GENERAL DYNAMICS
Ordnance and Tactical Systems–Canada Valleyfield

POLYTECHNIQUE MONTRÉAL
WORLD-CLASS ENGINEERING

Implementation of Multilayered Propellant in Concentric Cylinders

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1- Introduction:

To establish the criteria that render possible the extrusion of multilayered propellants in concentric cylinders, this study optimized a die design that enables the widest possible range of material viscosities while keeping the flow balanced. The main challenge originated from the different path lengths between the inner and outer sections of the die, both coming from the same pressure driven flow as shown in **Figure 1**:

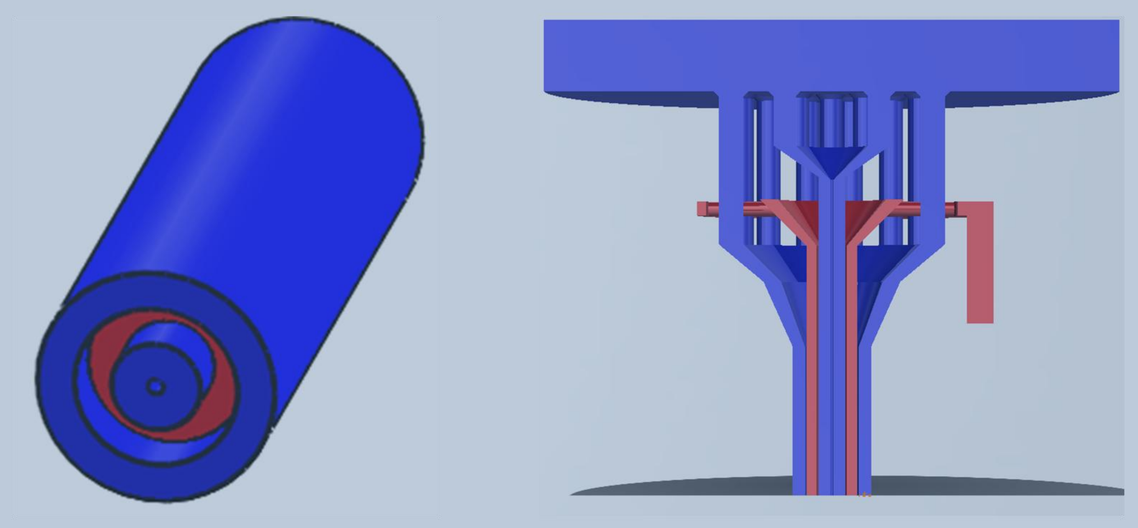

Figure 1. Geometry involved during this study.

The mid section of the geometry is filled with a low viscosity fluid whose flow rate can easily be set to match the flow in the other adjacent sections. This study collected rheology data and used these data in finite element simulations for extrusion die optimization. The Computational Fluid Dynamics models included heat Transfer and viscous heating to study the non-isothermal steady state flow behavior.

2- Background:

In collaboration with US Army ARDEC, basic geometries of multilayered propellant extrusion have been successfully achieved at General Dynamics with promising ballistic results. **Figure 2** shows an example of the propellant manufactured:

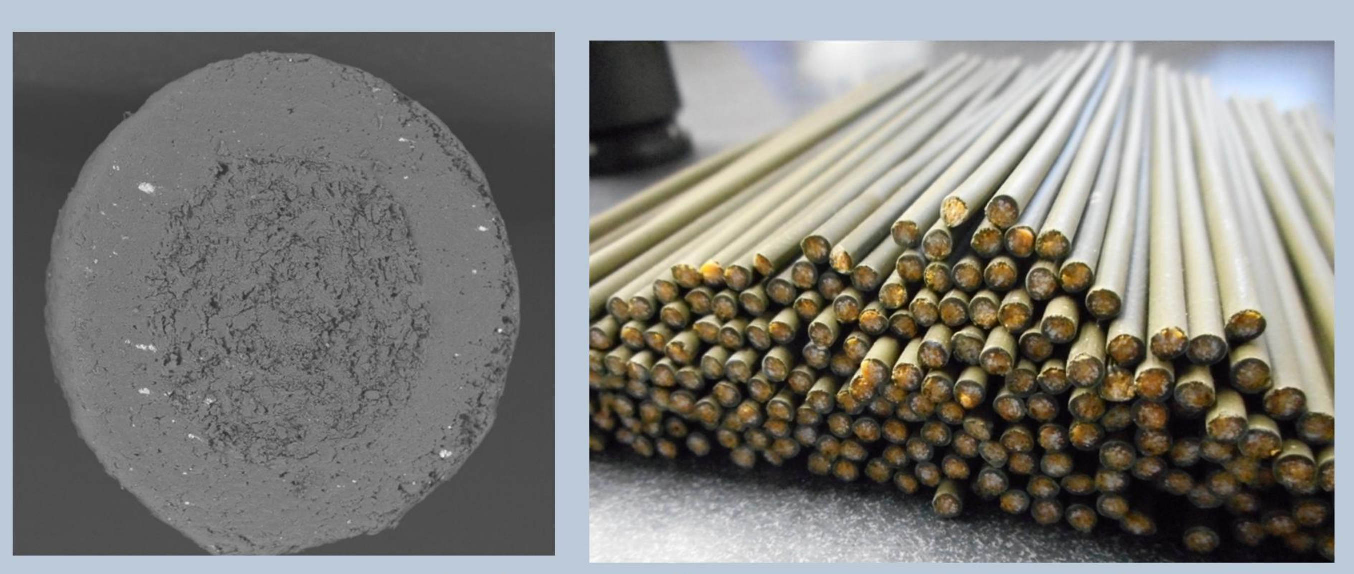

Figure 2: Coextruded propellant manufactured at GD-OTS Valleyfield and electronic imagery showing the bounding between the two layers.

