Solid Hydrogen Extrusion Modeling

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The Service des Basses Températures of CEA-Grenoble has developed a cryostat able to produce solid hydrogen ribbons of thickness between 50 and 100 µm [1]. These ribbons are intended to be used in high-power laser facilities to study proton-laser interactions.

Numerical simulations are needed to estimate the extrusion parameters for the lowest sizes (5-10 µm).

Prior to calculations, a better understanding of solid Hydrogen is needed. A cryogenic Searl rheometer allows the experimental study of the solid hydrogen rheology. The results are a series of shear stress σ and shear rate $\dot{\gamma}$ relatio

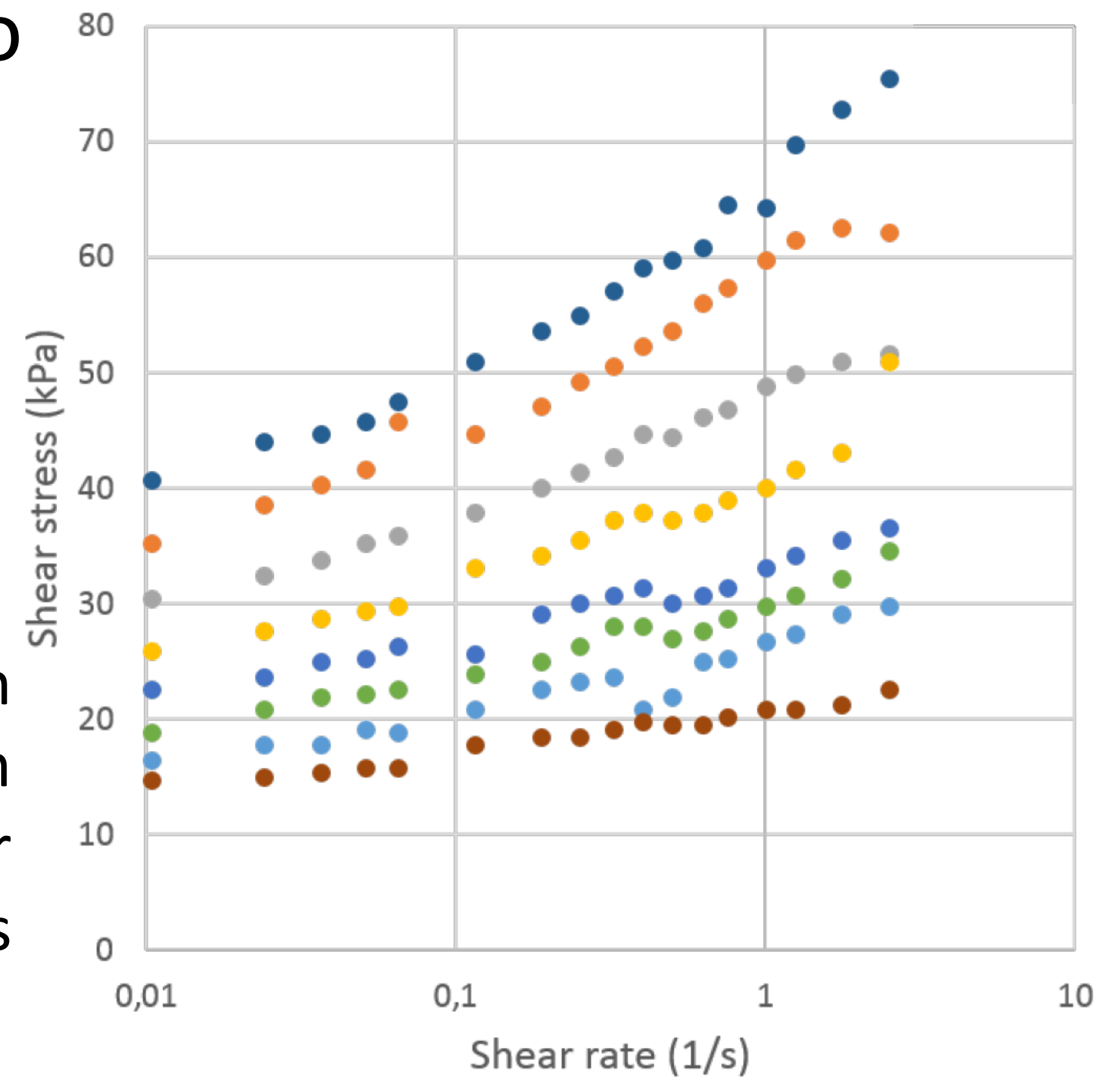

Figure 1. Deformation curves extracted from cryogenics rheometer experiments

COMPUTATIONAL METHODS: The problem is treated as a CFD problem with a non-Newtonian fluid with a threshold:

$$\sigma = \sigma_0 + \mu^*(T, \dot{\gamma}).\dot{\gamma} \text{ if } \sigma > \sigma_0$$

$$\dot{\gamma} = 0 \text{ if } \sigma \leq \sigma_0$$

This formulation can't be used as-is because of the discontinuity at $\sigma = \sigma_0$. Morton et al. [2] give a good insight to the way of obtaining formulations compatible with numerical calculations. Here, a Bercovier-Engelman [3] formulation has been chosen and injected in a user-defined viscosity:

$$\mu\,[Pa.s] = \mu^*(T, \dot{\gamma}) + \frac{\sigma_0}{\sqrt{\dot{\gamma}^2 + \epsilon^2}}$$

The numerical problem converges to the real threshold problem for $\epsilon \to 0$. In fact, calculations show that the results become independent of ϵ for

$$\epsilon < 10^{-6}\,[1/s]$$

σ_0 and μ^* are determined from Shear stress/rate relations:

$$\sigma_0[Pa] = 5{,}997.10^4 - 3{,}75.10^3\mathrm{T}$$

$$\mu^*[Pa.s] = (1{,}25.10^5 - 8{,}08.10^3\mathrm{T}).\dot{\gamma}^{-0.82}$$

The hydrogen flow shows shear-thinning properties.

First, the rheology experiments are modeled to check the viscosity law. The rheometer geometry is the following:

