Simulating the Pouch Forming Process Using a Detailed Fluid-Structure Interaction

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Abstract: A deeper understanding of the interaction between machine, packaging material and liquid product during the forming process of pouches is enabled by the use of numerical simulation.

Tetra Pak pouch forming system forms the pouches in a continuous fashion starting from a tube of packaging material filled with the liquid to be packaged.

A bunch of jaws, moved with special laws, shape the tube of packaging material into pouches. The liquid into the tube is supplied through an inlet pipe, placed inside the tube. Additionally a pouch forming systems has a counter-pressure flange and a floater that moves along the inlet pipe and floats on top of the liquid column. The floater is used to control the flow rate at the inlet pipe. Thus a complex problem with flexible walls, free surface flows and kinematic motion of different bodies under hydrodynamic and gravity forces needs to be simulated.

Simulating the pouch forming, including a detailed fluid-structure interaction is the goal of this paper. The simulation is performed coupling Abaqus for the structural side and FlowVision for the fluid side through a Direct Coupling interface. The definition of the problem as well the results of the simulation are presented in the paper.

Keywords: Package, Forming, FSI, Code Coupling, FlowVision

1. Introduction

Tetra Pak is the world's largest supplier of aseptic packaging.
Its founder, Dr. Ruben Rausing, began the company in Lund, Sweden in 1951 with a simple principle: "A package should save more than it costs." Rausing invented the packaging technology that still forms the basis for much of Tetra Pak's business.

Tetra Fino Aseptic is an easy to install, cost-efficient packaging system that protects products and keeps them tasting fresh and natural for a long time. Friendly, safe and natural, people can carry it, pour and drink from it, and enjoy its contents everywhere – while making less impact on their environment.
The price and design attract families looking for quality beverages at a low cost, including all kinds of milk, juices and teas.

Key benefits:

- Reliable. This pillow-shaped package keeps things fresh and offers a tough seal. Produced in the reliable Tetra Pak A1 filling machine with superior aseptic technologies, it guarantees to keep things safe for a long time, protects against odours, light and oxygen keeping things as fresh, nutritious and tasty as the day they were packaged.
- Responsible. Tetra Fino Aseptic is made from renewable, recyclable paperboard. It doesn't need refrigeration when it's distributed and stored. It's a great way to transport and sell products as safely as possible – the responsible, environmental choice.
- Low Cost

- **Figure 1. A 220 ml Pouch.**

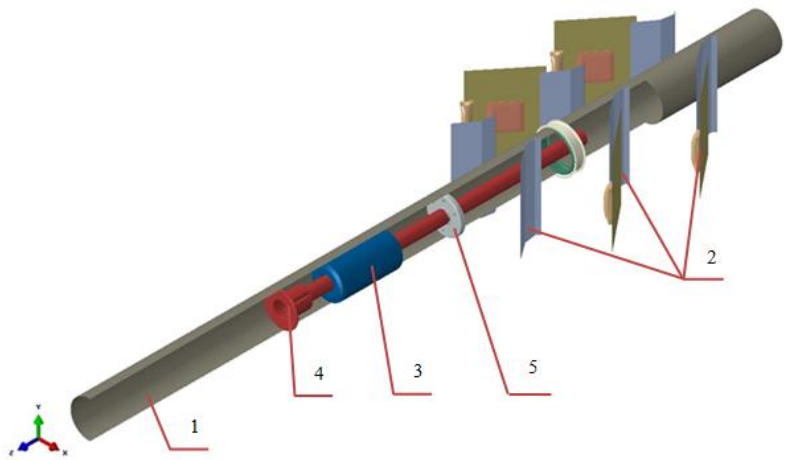
The Tetra Fino Aseptic (TFA) packages are produced with the Tetra Pak A1filling machine for aseptic production of dairy products.
The machine's high production capacity coupled with low investment costs makes it a very cost-efficient aseptic packaging system.
The Tetra Pak A1 for TFA produces TFA packages in sizes from 200 to 500 ml, at a capacity of 9,800-14,000 packages/hour.

- **Figure 2. Tetra Pak A1.**

The use of Simulation for the development of our filling machines is extremely important.
The filling process is a complex interaction of the fluid to be packaged, the packaging material and the machine.
The problem is a strongly coupled fluid structure interaction; in fact the action of the machine exerted through the packaging material influences the fluid behavior and in turn the fluid pressures influence the package shape.
The use of simulation enables a deeper understanding of the complex interactions involved during the filling and forming process and makes it possible to evaluate the effects of different solutions and modifications of the machine design without necessarily building expensive test rigs. It also enables the estimation of quantities that is extremely difficult measure in a real machine like the evolution of the pressures inside the package during the forming process.

