

Simulating the flow of native silk dope in silk glands

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Introduction: The ability to artificially produce silk fibres has great commercial, industrial and scientific implications. Much has been made of natural silk's remarkable mechanical properties but few have considered how they are imparted on the initially liquid silk feedstock.¹ I am exploring how silk duct geometry affects the fibres produced, as by understanding the flow conditions within the model, and comparing them to experimental data, we can progress to the production of fibres with tailored mechanical properties.



Figure 1. Major silk producers: Spiders (L) and silkworms (R)

What is silk?: Silks are a family of naturally produced polymers (biopolymers) produced by spiders, silkworms and many other arthropods. Silks are used in a multitude of environments, for many different tasks, such as building cocoons, lining burrows, catching and preserving prey, and as swaddling cloth for their offspring. However, their defining characteristics are that they are *spun* rather than grown, and that this spinning takes place at the point of delivery. Of all the known silks, it is that produced in spider's major ampullate glands which proves most attractive as a biomaterial, due to its combination of strength, toughness and extensibility (see figure 2).

Industrial challenge: Although silk can be (and is) reeled from live animals, it is time, space and labour intensive, making industrial upscaling difficult. However, if the animal can be removed from the equation through better understanding their internal systems so that a bio-inspired processing tool can be put in its place, we could progress to larger-scale production of this remarkable material.

