Novel High-Speed Elongation Rheometer- Improving the simulation of the fiber spinning process

Alexander M. Bier[1], Walter Arne[2], Dirk W. Schubert[1]

[1]Institute of Polymer Materials, Friedrich-Alexander-University Erlangen-Nuremberg, Martensstrasse 7, 91058 Erlangen, Germany
[2]Fraunhofer Institute for Industrial Mathematics ITWM, Fraunhofer-Platz 1, 67663 Kaiserslautern, Germany

ABSTRACT

The elongational viscosity of polymers can be determined by utilising different devices such as extensional rheometer after Sentmanat (SER), oil bath rheometer after Meissner or tensile rheometer after Münstedt (MTR). With those existing methods the elongational viscosity at high elongation rates as they occur in fiber spinning was not accessible. With the "Rheotens" slightly higher elongation rates of 40 s^{-1} can be achieved, but in comparison to the aerodynamic fiber stretching via an aspirator with elongation rates over 100 s^{-1} it is still by far insufficient for an industrial relevant range. Therefore, a novel method is developed to calculate the elongational viscosity of polymers utilizing the fiber spinning process itself in combination with simulations to describe the temperature profile of the polymeric strand along the spinline. With the known diameter of the polymeric strand from the die exit to the aspirator, determined by a high-speed camera and a novel force calibration of the aspirator it is possible to determine the elongational viscosity of polymers in dependence of temperature and strain rates up to 100 s^{-1}. For a preliminary study, two amorphous PMMAs were used to reduce the complexity of the system. With the knowledge of the strain rate dependent elongational viscosity it was then possible to further improve the simulation of the fiber spinning process.

INTRODUCTION

Fiber spinning is a common method to produce continuous fibers. Very high take-up velocities and therefore thinner fibers can only be achieved by aerodynamic stretching via an aspirator. The airflow in the aspirator applies a force on the surface of the polymeric strand and stretches it. Investigations of the fiber spinning process are preferably performed on pilot melt spinning devices with small throughput per hour to test different process setting with low expense to then transfer the knowledge to big industrial systems with several tons of throughput per hour. Another tool to transfer the in-depth knowledge is the simulation of the spinning process. However, the complexity of the melt spinning is far beyond to be understood.

During the spinning molecular motions, crystallization and orientation along the fiber occur at high stresses and deformations to just name a few. Also, in theory radial variations of the temperature within the polymeric strand occur, but those are neglectable for thin filaments.[1] However, the most discussed and controversial problem during spinning is the influence of

elongational viscosity. In 1906 the first connection between shear and elongation was made by Trouton.[2] But the three times higher elongational viscosity is only valid for Newtonian fluids, which polymers are not. Therefore, different devices were developed to determine the elongational viscosity in dependence of strain rate and temperature. Examples are the extensional rheometer after Sentmanat (SER), oil bath rheometer after Meissner or tensile rheometer after Münstedt (MTR).[3,4] However, those devices are limited by low Hencky strains and strain rates of up to 10 s^{-1}. Nearer to the spinning process is the "Rheotens" where two rotating wheels are used to take-up the polymeric strand to measure the force that acts on the fiber. Next to the non-isothermal investigation, the "Rheotens" is limited to elongation rates of typically 40 s-1 and therefore curves only a less industrial relevant range. Therefore, for proper understanding of the fiber spinning a new technique was developed.

EXPERIMENTAL

For a preliminary study the complexity of the system was reduced by using two amorphous PMMAs (6N/7N) with a linear molecular architecture to neglect strain hardening and crystallization. A capillary rheometer in combination with an aspirator and a spinning length of 53 cm is used as the fiber spinning device (see **Fig. 1)**. An extended description is given here.[5]

The polymeric strand was investigated at different positions during the fiber spinning process while varying the material throughput and the take-up pressure P. Simulations of the fiber spinning process were used to determine the temperature of the polymeric strand along the spinline. For the simulation, the fiber is described as a one-dimensional object and the cooling by air and the gravitation are included as external forces. Internal stresses are modelled by viscous material laws and material parameters are determined by experiments. The non-linear system of equations is solved using Newton's method.[6]

