

Validation of flow simulation on ABAQUS/CEL™

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Abstract: *The main topic of the paper is to show the validation of the Coupled Eulerian-Lagrangian (CEL) analysis technique applied to Newtonian fluid dynamics simulations described by an equation of state (EOS) suggested by Mie-Grüneisen. The model is driven only by body forces through cavity filling. This implementation allows to obtain free surfaces profile, splash droplet formation, velocity field, instantaneous pressure at the contact points between solid and fluid, as well as in solid parts, stresses and strains, all at the same time.*

The free surface validation obtained in the fluid is made through comparisons with radiographs obtained experimentally.

The filling is achieved through solid-fluid interaction (FSI) with "General contact (explicit)" (GC) this is able to track the material distribution during the free surfaces formation and applies non-slip boundary condition as interaction between fluid and solid in order to determine the effect of this approach on the material flow. As a result the complete standardized cavity filling is achieved satisfactorily using CEL analysis.

Keywords: *Cavities Filling, Material Flow Analysis, CEL, Fluid-Solid Interaction (FSI).*

1. Introduction

The cavity filling modeling research already has accurately dynamic fluid behavior results on the entering into a specific geometry; but the approach accuracy depends on the geometry complexity, material properties defined, the quality and experimental information repeatability of for comparison.

Using the model proposed by (Campbell, 1996), several researchers have conducted their own analysis to determine the values range expected under exposed conditions, for filling time is about 2 s (Domanus, 1996; Usmani, 1995; Rigaut, 1996; Xu, 1996; Barkhudarov, 1996; Ohnaka, 1996), (Layton, 1996), that matches the experimental time recorded, on the other hand the interaction with the air inside the mold is negligible due to the porous nature of the mold and is considered that the porosity does not affect the material flow. Finally, a system using water is able to compare

with system using molten metal and determine the correct fluid pouring speed due to kinematic viscosity (Stefanescu, 1992).

The simulation of this phenomenon arises through an alternative CEL analysis that allows to define in easy way all restrictions and avoid programming several conditions like contact type by considering the simultaneous application of Lagrangian and Eulerian coordinates interaction (Fan, 2009). The main advantage of this is that eulerian mesh integrity is preserved during all calculation because never is distorted (Tippmann, 2009). To enforce the right interaction between coordinates a ratio of minimum 3 Eulerian elements and maximum 5 Lagrangian must be asgurate (Latorre, 2012).

Hence this method is applied to take advantage of the possibility to restore calculation from a specific increment, cycle or iteration defined, hence this allows to watch the calculation progress at very short time intervals and if necessary stop and correct the model avoiding to lose the progress already made. Finally if a numerical error has occurred or equipment failure happened, also is possible to restore de calculation from the last correct result (Alameda, 2010).

2. Methodology

2.1. Geometry

The solids for the simulation are: the standard cavity for code and software validation, Figure 1 (a) front view and (b) right view; this is the reference piece that defines the fluid within the Eulerian domain and ensure that the model considers the equivalent volume, 2 kg of molten aluminum (Campbell, 1996) Figure 1 (c); pouring basin was simplified into a cylindrical section and a truncated cone that leads smoothly to filling system geometry, Figure 1 (d); the three solids were defined as a shell constrained with rigid body condition.

Domain is a 3D Eulerian solid type with dimensions such that enclose all solids assembly, also limits the region where the Eulerian fluid will be calculated, has a L shape with depth 150 mm Figure 1(e).

