ANALYSIS AND OPTIMIZATION OF MESHING TECHNIQUES FOR CFD SIMULATIONS OF RUBBER EXTRUSION DIES

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Rubber profile manufacturers are aiming to develop CFD models of their extrusion dies to optimize die design. Real extrusion dies are characterized by an intricate geometry derived from the elaborated profiles demanded by automotive industry as well as the turning and narrowing ducts in dies. To obtain well performing simulations, the major challenge remains in developing an adequate mesh for these complex geometries without an important increase of the computational cost.

This communication deals with the most frequent drawbacks that arise when meshing real extrusion dies. Different meshing techniques for creating CFD models are compared in suitability. On one hand, we use different elements with distinct shape and of different interpolating polynomial order, and in the other hand we vary the global number of elements and the number of elements per each region.

The results show that it is critical to use at least three or four elements for the smallest regions of the domain for obtaining reliable results. Regarding meshing techniques, hexahedral meshes achieve the same degree of accuracy as the tetrahedral ones with a smaller number of elements or with interpolating polynomial of less order.

Keywords: *Rubber extrusion dies, CFD; Extrusion process; Rubber compound; Meshing techniques.*

ANÁLISIS Y OPTIMIZACIÓN DE TÉCNICAS DE MALLADO PARA SIMULACIONES CFD DE MATRICES DE EXTRUSIÓN DE ELASTÓMEROS

Los fabricantes de perfiles elastoméricos buscan desarrollar modelos CFD para modelar el comportamiento de las matrices de extrusión con la finalidad de optimizar el proceso de diseño de las mismas. La característica principal de estas matrices es la complejidad de sus geometrías. Por tanto, el reto para obtener simulaciones numéricas coherentes reside en el mallado óptimo de la geometría, que debe tener la suficiente precisión para resolver correctamente el problema pero sin aumentar en exceso el coste computacional.

Este trabajo analiza los problemas más frecuentes que surgen durante el proceso de mallado de estas matrices. Se examina la idoneidad de diferentes técnicas de mallado utilizando elementos de distinta forma y polinomios de interpolación de diferente orden. También se incluye un estudio sobre el número total de elementos y el número de elementos por cada región.

El estudio muestra que para obtener resultados fiables es fundamental emplear al menos tres o cuatro elementos en las regiones más pequeñas del dominio. En cuanto a las técnicas de mallado, las mallas hexaédricas alcanzan el mismo grado de precisión que las tetraédricas pero utilizando siempre un número menor de elementos o empleando polinomios de interpolación de un orden menor.

Palabras clave: *Matriz de extrusión de goma; CFD; Proceso de extrusión; Compuesto de caucho; Técnicas de mallado*

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1. Introduction

Long rubber profiles are usually required to seal several opening and shutting regions inside a vehicle such as doors, trunks or windows. Rubber compounds, which belong to the elastomer family, comprise all the desired properties for this purpose. They are easily shaped using the extrusion technique. Besides, different material properties can be easily obtained, even for the same profile, by varying the quantities and types of raw substances used during the mixing phase. As a consequence, the automotive industry is considered one of the main customers of rubber extrusion manufacturers.

Supplying rubber profiles to the automotive field is not an easy task. This entails major technical challenges for rubber manufacturers. Automotive companies not only demand rubber profiles with intricate geometries, but also these geometries are particular for each part of cars and for each class of vehicle. Thus, each new profile involves a new extrusion die, the key part of the extrusion process. In addition, the die design process is unique, and therefore, the degree of automatization is low.

This design process is actually based on trial-and-error procedures (Pittman 2011). First, the die geometry is designed using different CAD packages. Then, the first prototype is manufactured based on the theoretical geometry of the CAD design. However, the profiles obtained with this first prototype differ considerably from the customer requirements. This is the starting point of the trial and error procedure. Operators manually modify different parts of the dies in until the desired profile is obtained. The procedure usually extends over a dozen of times and its success strongly depends on the ability of the worker.