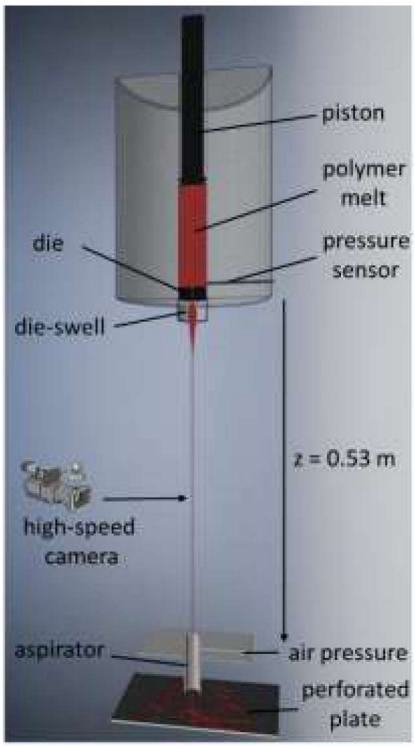

FIGURE 1: Schematic half cut sketch of the spinning process

RESULTS

Determination of the aspirator force

Challenging was the determination of the force applied by the aspirator F_A, which is needed to calculate the elongational viscosity η_E. This was achieved by two scenarios.
First, static copper wires, fixed on a spring balance, were used to measure the force acting on the wire with K_1, K_2 and n as fit parameters.

$$\frac{F_A}{r} = K_1 \cdot \left(K_2 \cdot \sqrt{P} - v_e\right)^n \quad (1)$$

The force is dependent on the applied air pressure and the radius of the wire, wherefore the wire radius was chosen in the appropriate range of the final polymer fiber. The problem is that in this scenario the traveling speed of the fiber v_e is neglected ($v_e = 0$ in Eq. 1), wherefore in scenario

two the fiber itself at the die exit is used to calculate the force as the applied force of the aspirator is acting on every point of the polymeric strand. As the melt spinning process is extensional driven, it must be supposed that during spinning mainly elongational viscosity is dominant and for low strain rates (occurring at the die) the Trouton factor of three is valid for the zero elongational viscosity.[7] From the high-speed camera measurements the fiber diameter (therefore the cross section A) and the velocity (due to constant mass throughput) is known and with the first derivation of the velocity, the strain rate ($\dot{\varepsilon}$) is also known. The following Eq. 2 can therefore be used to determine the aspirator force at the die exit (index start in Eq. 2).

$$F_{exp} = A_{Start} \cdot \dot{\varepsilon}_{Start} \cdot \eta_{E0} = A_{Start} \cdot \dot{\varepsilon}_{Start} \cdot 3\eta_{S0} \quad (2)$$

The combination of both scenarios reveals an entire calibration of the force applied by the aspirator on the polymeric fiber by using a linear regression model (Eq. 3).

$$\left(\frac{F_A}{r}\right)^{1/2} = a_1 \cdot \sqrt{P} + a_2 \cdot v_e \quad (3)$$

A plot of the calculated values as a function of the experimental force values normalized to their respective radii is used to evaluate the consistency of approach 1 and approach 2 and shows excellent agreement (indicated by the red bisector line in **Fig. 2**).

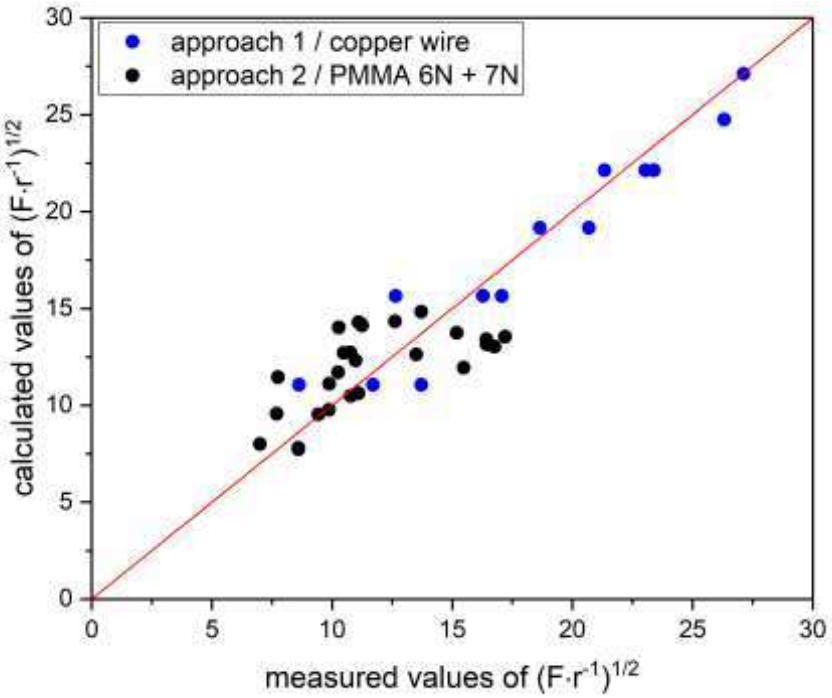

FIGURE 2: Comparison of the calculated values from the linear regression model and the experimental ones. Approach 1 reflects the scenario of the copper wires with zero travelling speed and approach 2 the calculation of the force by Eq. 3 using both PMMAs.

