Enhanced Oil Recovery and Elongational Flow – The Thermo Scientific HAAKE CaBER1

Klaus Oldörp, Thermo Fisher Scientific, Material Characterization, Karlsruhe, Germany

Introduction

When a new oilfield starts producing oil, the oil is driven up the well by the internal pressure of the oil deposit. Unfortunately only about 10 % of the oil in place can be recovered like this (primary production). With supporting technical methods like e.g. pumping water into the oilfield to push the crude oil out of the porous stone or sand layer towards the production well, oil production can be increased up to approximately 20 – 40 % of the oil in place (secondary production). Due to the viscosity difference between water and oil sooner or later so-called fingering will occur, where the water injected will break through the oil instead of pushing the oil towards the production well.

To push the total recovery up to 30 – 60 %, so-called enhanced oil recovery (EOR) techniques are utilized (tertiary production). One of these techniques is polymer flooding. Here polymers are used to increase the viscosity of the injection fluid to suppress the fingering.

Unfortunately the standard oilfield does not exist. Every oil deposit has its individual characteristics depending on a large number of parameters like for example temperature, pressure, crude oil viscosity, crude oil composition, salinity, and pore size distribution. Consequently, the polymers used for flooding have to be selected or even tailored to perform effectively under the conditions of the individual oil deposit.

Already several decades ago it has been observed that the flow of polymer solution through a porous medium cannot be described based on shear flow alone [1]. Instead of a continuous viscosity drop with increasing flow rate, polymer solutions can show an increase in viscosity above a characteristic flow rate. This effect has been called “shear thickening“ in earlier works. Currently it is commonly accepted that extensional effects (Fig. 1) are the cause for the viscosity increase observed [2]. In some cases it is even suspected to be the key factor to the effectiveness of polymer solutions in EOR [3].

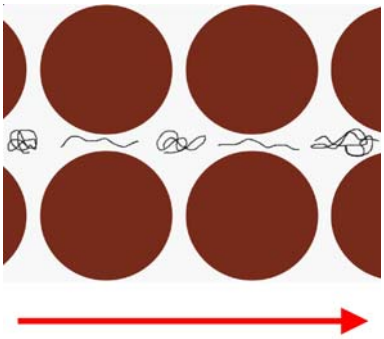

Fig. 1: Schematic illustration of the elongation and relaxation of a polymer coil during its flow through a porous medium. The red arrow indicates the direction of flow from the injection well to the production well.

As a consequence there is an increasing demand for analytical techniques capable of characterizing the extensional properties of low viscous polymer solutions used in polymer flooding.

Experimental

Classical studies have mostly been done via flooding real rock material retrieved from the well or synthetic porous media made of sand or similar materials. These porous media are difficult to make, difficult to characterize and difficult to maintain due to absorption of the polymers.

For a systematic characterization it is much easier to expose polymer solutions to an extensional field directly. The most convenient and time efficient approach is using the Thermo Scientific HAAKE CaBER 1, the only commercially available extensional rheometer for low viscous fluids (Fig. 2).

This Capillary Breakup Extensional Rheometer quickly pulls a small volume of a liquid apart to form a liquid filament. It measures the thickness of this filament (Fig. 3a) or, more precisely, how quickly this filament collapses. The thickness of the collapsing filament is measured at the mid-point between the two plates and plotted as a function of time (Fig. 3b).

In total, the collapse of the filament happens because the liquid flows away from the centre of the filament towards the upper and the lower plate, which causes its diameter to shrink until it breaks. The central point of the filament is located between two opposing flows, a so-called stagnation point where the flow speed is zero. Therefore the central volume element is exposed to a uniaxial elongational strain (Fig. 4).

Fig. 2: The HAAKE CaBER1, the only commercially available elongational rheometer for liquids.