In contrast to this approach, the every changing conditions in the automotive field demand faster solutions to gain new customers while maintaining the existing ones. Rubber profiles manufacturers have to develop new profiles according to the automotive industry necessities as soon as possible if they want to keep their current status. A higher degree of automatization may be really helpful in the development of the new dies. In this context, manufacturers aim to obtain models of the extrusion process to cut the number of trials and to reduce the time and money expenses.

So far, a wide variety of modelling approaches have been tested in this field. Michaeli (1992) proposed several analytical formulas to predict critical parameters of the extrusion process. Heuristic models have been applied to describe the die swell effect in Liang (1996) and to estimate the length of the entry region of the die Liang et al. (1998). Furthermore data-driven-based models have been used for to create on-line applications based on artificial neural networks (Marcos González et al. 2007) or support vector machines (Martínez-de-Pisón et al. 2008). The combination of different numerical and analytical models has also been evaluated by Milani (2012).

This paper focuses on developing numerical models based on computational fluid dynamics (CFD), which nowadays seems to be the most powerful and promising modelling technique in the field. Two main problems arise when modelling real extrusion dies: the non-linear constitutive equations of the material and the complexity of the geometries of the simulation domain. Our main goal is to face the later. When the geometry of the die presents so high degree of complexity, most of convergence issues during the numerical computations are consequence of inappropriate meshes. Hence, we tackle the most frequent problems that appear when developing the meshes for the extrusion dies. The aim is to provide a helpful meshing guide for rubber profile manufactures implementing CFD techniques in their design process.

2. Problem description

The head region of commercial extrusion processes can be modelled using CFD models. In this process, the melted rubber is forced into the forming die by the compression of the extruder screw. The die is in charge of shaping the material to obtain the desired profile. As aforementioned, the two main difficulties when modelling extrusion dies are related to the equations of viscosity and the die geometry. The prior depends on the viscoelastic behaviour exhibited by the rubber materials used for the extrusion of new profiles. However, the common rule is often to remove the elastic effects and to model the rubber with non-Newtonian viscosity curves (Pittman 2011).

Sometimes this simplification is not enough to obtain convergence in simulations. This is due to the complex geometry of the rubber extrusion dies. The wide variety of narrow channels and the intricate sections of the profiles hinder the development of suitable meshes for the simulations. Besides, having profiles with small flaps or steel strips worsens the simulation. The solution is not as simple as increasing the number of elements; a real balance between mesh complexity and convergence of the numerical procedure is needed.

Even when convergence of CFD simulations is achieved, the reliability of their solutions is still unsure. Important deviations between simulated and real data may occur due to failures in the numerical procedure or inappropriate assumptions when defining the model. Additionally, the system of governing equations, regarding the numerical procedure, has often more than one solution and the solution achieved may not be the expected one. Finally, despite of finding the correct solution, the convergence criterion may not be tight enough to make the results inaccurate.

On the other side, even overcoming the numerical problems, if the assumptions undertaken in the system of governing equations are not appropriate, real and simulated solution will differ too. Thus it is strongly advised to contrast the obtained results with numerical data gathered from real extrusion processes. The real situation is the main process variables, such as velocity, pressure or viscosity, are rarely recorded due to the difficulties of installing sensors inside the dies. Therefore, the majority of reported works on CFD modeling of extrusion dies are not really validated (Ha et al. 2008, Gonçalves, Carneiro, and Nóbrega 2013).

For these reasons, the present validation problem is tackled by analyzing different meshing approaches. When two models using meshes with different types of elements yield similar results, this hints that at least the numerical procedure is giving the expected solution of the governing equations. Deviations due to the assumptions undertaken in the model may still remain but this can be considered as a good starting point to face the validation problems in CFD modeling of extrusion dies while new sensors are being developed to obtain accurate values of pressure, velocity and viscosity inside the dies.

The present work focuses on the meshing phase of the rubber extrusion die modeling with a double purpose. The first one is to address the convergence issues caused by the complexity of the geometry (narrow ducts, flaps and moving strips). The second objective is to implement a validation procedure by comparing the results obtained in simulations based on different meshes varying the type of elements.