Determination of the elongational viscosity

With all the information (force, temperature, diameter and strain rate) it is now possible to calculate at least the apparent elongational viscosity. Considering the elongational viscosity and strain rate along the polymeric strand at different temperatures from all different parameter sets (varying air pressure and throughput) a considerable amount of data is accessible. To master all

these values the following assumptions are utilized, motivated by well known relations of shear viscosity and shear rate.

- A Carreau-like behaviour:

$$\boldsymbol{\eta_e(T,\dot{\varepsilon}) = \frac{\eta_{e0}(T)}{\left(1+\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_c(T)}\right)^2\right)^m}} \tag{4}$$

- With Vogel-Fulcher-Tammann from shear experiments (with C, D and T_{VFT} as Fit parameters) to calculate the zero shear viscosity:

$$\boldsymbol{ln\left(\frac{\eta_{s0}(T)}{Pa\cdot s}\right) = C + \frac{D}{T - T_{VFT}}} \tag{5}$$

- The characteristic elongation rate $\dot{\varepsilon}_c(T)$ times $\eta_{e0}(T)$ is constant.

$$\boldsymbol{\rightarrow \eta_e(T,\dot{\varepsilon}) = \frac{\eta_{e0}(T)}{\left(1+\left(\frac{\dot{\varepsilon}\cdot\eta_{eo}(T)}{K}\right)^2\right)^m}} \tag{6}$$

$$\boldsymbol{with:\ \frac{1}{\dot{\varepsilon}_c(T)} = \frac{\eta_{eo}(T)}{K} = \frac{3\cdot\eta_{so}(T)}{K}} \tag{7}$$

Eq. 6 can be used to master all data points of the different spinning settings. The exponent of 2 was used due to symmetry arguments known from oscillating shear experiments. The following **Fig. 3** shows the result up to high strain rates with K and m as fit parameters and all identified parameters that are needed to calculate the elongational viscosity are given in **table 1**.

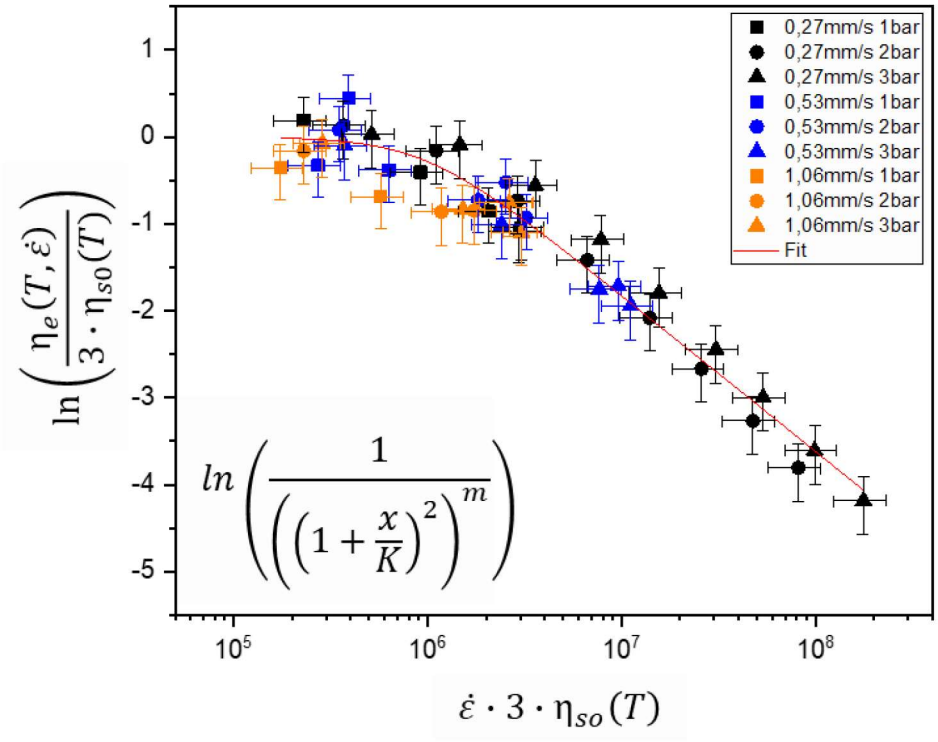

FIGURE 3: Mastered curve of PMMA 7N for all parameter sets varying throughput (mm/s) and aspirator pressure (bar), covering a temperature range of 110°C to 240°C.

