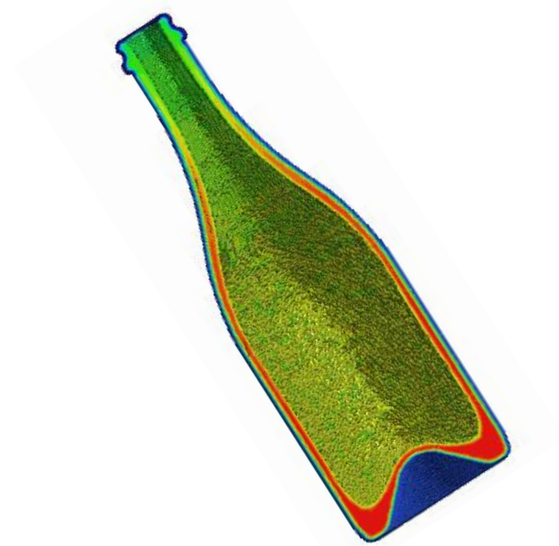
IQS

Ramon Clemente GLASS

KRATOS MULTI-PHYSICS

Lagrangian FE model for bottle manufacturing simulation



Pavel Ryzhakov, M.-A. Celigueta

Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE)

International Center for Numerical Methods in Engineering CIMNE

CIMNE

The International Center for Numerical Methods in Engineering (**CIMNE**) is a research organization created in 1987 at the heart of Technical University of Catalonia (UPC) as a partnership between the Government of Catalonia and UPC, in coop. with UNESCO.

The aim of CIMNE is the development of <u>numerical methods</u> and computational techniques <u>for advancing knowledge and technology in engineering</u> and applied sciences.

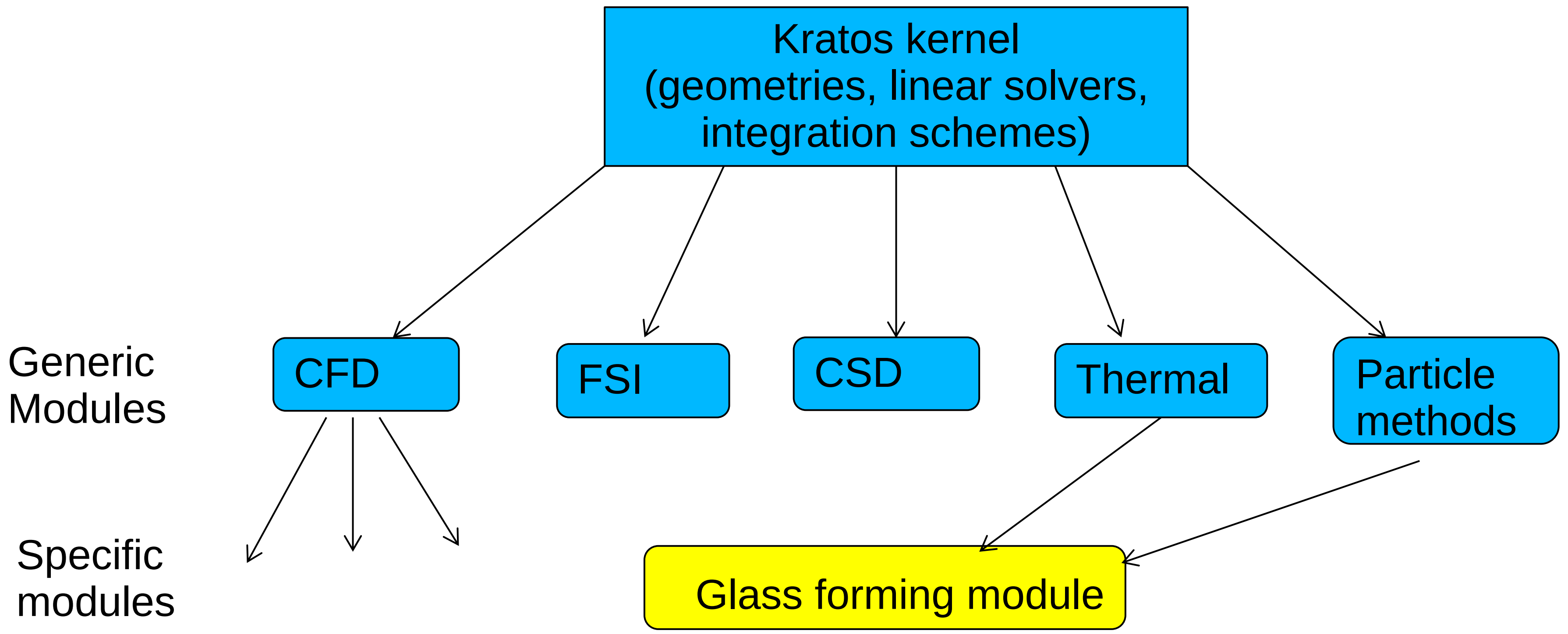
CIMNE employs some 250 scientists and engineers who work in the different offices of CIMNE around the world. CIMNE has also established a network of 30 Classrooms in partnership with Universities in Spain and 11 Latin American countries.

Over its history, CIMNE has taken part in over 2,000 RTD projects in cooperation with some 500 companies, universities and research centers worldwide.

KRATOS Multiphysics

Kratos is designed as an Open-Source HPC framework for the implementation of numerical methods for the solution of engineering problems. It is written in C++ and is designed to allow collaborative development by large teams of researchers focusing on modularity as well as on performance.

Kratos Team is a continuously growing community with its current core located in CIMNE, Barcelona. It also has branches in Germany, UK, Russia, Iran and China.



KRATOS Multiphysics team

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Outline

1. Motivation and objectives
2. Technological context
3. Numerical model
4. Algorithmic issues
5. Examples
6. Challenges and open questions
6. Conclusions

1.1 Motivation

Bottle manufacturing is a billions-euro industry world-wide

- Beverages, fragnances, containers...

Competition: <u>optimization necessary</u>

Technological procedure: mainly based on craftmanship and experience

Questions to answer:

- How can the container weight be reduced without compromising on its strength?
- How to design the parison mould in the best way?
- What is the optimal air pressure at different stages?
- What would different cooling conditions lead to?

1.2 Objectives

- Develop a robust and efficient tool for bottle manufacturing simulations.
- The tool must be developed in axisymmetric and in 3D (many containers are not axissymmetric, thermal conditions are often not axis-symmetric even for bottles with circular cross-sections)
- Predict wall thickness, temperature and stress distributions

1.3 Challenges

- Strongly temperature-dependent properties
- Moving surfaces and interfaces
- Necessity of good precision on relatively rough meshes to obtain solution in reasonable time
- Contact modeling

"Validation" problems:

- Absence of well-defined benchmarks (mostly conference papes, the few journal articles present simulation realizations, not providing the data necessary for reproducing the simulation)

State-of-the-art

Scientific community:

Eulerian+Level Set:

C.G. Giannopapa et al: Modeling the blow-blow forming process in glass container manufacturing. *Journal of Fluids Engineering, 2011.*

Lagrangian formulation, const. viscosity, no thermal model

(Feulvarch et al.: 3D simulation of glass forming process, *J. Mat. Processing technology*, 2005)

Lagrangian axis-symmetric formulation, thermally coupled: J.M.A. Cesar de Sa: “Numerical modelling of glass forming processes”, *Eng. Computations*

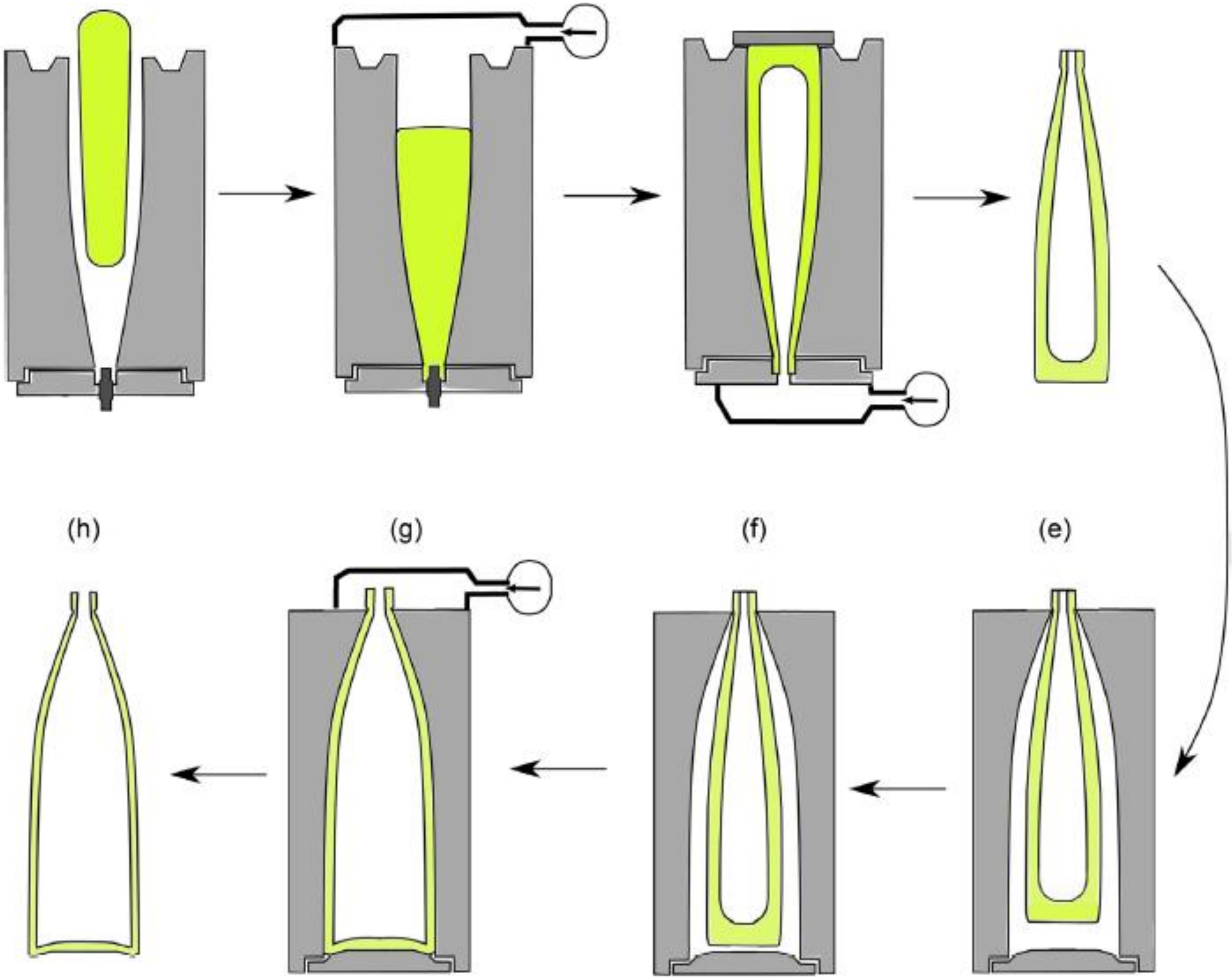
Commercial:

Specific: **NoGrid** (meshless method in 3D (Finite Pointset Method)