3- Rheology study:

3.1- Slow formulation:

To cover the maximum range of formulation available for coextrusion, a complete rheology study has been conducted on several samples:

Capillary rheometers

A first study by capillary rheometers determined the absence of wall slip and general flow behavior of the triple base (**Figure 3**) and double base samples (**Figure 4**)

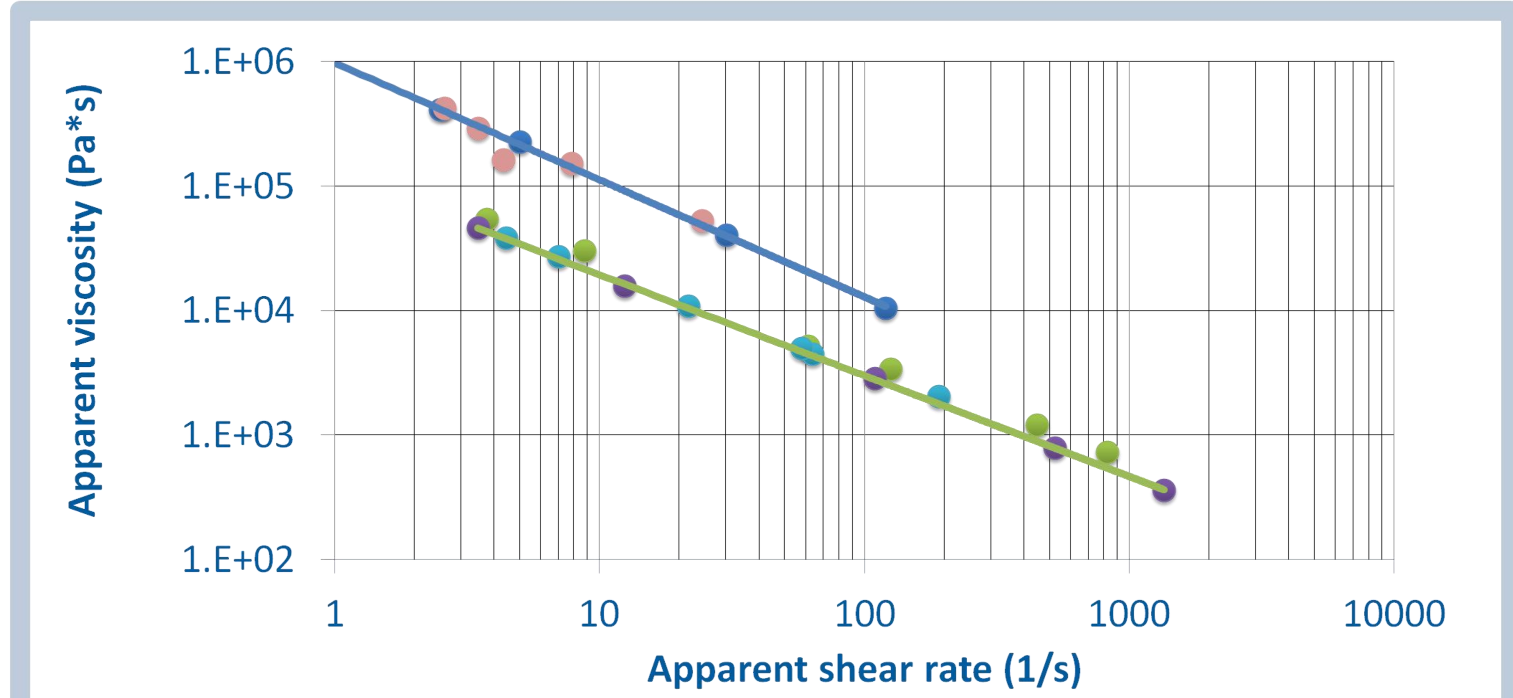

Figure 3: Example of data superposition, apparent viscosity vs. apparent shear rate of the two triple base samples, "average" in green and "high" solvent concentration in blue.