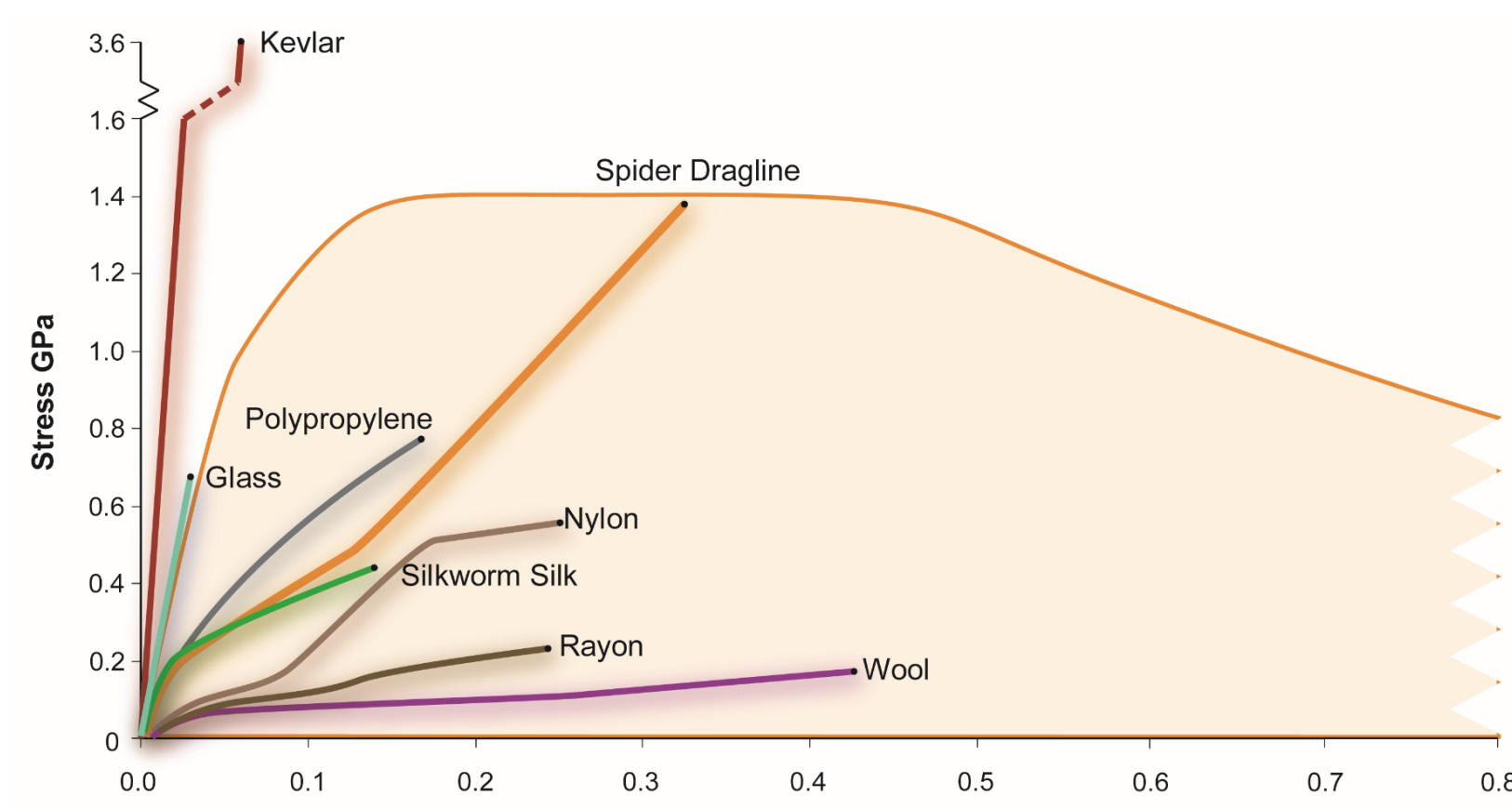


Figure 2. Silk's stress-strain properties

Natural spinning processes: Silk is stored as a concentrated aqueous solution of liquid proteins in the rear of the gland. To turn this into a fibre, it flows along a duct (see figure 3), where fibrillation is induced through a combination of pH change and mechanical shear, arriving at the point of delivery ready for use in its intended purpose.