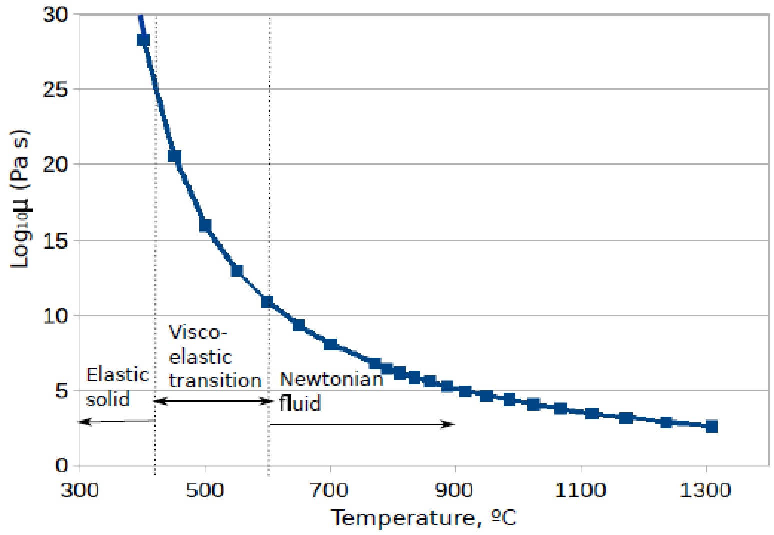
General purpose: **ABAQUS** (Eulerian formulation+Level Set)

Problem: no well-established benchmark. No reference data!
Multiple conference papers, very few journal articles

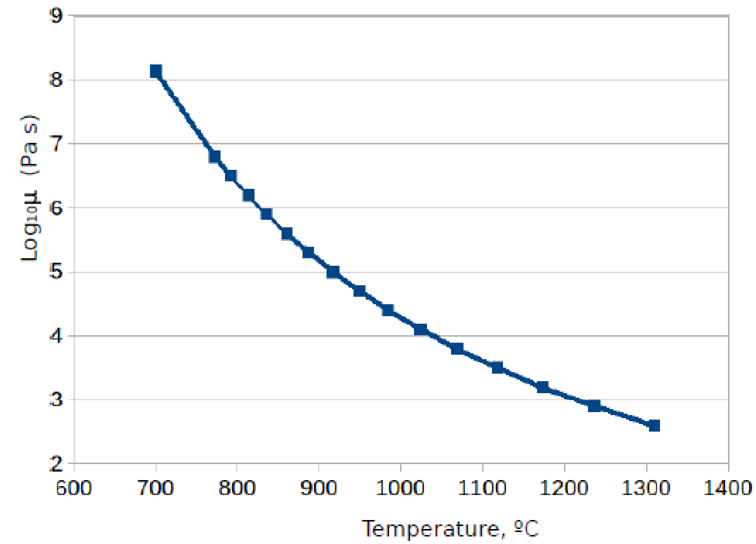
2. Technological context: bottle manufacturing stages



Material properties: commercial silicate glass



(a) Visco-elastic behavior



(b) Forming temperature range

$$log_{10}\mu = A + \frac{B}{T - T_0}$$

Visco-elastic material, however at forming temperature range **viscous** approximation is acceptable

Viscocity changes from 140^E06 Pa.s to 400 Pa.s between 700ºC and 1200ºC

Glass **density** (almost **constant**): 2438 kg/m3 at 700C - and 2367 kg/m3 at 1100 ºC

Specic heat almost **constant** (1400-1420 J/kg*K)

Diffusivity changes from 0.0000015 m2/s at 700 C to 0.0000065 m2/s at 1100 C.

3. Numerical model

Viscous incompressible fluid

Thermally-coupled

Air is neglected (only glass+mould or wall)

Important features:

- Moving boundaries
- Changing properties

PFEM-like
Lagrangian strategy

Advantageous paradigm
for convecting properties

What is PFEM?

The **PFEM** is a numerical method that uses a Finite Element mesh to discretize the physical domain and to integrate the differential governing equations.

In **PFEM** the nodes of the mesh move according to the equations of motion in a Lagrangian fashion. The <u>nodes transport their momentum together with all their physical properties</u> thus behaving as particles.

At the end of each time step the <u>mesh has to be rebuild</u> as the nodes have been moved to their new time step position.

What is PFEM?

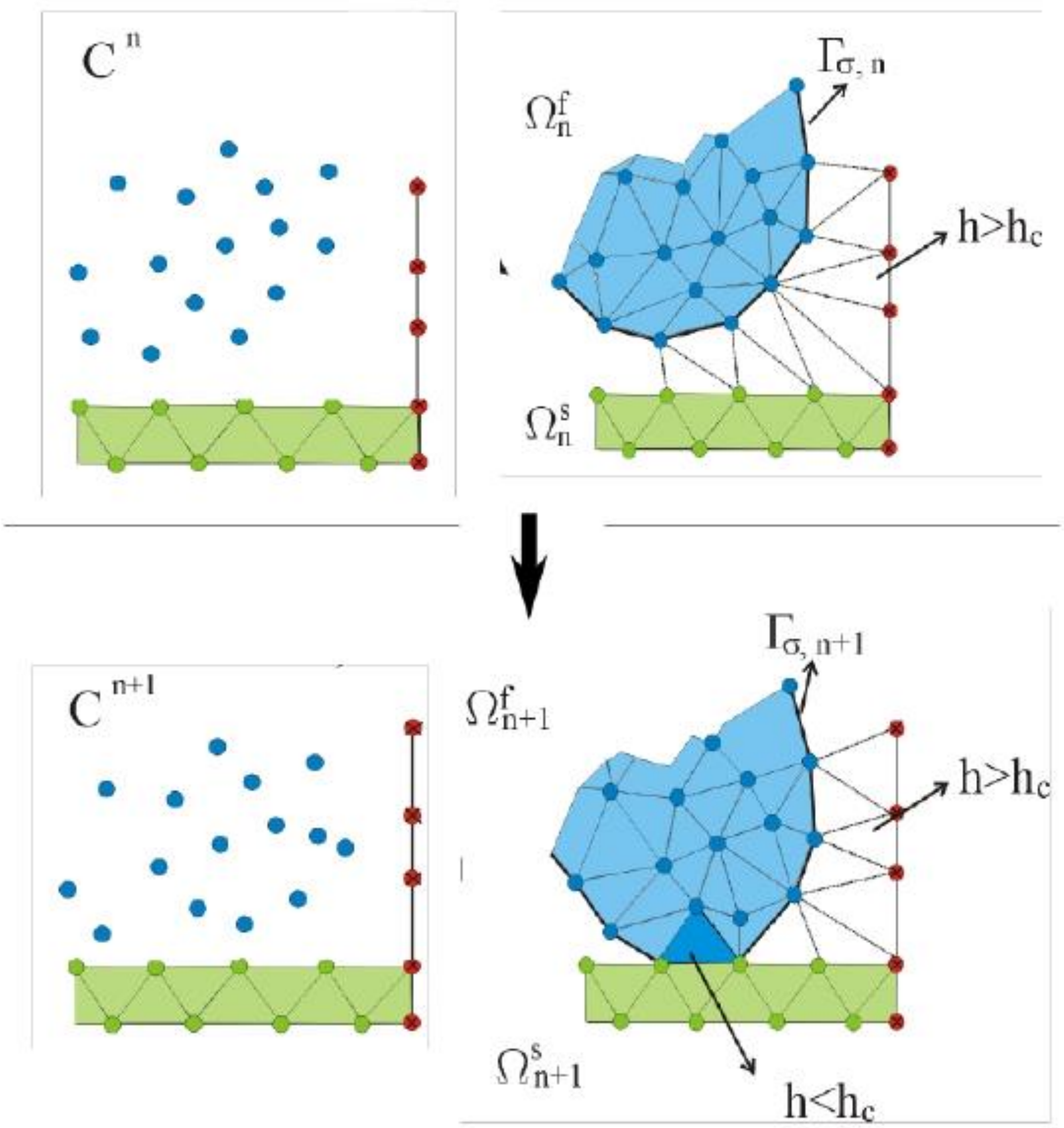
Main **PFEM** features are:

- FEM mesh + properties stored at nodes
- Moving mesh (Lagrangian formulation)
- Re-meshing (Delaunay)
- External boundary identification (using the alpha-shape technique + boundary markers)

PFEM for glass forming simulation?

PFEM + ? = **PGLASS**

PFEM steps



Governing equations

$$\rho\frac{\partial \mathbf{v}}{\partial t} + \nabla p - \nabla\cdot(2\mu\epsilon(\mathbf{v})) = \rho\mathbf{g}$$

$$\nabla\cdot\mathbf{v} = 0$$

$$\rho c\frac{\partial T}{\partial t} = k\nabla^2 T + Q$$

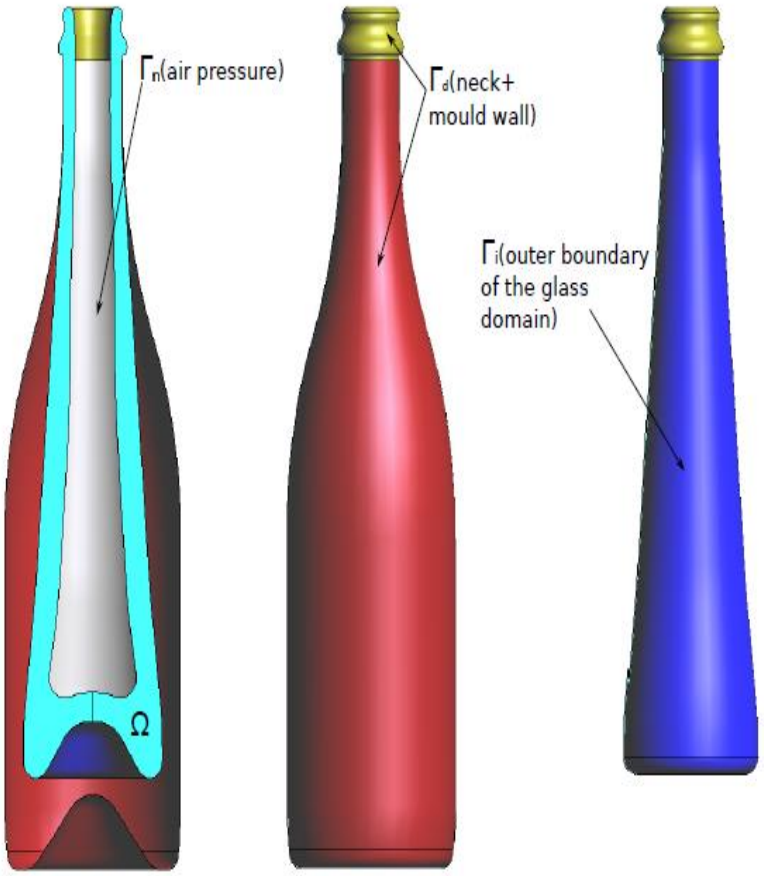
No-slip condition at the contact with the mould $\mathbf{v} = 0$

Inlet air pressure: Neumann b.c. $\mathbf{t}_p = p_a\mathbf{n}$

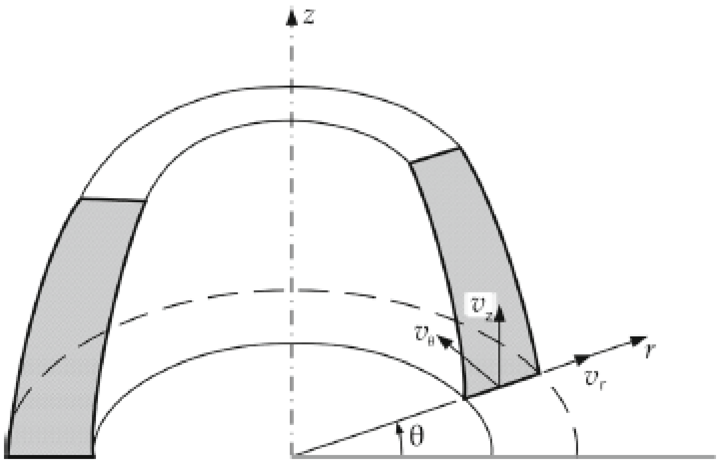
Dirichlet condition at the bottle neck: $T=T_d$

Glass-air interaction is not considered

Mould thermal conditions?



