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Rheology of entangled active polymer-like *T. Tubifex* worms

Antoine Deblais, Sander Woutersen, Daniel Bonn *

University of Amsterdam, Netherlands

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ABSTRACT

We propose a new 'active particle' system in which the particles are in fact polymer-like. We experimentally study the rheology of long, slender, and entangled living worms (*Tubifex Tubifex*, or 'sludge worms'). Performing classical rheology experiments on this entangled polymer-like system, we find that the rheology is qualitatively similar to that of usual polymers, but, quantitatively, (i) shear thinning is reduced by activity, (ii) the characteristic shear rate for the onset of shear-thinning is given by the time scale of the activity, and (iii) the low shear viscosity as a function of concentration shows a very different scaling from that of regular polymers. The level of activity can be controlled by changing the temperature but also by adding small amounts of alcohol to make the worms temporarily inactive. I will also briefly discuss phase separation by entanglement, and our first attempts to perform hydrodynamic chromatography of these wormy polymers.

Videos to this article can be found online at https://doi.org/10.1016/j.sctalk.2022.100033.

Figures and tables

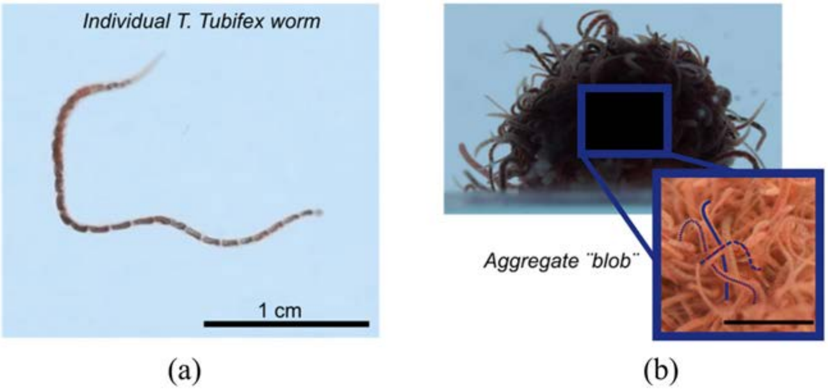

Fig. 1. Active living polymer. (a) Top-view picture of a single active polymerlike *T. Tubifex* worm aka "sludge" worm. (b) A collection of these worms spontaneously aggregate through entanglement to form large "blob" that are reminiscent to polymer melts. The inset shows the entanglement state of the worms within the blob. Scale bar in the inset represents 2 cm.

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* Corresponding author.
E-mail address: D.Bonn@uva.nl (D. Bonn).

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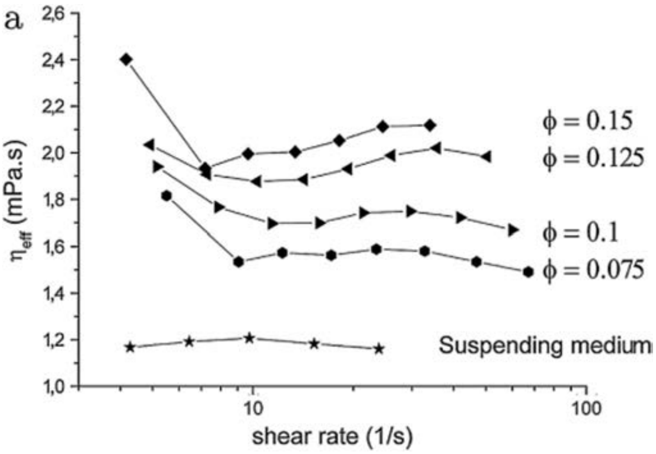

Fig. 2. Effective viscosity of active point-like *Chlamydomonas* suspensions as a function of shear rate. Data are shown for different volume fractions of the suspension and compared to the viscosity of the suspending medium (stars). Figure taken from [1].