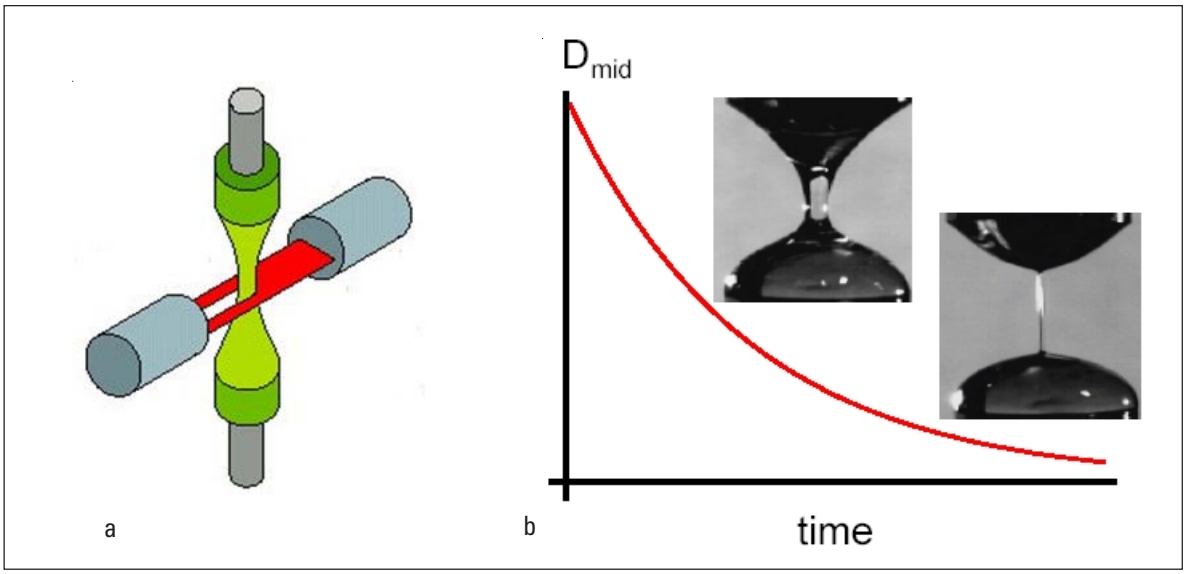

Fig. 3 a: Simplified principle of the HAAKE CaBER 1. The liquid sample is pulled upwards to form a filament (light green). The thickness of the filament is measured at its thinnest point with a laser micrometer.
b: Schematic depiction of the raw data from a CaBER test. The diameter of the liquid filament is measured in the middle between the two plates and plotted as a function of the time.

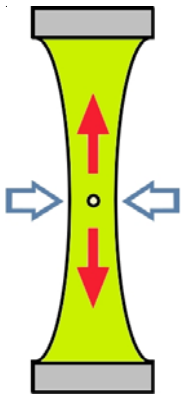

Fig. 4: During the collapse of the filament the liquid flows away from the centre point of the filament (red arrows) leaving a central volume element where the speed is zero. At this so-called stagnation point the liquid is exposed to a uniaxial elongational strain.

From a variety of powder polyacrylamides for polymer flooding, 2 different samples have been selected. According to the chemical characteristics of the oilfield, the tests were done for, a salt solution containing $CaCl_2$ and NaCl that was prepared to simulate the real-life chemical conditions in the field. A 5000 ppm polymer solution has been prepared from both polymer samples. To prepare each solution, a measured amount of the salt water has been filled into a glass container with a screw-on lid. A stirring magnet has been added and the polymer was introduced into the vortex of the stirred salt water. The glass was closed with its lid and carefully sealed with a flexible sealing tape to avoid any changes in concentration due to evaporation.
After some hours of slow stirring, the polymer solutions have been tested with the HAAKE CaBER 1. Due to the low viscosity of the samples the 4 mm plates have been selected. Using a small syringe without needle (!) the samples have been filled into a 2 mm gap between the plates of the HAAKE CaBER 1 at 20 °C. Within 50 ms the upper plate was lifted to 6.5 mm above the lower plate, which equals a Hencky Strain of 1.2.
Under these test conditions the 2 polyacrylamides showed a significant difference in break-up time. The filament formed by Polymer 1 was less stable collapsing after approx. 0.01 s whereas the filament of Polymer 2 lasted for 1.1 s (Fig. 5).