Axisymmetric model



Navier-Stokes equations

$$\rho \frac{D\mathbf{v}_a}{Dt} + \nabla p_a - \nabla \cdot (2\mu \dot{\epsilon}_a(\mathbf{v}_a)) = \rho \mathbf{g}_a$$

$$\nabla \cdot \mathbf{v}_a = 0$$

$$\mathbf{v}_a = [\mathbf{v}_r(r,z) \quad \mathbf{v}_z(r,z)]^{\mathrm{T}}$$

$$p_a = p(r,z)$$

Strain vector

$$\dot{\epsilon}_a = \begin{pmatrix} \dot{\epsilon}_r \\ \dot{\epsilon}_z \\ \dot{\epsilon}_\theta \\ \dot{\gamma}_{rz} \end{pmatrix} = \begin{pmatrix} \frac{\partial \mathbf{v}_r}{\partial r} \\ \frac{\partial \mathbf{v}_z}{\partial z} \\ \frac{\mathbf{v}_r}{r} \\ \frac{\partial \mathbf{v}_r}{\partial z} + \frac{\partial \mathbf{v}_z}{\partial r} \end{pmatrix}$$

FEM-descritization and numerical algorithm

Mechanical

$$\begin{pmatrix} \frac{\mathrm{M}}{\Delta t} + \mu \mathbf{L} & \mathbf{G} \\ \mathbf{D} & \tau \mathbf{L} \end{pmatrix} \begin{pmatrix} d\bar{\mathbf{v}} \\ d\bar{p} \end{pmatrix} = \begin{pmatrix} \bar{\mathbf{r}}_m \\ \bar{\mathbf{r}}_c \end{pmatrix}$$

$$\left(\mathrm{M} \frac{\tilde{\mathrm{v}} - \bar{\mathrm{v}}_n}{\Delta t} + \mu \mathrm{L} \tilde{\mathrm{v}} + \mathrm{G} \bar{\mathrm{p}}^g_{n+1} \right) = \bar{\mathrm{F}}$$

$$\mathrm{D} \tilde{\mathrm{v}} = \Delta t \mathrm{L} \left(\bar{\mathrm{p}}_{n+1} - \bar{\mathrm{p}}^g_{n+1} \right) + \mathrm{S} \bar{\mathrm{p}}_{n+1}$$

$$\mathrm{M} \frac{\bar{\mathrm{v}}_{n+1} - \tilde{\mathrm{v}}}{\Delta t} + \mathrm{G} \left(\bar{\mathrm{p}}_{n+1} - \bar{\mathrm{p}}^g_{n+1} \right) = 0$$

Modified fractional step split

Excellent effficiecy and mass conservation

Staggered solution: mechanical-thermal equations

Thermal

$$\mathrm{M} \frac{T_{n+1} - T_n}{\Delta t} - k \mathrm{L} T_{n+1} = \mathrm{Q}$$

$$log_{10} \mu = A + \frac{B}{T - T_0}$$

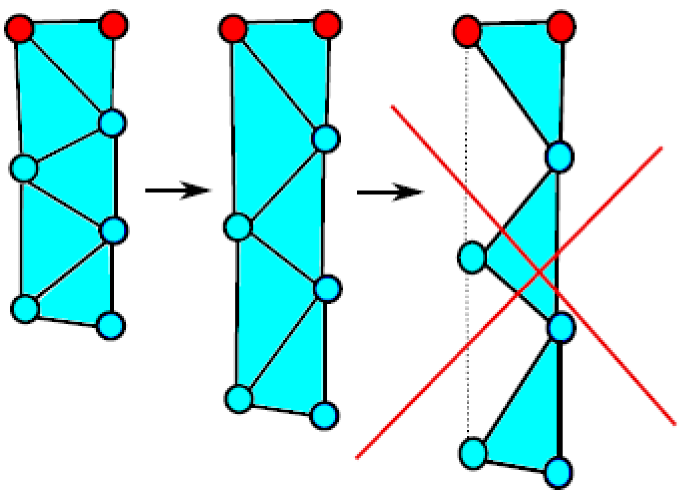
Fulcher equation

Improving mass conservation in simulation of incompressible flows. Ryzhakov P. et al *Int. Jour. for Num.Methds. in Eng., 2012.*

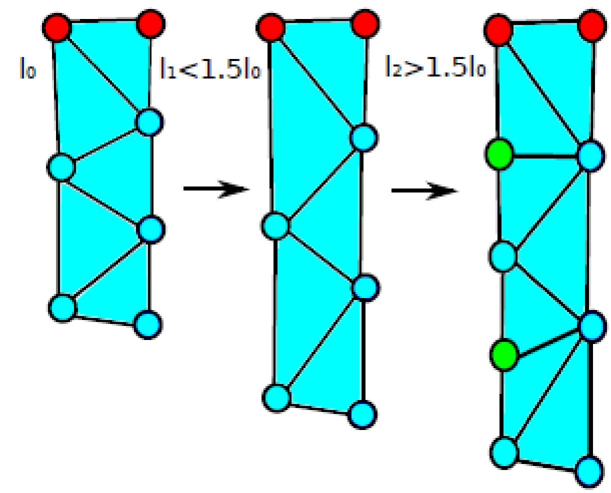
An algorithm for the simulation of thermally coupled low speed flow problems: P. Ryzhakov, R. Rossi, E. Oñate, Int. Jour. Num. Meth. in Fluids, 2012.

Algorithmic issues

Boundary preserving refinement, boundary markers



(a) Mesh deterioration



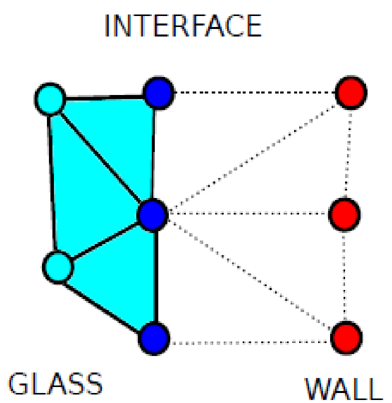
(b) Mesh-preserving refinement

Identify the boundaries with boundary markers. Ensure that no “holes” are created: subdivide stretched edges/faces maintaining mesh resolution

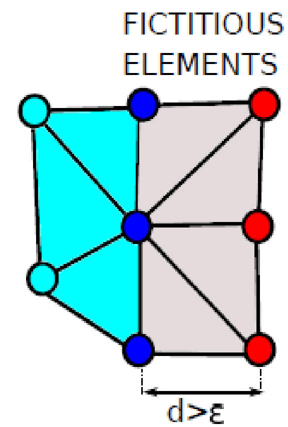
Algorithmic issues

Pre-matured contact must be avoided
Otherwise an error in bottle wall thickness will be of order ***h***. (unacceptable, since the final wall thickness is descretized with several elemets only, otherwise meshes will count millions of elements).

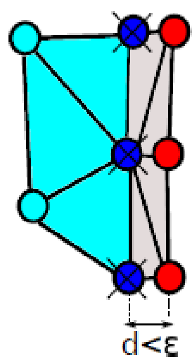
Contact detection



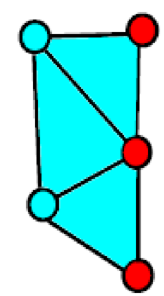
(a) Glass and wall are separated



(b) Fictitious contact elements are created



(c) Removal of interface nodes close to the wall

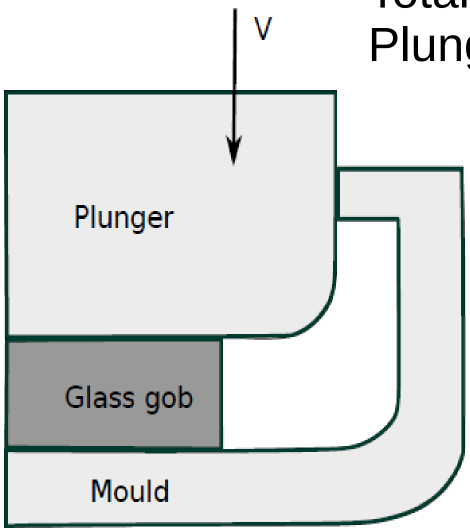


(d) Stick contact between the glass and the wall

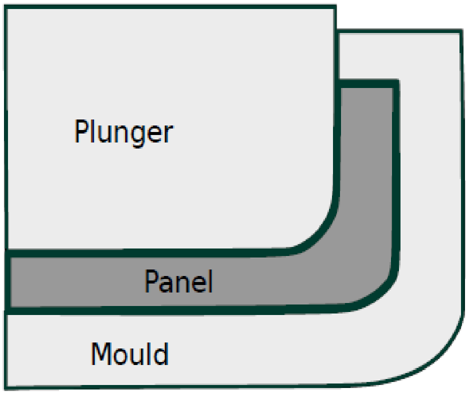
5. Examples

Validation example: TV panel pressing

Total time: t=3 s
Plunger moves during t=1.5 s



Initial config.

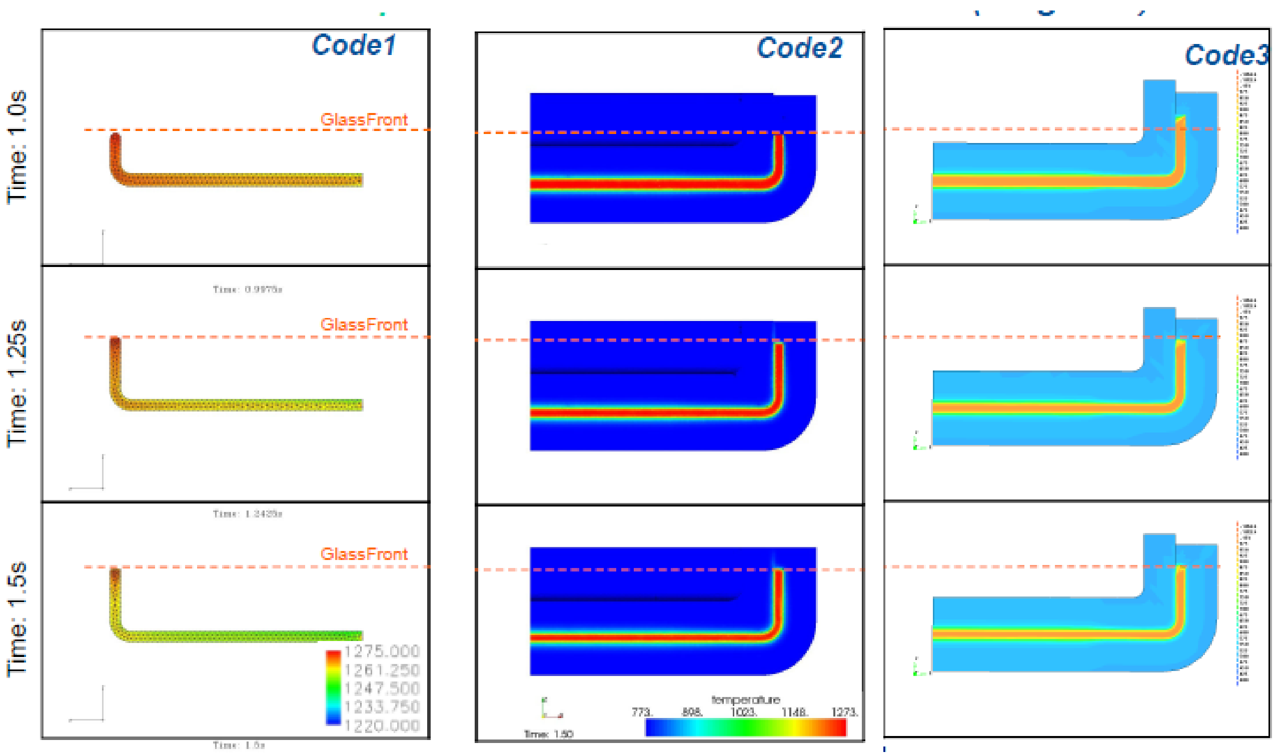


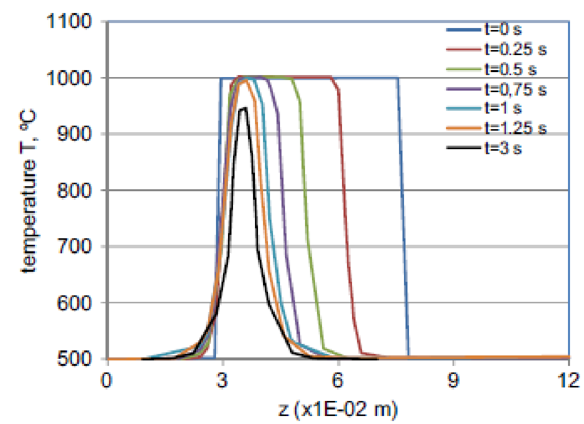
Final config.

