnellement, les écoulements de fibre technique sont modélisés comme des écoulements de fibres en suspension dans un milieu. Ici, ils sont traités comme des écoulements encombrés de flocs de fibre dans lesquels le liquide peut être aspiré ou expulsé. Les écoulements de compression sont communs dans les procédés industriels de fibres. On peut par exemple les rencontrer dans la tête des machines à papier, dans les buses d'extrusion en technologie des polymères, dans la zone de mélange des mixeurs, etc. Traditionnellement, ces écoulements sont analysés en termes d'écoulement d'extension. Ici il sera démontré que les écoulements de compression et d'extension diffèrent qualitativement dans le cas des suspensions de fibres techniques. La nature des flocs de fibre technique est aussi discutée. Pour des raisons histo-

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nically uninteresting dilute systems, the development along the earlier lines were sidelined and the knowledge even forgotten. The development of theoretical models for technical fibre flow systems based mechanistic insights has as a result been delayed with about a century. Hydrodynamics can, however, not solelly be blamed since the development has mostly taken place within or in cooperation with paper industry. Hydrodogmatic thinking seems infuse most branches of fluid dynamics to varying degree. Its share appears to be higher in theoretical fields, with a clear peak in turbulence. Navier-Stokes' equation is here held as something immensely deep, instead of just Newtonian mechanics applied on a smeared out model substance. That its foundation never can be transcended or violated is normally not understood, and may even among all huge equations be forgotten by the greatest scientific thinkers like Kelvin and Einstein. But when more normal persons ask for explanations of a specific flow problem and gets a simple one for free but anyhow due to hydrodogmatism cannot change mind to what they are fully capable of understanding, it implies something more. One cannot then avoid thinking of the late Stikkan Andersson, well-known music publisher in Sweden who became seriously rich and liked to play a cynic by merrily sprinkling his surrounding with "People hear the song texts they deserve", "People are not as stupid as you believe – They are even more stupid!" etc.

To lift oneself in the hair is not easy (without long hair and a tackle – symbolically), and to wear a too large hat not only look ridiculous but restricts sight. To on and on and on collide with the same lamp post due of a too large hat, while trying to lift oneself in the hair that isn't, without doubt looks interesting but circus is funnier – also going round in circles but intentionally and professionally. With Anderson we may therefore conclude that "Paper technology has the flow theories it deserves," and "Hydrodogmatics is not as stupid as you believe – It is even more stupid!"

7 CONCLUSION

The present state of fibre flow theory can thus be understood fairly well through the historic development. Fibre flow theories have been developed in the blue, without serious ambitions to check how the look in practice in spite of, and in addition often developed in university chambers (like Bachelor's) filled from floor to roof with suitable experimental raw material. Theories have been lifted over without even experimentally checking that the prerequisites are fulfilled adapted to fibre flow results. Technical fibre flows has also been regarded as very special and of small general interest. As a result, it has become a subject for very few researchers.

Few substances are, however, more readily available. Paper product surround us everywhere and can be with simple means converted by everyone be converted to a technical fibre suspension, in contrast with but economically much less important, substances filling the rheological literature. Yet, here is a vast field for experiments and developing theories. By studying technical fibre flows more ingoing one, however, finds that their flow behaviour and the mechanisms behind them are very general. By studying compressive flow of technical fibre suspensions, which firstly may seem a rather special, we have in this work arrived at the mechanistic core of these economically important non-Newtonian flow systems (and possibly also for other flows). One may even go so far as saying that technical fibre flows, due to the incoherence, always is compressive on micro-level.

A simple theory, the module suspension theory, which is based on observable facts, has been presented and shown to apply well in a number of cases ranging from the lowest to highest technically used velocities as well from lowest to highest used concentrations in paper technology. With this, the author feels that he used a more than sufficient part of his only life on fibre flows, and with the best wishes leaves this vast, still largely unexplored and interesting field to others.

SYMBOL LIST

c_v: volumetric fibre content [–]
d_f: fibre diameter [m]
D: plate distance [m]
E_p: potential energy [Nm]
h: channel height, z-direction [m]
l: length [m]
l_f: fibre length [m]
l_o: initial length [m]
$n_{cs} = (2/3)cv(l_f/d_f)^2 \approx 0.74 N_{cs}$: crowding factor [–]
N_{cs}: $= [(2\sqrt{2\pi})c_v(l_f/d_f)^2]^{1/3}$: fibre centre span (number) [–]
Q: volumetric flow rate [m3/s]
t: time [s]

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v: velocity vector [m/s]
v_c: floc pair centre velocity [m/s]
v_f: floc centre velocity [m/s]
v_{sq}: squeeze velocity [m/s]
V: volumetric flow velocity [m/s]
W: channel width, y-direction [m]
x: flow direction coordinate [m]
x_c: floc pair centre x-coordinate [m]
x_f: floc centre x-coordinate [m]
y: cross direction coordinate [m]
z: coordinate in the third direction [m]
$\dot{\gamma}$: shear rate [1/s]
δ: streak width [m]
δ_o: initial streak width [m]
$\epsilon_{parallel}$: strain parallel to compression direction [–]
$\epsilon_{perpendicular}$: strain perpendicular to compression direction [–]
$\epsilon \equiv (l - l_o)/l_o$: strain [–]
$\nu \equiv -\epsilon_{perpendicular}/\epsilon_{parallel}$: Poisson ratio [–]
ν_f: floc network Poisson ratio [–]
ν_l: liquid Poisson ratio [–]
$\Delta\nu \equiv \nu_l - \nu_f$: Poisson ratio difference [–]
ρ: density [kg/m^3]
τ: shear stress [Pa]
τ_o: yield shear stress [Pa]

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