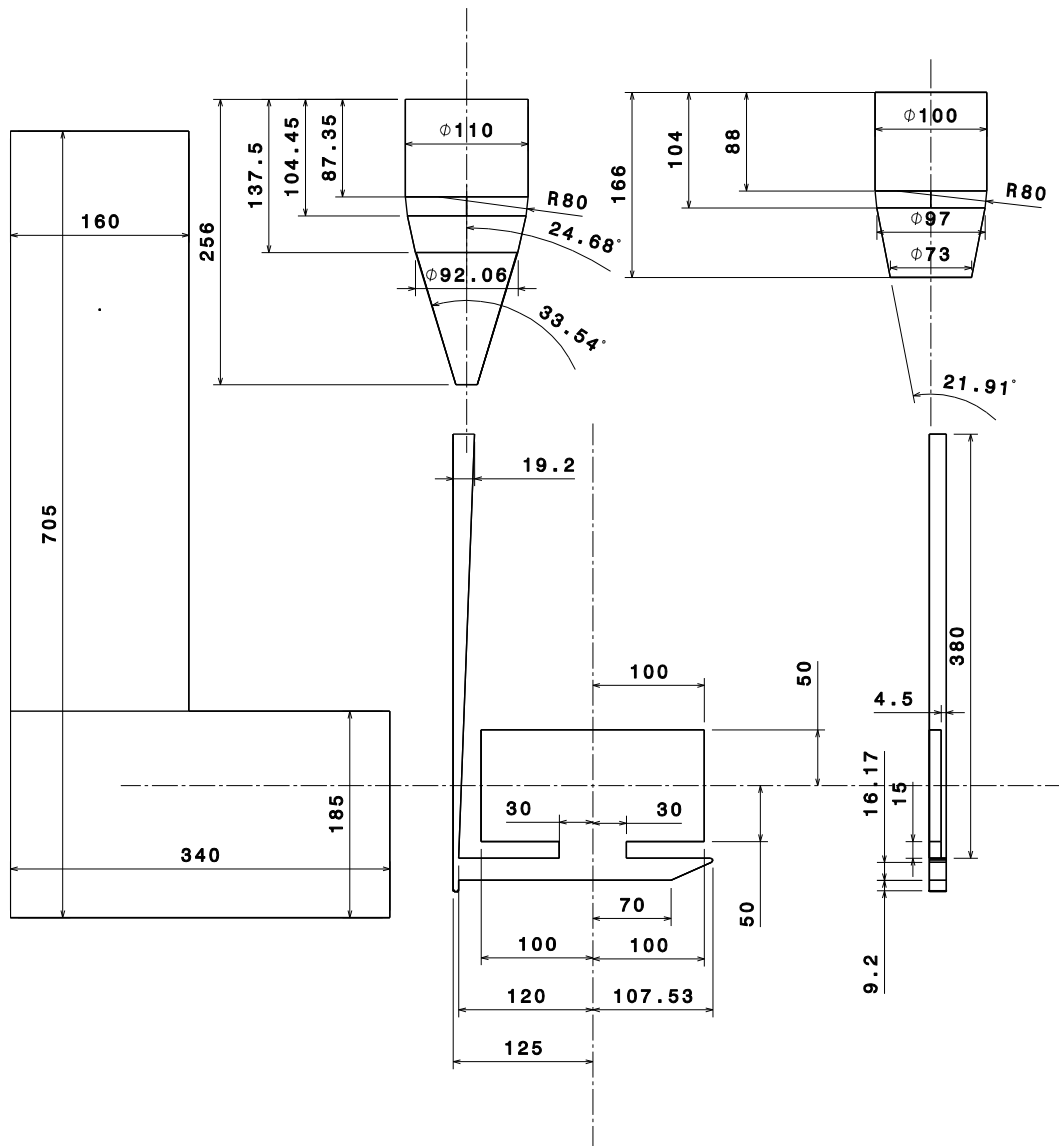


Figure 1. Dimensions of the parts used in the model a) validation standard cavity, b) validation standard cavity right view, c) auxiliary part, d) pouring basin, e) Eulerian domain. Measurement units in mm.

2.2. Material Properties.

The molten metal and water flow inside a cavity can be compared reliably because the two fluids behavior in the casting conditions is incompressible ($\Gamma_0 = 0$), Newtonian and the kinematic viscosities are similar (Stefanescu, 1992). Therefore the water properties used in the simulation are shown in Table 1, these properties are used to satisfy the Mie-Grüneisen EOS and Hugoniot model.

Table 1. Eulerian material Properties (Simulia, 2012).

Property	Magnitude
ρ_0	998.2 kg/m ³
ν	0.001003 Ns/m ²
c_0	1500 m/s
s	0
Γ_0	0

2.3. Analysis conditions.

CEL analysis needs dynamic explicit steps, in order to allow efficient solution for nonlinearities that occur in the material flow during the filling, using known position and velocity values to obtain the next state of the system, which prevents the stiffness matrix formation and converge to a solution using less calculation time (Alameda, 2010).