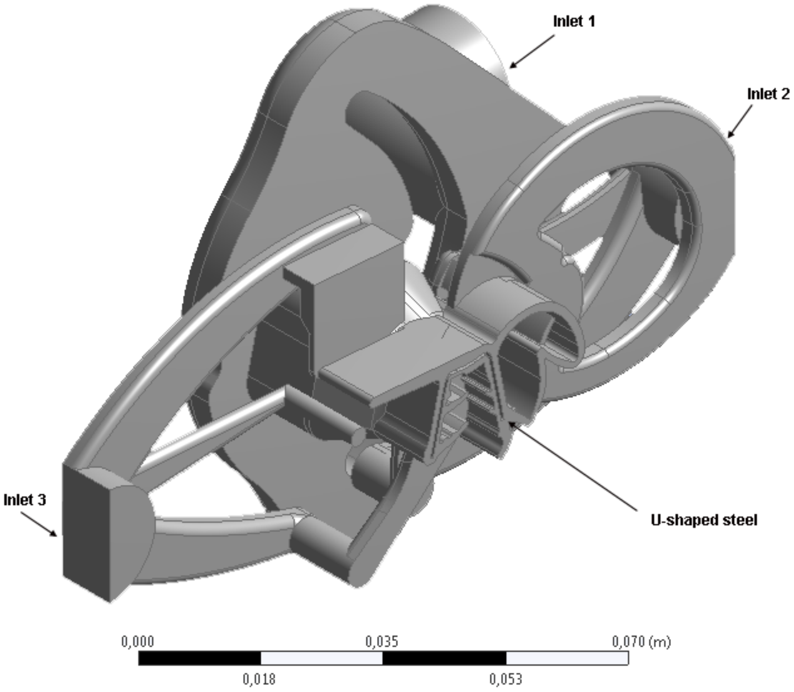
3. Case of study and methodology

3.1. Description of the extrusion die

The extrusion die modeled is presented in figure 1. It was designed and manufactured by Standard Profil S.A., a leading company in the rubber extrusion field. Profiles obtained with this die are used to seal the vehicle doors of different automotive firms.

The die is design with three inlets to ease rubber circulation through the narrowest ducts. Inlets 1 and 2 are used to feed the main bulk of the profile while inlet 3 improves rubber flow trough the small interior flaps. A U-shaped steel strip is added in the central part to reinforce the profile enhancing its rigidity. The strip sticks to the rubber profile leaving both the die at 0.4 m/s.

Figure 1. CAD geometry of the commercial extrusion die



3.2. Model descritpion

Extrusion die is modeled as a steady-state process where rubber is considered to be an isothermal, incompressible and non-Newtonian fluid. According to these conditions, the system of governing equations is comprised of by simplified versions of momentum (Navier-Stokes) and continuity equations as follows (Cengel and Cimbala 2006):

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

$$-\Delta p + \nabla \, [T_{i,j}] = 0 \tag{2}$$

Here, v is the velocity, p is the pressure, and $[T_{i,j}]$ is the stress tensor. Inertia terms are neglected according to the creeping flow assumption. Gravity and inertia terms are neglected given the small die dimensions. Additional volume or surface forces are not considered.

Rubber behavior is modeled as a generalized Newtonian Fluid (GNF). As stated in (Chabra 2010), the stress and strain rate tensor relationship is defined by the Newtonian fluid equation (equation 3). However, on the contrary to a pure Newtonian fluid, the viscosity μ depends on the local shear rate γ (equation 4).

$$[\tau_{i,j}] = 2 \cdot \mu \, [\varepsilon_{i,j}] \tag{3}$$

$$\mu = f(\gamma) \tag{4}$$

Function *f* models the relationship between viscosity and the local shear rate. This function, also known as the material viscosity curve, is obtained by characterization experiments.