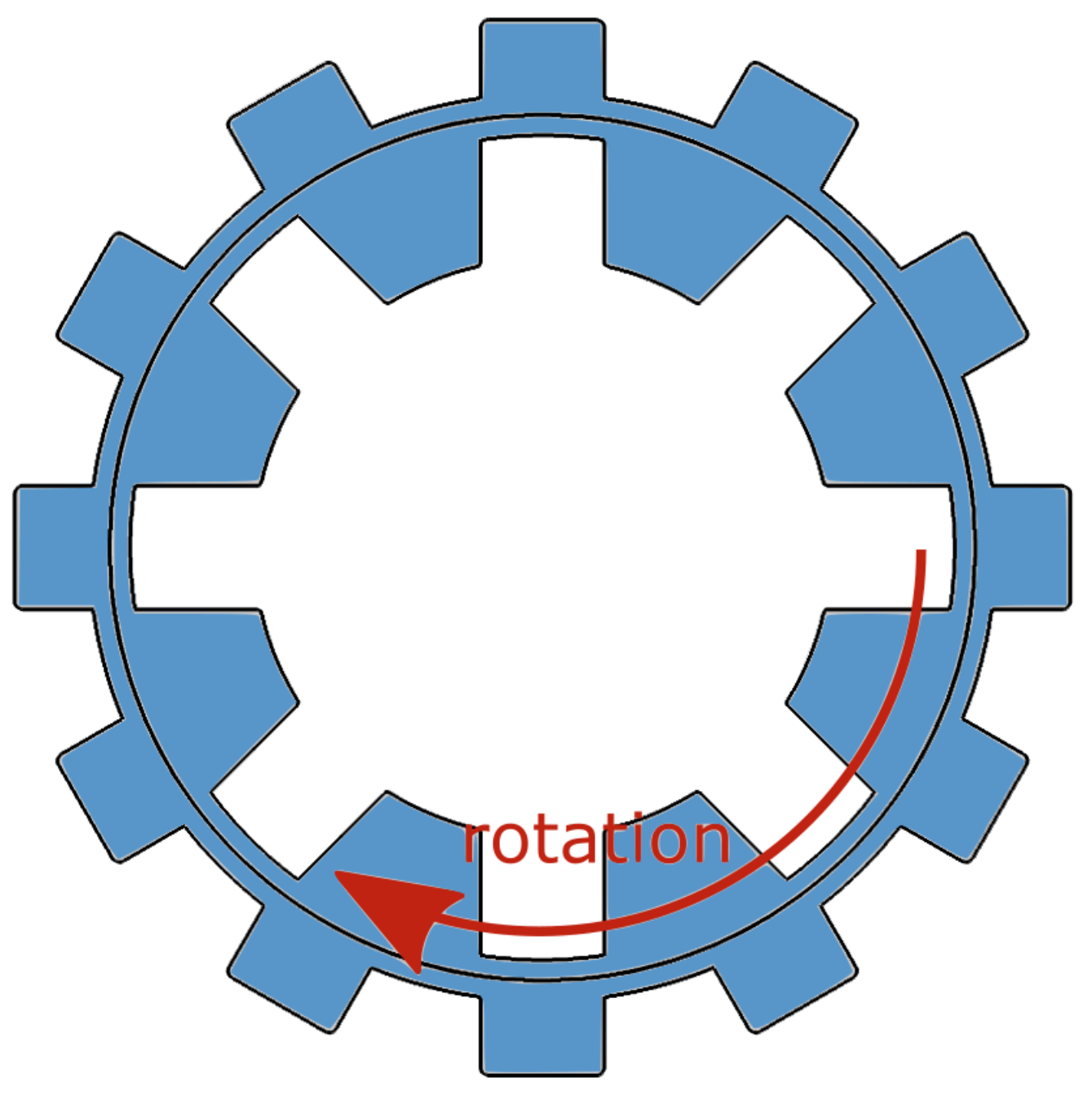

Figure 2. Geometry of rheometer.

This is a frozen-rotor problem, the inner wall is moving. A moving mesh is setup and a revolution f[1/s] is applied to the inner domain.

The couples as a function of f obtained are in good agreement with measurements.

The relevance of the non-Newtonian problem modeled by a user-defined viscosity is proven.

Then, extrusion experiments are modeled. The model geometry is 2D axisymmetric, taken from the CAD.

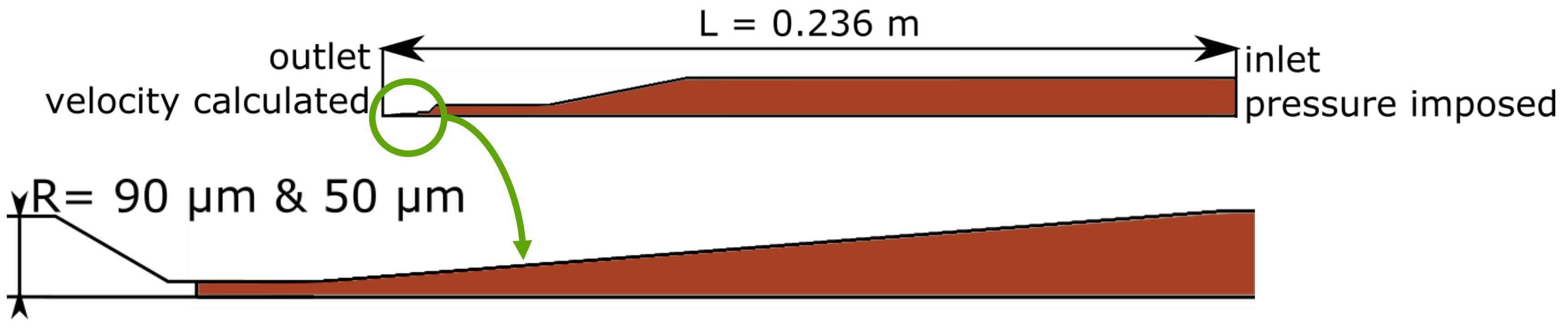

Figure 3. Geometry of the cell and nozzle close-up

The results are somewhat mixed. Qualitatively, the outlet velocities show similar shapes. But the order of magnitude is very different and the velocity evolution with pressure is too important.

