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Simulation of gelled propellant doughs isothermal flow through extrusion dies using finite difference method

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Abstract

During the ram extrusion of gelled propellants, the possible flow instabilities can affect the extruded propellant quality. The numerical modelling helps to enhance the geometry of extrusion die, by minimizing the product distortion caused by material flow during this forming process. In the present work, a numerical model based on the finite difference method is proposed to analyze the flow simulation of double-base gelled propellant doughs through annular channels of extrusion dies. The proposed model implements the pseudo-plastic behavior described by these energetic materials. This model will be used to deduce the configuration of spider legs and annular channels that allow optimize the quality of extruded gelled propellant.

Keywords: gelled propellants, ram extrusion, numerical simulation, extrusion die, annular channels

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1. Introduction

Gelled propellants present a very high viscosity and complex rheological response during their processing in semisolid state. Specific applications of the colloidal or gelled propellants are fundamentally medium-caliber ammunition, artillery ammunition and mortar ammunition. Within the context of multi-base propellant manufacturing at industrial systems, the extrusion process has a remarkable importance due to severe requirements about mechanical and also ballistic properties to be guaranteed in these special materials.

During ram extrusion of gelled propellants, flow instabilities affect the extruded propellant quality, and so numerical modelling is needed to enhance the extrusion die for minimizing the product distortion and power consumption [1-3]. There are diverse studies about the numerical modelling of extrusion flow of Herschel-Bulkley materials and gelled propellants, as well as about the extrusion flow in annular dies [4-6].

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Some of these works are focused on the numerical simulation of axysimmetric extrusion flows, and the extrusion flow in annular channels [6-7], with numerical models based on the finite element method (FEM). The shear flow behavior of propellant doughs is usually represented by the Herschel-Bulkley model, which includes shear-thinning behavior with yield stress, while the lineal elastic behavior under shear have been described by the shear elastic modulus G' (storage modulus) [8-10].

In the present work, a numerical model based on the finite difference method is proposed to analyze the flow simulation of double-base gelled propellant doughs through the annular channels of extrusion die. This model will be applied to deduce the optimum geometry of spider leg (mandrel support system) and the optimum shape and length of annular channels, in order to enhance the quality of extruded gelled propellants, considering the pseudo-plastic behavior of these compounds.

The numerical model proposed in this paper is based on the finite different method (FDM), using the commercial software FLOW-3D. This model allows analyze the rheological behavior of propellant doughs through the complex geometry channels of extrusion die. For a given mandrel size, the influence of spider leg configuration and die land holes distribution on the extrusion process performance and distortion conferred to the extruded grain are studied by the numerical model, considering different geometrical alternatives for spider leg and die land holes.

2. Procedure

2.1. Methodology

The numerical modelling of this study is focused on the shear flow in annular channels of extrusion dies, which represents the second stage of extrusion process. This stage includes the analysis of material flow through the spider legs and annular channels that allow the shaping of gelled propellants.

The rheological data about the double-base gelled propellant required for numerical model were measured by torsional flow tests using a TA Instruments DHR-1 rotational rheometer with parallel disk geometry, and the software TRIOS was applied for rheological data processing.

The rheological parameters for the Herschel-Bulkley model were deduced from a combination of torsional flow and steady torsional flow tests, as a consequence of the difficulty of flow tests for these concentrated suspensions [3, 5].

Two different alternatives about the spider legs geometry and three distinct wall conditions at the extrusion die were evaluated. This comparison served to identify the optimum friction wall conditions to implement in the theoretical model.

For numerical simulation of extrusion process, creeping flow conditions with isothermal flow and incompressible fluid can be considered. The material forming is governed by the conservation equations of mass and momentum, which in this case would take the following tensorial expressions [11]:

$$\nabla \cdot \boldsymbol{v} = 0 \tag{1}$$

$$-\nabla p + \nabla \cdot \bar{\bar{\boldsymbol{\tau}}} = 0 \tag{2}$$

where $\mathbf{v}$ is the velocity vector, p is the hydrostatic pressure and $\bar{\bar{\boldsymbol{\tau}}}$ is the stress tensor.