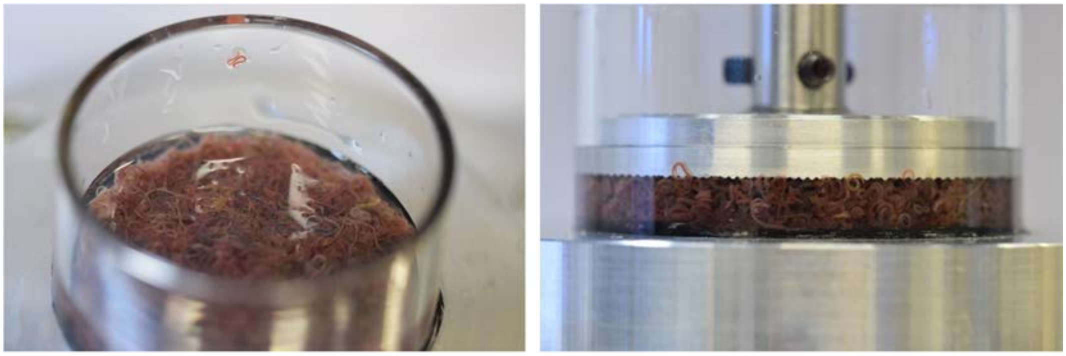

Fig. 3. (*Left)* A known mass of worms is mixed with water and placed in a custom designed rheology cell. *(Right)* The rough plate-plate rheology cell allows us to perform rheology measurement on the living worm suspension.

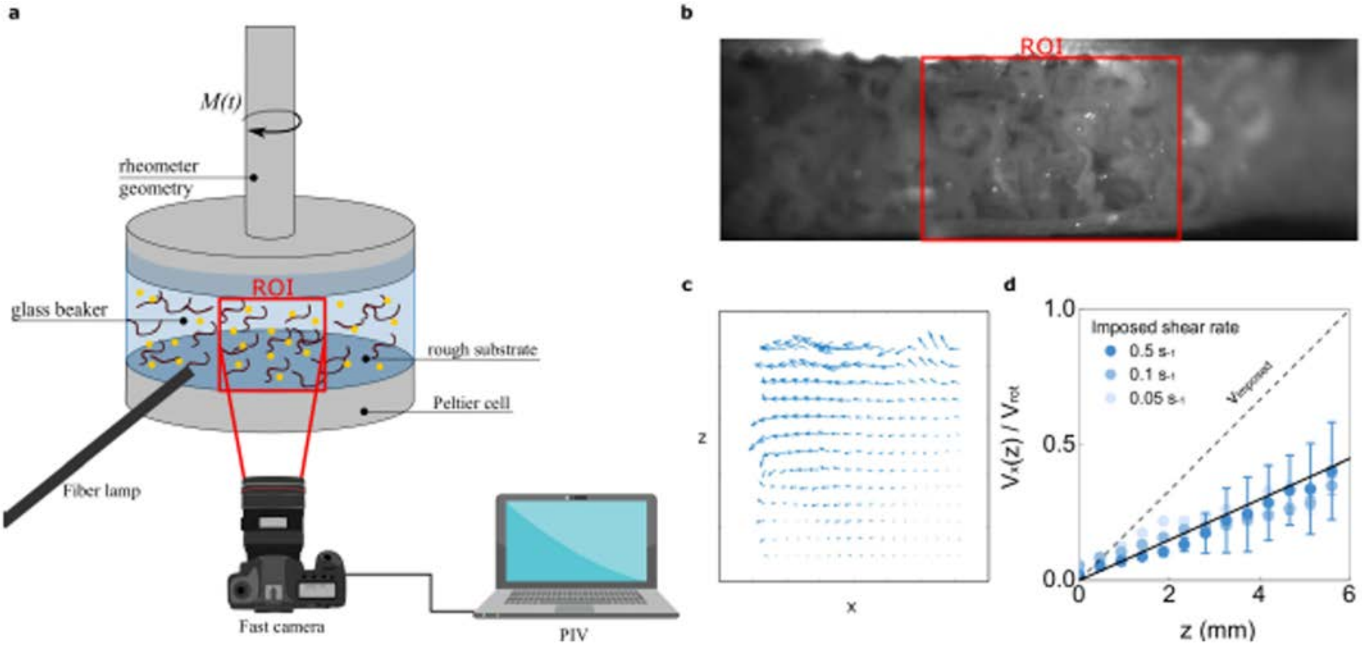

Fig. 4. a. Schematic of the experimental setup, b. picture of the worms in the plate-plate rheology cell, c. PIV imaging of the velocity field, d. measured z-dependence of the velocity, showing a linear velocity profile with addition of a significant amount of wall slip.

