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The observation and evaluation of extensional filament deformation and breakup profiles for Non Newtonian fluids using a high strain rate double piston apparatus

M.R. Mackley [a,*], S.A. Butler [a], S. Huxley [b], N.M. Reis [c], A.I. Barbosa [c], M Tembely [d]

[a] Department of Chemical Engineering and Biotechnology, University of Cambridge, CB2 3RA, UK
[b] Huxley Bertram Engineering Ltd, Waterbeach. Cambridge CB25 9QP, UK
[c] Department of Chemical Engineering, Loughborough University, Loughborough, LE11 3TU UK
[d] Department of Mechanical and Industrial Engineering, Concordia University, Montreal. H3G 1M8, Canada

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ABSTRACT

This paper reports a new design of experimental double piston filament stretching apparatus that can stretch fluids to very high extensional strain rates. Using high speed photography, filament deformation and breakup profiles of a strategically selected range of fluids including low and higher viscosity Newtonian liquids together with a viscoelastic polymer solution, biological and yield stress fluids were tested for the first time at extensional strain rates in excess of 1000 s^{-1}. The stretching rate was sufficiently high that observation of low viscosity Newtonian fluid stretching, end pinching and break was observed during the stretching period of the deformation, whereas for a higher Newtonian viscosity, filament thinning and breakup occurred after the cessation of piston movement. Different fluid rheologies resulted in very different thinning and breakup profiles and the kinetics, in particular of yield stress fluids showed a striking contrast to Newtonians or viscoelastic fluids. Surprisingly all the tested fluids had an initial sub millisecond "wine glass" profile of deformation which could be approximately captured using a simple parabolic mass balance equation. Subsequent deformation profiles were however very sensitive to the rheology of the test fluid and where the final breakup occurred before or after piston cessation. In certain cases the thinning and break up was successfully matched with a 1D numerical simulation demonstrating the way numerical modelling can be used with the fluids correct rheological characterization to gain physical insight into how rheologically complex fluids deform and breakup at very high extensional deformation rates.

1. Introduction

This paper is concerned with the development of a fast strain rate filament stretching device that can stretch fluids at strain rates in excess of 1000 s^{-1} and thereby enables low viscosity and other fluids to be observed during fast filament extensional stretching. A scientific objective of the paper is to observe and understand how a range of different fluids deform and breakup under extreme extensional conditions. There is an extensive literature on extensional stretching devices, however in the past these have been essentially universally used to obtain rheological extensional viscosity data on fluids with a base viscosity higher than 1 Pas, either from coupled force extension observations during stretching [1] or filament thinning data during filament relaxation after stretching [2]. The extensional droplet breakup of Newtonian and Non Newtonian droplets has also been extensively studied, James et al. [3] and review [4], however again most experimental observations have generally been limited to high viscosity fluids.

Obtaining high extensional strain rates is a challenging problem and many devices that achieve this involve high velocity jet flow or confined constriction flow which can contain upstream simple shear components in addition to extensional deformation [5,6]. Low viscosity viscoelastic polymer solutions are particularly challenging in extensional flow because viscoelastic effects can be expected to occur when both the fluid Weissenberg $We = \lambda\,\dot{\varepsilon}$ number is greater than one and when the total strain is high, where λ, is the relaxation time and $\dot{\varepsilon}$ the strain rate (Crowley et al. [7]). For a dilute polymer or biological solution λ might be of order 10^{-3} s or less which means for $We > 1$, the extensional strain rate needs to exceed 10^3 s^{-1}. In addition, chain stretching may be necessary to induce a rheology change or changes in deformation

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[*] Corresponding author. Fax 44 1223 334796.
E-mail address: mrm5@cam.ac.uk (M.R. Mackley).

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profiles and so there is an added strain requirement that $\gamma \gg 1$. These conditions greatly constrain experimental configurations for this type of deformation at high strain rates. The double jet apparatus (Mackley et al. [8]) was specifically developed for high *We* extensional flow and although the apparatus was successful in optically detecting localised chain stretching it was not particularly effective as a rheometer and was a closed system so that free surface deformation profiles could not be observed.

In the past, essentially pure extensional filament stretching using one moving opposed piston and coupled force measurements has been successfully used for reasonably high viscosity Newtonian and polymer based fluids (see for example reviews by Anna et al. [1], and McKinley et al. [9], where fluids investigated had viscosities typically greater than 1 Pas. In this class of experiment the key objective was to extract rheological extensional viscosity parameters. The idea of using capillary thinning after stretching as an additional way of determining the extensional viscosities of structured fluids was introduced by Bazilevsky et al. [10] who developed a device that involved the stretching of a fluid filament and then following the subsequent time evolution of surface tension driven capillary thinning, where again in general but not exclusively, high viscosity fluids were used (see for example reviews by Anna et al. [11], McKinley [2]). In general these filament thinning experiments were carried out without the necessity of force measurement and both extensional viscosity and relaxation times of Non Newtonian fluids could be extracted from the data. A key finding of the extensive filament thinning experiments that have been carried out was that Newtonian fluid centre line thinning occurred with a linear decay and viscoelastic fluids with an exponential decay, see for example, [12,13,14,15]. For essentially all the cases of extensional filament thinning and breakup studied, data was obtained after the initial stretch process was complete.