The Herschel-Bulkley model was employed to describe the rheological behavior of this double-base gelled propellant. This model provides the viscous law for this energetic material according to the following expression [2]:

$$\begin{aligned} \bar{\bar{\boldsymbol{\tau}}} &= \frac{\tau_y + K\,\dot{\gamma}^{\,n}}{|\dot{\gamma}|}\,\bar{\bar{\dot{\boldsymbol{\gamma}}}} && when\ |\tau| > \tau_y \\ \dot{\gamma} &= 0 && when\ |\tau| < \tau_y \end{aligned} \tag{3}$$

where $\bar{\bar{\boldsymbol{\tau}}}$ is the stress tensor, $\bar{\bar{\dot{\boldsymbol{\gamma}}}}$ is the shear rate tensor and τ_y is the yield stress.

For numerical modelling of the elastic behavior of the gelled propellant doughs, this material is consider as a Hookean elastic solid below yield stress, and so the storage modulus or shear elastic modulus G' is adopted to simulate the elastic stress [10]:

$$\overline{\overline{\boldsymbol{T}}} = 2\ G'\ \overline{\overline{\boldsymbol{E}}} \tag{4}$$

where **T** is the Cauchy stress tensor and **E** is the strain tensor.

Among the boundary conditions assumed for the FDM numerical model, wall shear stress was evaluated through a friction factor, and so the shear rate at the wall is $\mathbf{v}_w = 0$. The boundary condition of no normal flow to the surface was imposed at the free surfaces, which means $\mathbf{n} \cdot \mathbf{v} = 0$, where n is the unit outward normal vector. As initial conditions for the flow domain, the axial velocity at the entry section $\mathbf{v}_0$ was adopted [11].

2.2. Results

Two different configurations of extrusion die in terms of the mandrel support system (spider legs) and the die land (extrusion channels), were evaluated by a three dimensional numerical model in order to determine the extrusion process performance. The converging and die land regions of these different configurations are presented in Fig. 1. The madrel that will produce the annular shape of extruded products is also illustrated at the right of these three illustrations.

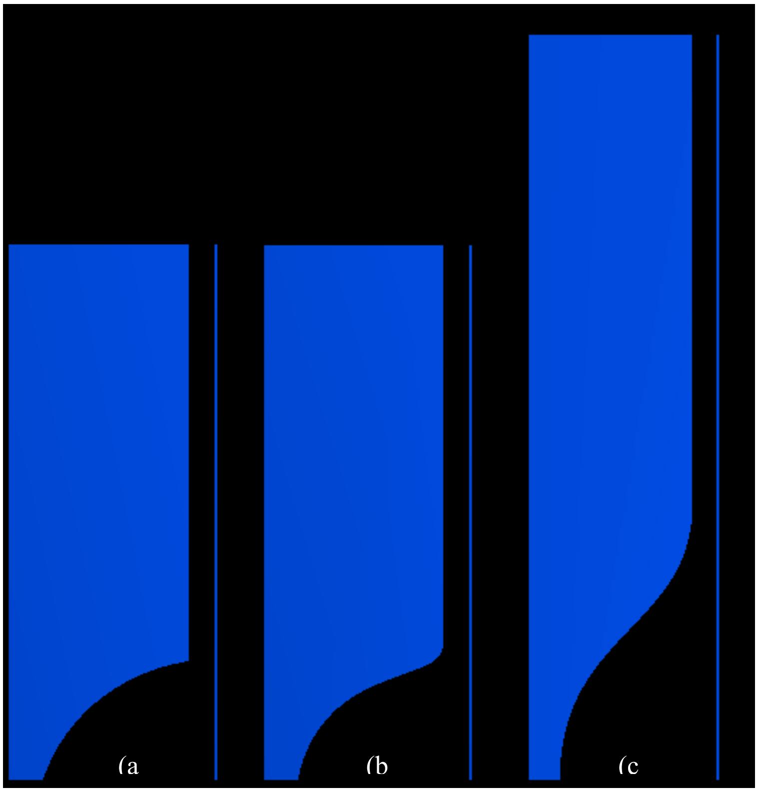

Fig. 1. Extrusion die geometries under study (spider system is not shown); a) circular converging profile and short channel; b) streamlined converging profile and short channel; c) streamlined converging profile and long channel.

The overall value of pressure drop in the extrusion die was assumed as the main technical criterion to analyze the efficiency of material flow in both alternative configurations (Fig. 2 and 3).

Fig. 2 shows the pressure distribution inside one of the spider legs according to the first geometry, in which the converging zone consists of a circular profile. Symmetry boundaries were applied for numerical simulation of ram extrusion and so the working zone was simplified to a sector of 90 degrees, as can be observed in this figure. Four input channels are contained in this configuration, although a unique channel is represented in this figure thanks to the above-mentioned symmetry boundaries.