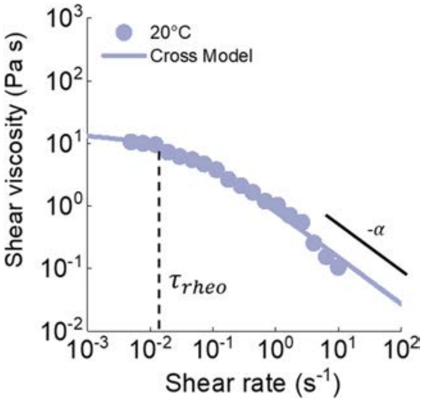

Fig. 5. Fit of the Cross model for 'normal' polymer solutions to our living polymer suspension. The two characteristic parameters are the time at which there is a crossover from the Newtonian plateau to shear thinning, and the shear thinning exponent.

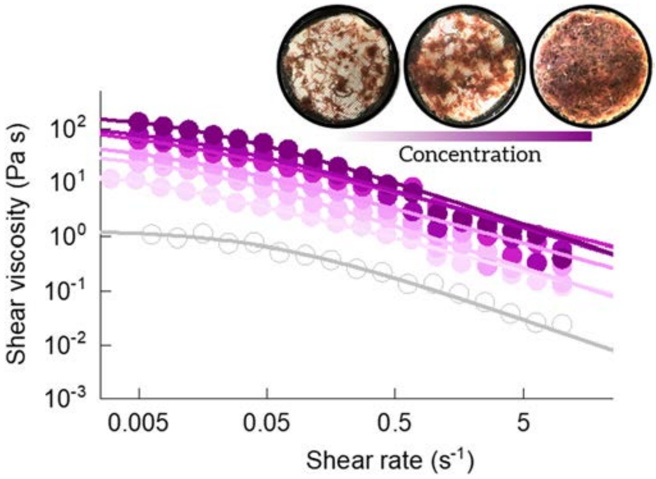

Fig. 6. Shear thinning behavior of the worm suspensions, the higher the worm volume fraction, the higher the viscosity. The curves clearly show a transition from a Newtonian plateau at low shear rates to a power-law shear thinning behavior at higher shear rates.

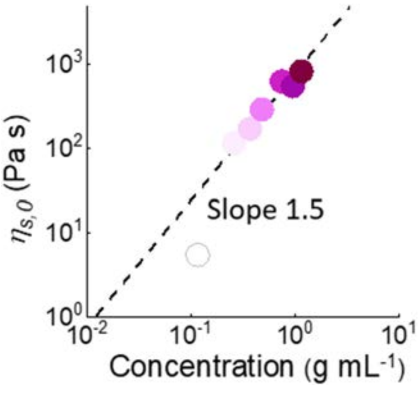

Fig. 7. Zero-shear viscosity as a function of the worm concentration. We observed a zero-shear viscosity dependance different from what is usually observed in regular polymer solutions.