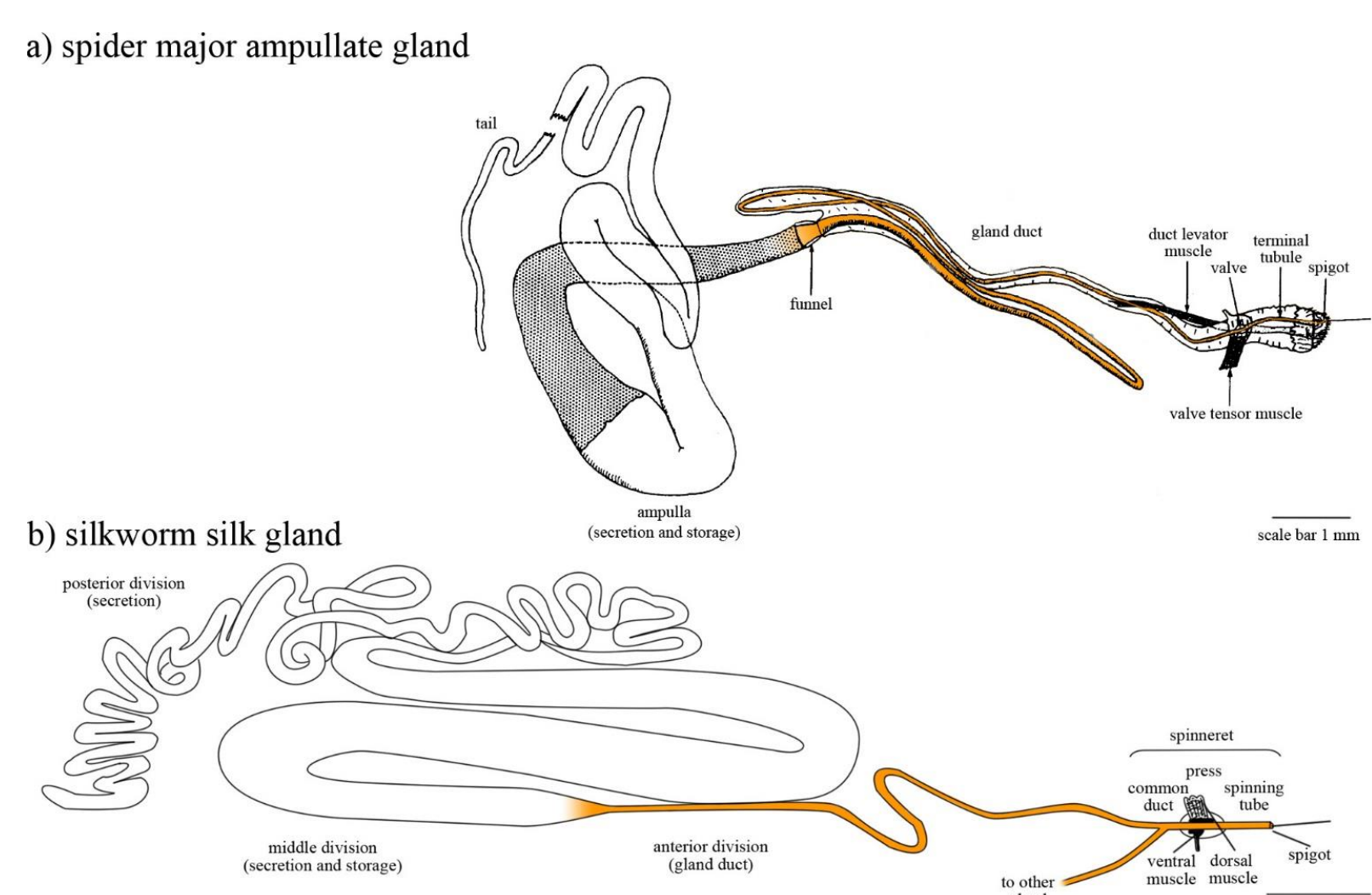


Figure 3. Spider and silkworm glands

Our approach: There have been multiple attempts to create silk protein solutions, but they have generally been frustrated by problems with length, aggregation, and concentration, with the fibres produced so far surprisingly unremarkable. We believe that this is due to not fully understanding how Nature processes the solution, and that this is key to successfully handling these wilful proteins. Thankfully we have access to a detailed silk rheology database, which will allow us to do this.³

Computational Methods: In these early stages, a simplistic model has thus far been used.² The duct is modelled as a hyperbolic taper⁴ using a 2d axisymmetric system.

$$r(z) = ae^{bz} + ce^{dz}$$

r - duct radius
 z - distance along duct
 a, b, c, d - curve fitting parameters

The system has been analysed using a fully parameterised single phase laminar flow model, with inlet conditions specified as the pressure required to achieve natural spinning rates as measure by volumetric flowrates.

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot \left[-p\mathbf{I} + \mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^T) - \frac{2}{3}\mu(\nabla \cdot \mathbf{u})\mathbf{I} \right] + \mathbf{F}$$

$$\nabla \cdot (\rho\mathbf{u}) = 0$$

The viscosity is specified as a Carreau-Yasuda model, which describes a shear thinning behaviour between two plateaus.

$$\eta(\dot{\gamma}) = \eta_0 \left[1 + (\dot{\gamma}\lambda)^a \right]^{\frac{n-1}{a}}$$

η - viscosity
 η_0 - zero shear viscosity
 λ - relaxation time
 $\dot{\gamma}$ - shear rate
 a, n - curve fitting parameters

Results: Variation in viscosity does not affect the total accumulated shear strain, but it does affect the rate at which it is applied in the duct. Broadly speaking, thinner fluids are subjected to faster to shear rates. For a given zero shear viscosity, silkworms show faster exit velocities by an order of magnitude. This is more pronounced at low zero-shear viscosity, becoming rapidly more similar as viscosity increases.