The other geometry to exam in this work is depicted in Fig. 3, with a converging zone that follows a streamlined profile. Symmetry boundaries were also assumed, although in this case the working zone corresponds to a sector of 180 degrees.

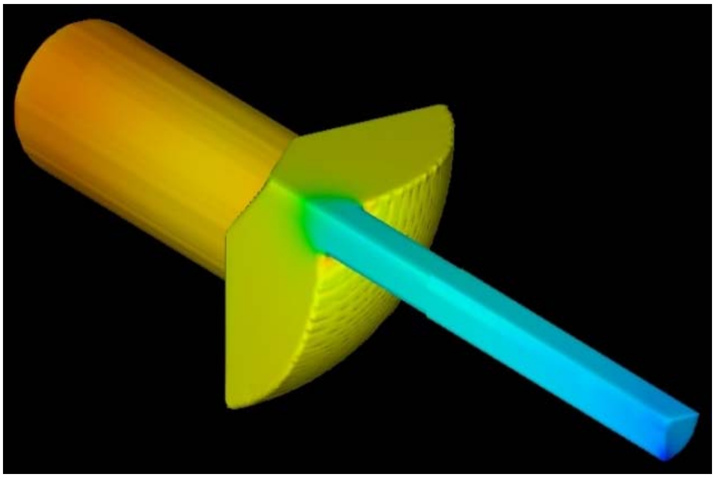

Fig. 2. Pressure distribution in the spider, converging zone and die land for circular converging profile and short channel (non-optimized extrusion die).

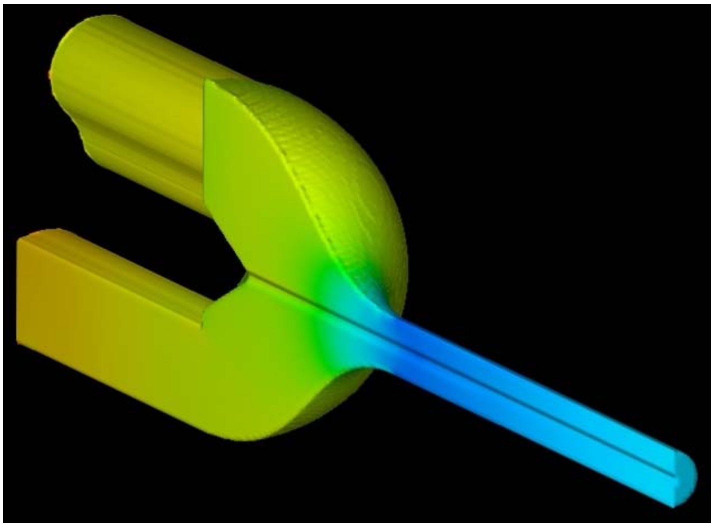

Fig. 3. Pressure distribution in the spider, converging zone and die land for streamlined converging profile and long channel (optimized extrusion die).

An excessive length of extrusion die channels can produce higher pressure losses due to the friction with die walls [12-13]. For this reason, a maximum limit for the length of converging and straight zones should be respected, with the purpose of reducing the distortion suffered by propellant dough and the power consumption inside the extrusion press [2].

After the analysis of alternative geometries of Fig. 2 and 3, the second configuration can be selected to improve the extrusion process. Fig. 3 reveals a lower pressure drop, which supposes the enhancement of material flow during the ram extrusion process.

From the shear stress distributions of both figures, the numerical predictions about the shear flow of propellant doughs serve to identify the yielded and unyielded regions, as can be seen in Fig. 4 and 5. These figures represent the regions that are under a plug flow regime (which only show elastic deformation) and those where the material is deformed viscously (caused by the existing shear stress) [4]. The greater is the shear deformation, the greater is the distortion conferred to the material, leading to a lower uniformity in the mechanical properties of extruded product [3].

From the results depicted in Fig. 4 and 5, the circular profile originates higher shear stresses over the mandrel, while a minimized shear stress is obtained in the case of a streamlined profile. In fact, the streamlined profile provokes a certain shear stress level around the mandrel inside the annular channel, but a moderate shear stress is found at the converging zone.