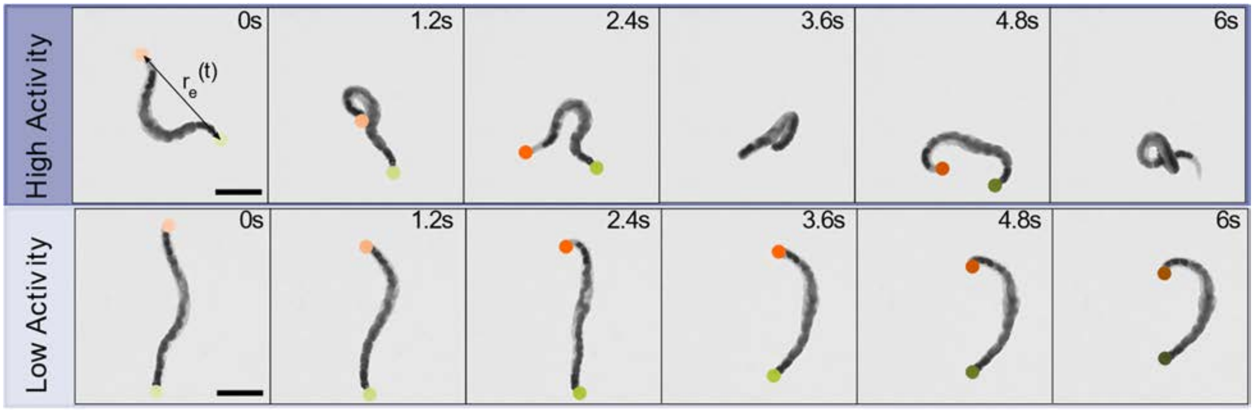

Fig. 8. Dynamics of a single worm at two different levels of activity. A lower level of activity can be achieved by lowering the temperature or by exposing the worm to a mixture of water and alcohol. From the fluctuations of the worm's shape, a characteristic time of the wiggling motion can be deduced.

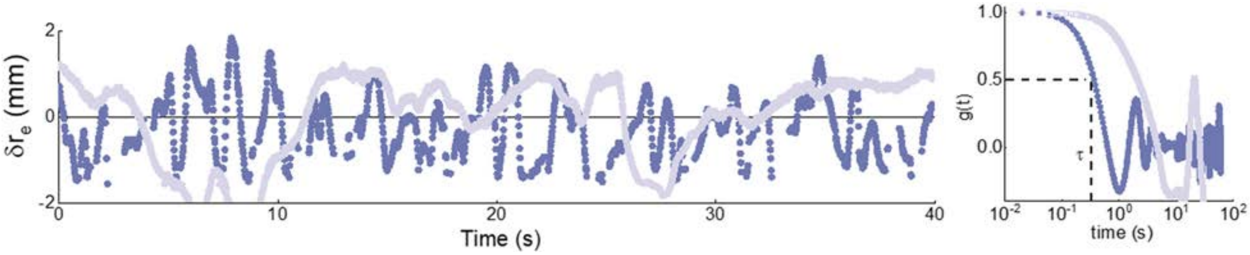

Fig. 9. (Left) Temporal fluctuation of the end-to-end distance with respect to its averaged values versus time. (Right) Corresponding correlation function from which we determined the microscopic characteristic time of a single worm as indicated by the dotted line. The lower the temperature (or by adding alcohol), the longer the relaxation time of the worm.

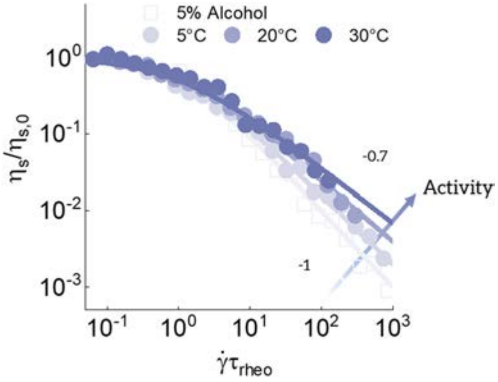

Fig. 10. Effect of the activity on the shear-thinning exponent. The shear viscosity for the different volume fractions is rescaled with the zero-shear viscosity and the shear rate with the crossover time. The higher the activity of the worm-solution, the lower the shear-thinning exponent.

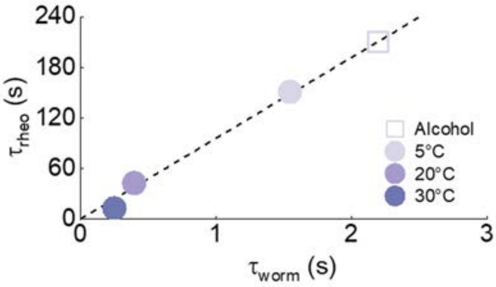

Fig. 11. Correlation between the crossover time (obtained from rheology, Fig. 5) and the characteristic time of the end-to-end fluctuations of a single worm (obtained from imaging, Fig. 8 & 9). The macroscopic rheology time is clearly proportional to but distinctly different from the ‘microscopic’ motion time for a single worm.