Glass	
Viscosity μ	$10^{-2.8+\frac{4700}{T-220}}$ Pa s
Conductivity λ_g	5 W/m K
Specific heat c_g	1400 J/kg K
Density ρ_g	2500 kg/m^3
Plunger and mould	
Conductivity λ_m	20 W/m K
Specific heat c_m	500 J/kg K
Density ρ_m	8000 kg/m^3

C.Berndhauser. Tc25 - modelling of glass forming processes short review of activities 2000 - 2009. In *GlassTrend - ICG seminar and workshop INNOVATION IN GLASS PRODUCTION*. International Comission on Glass, 2013.

ANSYS, TNO, NoGrid



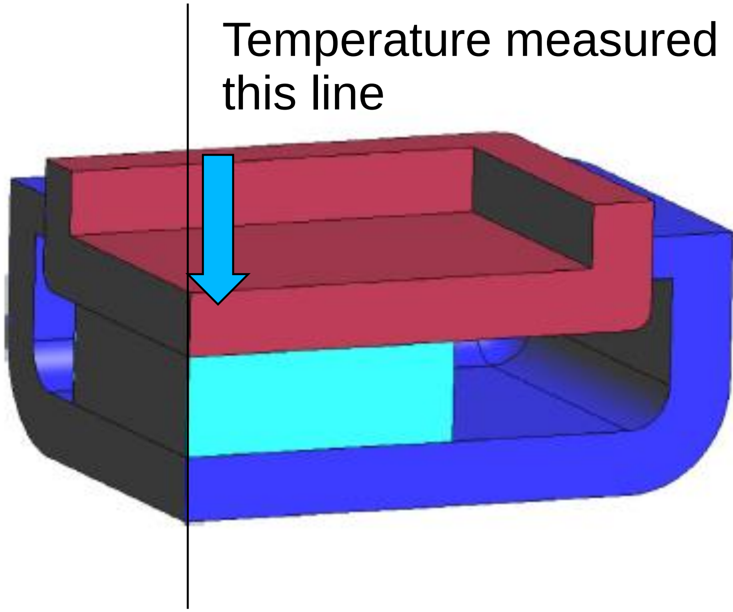


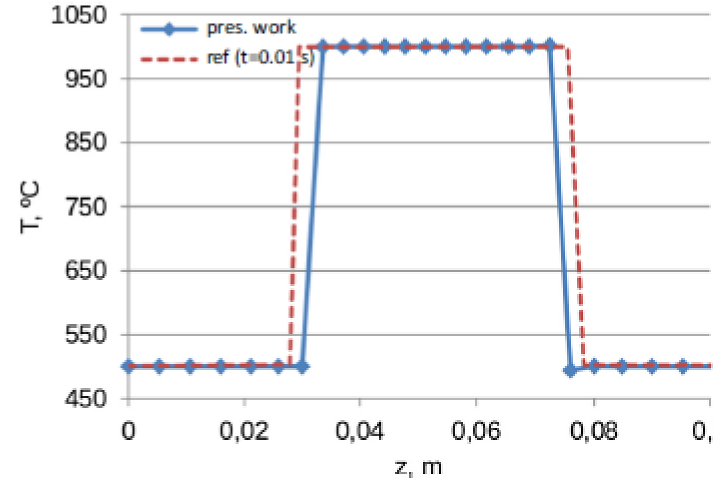
Temperature accross
the vertical cut in the middle

C.Berndhauser. Tc25 - modelling of glass forming processes short review of activities 2000 - 2009. In *GlassTrend - ICG seminar and workshop INNOVATION IN GLASS PRODUCTION*. International Comission on Glass, 2013.