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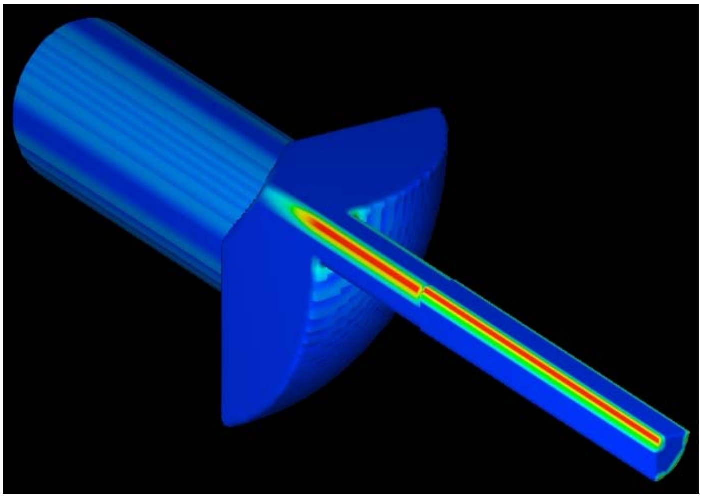

Fig. 4. *Shear stress distribution in the spider, converging zone and die land for circular converging profile and short channel (non-optimized extrusion die).*

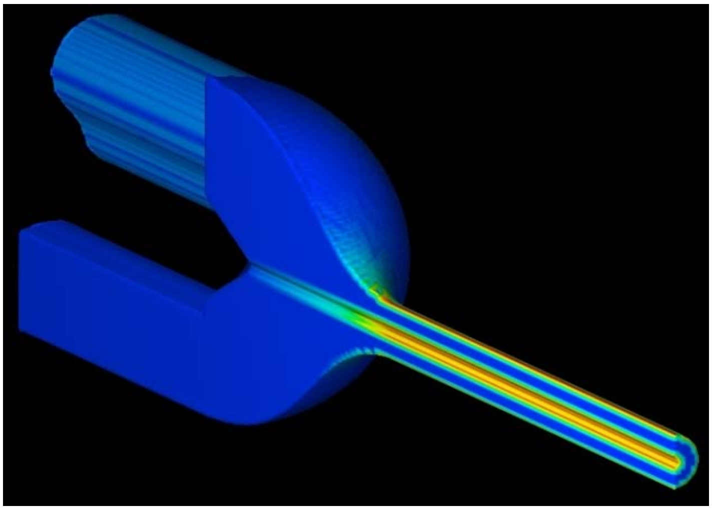

Fig. 5. Pressure distribution in longitudinal section of breaker plate for two different geometric distributions of homogenization holes: a) not optimized; b) optimized (with x and z axis as radial and vertical direction in extrusion die respectively).

Fig. 6 and 7 represent the strain rate distribution at the longitudinal section of die land. Three different configurations of converging zone are considered in these figures. The results for short length annular channels are represented in Fig. 6, while Fig. 7 corresponds to long channels.

Fig. 6a illustrates the strain rate distribution for die land holes with a circular converging profile, while the results of Fig. 6b correspond to a streamlined converging profile. These diagrams serve to evaluate the distortion in the material flow during this stage of extrusion process. According to these figures, a higher uniformity is evidenced in the shear rate distribution for the die land configuration with streamlined converging profile.

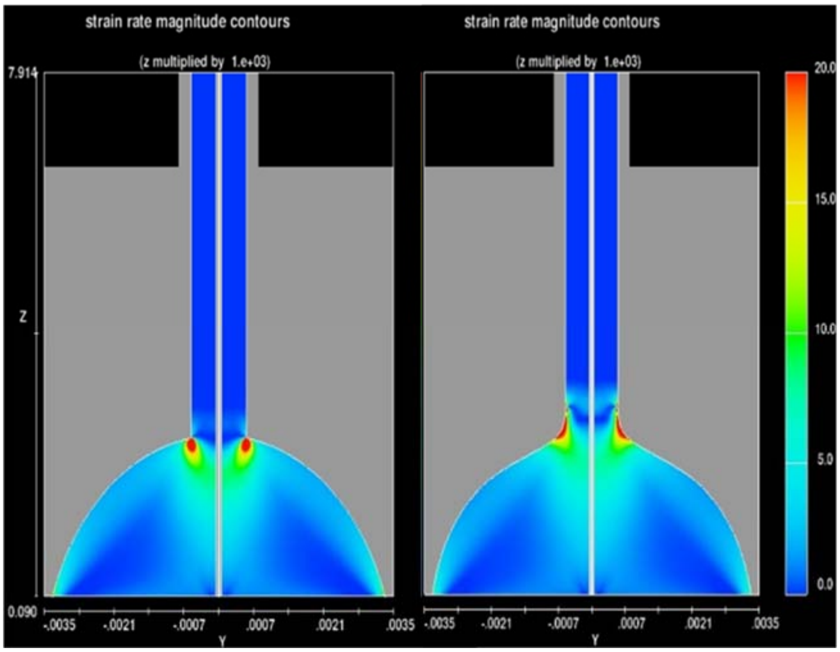

Fig. 6. Strain rate distribution in die land: a) circular converging profile and short channel; b) streamlined converging profile and short channel.