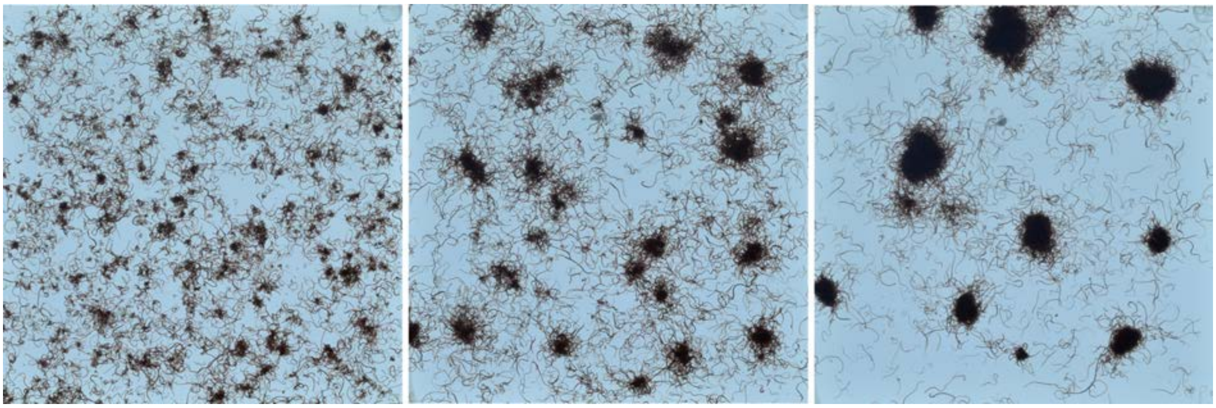

Fig. 12. Aggregation and phase separation of the living worms *Tubifex tubifex*. Snapshots of active-worm aggregation in a 25 × 25 × 2.5 cm volume at $t = 0$, 9.5, and 60 min (from left to right).

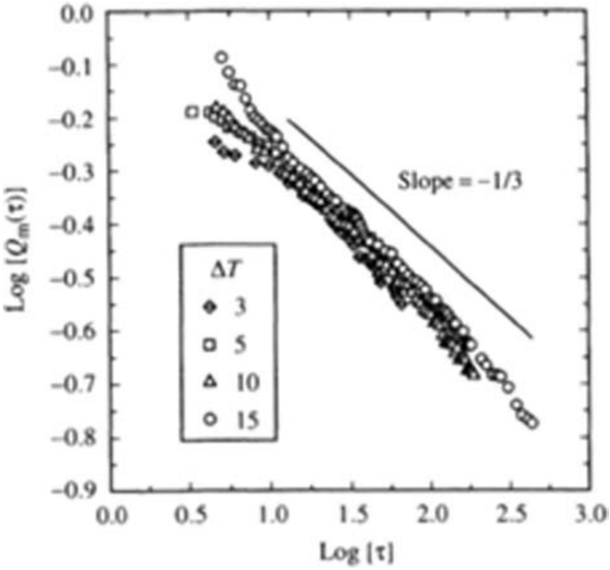

Fig. 13. Characteristics of domain growth during spinodal decomposition of a classical system, a binary fluid mixture that shows demixing upon a temperature quench. Figure taken from [2].

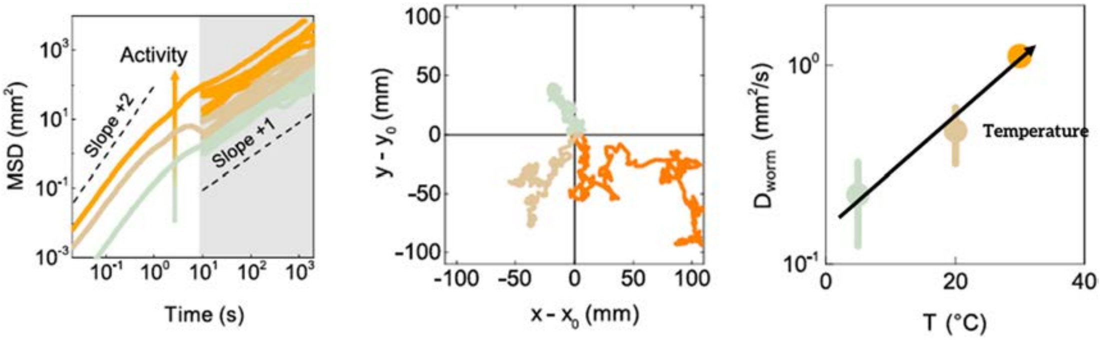

Fig. 14. Mean squared displacement of the worms, measured trajectories, and the effective diffusion coefficient for different worm activities.