A related experiment to extensional filament stretching is gravity driven drop filament thinning (see for example, Cooper-White et al. [16]) where both high and low viscosity Newtonian and Non Newtonian fluids have been studied for many decades. These experiments provide essentially constant external force boundary conditions and provide a useful way of observing extensional break up.

The apparatus developed in this paper was specifically designed to study the high strain rate deformation and breakup of initially low viscosity Non Newtonian ink jet fluids where the behaviour of ink jet fluids emerging from nozzles is of critical importance for ink jet performance, see for example [17]. The problem is however of general scientific and technological importance as droplet stretching and breakup of in particular low viscosity fluids, pervades many industrial and natural processes such as ink jet and spray technology together with silk worm and spider spinning. Up until the development of the apparatus described in this paper there was no piston device that was capable of the controlled high speed stretching of fluids where optical observations could be conveniently and systematically recorded.

The general experimental deformation geometry for most filament stretching and thinning devices are shown schematically in Fig. 1 where fluid is initially positioned between two pistons with diameter *D* at a starting gap of L_0 (Fig. 1a). Either one or both pistons are then moved at a constant speed V_p and stretching takes place (Fig. 1b). During this period, provided force measurements are carried out, it is possible to determine the transient extensional viscosity of the fluid using information on the capillary thinning at the centre of the filament, See for example [9]. Subsequently when the pistons stop moving (Fig. 1c), capillary thinning can take place due to surface tension forces and it is possible to derive a transient viscosity from this thinning action without the need to make force measurements. See for example Anna et al. [11], Clasen et al. [14]. Both the stretch and relaxation behaviour of Newtonian and viscoelastic fluids have been successfully modelled and simulated for high viscosity fluids. (see for example, Yao et al. [15] and Vadillo et al. [18]).

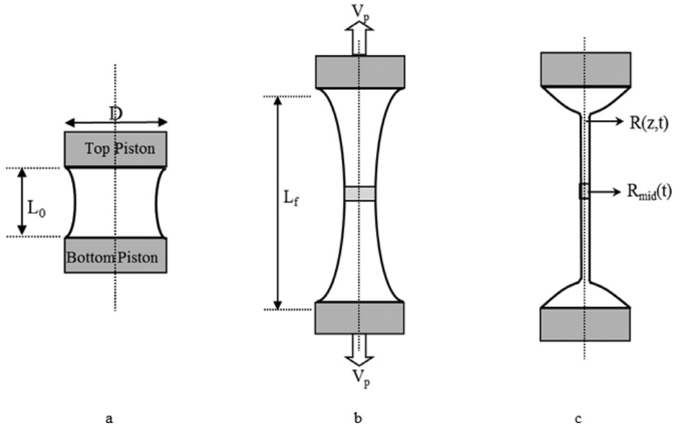

Fig. 1. Schematic diagram showing, (a) initial conditions, (b) filament stretching and (c) filament thinning.

One of the only commercial filament stretch and thinning apparatus currently available is the Caber Apparatus (http://www.thermoscientific.com/content/tfs/en/product/haake-caber-1-capillary-breakup-extensional-rheometer.html) and extensional viscosity results using this device are reported for example by Rodd et al. [19] and Clasen et al. [14]. The manufacturers of the Caber quote a maximum stretch rate for the apparatus of order $3\,s^{-1}$ and typically during the subsequent filament thinning stage the extensional strain rate is of order $10\,s^{-1}$. An alternative to the Caber instrument is the Trimaster series developed at the University of Cambridge (Vadillo et al. [20]). The device has two pistons that move in opposite directions thereby keeping the centre of the filament in the same central position and the maximum useful achievable stretching strain rate that can be obtained without excessive overshoot is of order $12\,s^{-1}$. In order to extend the strain rate range of the Trimaster a new Huxley Bertram (HB4) Cambridge Trimaster has been developed that uses a unique method of achieving high strain rate extensional piston movement. This paper describes the mechanical principle and performance of the apparatus and presents extensional deformation and breakup profiles for Newtonian fluids, a viscoelastic solution and a selection of other potentially rheologically complex fluids. The paper also matches some thinning and breakup results with analytic equations and a numerical simulation.

2. The development of the Huxley Bertram (HB4) Trimaster series apparatus

A schematic diagram of the HB4 fast filament stretching apparatus is shown in Fig. 2a and a photograph of the apparatus is given in Fig. 2b. The apparatus is designed around the principle of achieving the highest possible double piston separation velocity in order to obtain stretching strain rates greater than $1000\,s^{-1}$. This involves moving two mutually opposed pistons from rest as quickly as possible. Piston movement is achieved by the movement of two lever arms shown in Fig. 2a. and the movement of the lever arms are activated by ramps that are positioned on a separate horizontal wheel. The purpose of the wheel is to allow a servo motor that drives the wheel to accelerate the wheel to its maximum velocity before the ramp starts to move the lever arms and piston. In this way the inevitable finite start up inertia of the servo motor and wheel is overcome and the required high velocity of the piston pin achieved within sub milliseconds.