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FLOW THROUGH FIBRE NETWORKS – EFFECT OF FLUID RHEOLOGY

Mats Stading[1,2], Camilla Öhgren[1], Sandra Barman[1], Torben Nilsson Pingel[1], Innokenty Kantor[3] and Niklas Lorén[1]

[1]RISE Research Institutes of Sweden, Gothenburg, Sweden
[2]Chalmers University of Technology, Gothenburg, Sweden
[3]MAX IV, Science Division, Lund, Sweden

ABSTRACT

Fluid flow in fibrous networks is crucial for many technical applications such as wound care and hygiene products as well as for tissue paper. The flow of Newtonian, low-viscous fluids like water is well studied whereas the flow of viscoelastic fluids is less so. It is nevertheless highly important for the applications.

Model fluids could be used to determine the influence of important rheological properties such as viscosity, elasticity and shear thinning on the flow. Fluids containing the same components can be tuned to have constant viscosity (Newtonian), constant viscosity but elastic (Boger), and shear thinning to determine the influence of each property on the flow. Initially flow was determined in real time for Newtonian and shear thinning fluids using light microscopy and X-ray radiography. The results showed a large influence of the fluid rheology on the flow through the fibre networks.

INTRODUCTION

The flow of Newtonian fluids (water) through fibre networks has been extensively studied[1] and has even resulted in methods for predicting flow from 3D-structure (Gesualdo model)[2].

Viscoelastic flow in porous media has been extensively studied for its applications in geophysics, biology and especially enhanced oil recovery[3,4]. There are also some studies on the flow of viscoelastic fluids through fibre networks, especially modelling[5,6] and in models of fibre systems[7,8].

The flow of viscoelastic fluids through fibrous media is a complex phenomenon. Studies in fibre models have shown e.g. that fluid elasticity significantly increases flow resistance, with elastic effects becoming noticeable at Deborah numbers around 0.5 [7]. The pressure drop in these flows is influenced by both fluid and fibre network properties, with viscoelastic fluids exhibiting an "excess" pressure drop as compared to Newtonian fluids[8,9].

A set of model fluids, as introduced in the abstract (Newtonian, Boger and shear thinning) have previously been utilised for studies of swallowing[10,11] and perception[12]. Boger fluids[13] have a wider use especially for testing constitutive equations for polymer melts. The latter were however more viscous, and here we aimed for model fluids with lower viscosity to match the technical applications.

In an initial study a range of maltodextrin and xanthan solutions were evaluated for flow through fibre materials using light microscopy and X-ray radiography.

MATERIALS AND METHODS

Materials

The fluids used in this study were prepared using maltodextrin Glucidex IT 19 (Roquette, Lestrem, France) and xanthan (Grindstedt Clear 80 (IFF, Brabrand, Denmark).

Stock solutions of maltodextrin of 60% w/w and xanthan 1% were mixed and stirred over night on a magnetic stirrer. The stock solutions were then diluted into the final concentrations and stirred over night. The fluids used in the study were:

- Newtonian: 15%, 30% and 60% w/w maltodextrin
- Shear thinning: 0.01%, 0.1% and 0.8% w/w xanthan

The fluids were finally mixed with 10% Gadovist (Bayer Radiology, Leverkusen, Germany) as a contrast agent for the X-ray studies.

The fibrous matrix was consisted of PET fibres intertwined to a fibrous material as shown in **Fig. 1a**.

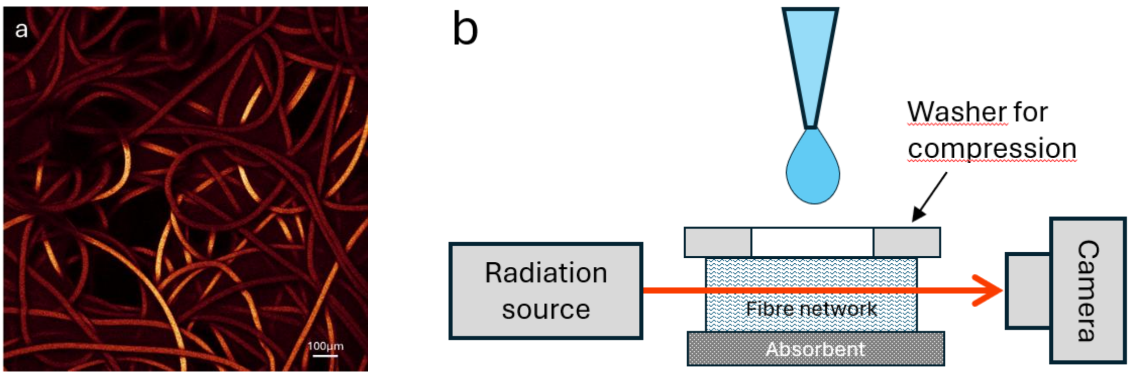

FIGURE 1: a) Microstructure of the fibrous material visualised by confocal laser scanning microscopy, b) Sketch of the experimental setup used for X-ray radiography and for light microscopy.

Methods

Viscometry was performed using an ARES-G2 (TA Instruments, New Castle, DE, USA) equipped with a concentric cylinder system (cup diameter 20 mm). The measurements were performed at 20°C.

A pipette was placed over the fibrous material and a drop of the fluid was dropped onto it while monitoring the fluid flow by light or X-rays, as shown in **Fig. 1b**. The drop volume was regulated by a syringe pump which was operated remotely. The fibrous material could be compressed lightly by a plastic washer and filter paper was placed under the fibrous material as an absorbent to facilitate drainage through the material.