Variable mass scaling option is currently not supported in the CEL method; hence, the stable time increment is controlled by the Eulerian element size and the material properties of the material defined through EOS definitions. A good option for optimizing computational requirements is scaling c_0 , which causes an acceptable compressibility in the system, if a c_0 is divided by a hundred the maximum compressibility calculated is 1.5% that is acceptable in this type of analysis but must be evaluate for a particular system (Tippmann, 2009).

The filling is driven only by gravity acceleration set at 9.81 m/s².

On the visualization module the first result is shown at twentieth of the total step time, in order to simulate 6 s were needed 60 steps with 0.1 s long, this generates a resolution of 5e-3 s, to ensure that the intervals shown in radiographs (Campbell, 1996) were displayed on the simulation.

The only restriction on the fluid is the solid geometry, so it is only required to define the interactions between them. The mechanical type "Rough" induces non-slip condition and simulates the effect of fluid adherence, which is assigned to the entire model by GC algorithm (Simulia, 2012).

Rigid body constrain was applied to each solid defining an inertial behavior (Simulia, 2011) and this allows the surface properties calculation, such as pressure or reaction force (Saucedo, 2013). This was applied at each part reference point.

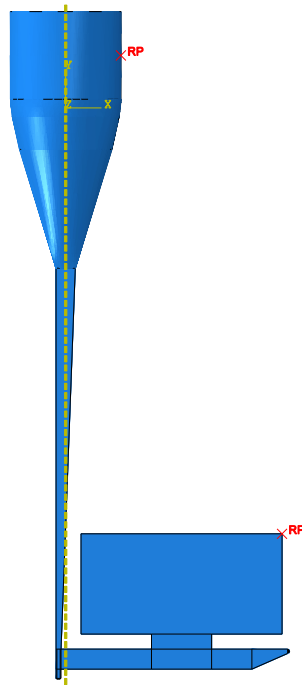


Figure 2. Solid pieces assembled with rigid body condition (yellow circles) and applied ENCASTRE (red circles).

The normal zero velocity boundary condition on the Eulerian surfaces prevents lack of material (Tippmann, 2009), thus ensuring that energy remains constant.

The Eulerian material was applied as an initial condition using a predefined field generated by the volume fraction tool (VFT) and the reference part located in the pouring basin. It is necessary that the domain and the reference part were meshed with the same element size to calculate which elements are interfered and assign volume correctly.

The mesh control used a predefined element type EC3C8R with 3 mm size. The reference part also has 3 mm, while the pouring basin has a 2.5 mm mesh size.

The cavity uses a global element size of 19.8 mm, which is refined in the front and back faces to achieve the minimum ratio between domains (Fan, 2009). In the solid parts, it was used linear element R3D4.

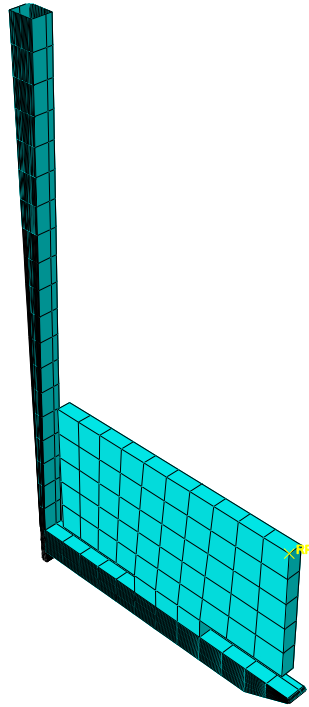


Figure 3. Cavity Mesh.

3. Results and Discussion

Velocity profile shows that the contact condition "Rough" induces fluid adhesion properly, Figure 4(a), element vectors in contact with both domains show where is possible to see change direction as a result of non-slip condition, while in Figure 4(b) is possible to observe some vectors flowing to the center, which is the expected direction for the material that have no contact with solid yet.