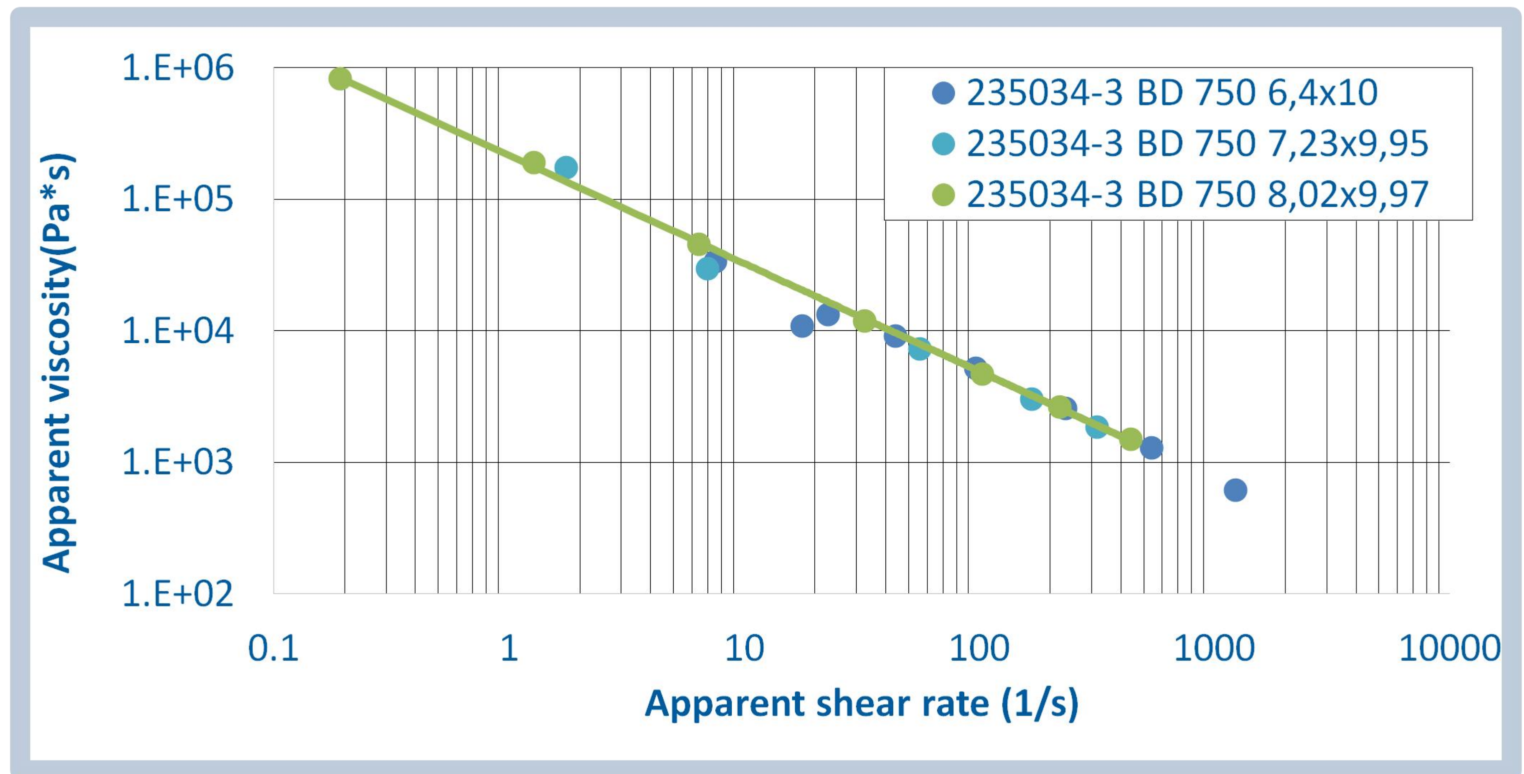

Figure 4: Example of apparent viscosity vs. apparent shear rate of a double base sample (average solvent concentration)

Rotational rheometer

The absence of wall slip has also been verified on a rotational rheometer with the superposition of different gap between the 25mm parallel plates.

Finally, the influence of temperature has been studied on the flow behavior on the same double base sample **Figure 5** :

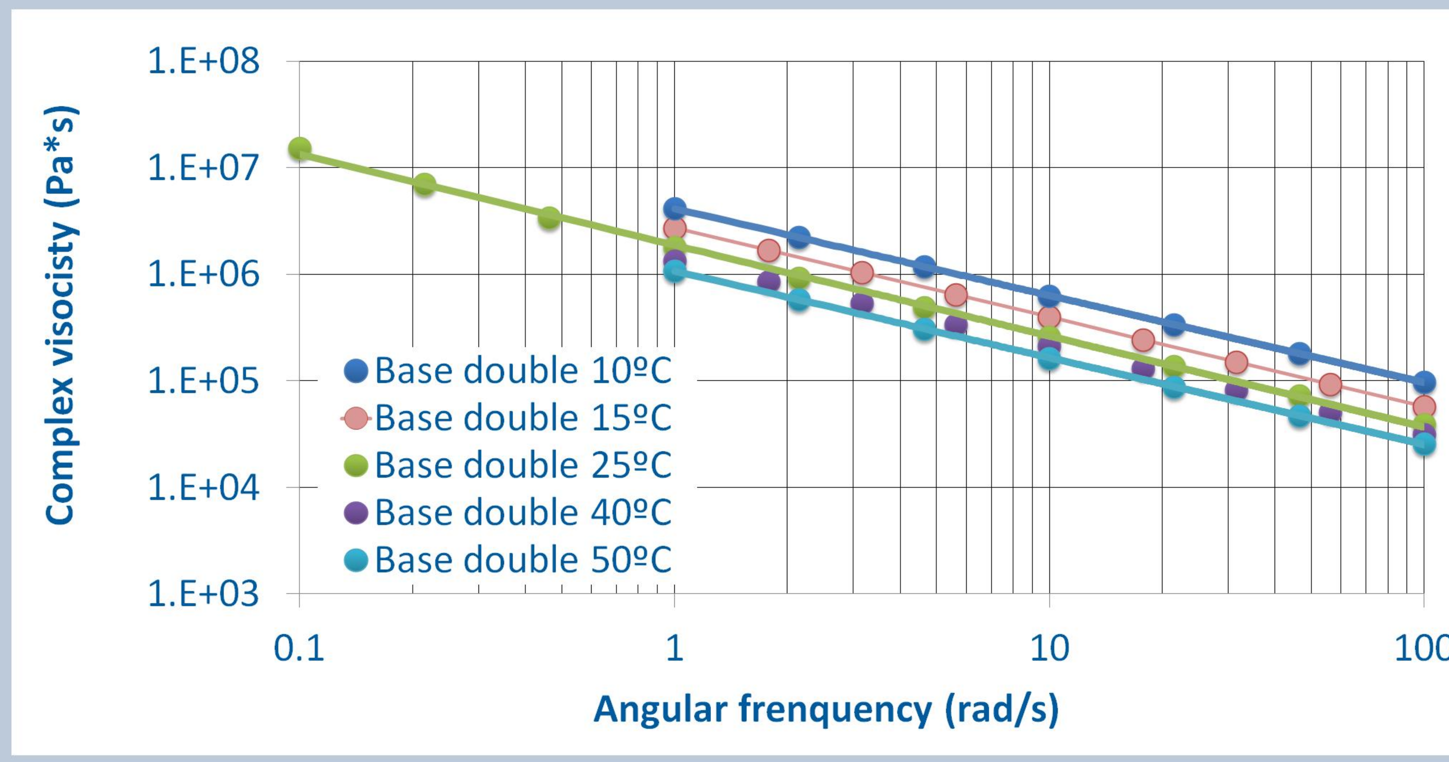

Figure 5: Temperature effect on paste viscosity

3.2- Fast formulation:

A similar approach by rotational rheometer has been conducted on the fast formulations as shown on Figure 6:

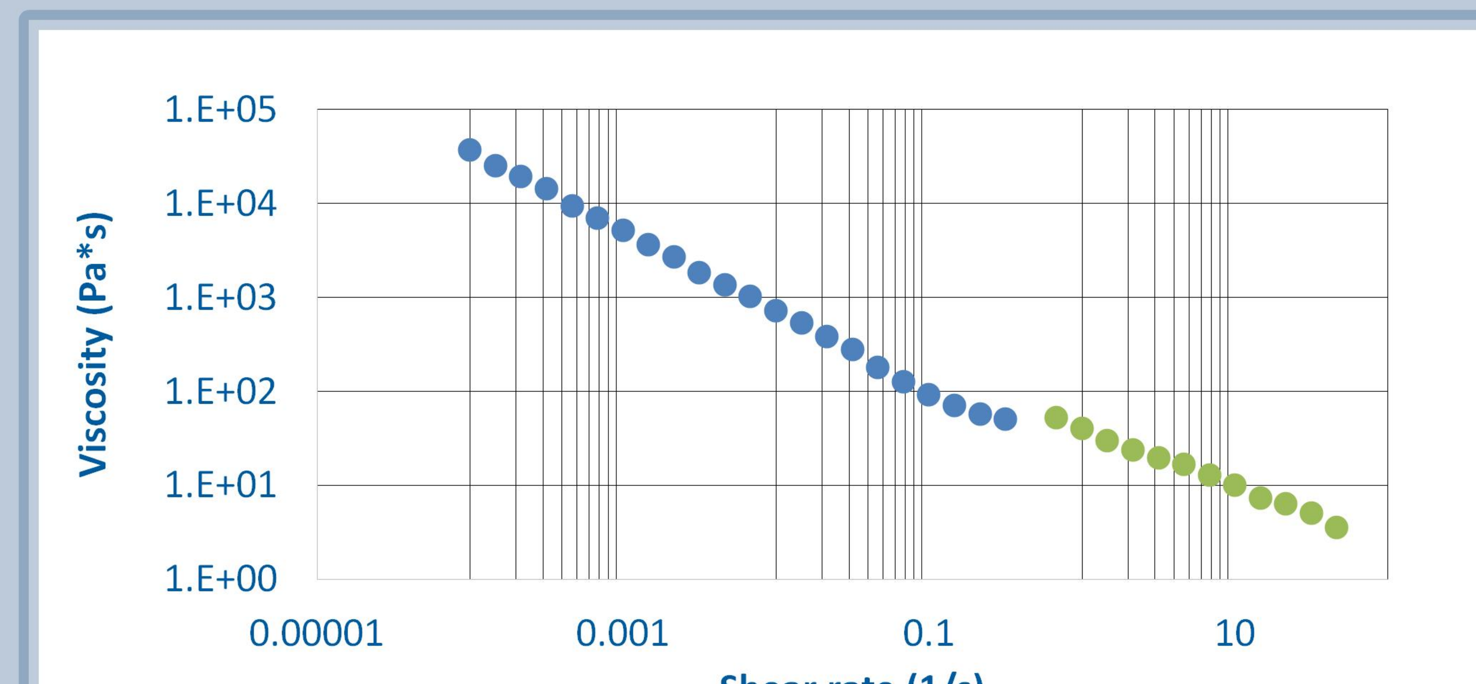

Figure 6: Example of viscosity as a function of shear rate, fast formulation.

The power law viscosity model without wall slip was the most suited model for all formulation studied, both fast and slow.

Power law model: $\eta = k * \dot{\gamma}^{n-1}$

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4- Computational Methods:

Using COMSOL CFD and Heat Transfer modules, a study has been conducted on multiple die configurations to find a design that enables a wide range of materials with different rheological properties while keeping the flow balanced. The viscosity as a function of temperature was expressed with the Arrhenius equation as follow:

$$\eta(\dot{\gamma}, T) = \eta_0 \exp\left[\frac{E}{R} * \left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

4.1- Results:

Fast formulation flow balance, isothermal:

The flow has been balanced through the fast formulation section of the extrusion die by modifying each channel diameter. **Figure 7** shows the meshed fast formulation internal flow geometry while **Figure 8** shows the velocity profile of different channel patterns:

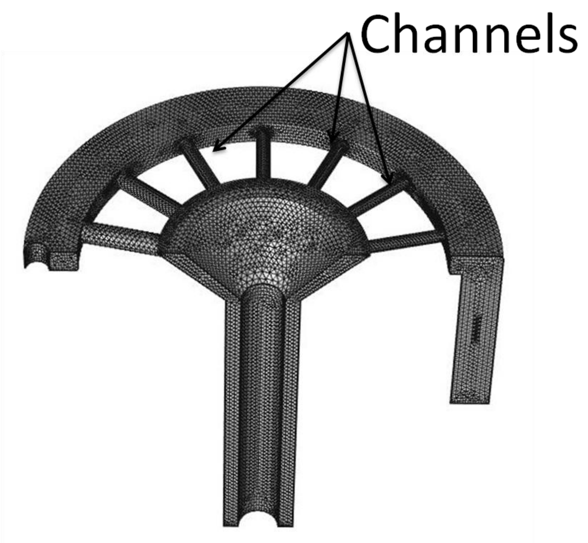

Figure 7: Meshed fast formulation flow pattern.