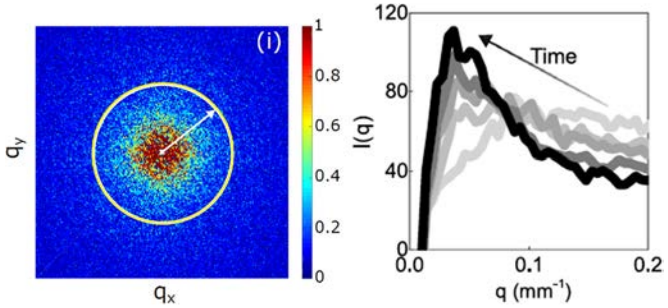

Fig. 15. (Left) Fourier transform of the diffraction pattern formed by 'phase separating worms'. (Right) Intensity as a function of wavevector for the 'phase separating worms'. The peak corresponds to a characteristic domain size, growing (i.e., moving to smaller wavevector) when time increases, similarly to what is observed for spinodal decomposition in a classical phase-separating system.

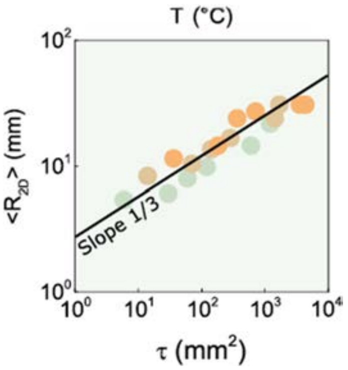

Fig. 16. Growth of the characteristic domain of the worm aggregates, showing a Lifshitz-Slyosov type behavior that is usually observed in 3D classical phase separating system upon a temperature quench.

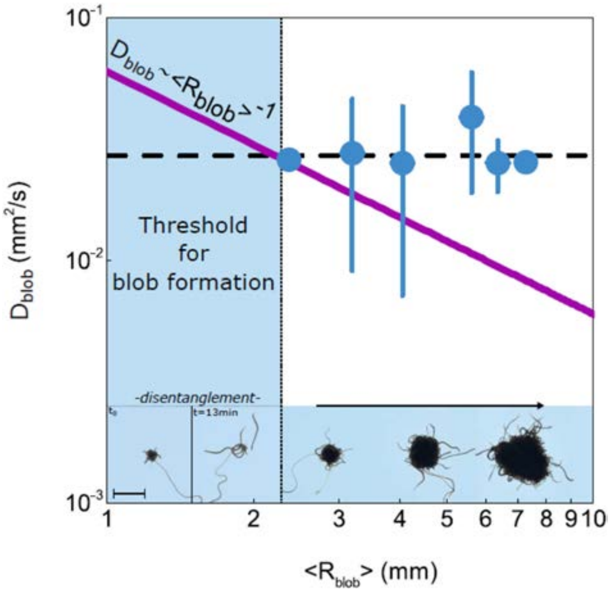

Fig. 17. Blob diffusion. Effective diffusion constant as a function of average blob size at $T = 20$ 20 °C. The purple line shows the expected scaling for particles undergoing Brownian random motion. The experimental data (blue symbols) indicate a diffusion constant independent of blob size.

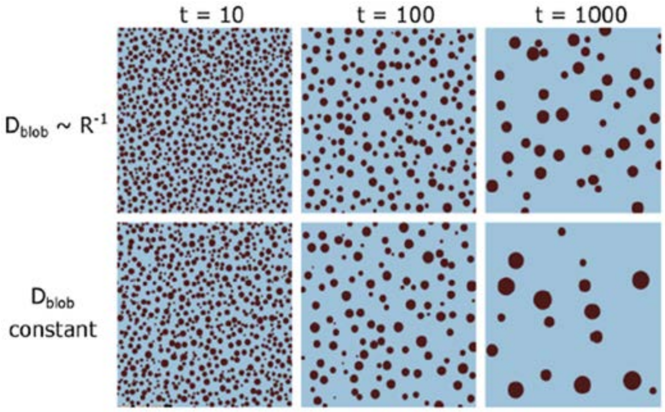

Fig. 18. Simulation of the dynamics of 'Phase separation' for the worm system. The top series is when the blob diffusion coefficient is inversely proportional to the blob size, as it is usually the case for classical systems. The dynamics in the living polymer/worm system is better described by the lower series with a constant blob diffusion coefficient (a shown in Fig. 16).