Regarding the curves shown in Fig. 5 shows that both collapses happen abruptly. The plot shows the normalized filament diameter (D_N = actual diameter divided by initial diameter) as a function of time. Both polymer solutions start with D_N-values around 0.3, which stay almost constant until the break-up occurs. This behaviour indicates that both polymers have an extended coil structure in this kind of solvent. The results from the CaBER tests give an insight into the polymer/solvent interaction and the rigidity of the polymer coil in solution [4].
Based on the raw data the HAAKE CaBER 1 software calculates the apparent extensional viscosity, shown in Fig. 6 plotted against the elongational strain. Again the behaviour of the two polymers differs significantly. While Polymer 1 shows an almost constant viscosity, Polymer 2 exhibits a strong viscosity increase around a strain of 3. For flooding projects a rather constant viscosity has the advantage of a more uniform behaviour independent of the actual strain, which depends on pore diameter and flow speed.

Summary

With the HAAKE CaBER 1 it is possible to test the elongational behaviour of even low viscous liquids like the flooding solutions tested for this report. Since the elongational viscosity of liquids is not accessible using a rotational viscometer or rheometer, this elongational rheometer is the perfect complement to get the full information needed to understand applications, which are clearly influenced or even dominated by elongational flow effects.
Especially when the real application cannot be accessed directly and any error could cause costly consequences, a reliable lab test, which can be performed quickly, is highly recommended. Polymer flooding of an oilfield is one of those applications where it is essential to gather as much relevant information as possible in the lab before trying something out in the oilfield deep underground. Regarding the costs involved in a flooding project and the financial benefit every improvement of the flooding efficiency yields, the investment in a HAAKE CaBER 1 is a very reasonable and foremost profitable one.

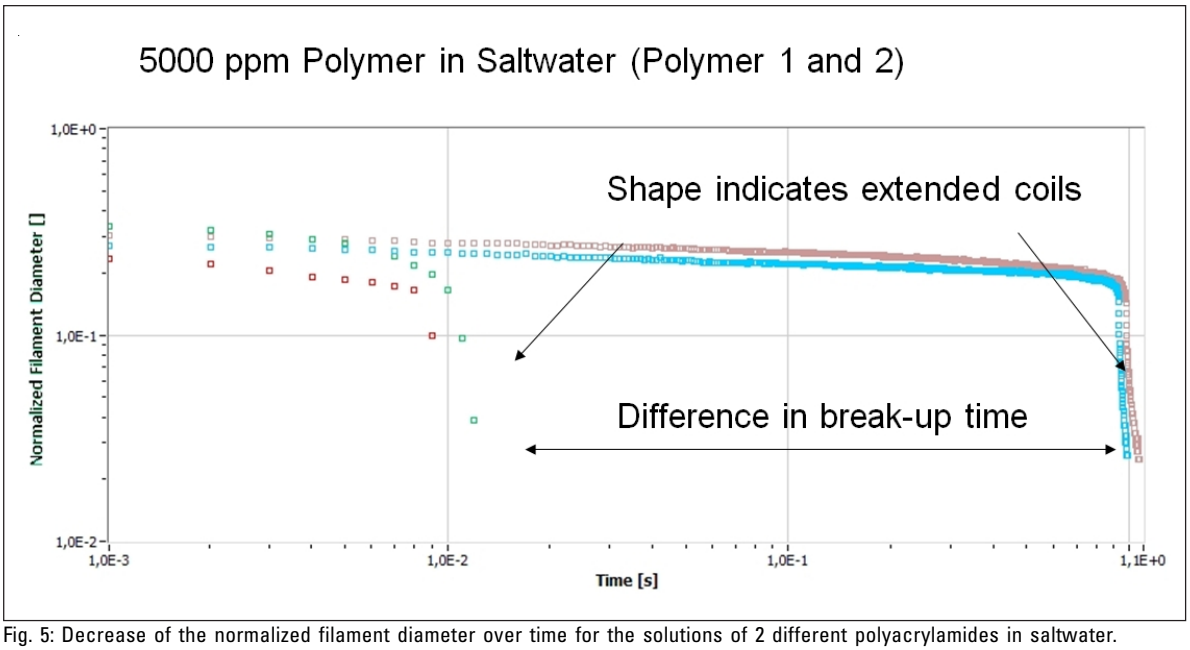

Fig. 5: Decrease of the normalized filament diameter over time for the solutions of 2 different polyacrylamides in saltwater. Although having the same concentration both solutions show different break-up times and different curve shapes.