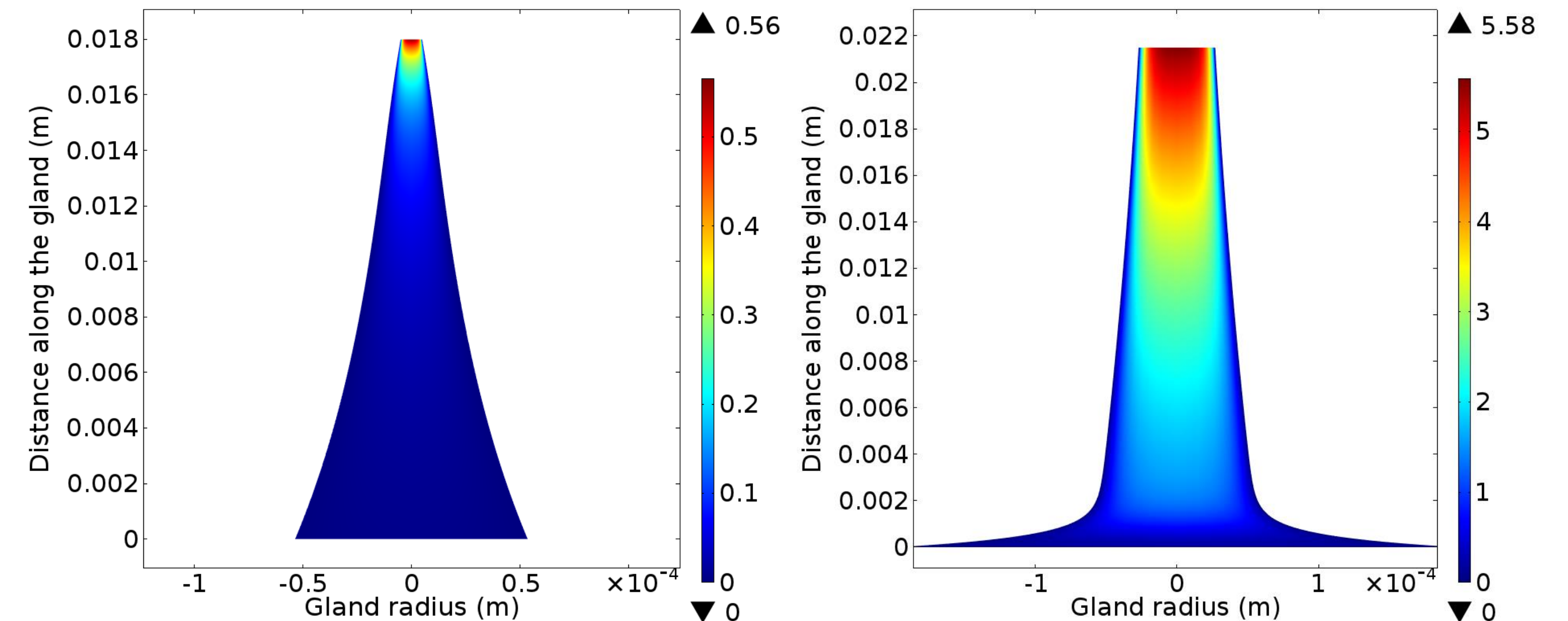


Figure 4. Velocity at 3500Pa.s zero shear viscosity for spider (L) and silkworm (R) ducts

The rates of extension are similar, in that lower viscosity, results in higher extension rates, yet the total accumulated extensional strain increases with viscosity. For both species, the accumulated strain appears independent of zero-shear viscosity. Dope in the spider gland progresses at an order of magnitude slower than in silkworms. The supposition of a hyperbolic taper providing constant elongation⁴ is not supported, as extension rate in both species is shown to be variable (see figure 5), possibly to counter strain hardening effects.