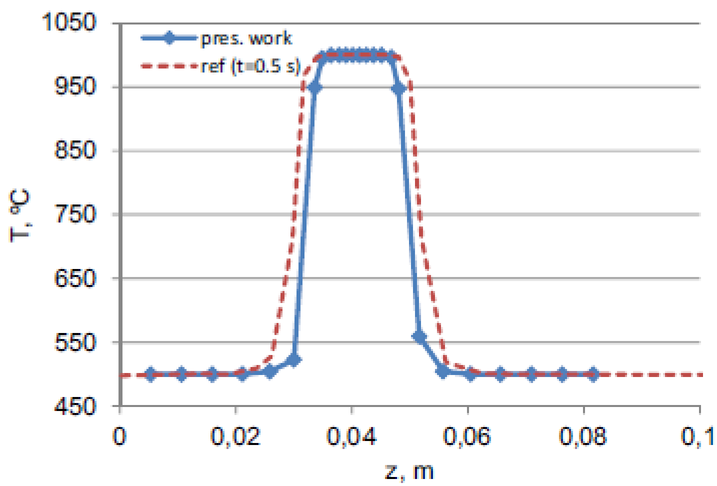
Present Lagrangian model

Temperature measured along this line

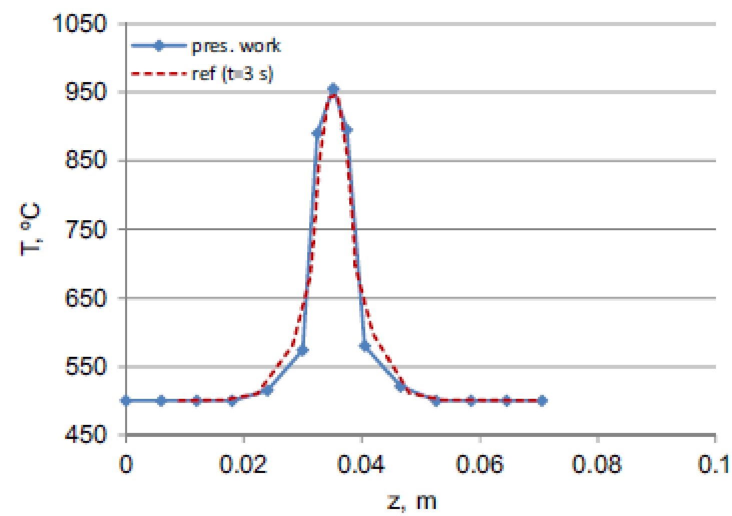




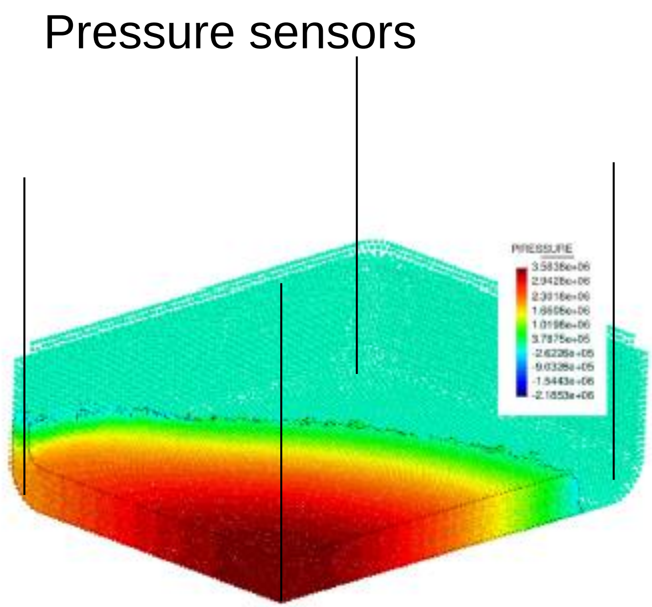
(a) t=0.01 s



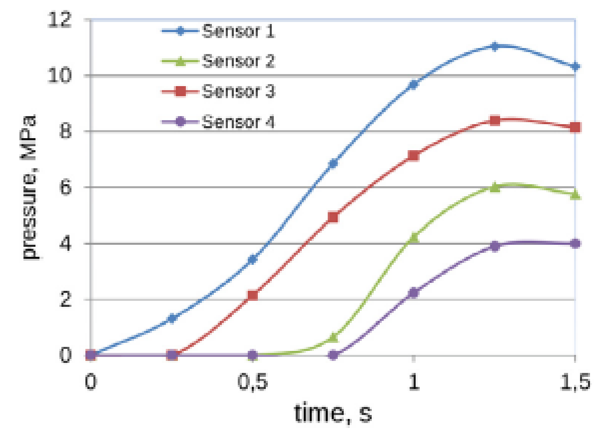
(c) t=0.50 s



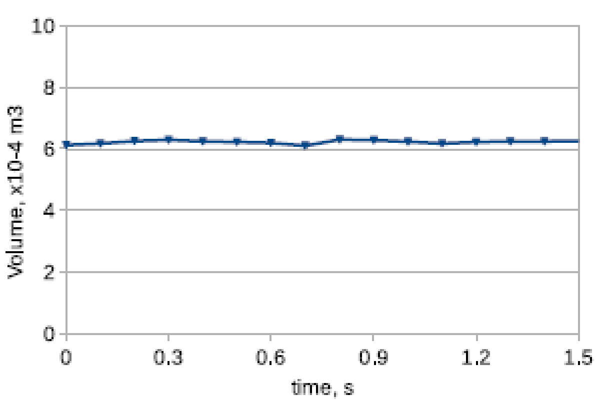
(f) t=3.00 s



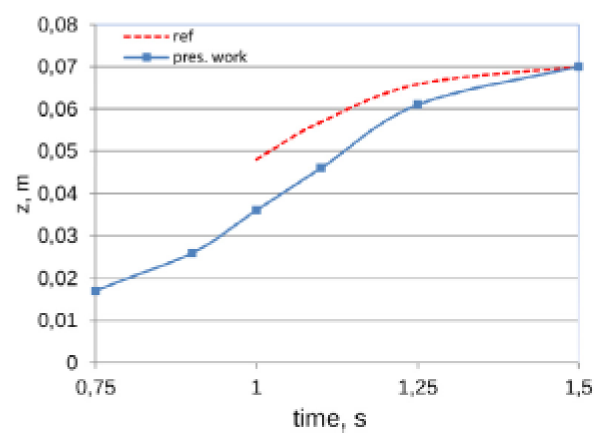
(a) Pressure distribution at t=0.50



(a) Pressure evolution



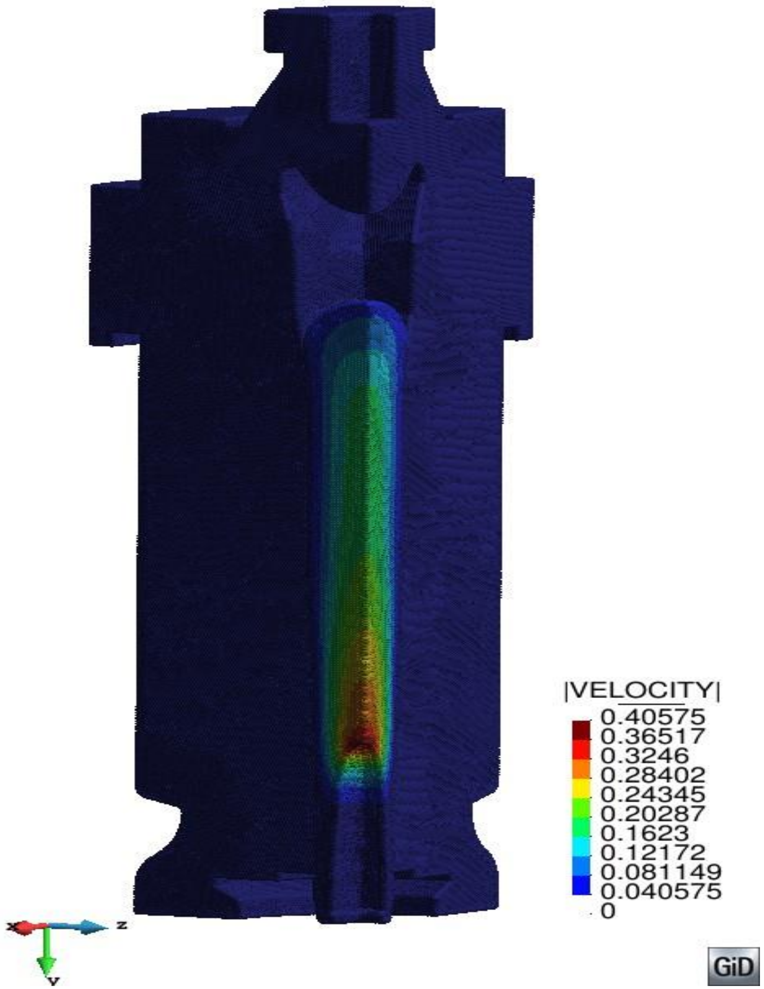
(b) Glass volume evolution in time

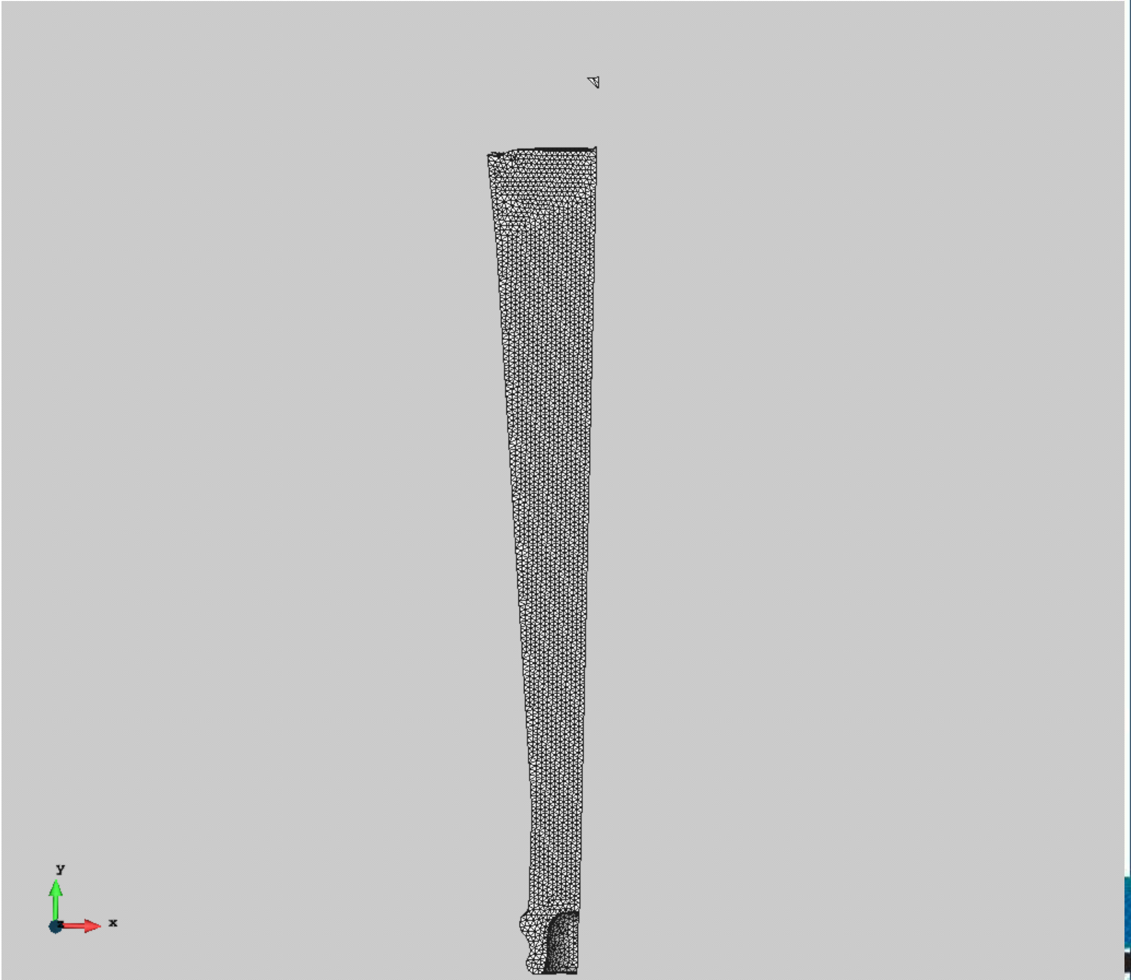


(b) Glass front evolution

Preliminary results for bottles

Counter blow process (domain's quarter)



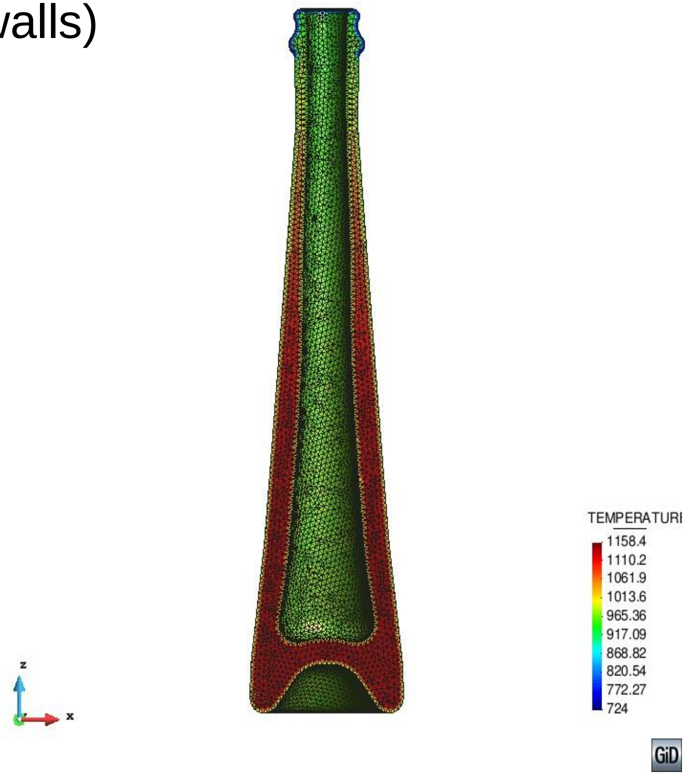


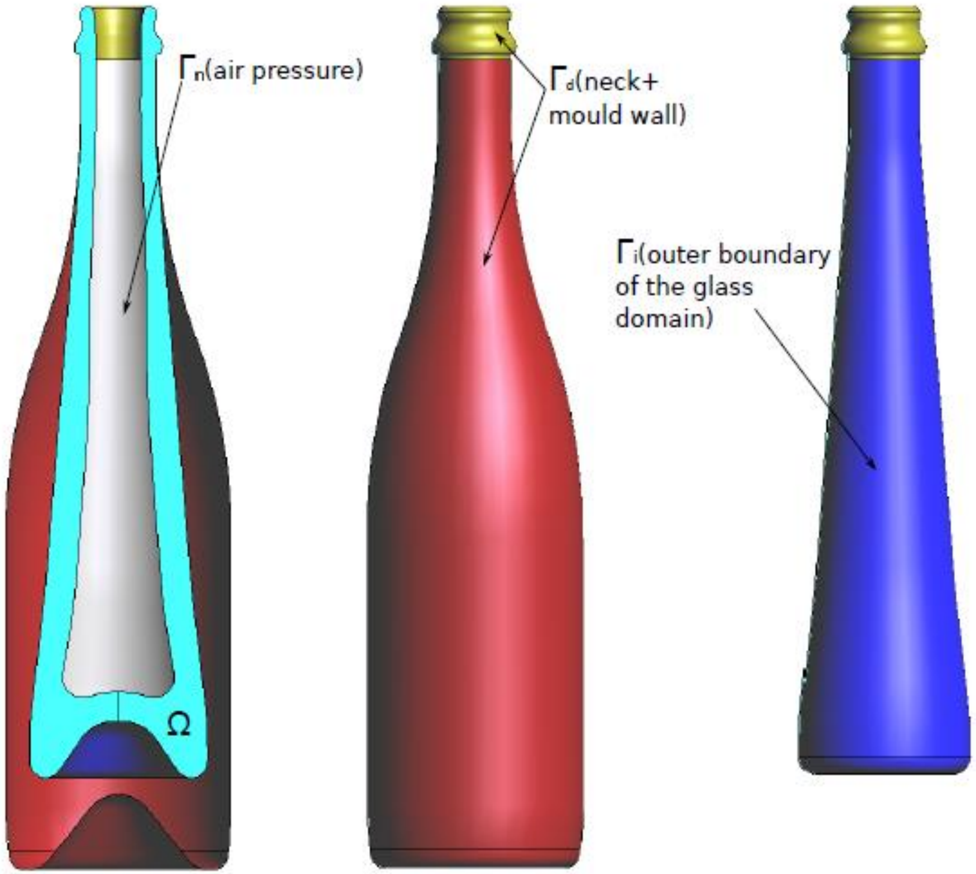
Benchmark proposal

Gravity stretch+final blow

Assumed iinitial temperature distribution

Real material properties,
Simplified thermal model (prescribed temperature at mould walls)