Table 1: Identified fit parameters to calculate the elongational viscosity.

material	C	D	T_{VFT}	m	K
	[-]	[K]	[K]	[-]	[Pa]
PMMA 7N	-7.9	3649	273.15	0.39	$9.5 \cdot 10^5$
PMMA 6N	-7.9	3434	273.15	0.53	$24.8 \cdot 10^5$

Improving the simulation software

With this knowledge, it is now possible to implement the Carreau-like function into the simulation software extending the simulation from a Newtonian model to a strain rate dependent elongational viscosity model. This requires two additional parameters m and K. Those parameters can be identified in the simulation software finding the best agreement between measured and simulated diameters. Now, with the adjustment of the model, the simulated fiber diameter along the polymeric strand do even better fit to the experimental ones (see **Fig. 4**), especially at high take-up velocities.

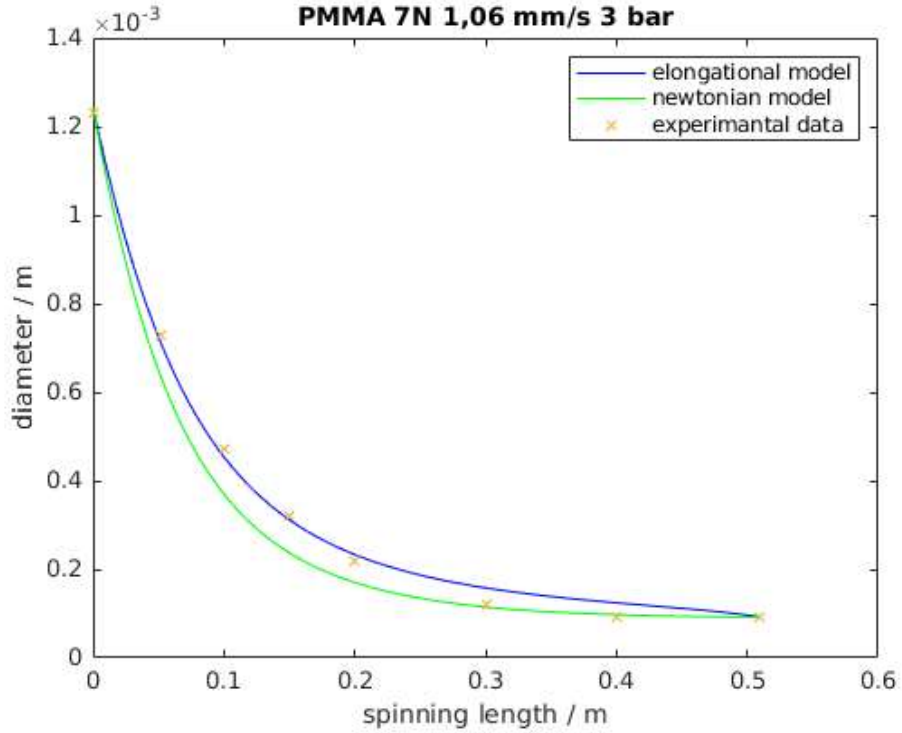

FIGURE 4: Comparison of the simulated diameter results with the experimental ones (measured via the high-speed camera).

CONCLUSION

Two different amorphous PMMAs (6N/7N) were used to investigate the elongational viscosity of polymers. With the use of the fiber spinning process as a high-speed elongational rheometer, it is possible to create a wide range of strain rates up to 100 s^{-1}, which were never reached before and are from great technical interest in fiber spinning. Independent of the used parameters it was possible to master all data points of the elongational viscosity revealing the same extensional thinning behaviour. This technique finally paves the way to learn more about the extensional behaviour of polymeric materials during spinning and enables a powerful tool for

benchmarking commercially available polymers. In further studies this will be extended to commonly used polymers as PP or PET where additionally crystallization plays an important role.

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