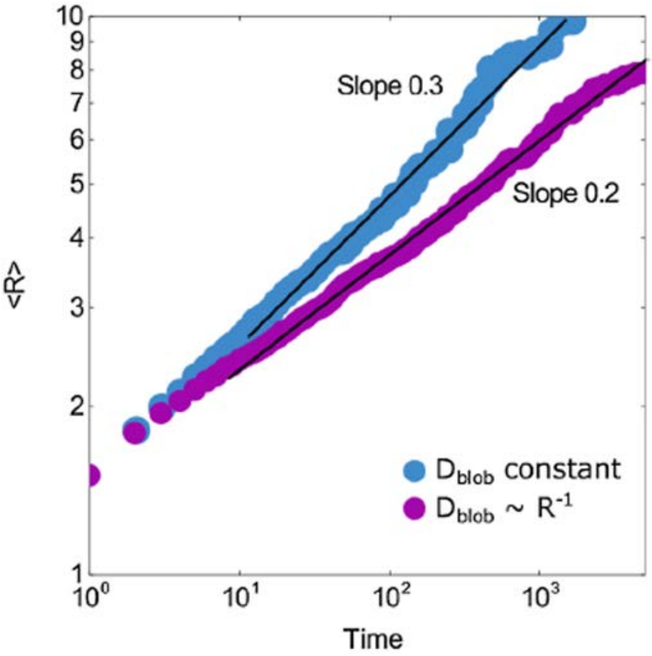

Fig. 19. Log-log plot of the (simulated) domain growth for the two conditions described above; the size-independent diffusion coefficient gives a significantly better description of the experiments.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Further reading

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[journal] A. Deblais, S. Woutersen, D. Bonn, Rheology of entangled active polymer-like *T. Tubifex* worms, Phys. Rev. Lett. 124 (18) (2020), 188002.

Antoine Debla is completed his PhD in physics in 2016 from Bordeaux Université (France), where he focused on the behaviour of complex fluids and the emergent behaviour of a collection of self-propelled bots. After his PhD, he expanded his research on fluid flow instabilities at the Institute of physics in Amsterdam in the group of Daniel Bonn. At this time, he pioneered the study of a new class of active polymer-like particles. He pursued his postdoctoral research with a joint position between Unilever R&D Wageningen and the Institute of Physics at the University of Amsterdam through an individual Marie Skłodowska-Curie fellowship. He established a relationship between the mouthfeel of liquid food product and their (complex) rheology. Since April 2021, he is a group leader at the University of Amsterdam as an assistant professor. His research spans the physics of liquids and complex fluids to active systems that give rise to emergent properties.

Sander Woutersen studied chemistry at the University of Amsterdam, and did his PhD at research institute AMOLF in Amsterdam. After a postdoc with Peter Hamm in Berlin, he returned to Amsterdam, where he eventually became professor in Physical Chemistry. Sander's research focuses on the intersection between spectroscopy and soft matter. His interest in active polymers dates from his teenage years, when he used to feed Tubifex worms to his aquarium fish.

Bonn is professor of Physics at the University of Amsterdam and CNRS Research director. He is serving as the head of the van der Waals-Zeeman Institute and leader of the Soft Matter Group. The overall aim of Bonn's research is to understand the flow behavior of fluids and soft matter systems, including wetting, free surface flows, singularities and instabilities. This is of fundamental interest, but also highly relevant for many applications; he has a lot of industrial collaborations and a successful startup company. He published more than 300 papers and has an established track record in Hydrodynamics, Non-linear Physics, Soft Matter Physics and Statistical Mechanics.