Previous experiments of Standard Profil S.A. identified the Bird-Carreau law as the best function f of to model the behavior of the rubber compound used in this extrusion die:

$$\mu = \mu_\infty + (\mu_0 - \mu_\infty)\cdot(1 + \lambda^2\ \gamma^2)^{(n-1)/2} \qquad (5)$$

The boundary conditions imposed to the model are as follows:

- Inlet: fully developed flow is assumed and the input flow is specified.
- Interface with the steel strip: $v_n = 0.4 m/s$
- Outlet: $f_n = 0$, $v_s = 0$
- Wall (no-slip condition): $v_n = 0$, $v_s = 0$

Simulations are run in the commercial solver Ansys Polyflow 14.0, specific software for modeling extrusion and injection processes with non-Newtonian fluids (ANSYS 2011b). All meshes are developed in Ansys Meshing (ANSYS 2011a). The connection between Ansys Polyflow and Ansys Meshing is carried out with Ansys Workbench.

3.3. Meshing techniques

Different meshing approaches are implemented with a double objective: to tackle the convergence issues derived from the complex geometry of the die and to check that the different techniques lead to the same solution.

Two main meshing approaches are presented:

1. Meshes based on tetrahedral elements. They are implemented in Ansys Meshing with the Patch Independent algorithm.
2. Meshes based on hexahedral elements. They are implemented in Ansys Meshing with the Cut Cell algorithm.

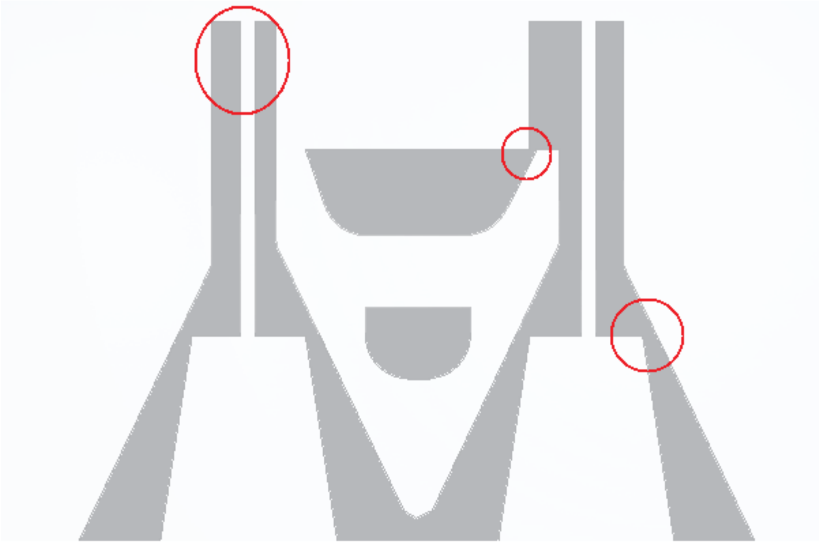
Besides, the accuracy of the interpolation functions is also varied for each type of element:

- Two options are available for pressure interpolation functions: constant or linear pressure.
- Three options are proposed for the velocity interpolation functions: linear velocity, quadratic velocity and the mini-element approach, a mixture between the two previous ones.

There are some limitations when implementing these previous variations in Ansys Polyflow. All options are available for tetrahedral meshes. However, constant pressure with the mini-element approach for velocities can be only used in the hexahedral elements. This is due to the fact that the cut cell algorithm has been recently added from another Ansys package, Ansys Fluent, and it is still in a developing phase.

In addition to the interpolation accuracy, the number of elements is also varied in each type of mesh. This is a critical parameter of the mesh design. It is strongly related to the RAM and CPU requirements and therefore to the computational cost of the simulation. Developing meshes, the goal is always to obtain the most accurate model but with the lowest number of elements. Thus, the key point is to increase the number of elements only in those regions where more accuracy is strongly required. These regions are usually very narrow ducts where rubber is suddenly accelerated or decelerates. Here, three problematic areas are observed (Figure 2).