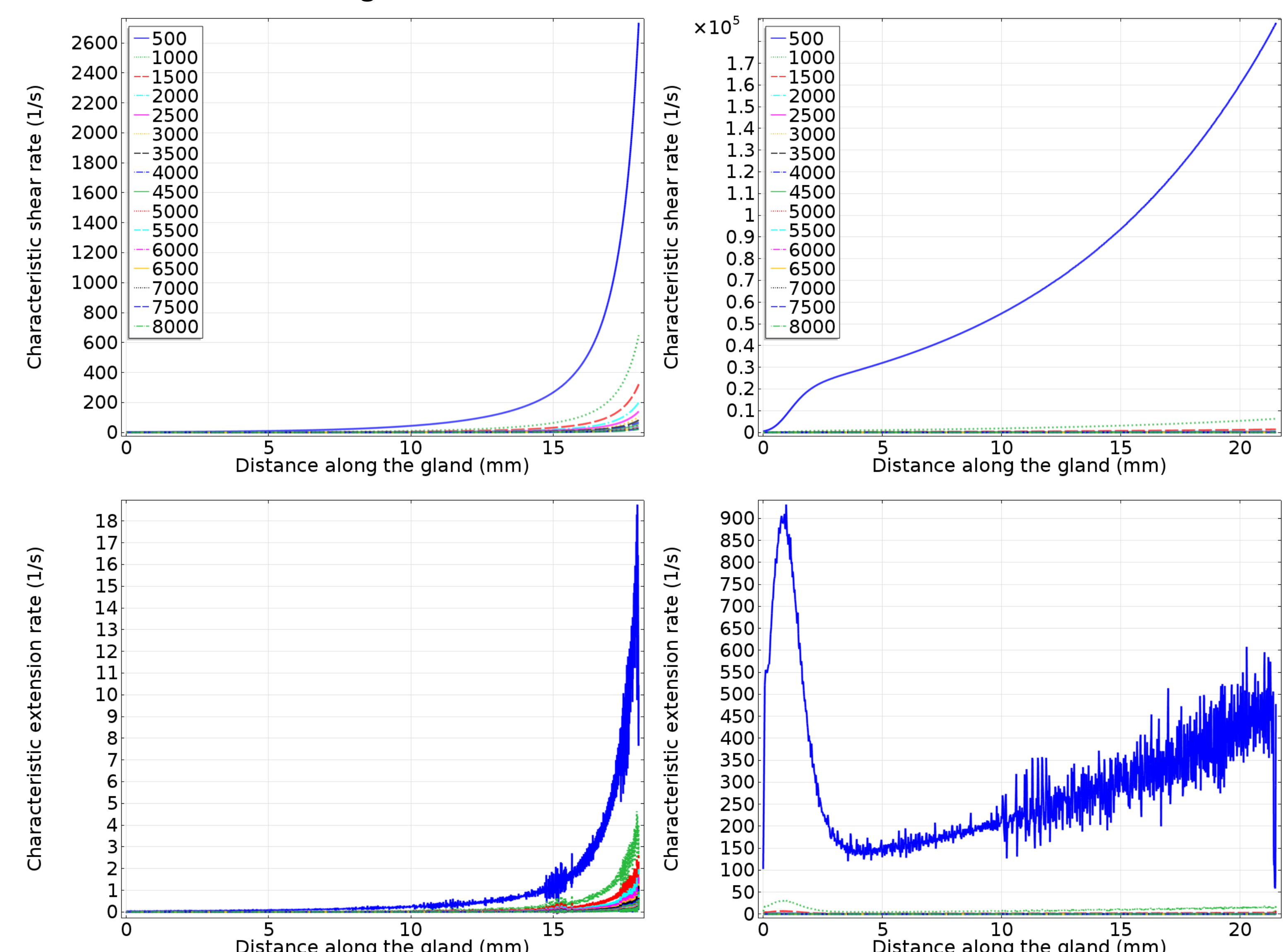


Figure 5. Characteristic shear (top) and extension rates (bottom) for spider (L) and silkworm (R) geometries at a range of zero shear viscosities.

Conclusions: The results broadly support earlier work² and with the more accurate data used, provide a solid foundation for exploring these interesting and unusual fluids.

Future work: Now that the validity of the model has been confirmed it is ready for expansion through developing a 3D model to incorporate bend effects, introduce multiphase flow and by exploring variation in critical shear as a result of geometric variation.

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