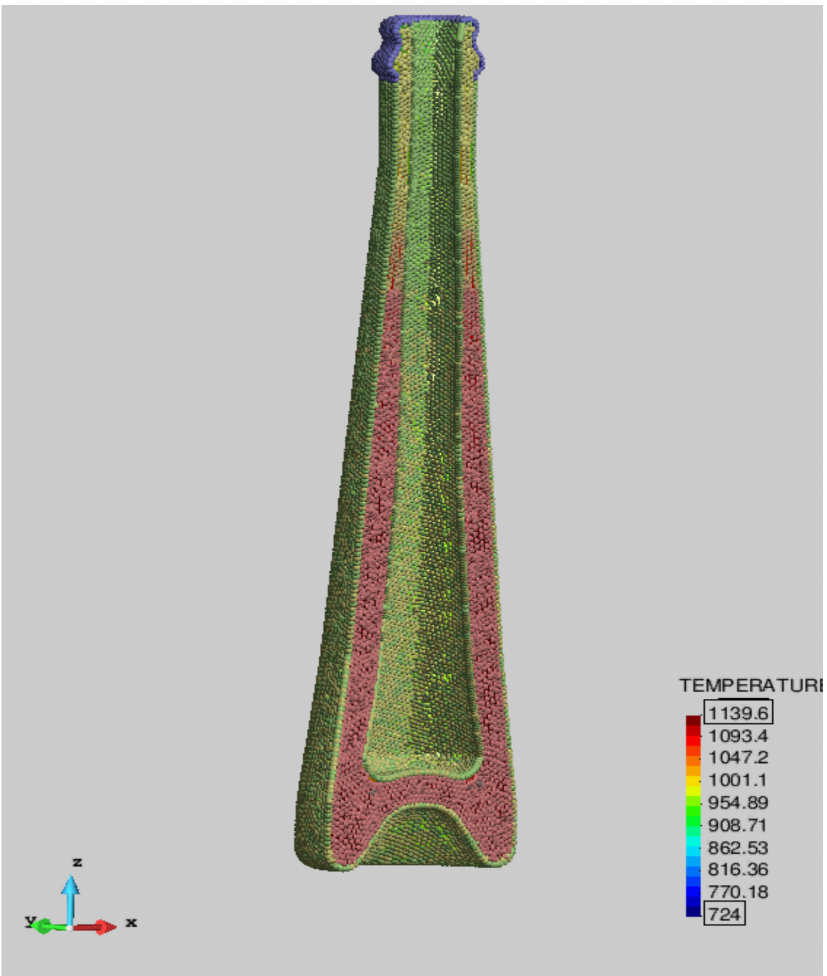




“SEKT bottle VP4679” (data: no industrial secret, data provided by Dr. J. Jimenez Vidrio&Eng. COMM)

Gravity stretch + Final blow

Thermo-mechanical simulation



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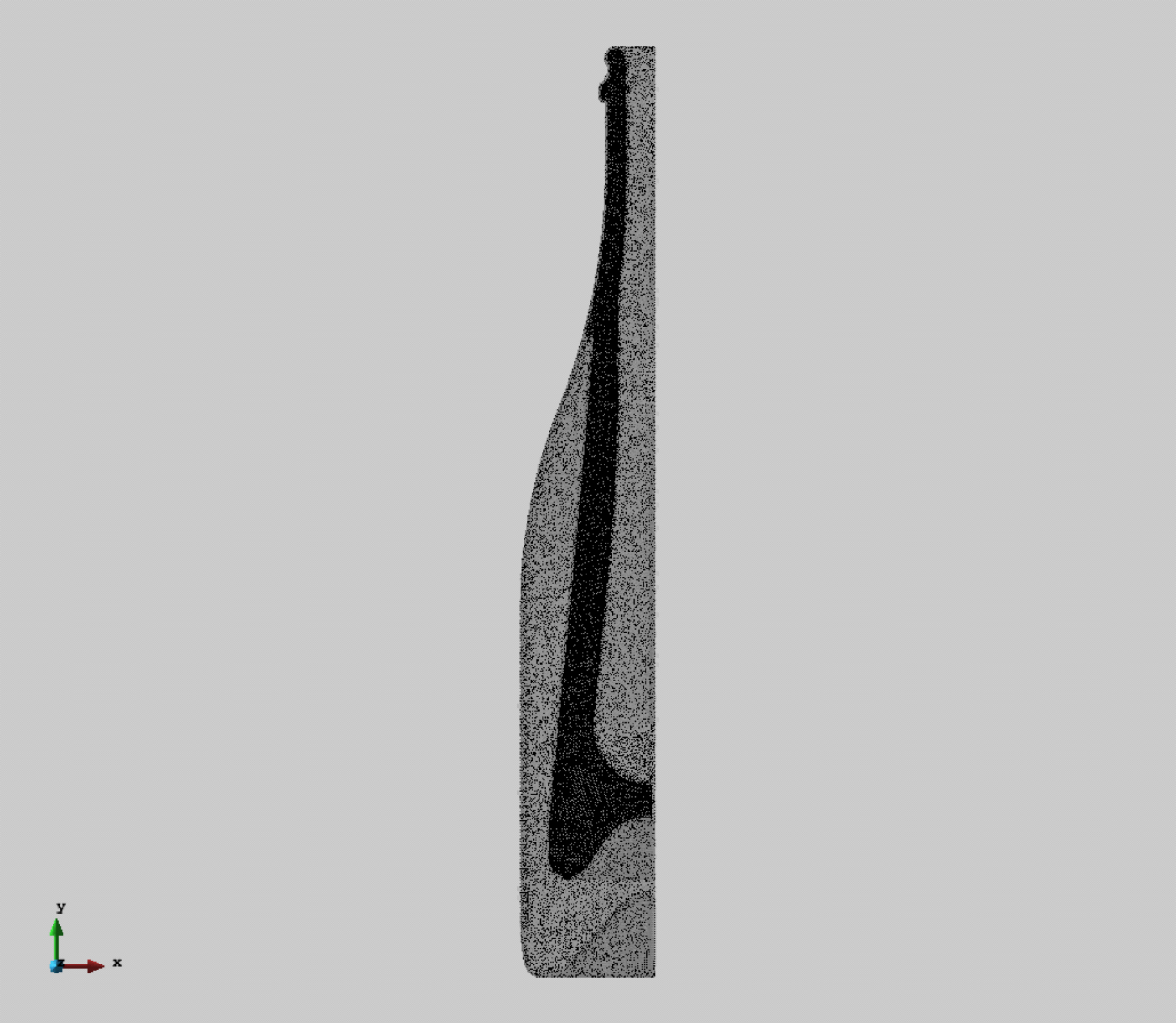
Interface elements close-up

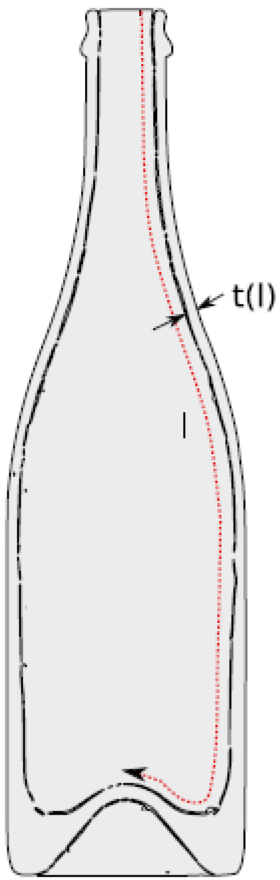
Premature blow

Premature pressure application

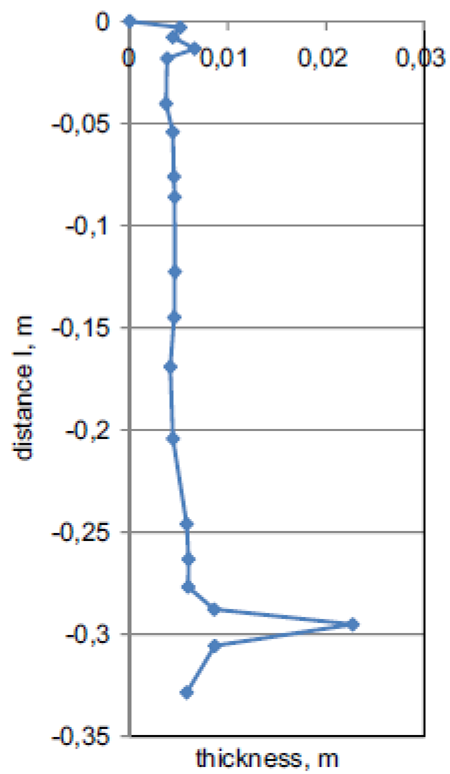
(must be applied once the glass reached the mould wall at the bottom)