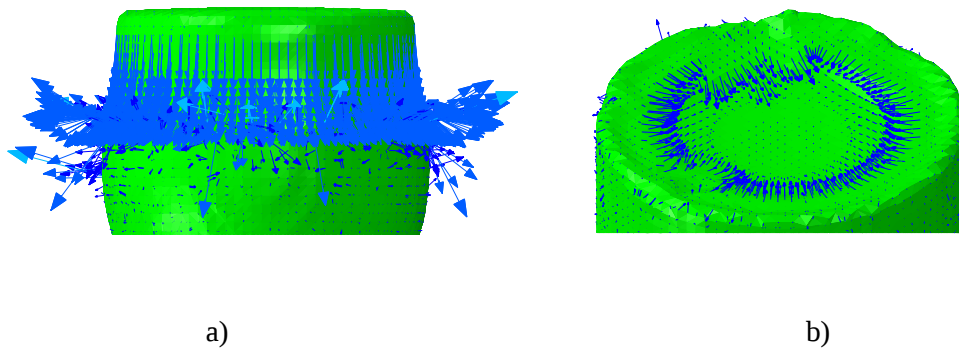


Figure 4. a) Fluid flow through the pouring basin, b) instant of material flow toward center.

The volume results and velocity profile are consistent together, in Image 5(a) two regions are identified, one at bottom in full contact with the pouring basin (black) conical section and second at top which is still in free fall (red), this effect is appreciated in vectors show in Figure 5(b) almost all vectors are changing direction from down to up where contact start between solid and fluid, and the bottom of the pouring basin the velocity has the biggest magnitude because this section of the fluid have no contact with any solid in Figure 5(c) the volume profiles shown that the preferential flow appears at center where is the expected zone and in Figure 5(d) is shown that the velocity profile is uniform when the entire volume has contact with the solid, resulting in the lowest value compared with instant in Figure 5(b). The above behavior shows that "Rough" condition stops the material flow, but guarantee the FSI from material runoff and made greater the minimum ratio needed for Eulerian and Lagrangian elements, as well as the contact material Eulerian stops moving and spreads the effect by viscosity , this could approximate the oxide layer formed in a common gravity cast.

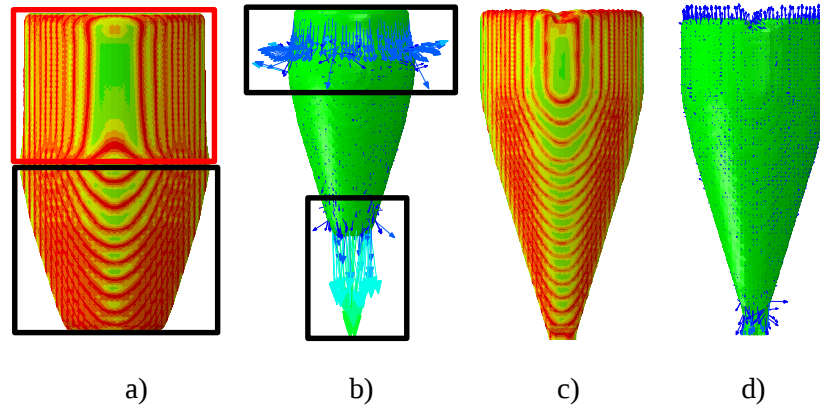


Figure 5. a) Contact with solid, b) velocity vectors showing the interaction between the fluid and solid, c) volume profile of central flow tendency d) velocity profile when total contact is achieve.

The fluid profile at pouring cup center is shown in Figure 6(a) is the natural sloshing behavior produced by a normal impact on the fluid free surface. In Figure 6(b) a meniscus forming is shown as a result of fluid displacement toward the free surface, meanwhile in Figure 6(c) is observed volume accumulation in a column shape precipitating and forming the shape in Figure 6(d). The previous results demonstrate that calculated profiles are comparable to known fluid behavior, suggesting that volume distribution results are suitable.