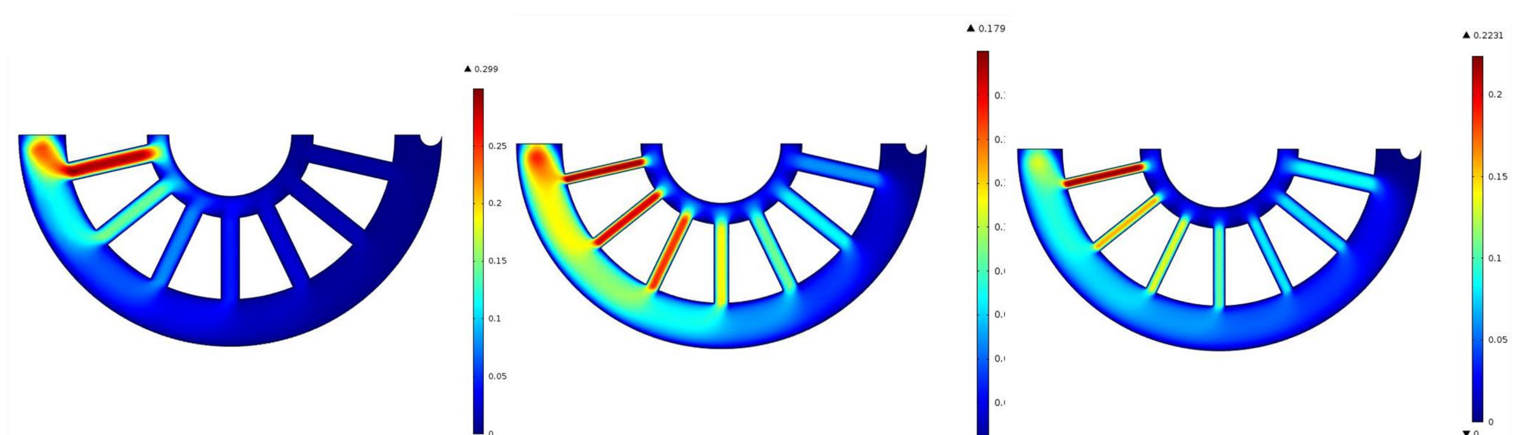

Figure 8: Cut section: Velocity profile of the fast formulation: from left to right: pattern of equal diameters , linear increase, exponential increase. Images taken at n=0.4

Slow formulation flow balance, isothermal:

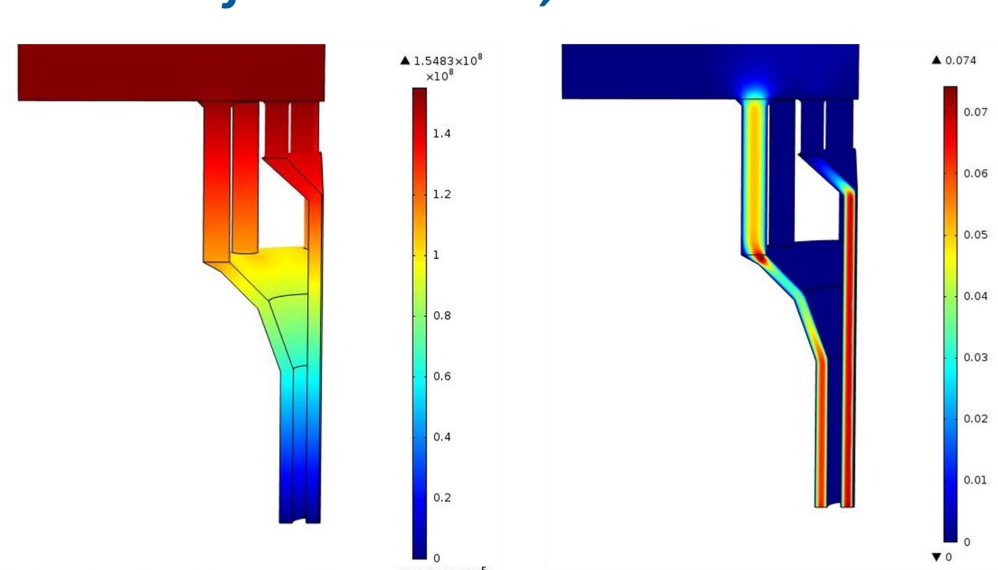

Figure 9: First design, the inner section is favored for low value of "n" . Pressure distribution (left) velocity profile (right.)