Figure 2. Horizontal cross section of the extrusion die: problematic regions



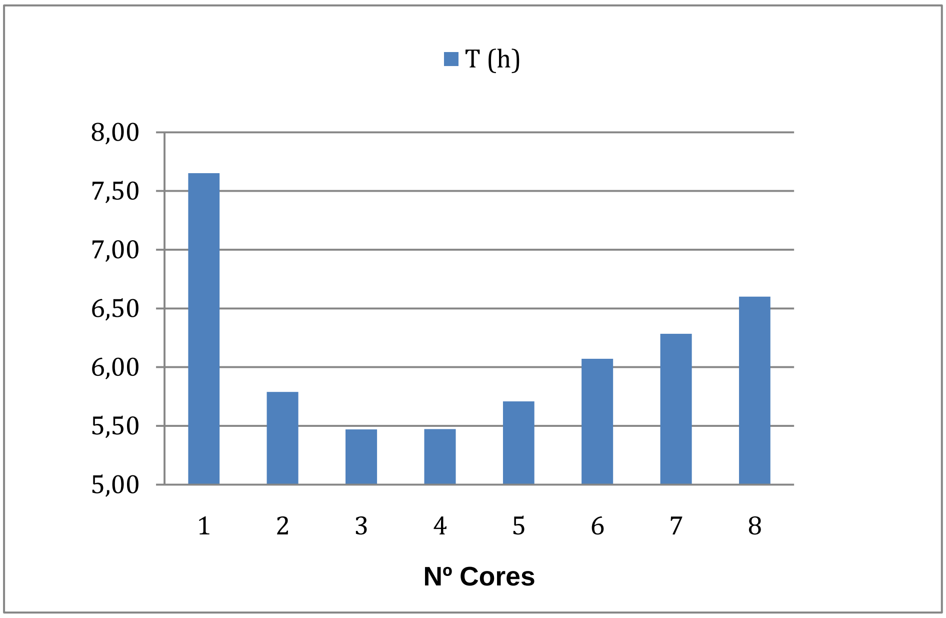
Finally, the maximum pressure at the die inlet and the velocity profiles at the outlet profile are used to compare the results of the two meshing approaches.

4. Results and discussion

4.1. Analysis of the optimum number of cores

It is well known that it is strongly recommended to do an initial evaluatation of the parallel options that the simulation software offers, mainly when several configurations in different simulations are going to be run. Not always a higher number of cores implies less simulation time. In this paper, the number of cores has varied from 1 to 8 in order to determine the best possible configuration.

Figure 3. Computational time of the simulations using different number of cores.



Hardware specifications: Intel® Xeon® Processor E5410 (12M Cache, 2.33 GHz, 1333 MHz FSB).

Figure 3 shows that an increase in the number of cores from 1 to 3 yields in a reduction about 30% of the total time. The use of more than 3 cores does not lead to obtain faster the results. The time required for arrange the workflow for each core becomes higher than the savings for splitting the tasks. In brief, these results demonstrate that all the simulations should be performed using only 3 CPU cores.

4.2. Comparison between tetrahedral and hexahedral meshes

This section includes the best simulations of both approaches as well as other results. In fact, the majority of them are included with the goal of analyzing possible trends after applying different settings. The simulations are arranged as follows:

- Simulations 1 to 4 used tetrahedral meshes.
- Simulations 5 to 7 used hexahedral meshes.