X-ray radiography was performed at the DanMAX beamline at the MAX IV synchrotron in Lund, Sweden. 2D projections of the sample were recorded in a side view (**Fig. 1b**) during the application of the liquid and the initial flow through the porous material. Each recorded sequence was 54 seconds long, with a time resolution of 5.4 ms, and a spatial resolution (pixel size) of 0.55 µm.

A microscope equipped with a CMOS camera (Olympus BX53F2, CAM-SC50, Tokyo, Japan) was used to study the flow through the fibrous material. The microscope was placed sideways instead of vertically and the same sample holder as used for X-ray radiography was placed in the microscope. The holder was directly on the microscope table so that the focus distance was fixed to the centre of the sample, i.e. so the flowing droplet was in focus. The syringe tip was connected to a Harvard Apparatus syringe pump (Harvard Bioscience, Holliston, USA). The frame rate was 9 frames/s.

RESULTS AND DISCUSSION

The viscosity of the model fluids was measured and the Power Law model was fitted to the data ($\sigma = K\dot{\gamma}^n$). The results in Table 1 show that the Maltodextrin solutions were Newtonian and the xanthan solutions shear thinning as expected.

Table 1. Power Law constants for the fluids containing 10% Gadovist contrast agent.

Polymer	Concentration	n	K
Maltodextrin	15%	1	0,00244
	30%	1	0,0072
	60%	1	0,27
Xanthan	0,01%	0,90	0,0069
	0,10%	0,62	0,054
	0,80%	0,098	4,9

The xanthan and maltodextrin solution with 0.1% Direct Red dye as were allowed to drain through the fibrous material and monitored by video. Snapshots of the videos are shown in **Fig. 2**. The first image shows when the liquid just reached the material, the second halfway during the flow and the last when the last drop of liquid goes into the absorbent material. This process takes very different times depending on the liquid. It was relatively fast for xanthan (1.5 – 25 s) but considerably slower for the concentrated maltodextrin solution (50 s – 7 minutes).

The study showed a large influence of the viscous behaviour on the flow through the fibre material. The lowest maltodextrin concentration as expected behaved similar to water as its viscosity is just about twice that of water, whereas the high viscosity of the concentrated solution considerably slowed down the flow. Xanthan showed a slightly different behaviour due to the shear thinning. The flow at higher shear rates, initially and when the fluid front reached the absorbent, was fast whereas the intermediate flow was slow.

This initial study is continued with evaluation of fluid dynamics and modelling of the effect of the fibre material and will be published separately.

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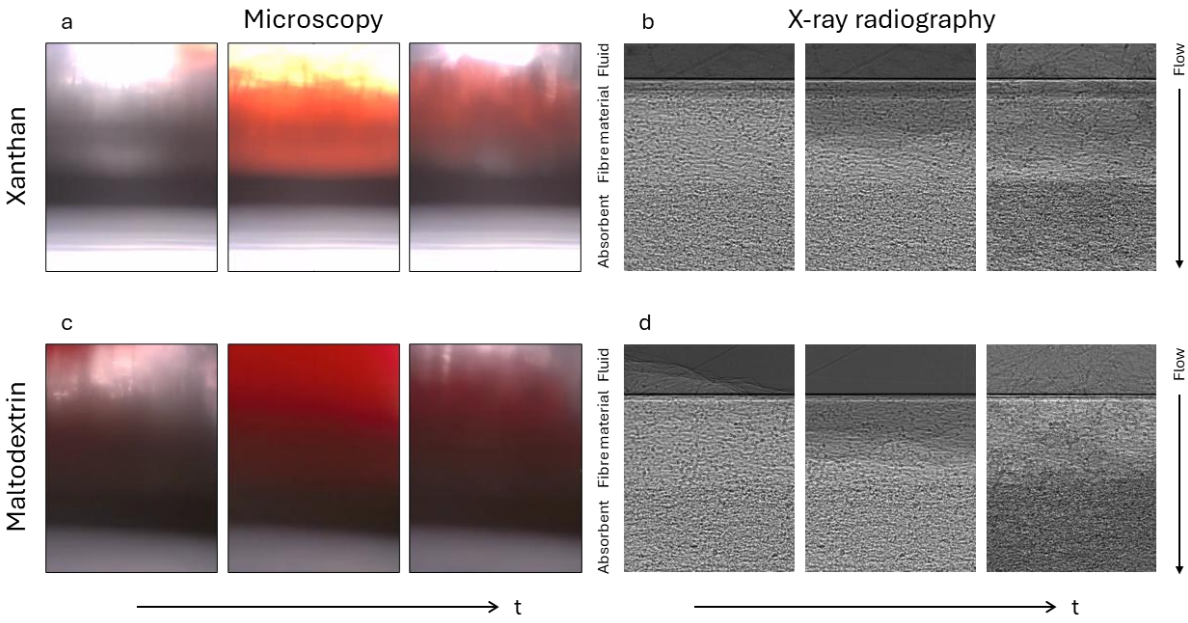

FIGURE 2: Example of the flow visualised as snapshots at the beginning, halfway and end of flow into the fibrous material by a xanthan solution (top, a and b) and a maltodextrin solution (bottom, c and d) visualised by light microscopy (a and c), and X-ray radiography (b and d).

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