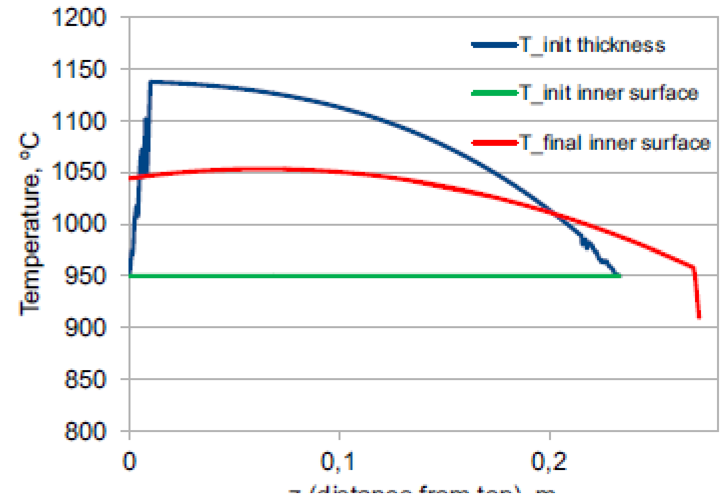
Bottle shape

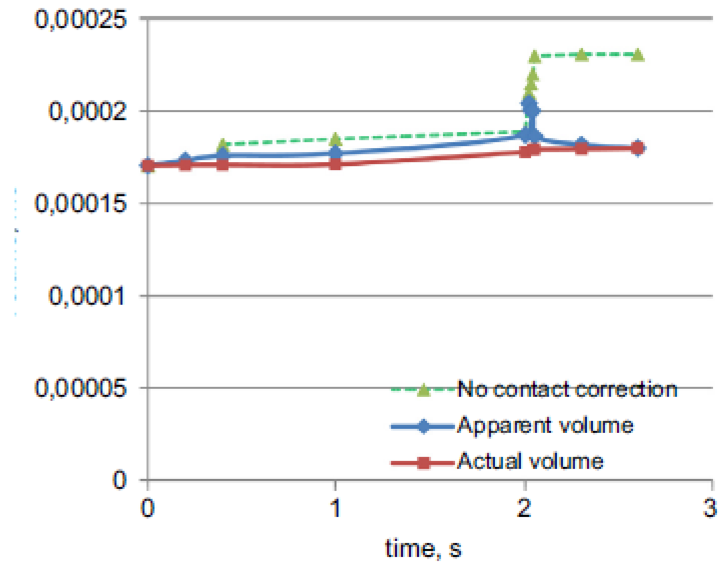


(a) Thickness measurement

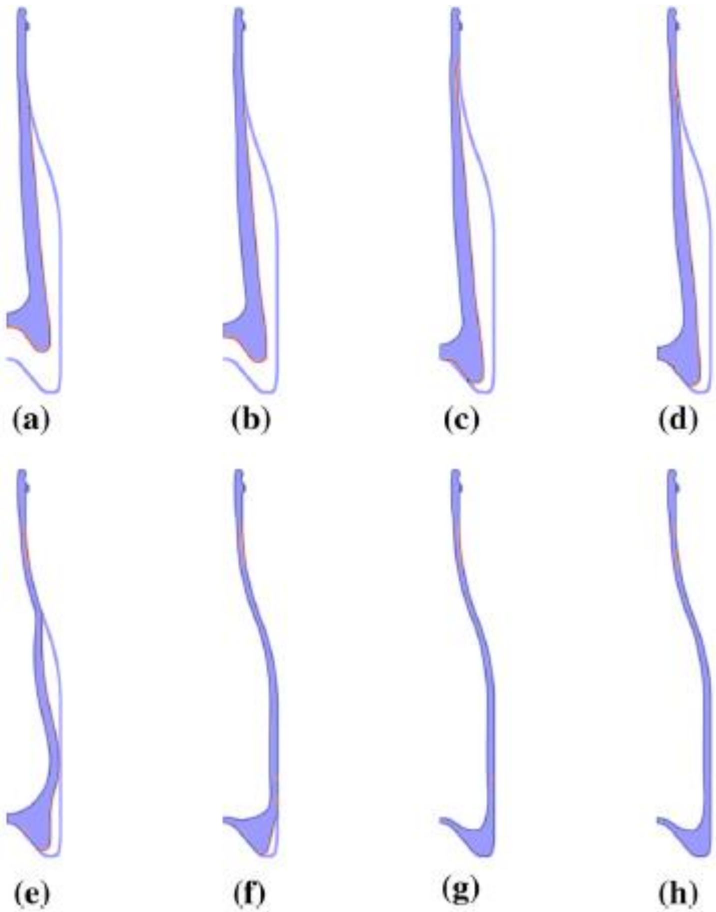


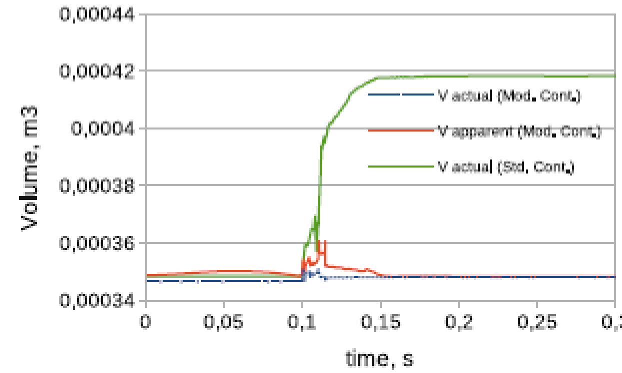
(b) Thickness distribution

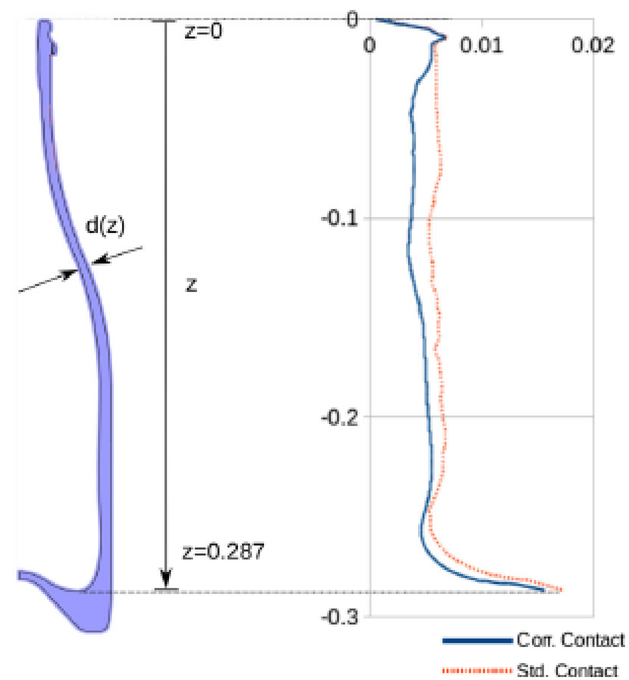




Thickness distribution. Axisymmetric simulation

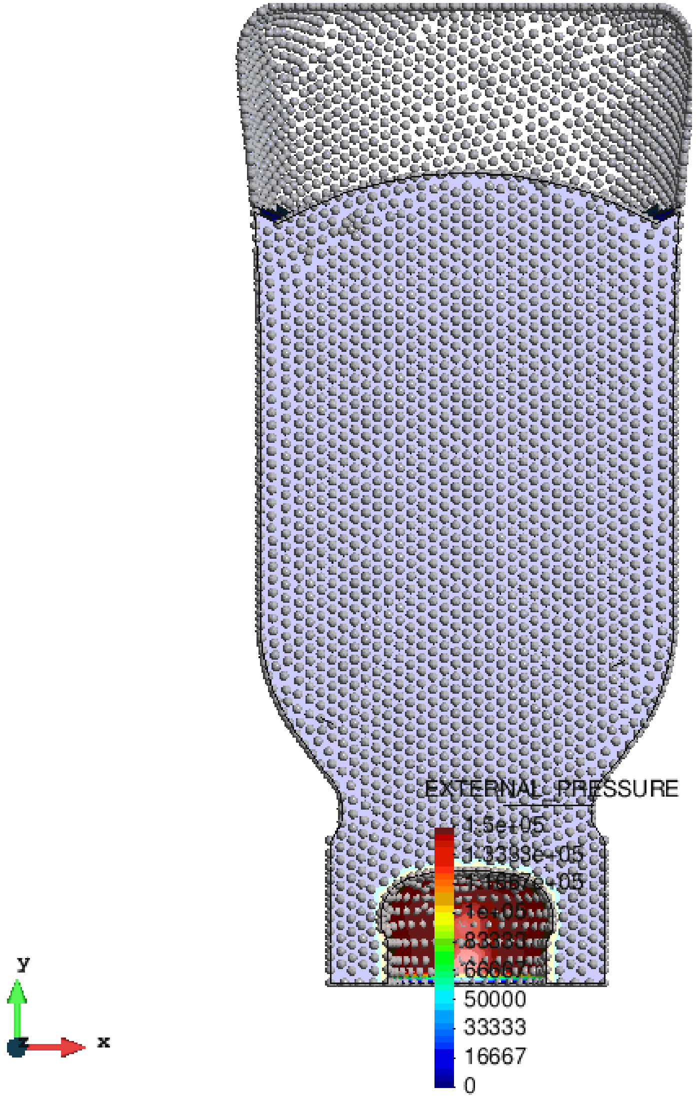


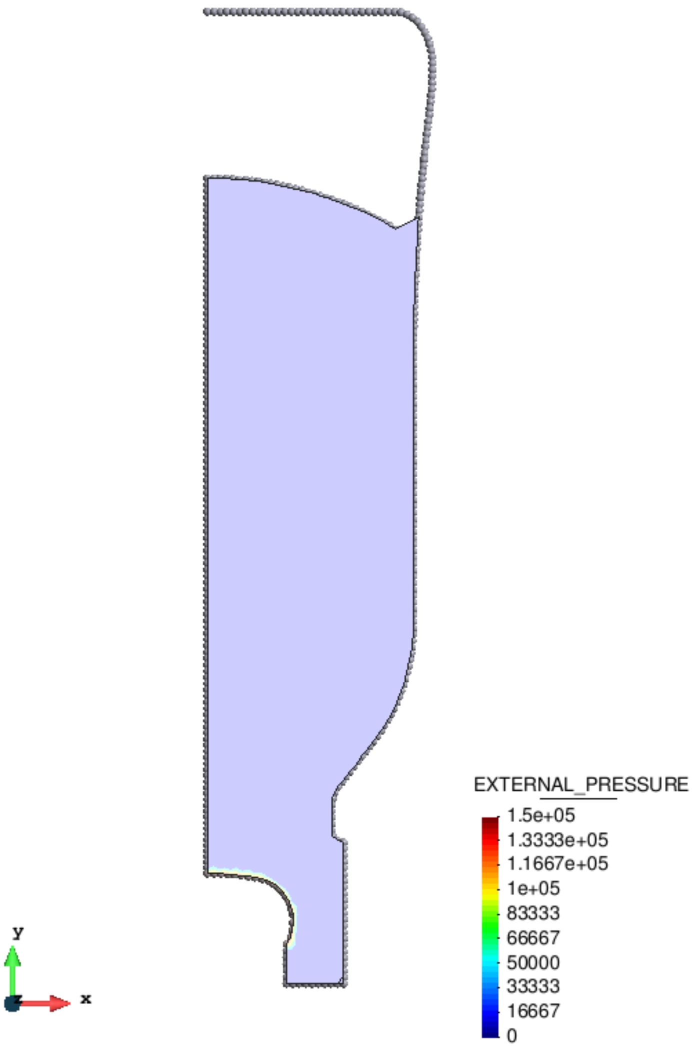




Axisymmetric - 3D comparison

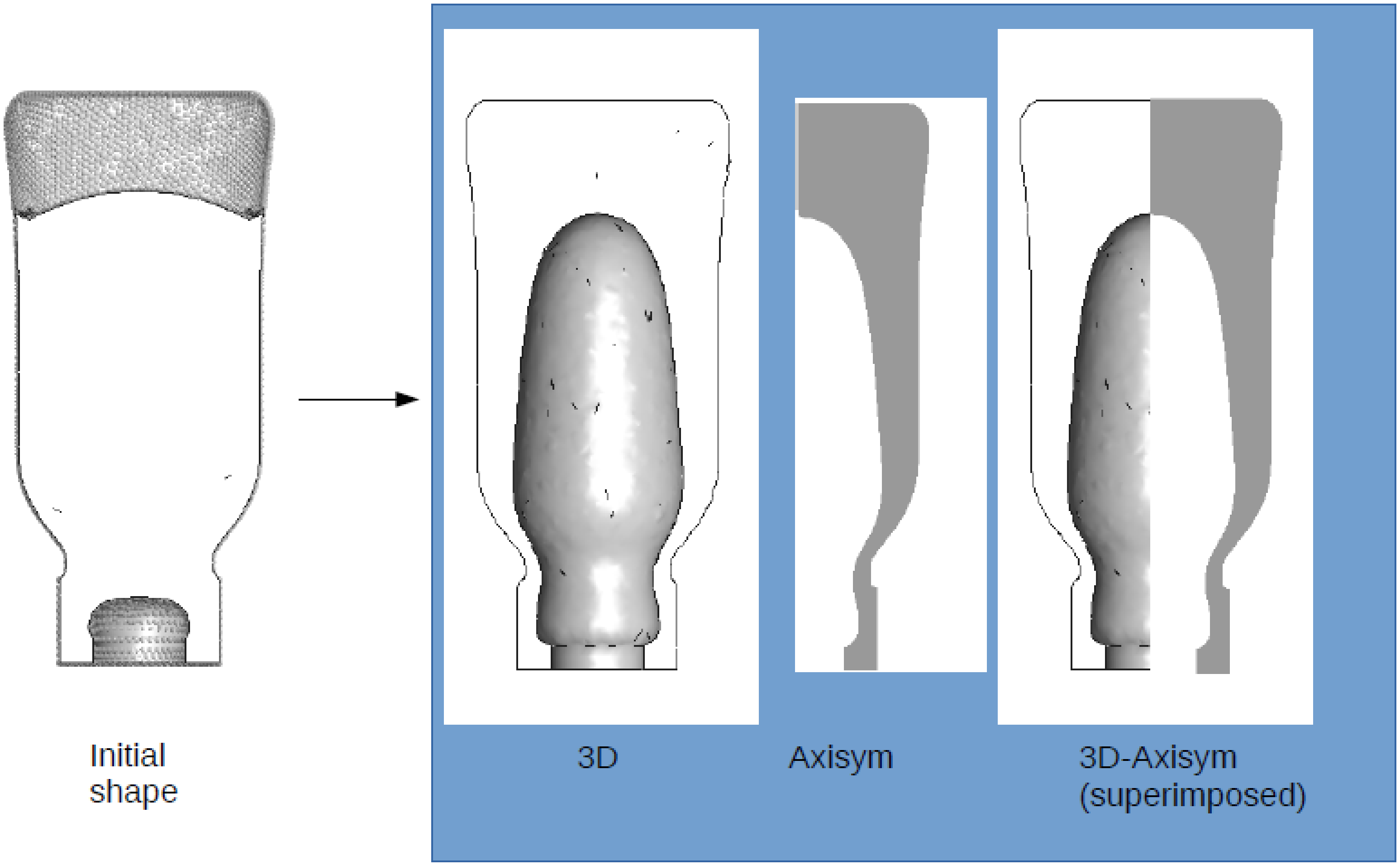
(soins60 bottle, geometry provided by *Ramon Clemente*)