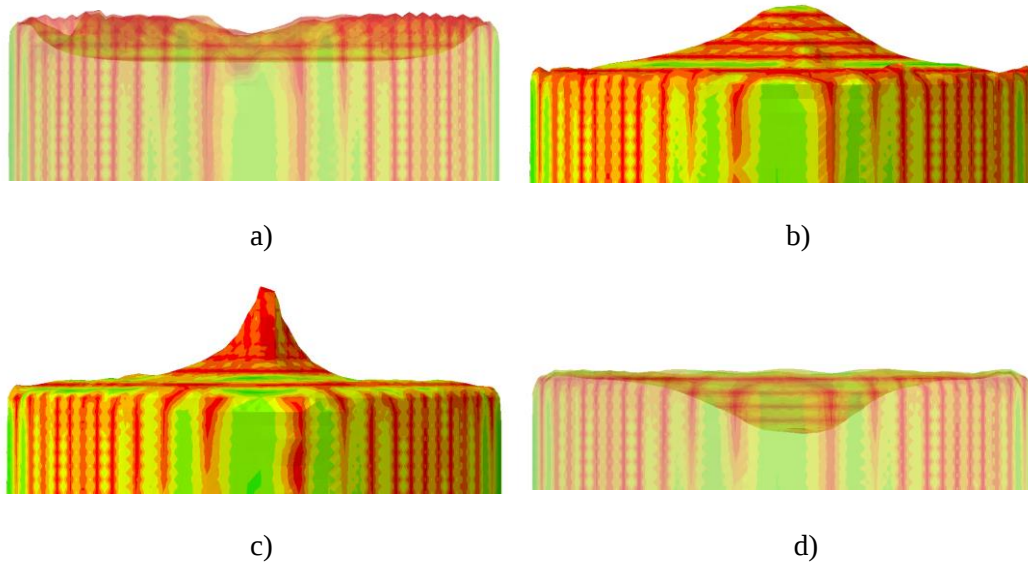


Figure 6. Behavior of the material at the pouring basin free surface, a) initial wave profile, b) meniscus formation, c) meniscus falling by gravity d) profile formed by fluid meniscus drop.

Determining flow validity along the cavity filling is made by comparison with radiographs taken by (Campbell, 1996) at intervals of 0.25 s, we selected the most representative orientation and filling percentage.

For volume distribution analysis, Figure 7(a) shows that filling system and the gate to the main cavity are completely full, as expected, but the fluid entering to the cavity shows discontinuities on the left side as a result of direction, speed and inertia calculated at this moment. On the other hand Figure 7 (b) shows all surfaces in complete contact and properly confined fluid, the main accumulation appears at center and free surface profile shows a wave type, in Figure 7(c) has completely filled the cavity, no discontinuities are observed.

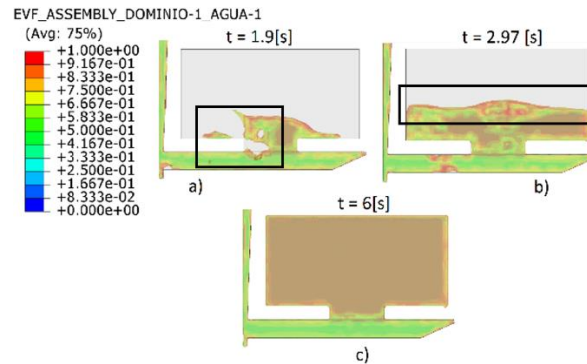


Figure 7. Eulerian volume profiles obtained in the simulation a) discontinuity at the beginning of the standard filling cavity, b) accumulation waveform, c) complete filling mould.

The velocity profile is presented at the same moment that the volume profile, except for the last which was earlier, in order to show a relative maximum recirculation rate. In Figure 8(a) the velocity vector direction are result of the collision with the right wall of cavity gate, Figure 8 b) the fluid has the highest density of velocity vectors at the center, suggesting that the material flow is stable at this moment and go almost vertically, while left accumulation suggests that induced flow by collision with the gate to the cavity is still present. Figure 8(c) is the instant before the cavity is completely full, at this moment is shown a vortex induced by the collision is still present.

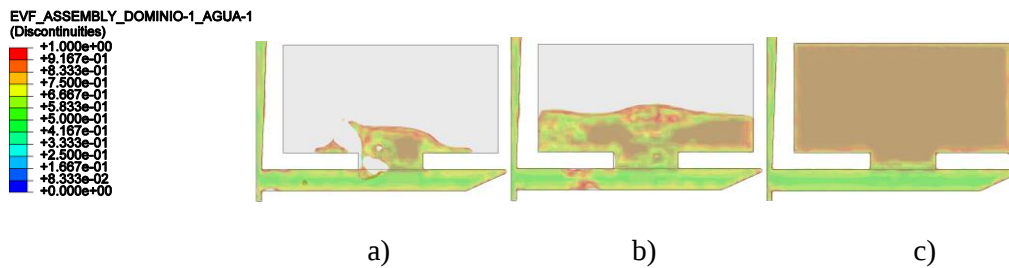


Figure 8. Velocities calculated by the software, a) discontinuity at the beginning of the standard cavity filling, b) waveform with center accumulation c) full cavity with vortex.