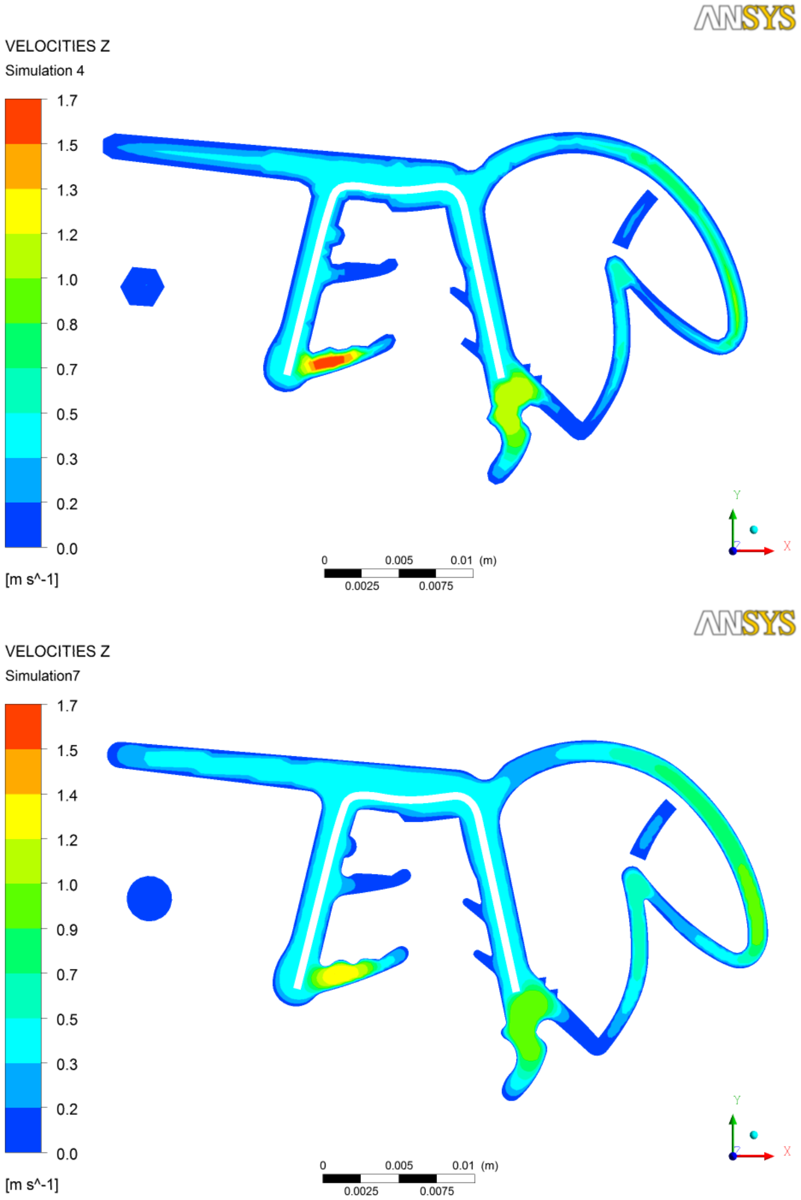
Table 1. Results of the different simulations

Simulation	Type of element	Interpolating polynomial		Nº Elements	Pressure (bar)
		Velocity	Pressure		
1	Tetrahedral	Mini-element	Constant value	185.000	830
2	Tetrahedral	Mini-element	Constant value	300.000	780
3	Tetrahedral	Quadratic value	Quadratic value	300.000	600
4	Tetrahedral	Quadratic value	Quadratic value	450.000	493
5	Hexahedral	Mini-element	Constant value	200.000	600
6	Hexahedral	Mini-element	Constant value	300.000	530
7	Hexahedral	Mini-element	Constant value	450.000	480

Table 1 shows that same results are obtained when both type of meshes are refined. In these cases, the maximum pressure at die inlet is stabilized in the same order of magnitude after the improvements undertaken (493 bar for the tetrahedral mesh and 480 bar for the hexahedral mesh). As aforementioned, this is a good indicator of numerical stability in the simulations. However, the results also suggest that achieving the optimal solution is more complicated when using tetrahedral meshes.

Initial simulations using tetrahedral mesh yield pressure values considerably out of magnitude. Besides, the best simulation with a tetrahedral mesh (simulation 4) uses a quadratic interpolating function, while the mini-element approach was implemented in simulation 7 that corresponds to the best hexahedral mesh. For the same amount of elements, tetrahedral meshes require interpolating functions with higher precision than hexahedral. This suggests us the type of element that is more adequate for modeling the extrusion process.