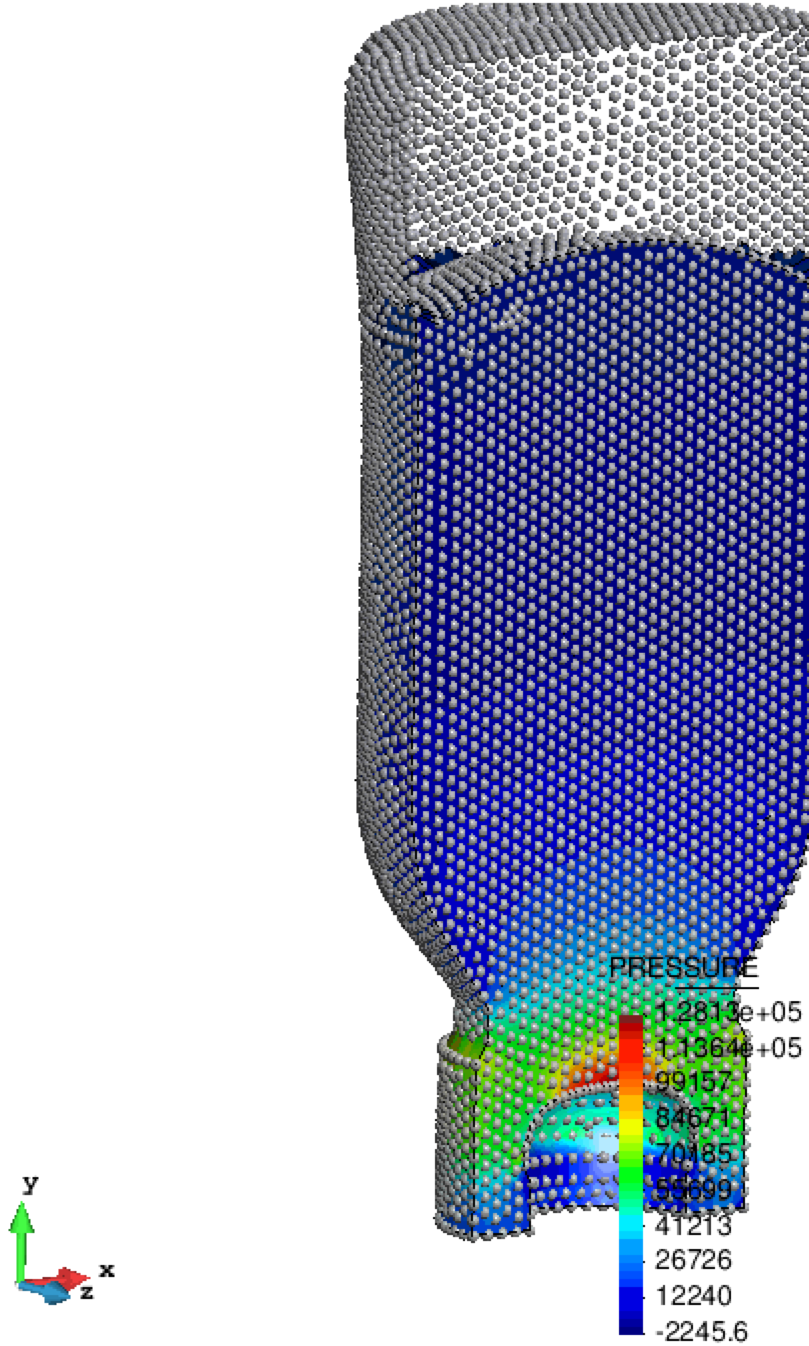




Axisymmetric - 3D comparison

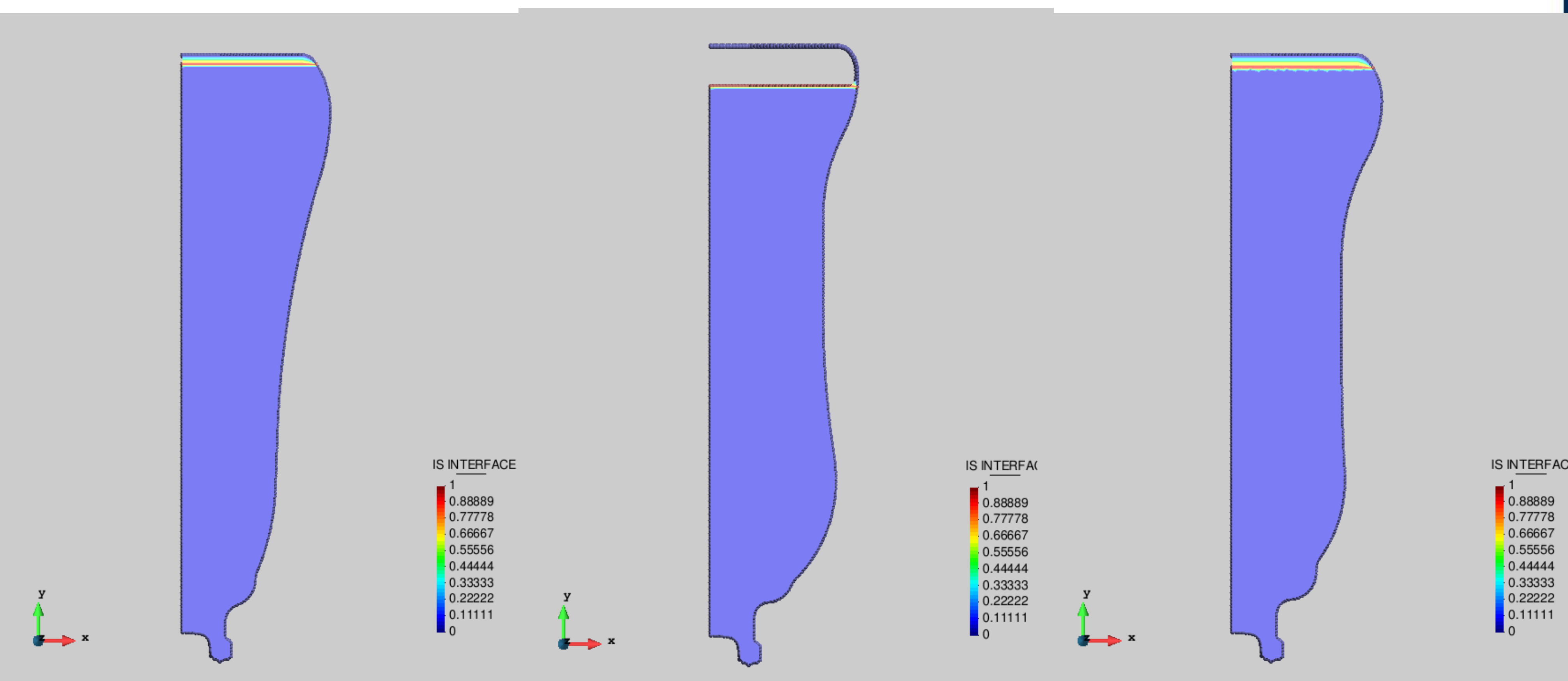
**SOINS60 flask
(parison)**




PRESSURE
1.2813e+05
1.1364e+05
99157
84671
70185
55699
41213
26726
12240
-2245.6
y
x
z

What is the use?

Parison mould design (trials on the computer instead of the real factory)



Summary and conclusions

PFEM was adapted to suit the problem of interest

Efficient **modified fractional step** method was implemented for solving the governing equations

Control over the error in thickness

Excellent mass conservation

Benchmark example elaborated

Computational times – hours (3D), minutes (axisymmetric)

3D – axisymmetric validated

Challenges

- Missing data… Precise viscosity maps in the glass (or even approximated ones) must be obtained from direct temperature measurements performed in multiple location.
- Incorporation of the mould in the thermal computations? (very large increment in comp. cost)
- Ad-hoc thermal model: heat sink at the

mould surface – experimental data necessary

Future work

- Graphical User Interface
- Incorporation of thermal data in the ad-hoc model – under development (thermal data missing)
- Comparison with experiments carried by IQS and Ramon Clemente
- Improve efficieny: apply Jacobian-independent time integration strategy (XIVAS)
- Coupling of the two steps (counter and final

Sergio Rodolfo Idelsohn, Norberto Marcelo Nigro, Juan Marcelo Gimenez, Riccardo Rossi, and Julio Marcelo Marti. A fast and accurate method to solve the incompressible Navier-Stokes equations. *Engineering Computations*, 30(2):197–222, 2013.

Acknowledgements

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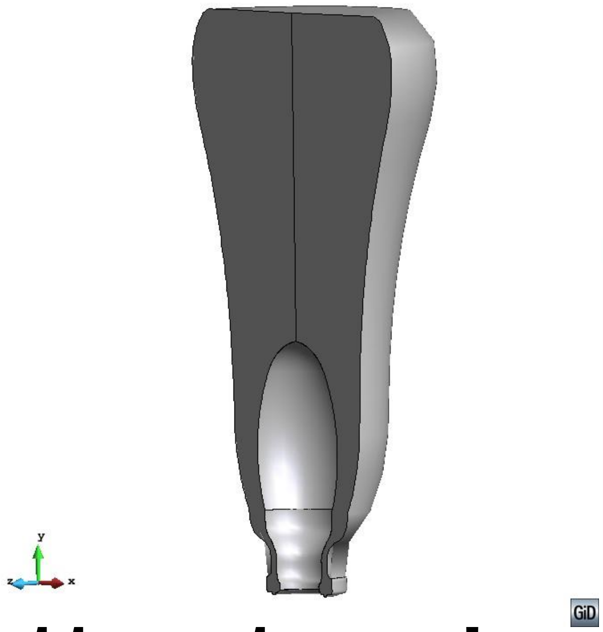
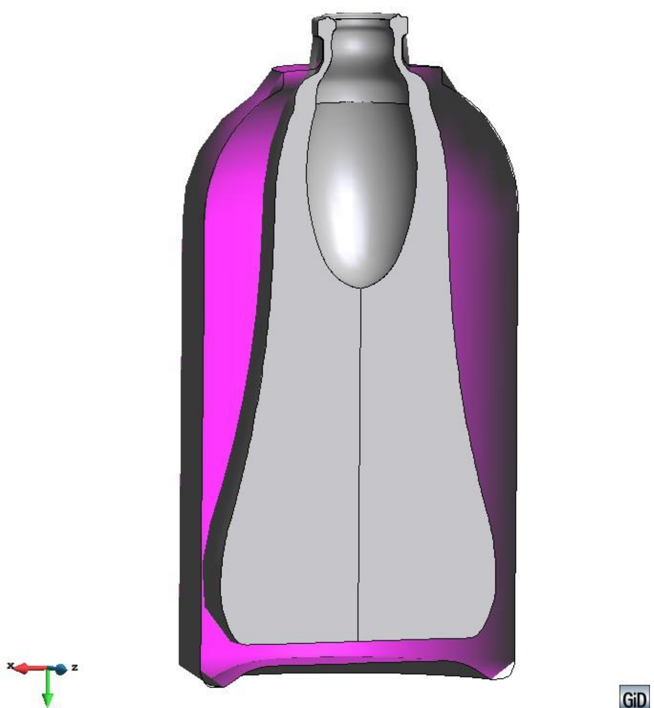


Thank you for your attention!



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