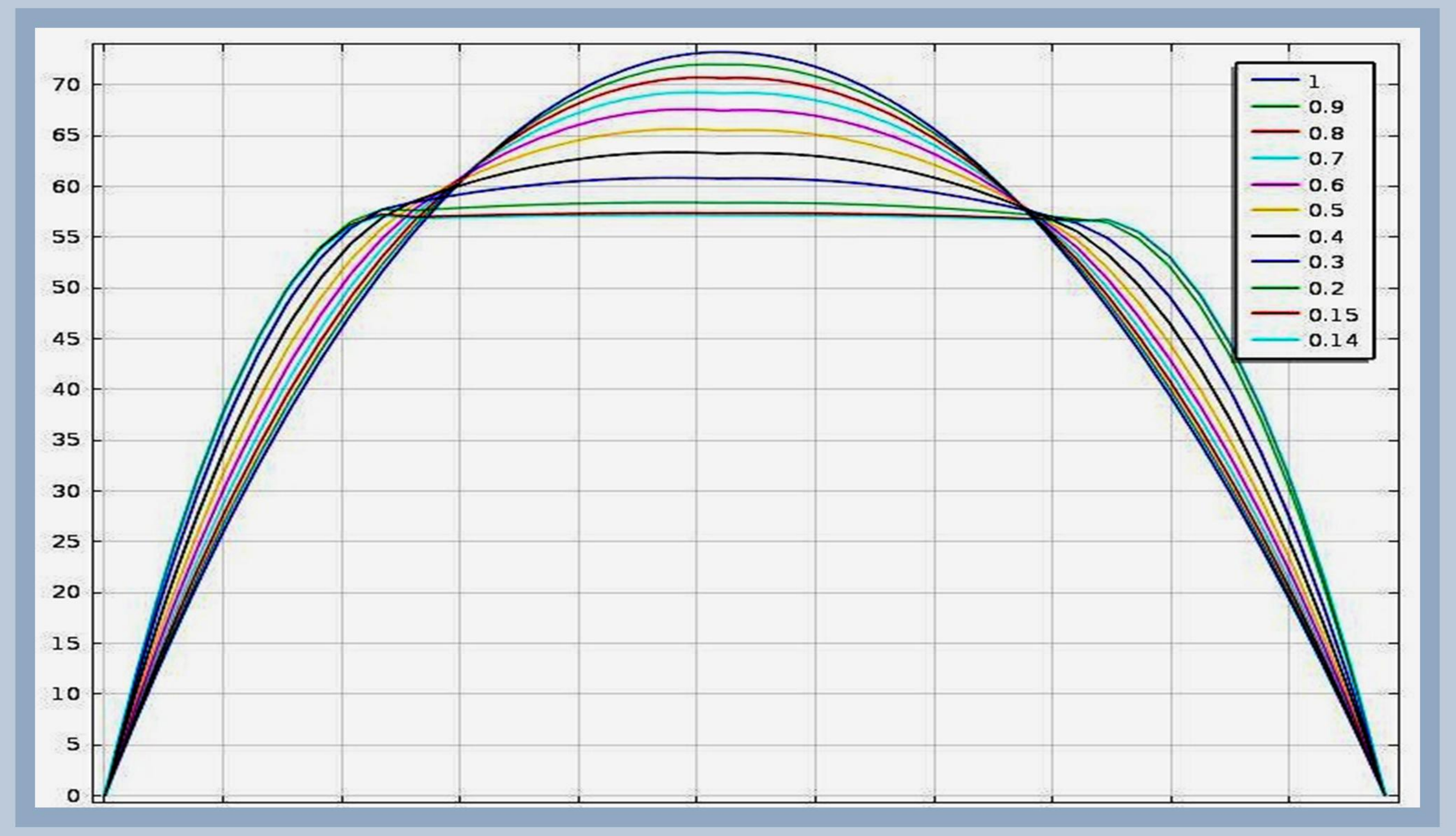

Figure 10: Velocity distribution example in the developed section of the die for different *n* values.