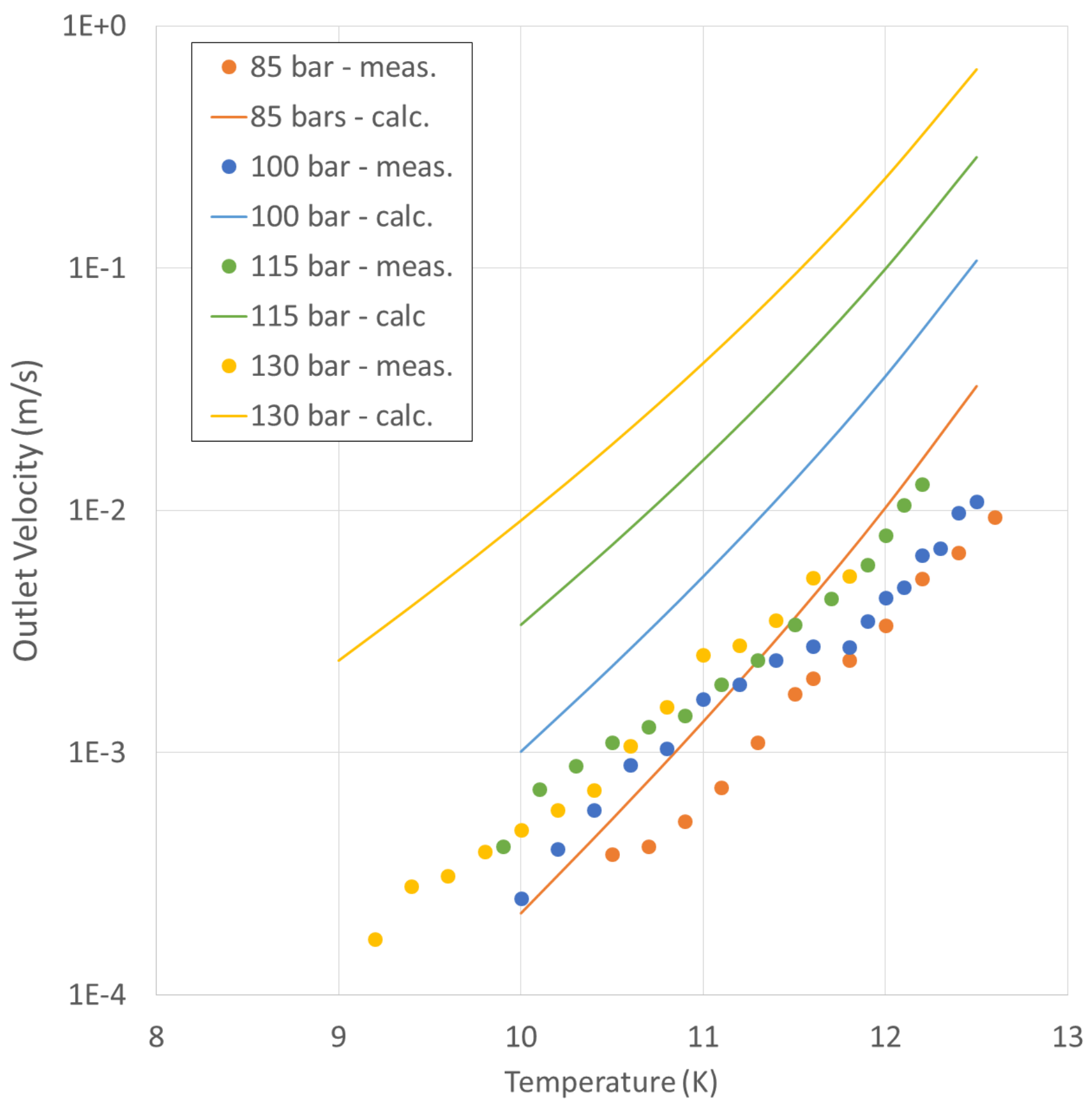

Figure 4. Calculated outlet velocity vs measurements.

These results shows that a mechanism is not understood in the solid hydrogen extrusion. In particular, the outlet velocity is very sensitive to variations of inlet pressure. Additional results shows that a 30 % pressure reduction from 130 bar allows to gain two orders of magnitude in the extrusion velocity and a reasonable fit of the measurements.

REFERENCES:

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2. Denn, M.M. & Bonn, D. Rheol Acta (2011) 50: 307
3. Bercovier M, Engelman M, A finite-element method for incompressible non-Newtonian flows. J comput Phys 36: 313-326