The simulation predict that the velocity magnitude is between 0.636 m/s and 1.273 m/s. To determine the accuracy of this result a basic calculus was done using Torricelli's theorem considering the filling system high and comparing the value with the predicted value at the filling

system bottom, the calculation obtained is 2.97 m/s and in Figure 9 the displayed result by the software is between 2.5 and 3.33 m/s this range is close enough to the analytical calculation, the minimum speed is result of viscosity consideration and no-slip boundary condition on the wall which retards the flow and the highest velocity is result of fluid natural oscillations and the solution method.

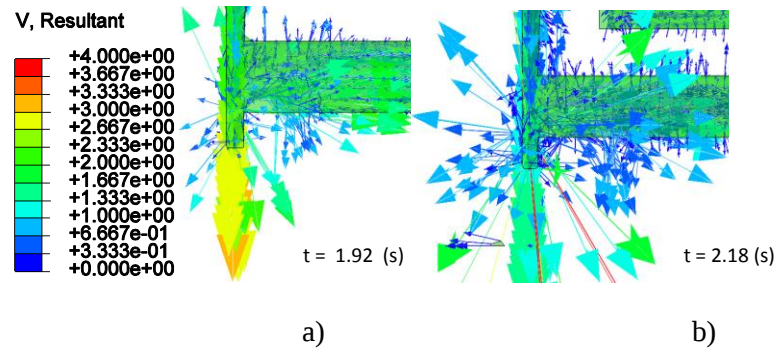


Figure 9. Filling system velocity profile.

Figure 8(c) shows how the inlet flow changes the material state inside the cavity, inducing two vortex with opposite direction, this is an expected result because it was filled from below and is also clear that the system enters in a stationary state showing average profile at any moment.

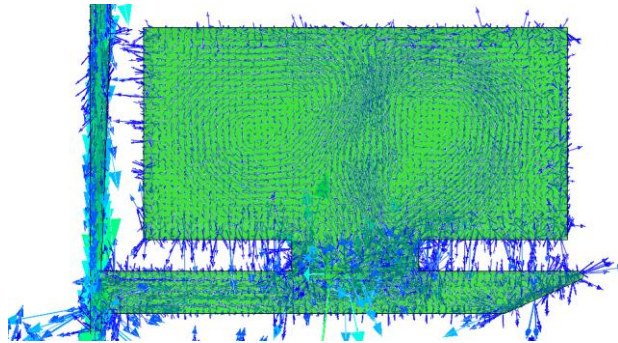


Figure 10. Vorticity moments before the full filling, the average speed shown is 1.66 m/s

Determining the profile validity obtained by the simulation is comparing with radiographs (Campbell, 1996) at the instant where an approximate profile appear, Table 2.



Figure 11. Radiographs obtained during Campbell test (Campbell, 1996)

Table 2. Comparison between simulation and radiographs

Figure 8	Figure 11	Similarities	Differences
t = 1.9	t = 0.74	Flow like fountain	In 8 the flow goes to the left and 10 to the right
t = 2.97	t = 1	Fluid accumulation at center	Volume accumulation on the right side
t = 5.42	t = 2	Filling system completely full	In 8 partial filling and in 10 full cavity

The most remarkable difference is a delay on filling time as a result of contact interaction "Rough" application.

Flow direction during cavity filling indicates that the filling in the simulation runs differently than shown on radiographs direction Figure 11. But both behaviors shows a wave profile, suggesting filling is cyclical in time, the flow go to the right and in the next increment goes to the left as a result of the vortex formation throughout the filling this is clearly seen in Figure 10, so the moment they compare are not coincident but in the wave profile are.

4. Conclusions

Filling the standardized cavity given by Campbell, implementing CEL method is suitably achieved by FSI without edges runoff, using contact type "Rough" causing Eulerian material flow delay.

Velocity vector field calculated on Eulerian material which is not in contact with solids is very accurate to real flow because at this zone just viscous properties and EOS are solved.

The profiles obtained are accurate according with the comparison with the experimental ones indicating that the fluid dynamics and free surfaces recognition are acceptable, however due to random behavior in fluid waves, turbulence and cycle behavior cavity filling should not be compared directly, but by observing trendings and characteristics of vortex areas is possible the comparison.

The velocity vectors, filling profiles and recognition surfaces along the entire calculation defines CEL as a useful for getting coupled systems analyzed, showing each domain response, both the solid and the fluid.

5. References

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