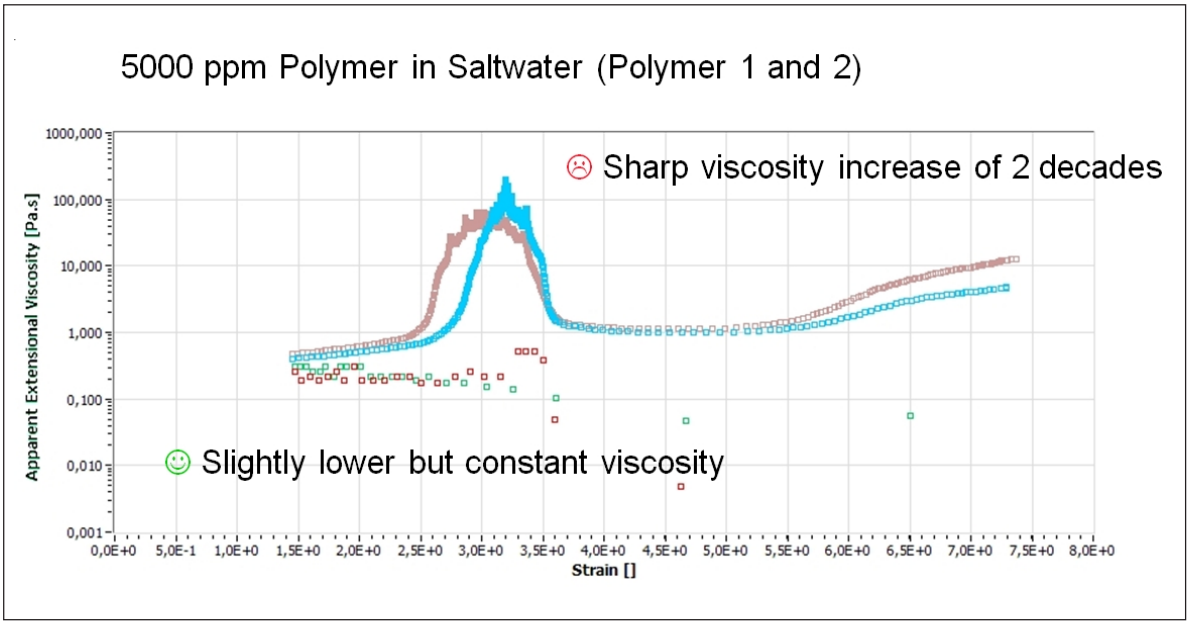

Fig. 6: Apparent elongational viscosities as a function of the elongational strain of 2 different polyacrylamides in salt water. One polymer shows a rather constant viscosity, the other one shows a sharp increase of viscosity by a factor of one hundred.

References

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Material Characterization

International/Germany
Dieselstr. 4,
76227 Karlsruhe
Tel. +49(0)721 40 94-444
info.mc.de@thermofisher.com

Benelux
Tel. +31 (0) 76 5 87 98 88
info.mc.nl@thermofisher.com

China
Tel. +86 (21) 68 65 45 88
info.mc.china@thermofisher.com

France
Tel. +33 (0) 1 60 92 48 00
info.mc.fr@thermofisher.com

India
Tel. +91 (20) 66 26 7000
info.mc.in@thermofisher.com

Japan
Tel. +81 45 453 9167
info.mc.jp@thermofisher.com

United Kingdom
Tel. +44 (0) 1606 54 81 00
info.mc.uk@thermofisher.com

USA
Tel. 603 436 9444
info.mc.us@thermofisher.com

www.thermoscientific.com/mc

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