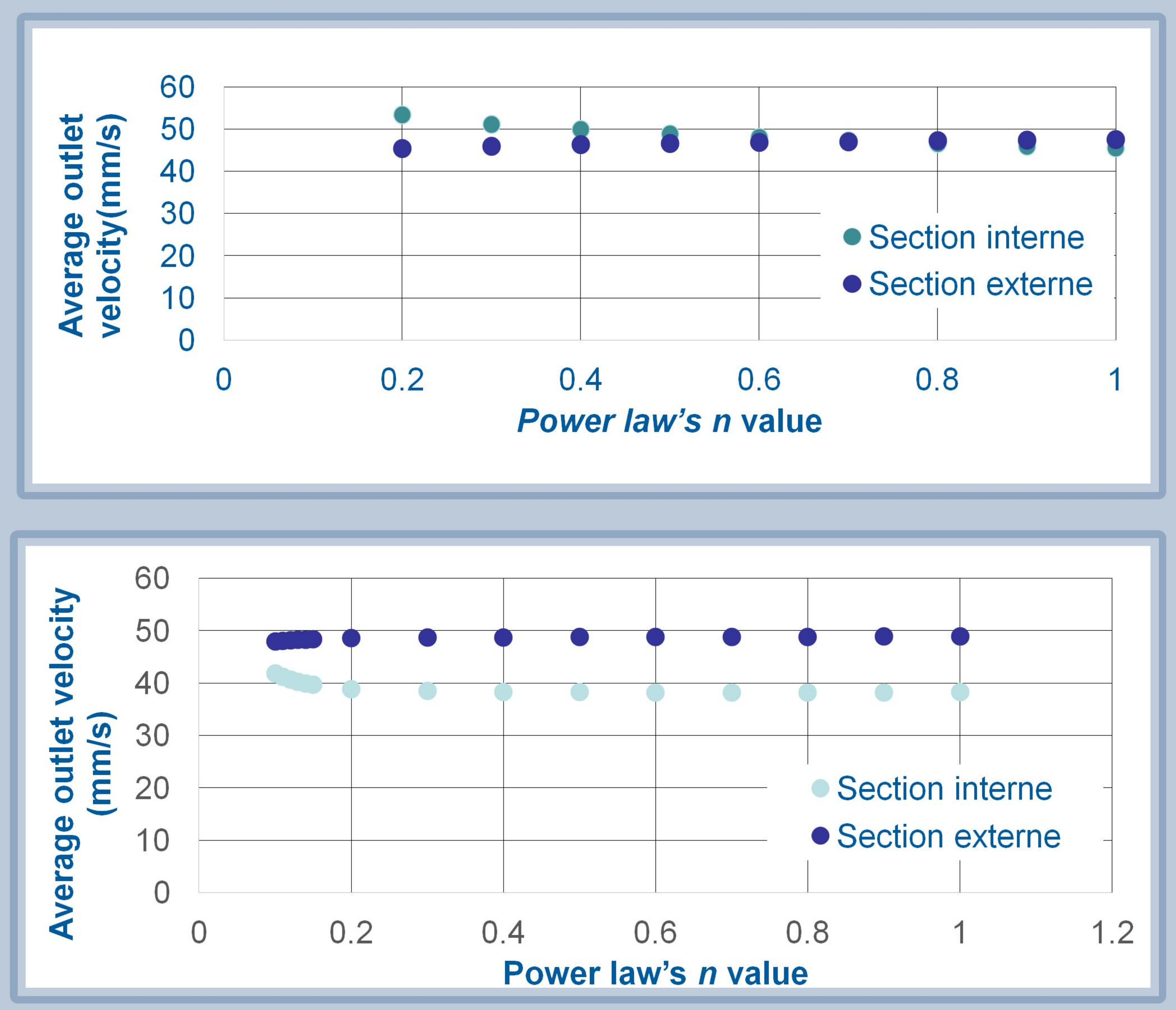

Figure 11: Average outlet velocity comparison between internal and external outlets as a function of *n*.
First design (above) vs. optimised design (below)

Non-isothermal complete flow study with viscous heating:

The propellant dough being a poor thermal conductor, the inner section becomes warmer than the mid and outer section due to viscous heating. These higher temperatures lower the viscosity of the dough in this particular section, enabling a higher flow rate.

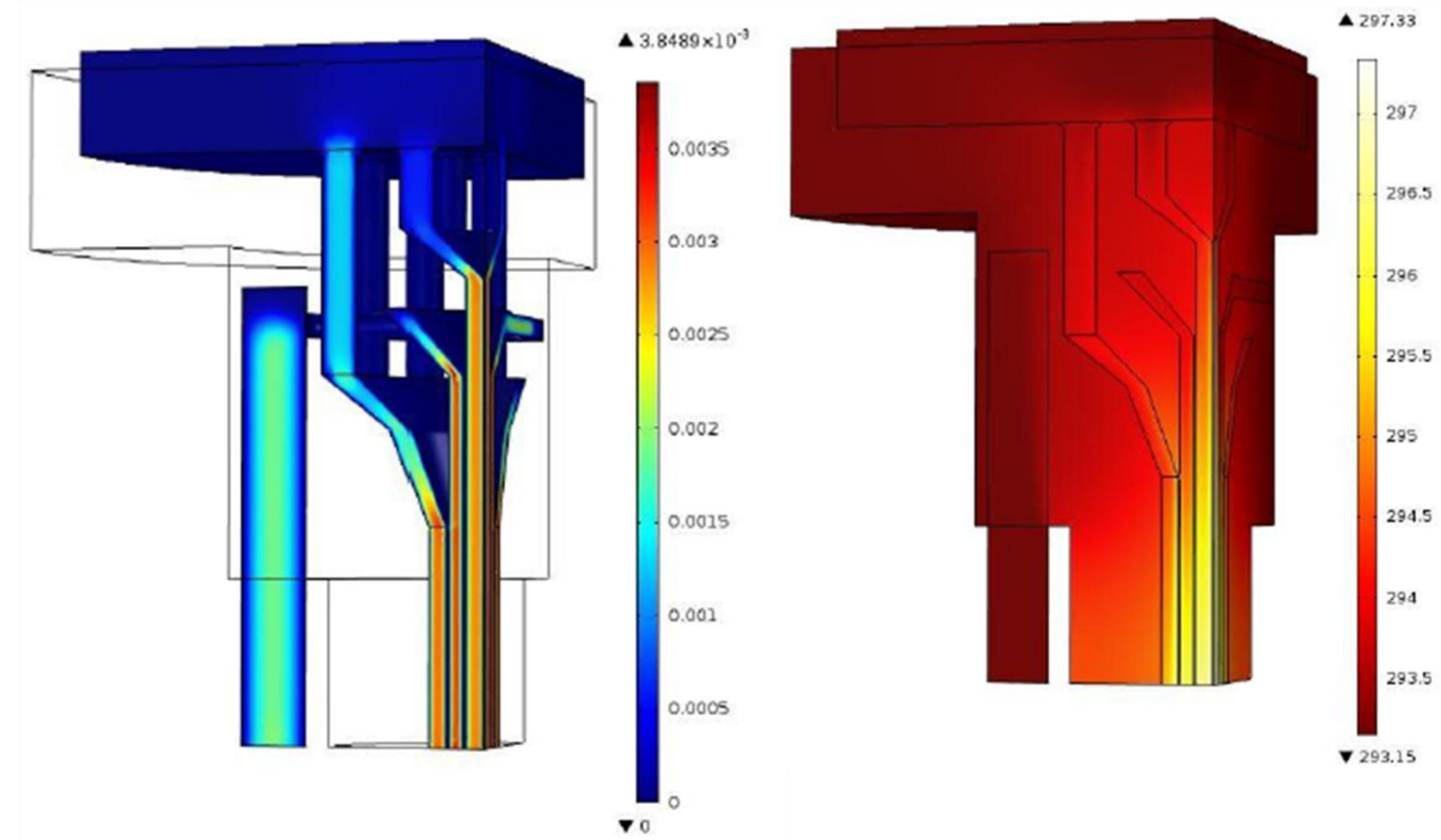

Figure 12 Velocity profile (left) and thermal distribution under steady flow conditions (right) of the optimised extrusion die design.