Figure 4. Velocity profiles at die outlet of simulation 4 (top) and simulation 7 (bottom)



Velocity profiles depicted in Figure 4 endorse the mentioned idea. Both simulations yield velocity profiles within the same order of magnitude under similar shape. However, rubber circulation in the narrowest regions clearly differs in both simulations. Simulation 4 shows rubber not passing through many of the smallest regions, just the opposite than simulation 7. This supports the idea that hexahedral meshes are more appropriate for modeling the extrusion process studied.

In addition, it is important to remark that increasing the number of elements during the depuration process of a mesh should be done paying special attention. The number of elements is critical in the narrowest regions such us the ones depicted in Figure 2. In Figure 4, the difference between including (simulation 6) or not (simulation 5) the appropriate number of elements in one of these regions is checked.

Figure 5. Velocity profiles of simulation 6 (left) and simulation 5 (right)

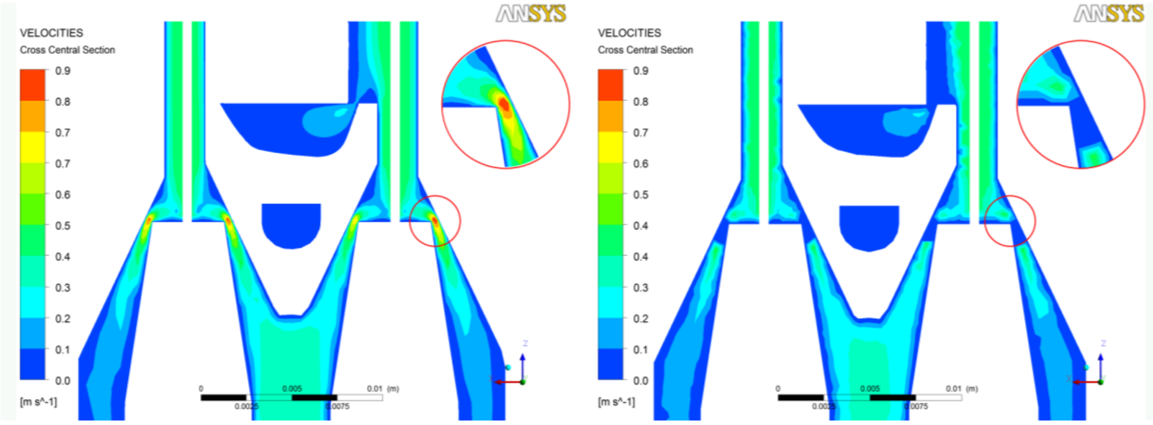


Figure 4 depicts that when the number of elements in a narrow region is not enough, a discontinuity in the velocity profile appears. Rubber gets blocked; it decelerates instead of getting accelerated. This rubber block results in a pressure increase. For example, in the simulations shown in figure 5 there is a difference of 130 bar between simulation 5 and 6. The number of elements in these narrow regions must be at least 4 in order to obtain reliable velocity profiles.

5. Conclusions

In the previous study, different meshing approaches and their settings have been analyzed with a double purpose. The first objective is to address convergence issues derived from the complex die geometries; a second objective is to propose a validation methodology based on the comparison of the results obtained with hexahedral and tetrahedral meshes.

Results show that the solutions converge after the refinement process of both types of mesh. The maximum pressure at die inlet is between 480 and 490 bar with a velocity profiles showing similar shapes and values. From a numerical point of view, this implies that both models may be considered validated. However, this is not a fully validation procedure but it could improve the quality of the simulations when no empirical data is available at all.

The performed study yields several useful recommendations for meshing real rubber extrusion dies. Hexahedral elements are preferable to tetrahedral ones. First, because computational time is directly saved; second, the results obtained with hexahedral mesh are slightly better; third the interpolation functions required are much simpler, The increase of the number of elements seems to be also critical to isolate the narrowest regions. All the simulations performed show results are not enough reliable when less than 4 elements are used in these regions. Finally, the use of more microprocessor cores does not always imply less computational time. When dealing with simulations of high complexity, a prior study about parallelism must be performed to determine the most appropriate number of cores.

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