The die land configuration of Fig. 7 also corresponds to a converging zone with streamlined geometry, although with a longer channel. As can be seen in Fig. 7, the larger length of converging zone provides a smoother strain rate distribution, and so the distortion conferred to the material can be drastically reduced.

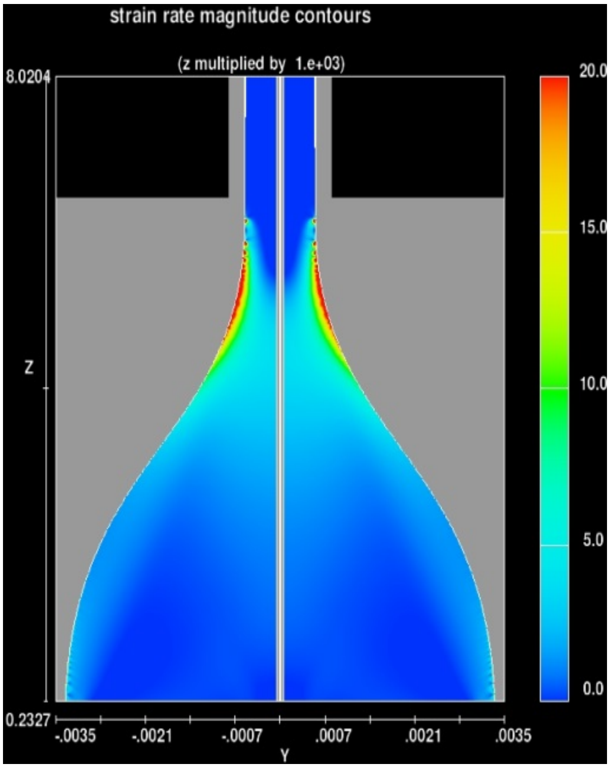

Fig. 7. Strain rate distribution in die land: streamlined converging profile and long channel.

The axial velocity of propellant dough at the exit section of extrusion die can be also analyzed in order to evaluate the possible improvement of extrusion process. The numerical results obtained for these different die land configurations are shown in the Table I.

A similar value of axial velocity is revealed for both configurations with a short length, but a slight increase is obtained when long length die lands are considered. This increase in the axial velocity implies a higher productivity in the extrusion process. It can be attributed to a lower energy dissipation by friction with the die walls and plastic deformation of propellant dough.

Table 1. Axial velocity at the exit cross section of the extrusion die.

Die land configuration	Axial velocity (mm/s)
Circular converging profile and short channel	11.90
Streamlined converging profile and short channel	11.88
Streamlined converging profile and long channel	12.25

3. Conclusions

In this work, the flow of gelled propellant doughs through extrusion dies has been numerically analysed employing commercial simulation software based on the combination of finite difference and finite volume methods.

In the first part, 3D simulations of the mandrel support system allow evaluating different spider legs design, in order to obtain a reduction in the power consumption of the extrusion process by diminishing the overall pressure drop along the die plate. Also, wall shear stress distribution on die surfaces has been studied to estimate the distortion conferred to the propellant being extruded. The coupled simulation of the mandrel support system and the die served to determine the design that allows minimizing the energy consumption during the extrusion process, as well as the minimum distortion of the extruded product. From numerical analysis of propellant doughs extrusion flow through different converging profiles and lengths, it can be deduced that streamlined profiles with a large channel length provide a minimized strain rate on the material. Nevertheless, an excessive length of converging and straight zones can leads to excessive pressure losses at the entry of the die land, due to the high elasticity and yield stress of propellant doughs.

In the second part of the numerical modelling, 2D simulations were performed to identify the specific contribution of the converging profile and the channel length to the distortion and the exit velocity of the extrusion process. The results indicate that optimizing exclusively the converging profile, while keeping constant the channel length is enough to achieve some reduction in the pressure drop along the extrusion die. Imposing a progressive cross section reduction (streamlined profile) with a larger channel length, a further decrease of pressure drop is obtained, that even compensates the increase of pressure drop produced by the increase in length, respect the circular converging profile.

Acknowledgements

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