5- Laboratory validation:

Effect of viscous heating without heat dissipation

• The inner section is extruded faster due to its lower viscosity resulting from viscous heating.

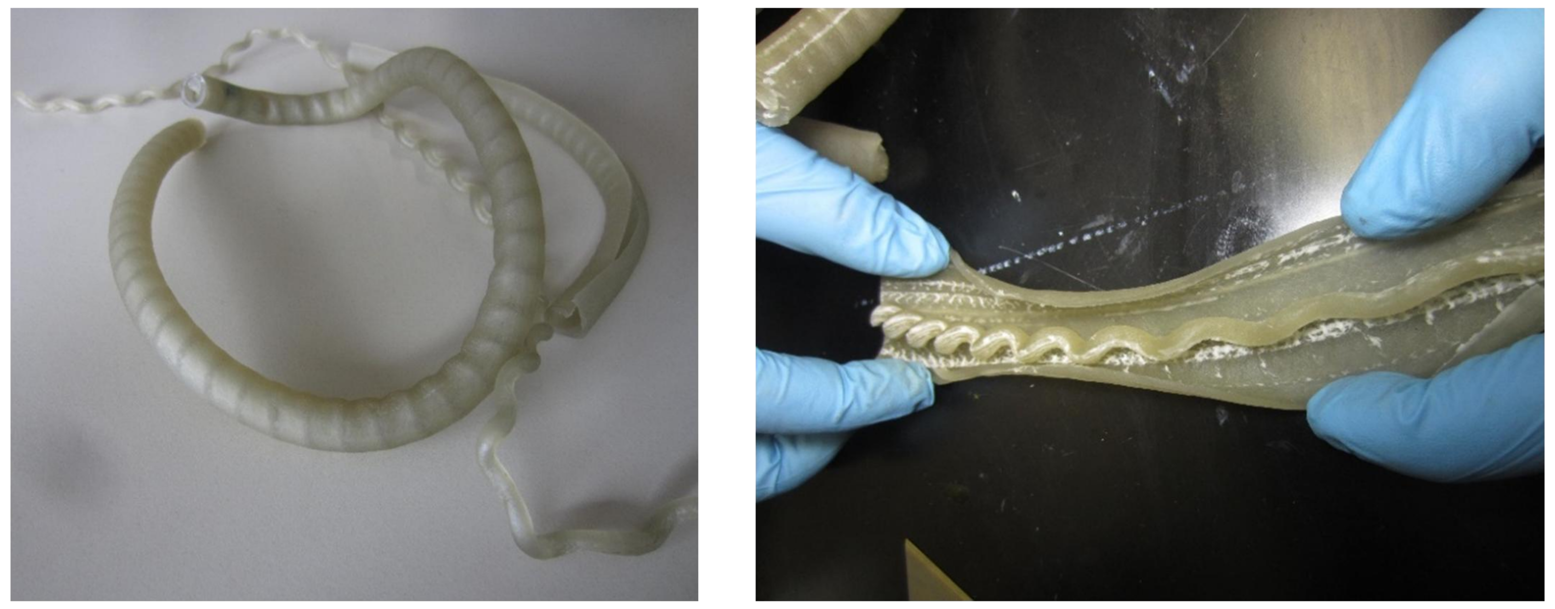

Figure 13: Extruded double base without the fast formulation.

6- Conclusion

Results emphasize the relevance of the **viscous heating** and the **shear thinning** behavior of this rheologically complex fluid in the design process of the extrusion dies.

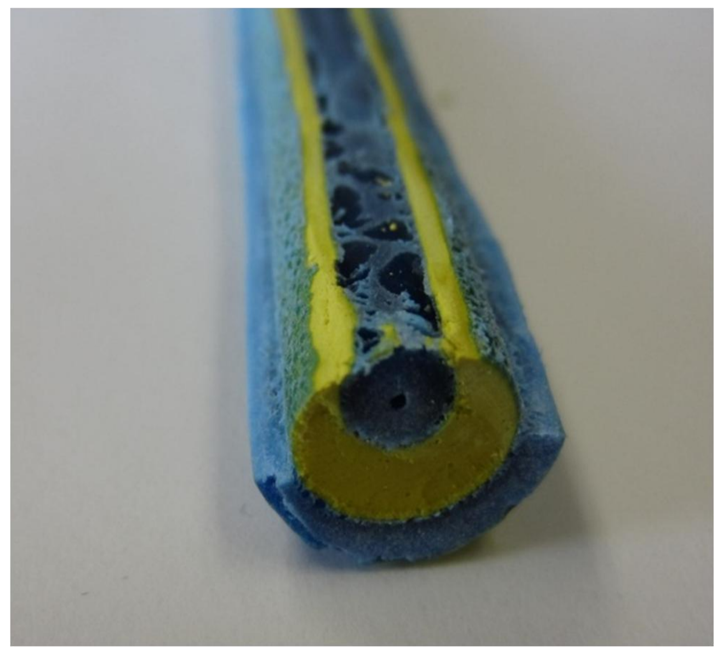

Figure 14: Coextruded complex geometry