2. Statement of the Problem

The simulation of the forming process includes the components shown in Figure 3.



- **Figure 3. Simulation components.**

The analyzed system consists of five major components:

1. The tube of packaging material
2. The forming jaws
3. The floater
4. The inlet pipe
5. The counter-pressure flange

The deformable tube made with a specific Tetra Pak packaging material (a multilayer composite material made of paperboard, polyethylene and aluminum) is shaped into pouches and dragged down with a time dependent velocity (in the negative z-direction shown in Figure 3) by the moving jaws while the liquid product is supplied into the tube through an inlet pipe. The floater moves under the liquid influence along the inlet pipe; its position is used to control the flow rate at the inlet.

3. Numerical model definition

3.1 Abaqus FE model

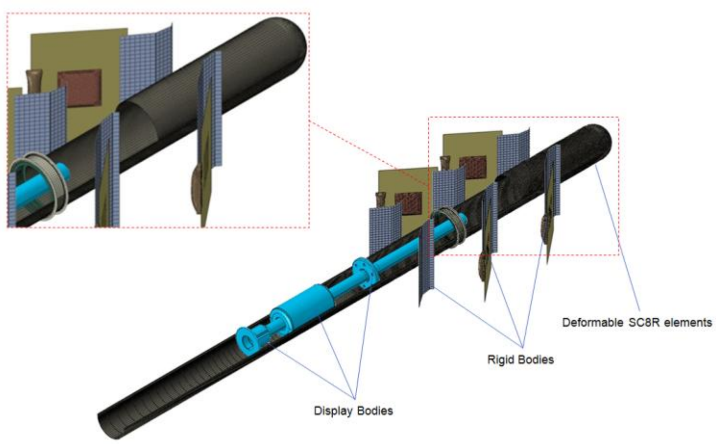
Since the metal jaws are much stiffer than the tube of packaging material it's reasonable to simulate them as rigid bodies interconnected by connector elements. The inlet pipe, the floater and the counter-pressure flange are included into the FE model as display bodies to visually control their relative position. The inertia properties of the rigid parts are applied to their reference points. The deformable tube is modeled using continuum shell elements SC8R; the tube mesh is non-uniform and consists of about 60000 continuum shell elements.

There are two groups of contact interactions in the FE model: interaction between tube and jaws with friction and tube self-contact without friction.

The analysis is divided into two main stages:

1. Preloading phase
2. Dynamic fluid-structure interaction

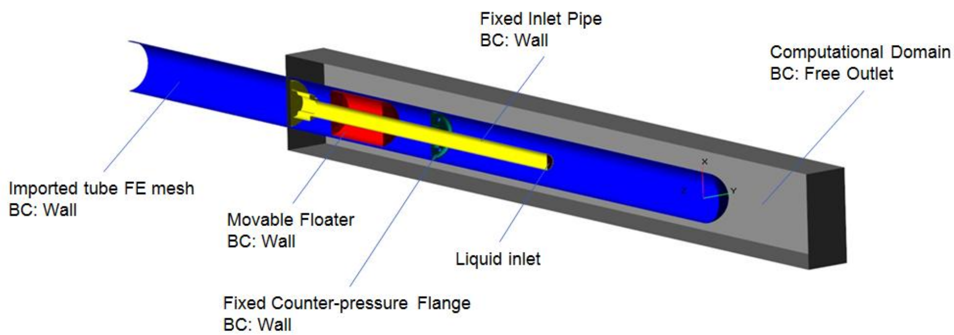
In the first stage Abaqus/Standard is used to perform a static analysis to compute the equilibrium configuration of the tube under the hydrostatic pressure exerted by the fluid, an axial load corresponding to the one exerted by the web tension device (not included in the simulation) and the gravity load. In the second stage performed with Abaqus/Explicit the Abaqus import capabilities are used to import the tube (in the configuration obtained at the end of the first stage) in a dynamic explicit analysis where the FSI is considered using the co-simulation strategy; during this step the jaws are moved with a proper set of boundary conditions and prescribed connector motions. The analysis time of the dynamic explicit step is 1.5 s which is enough to form two packages (excluding the one close to the end of the tube).



- **Figure 4. Abaqus FE model.**

3.2 FlowVision FV model

The CFD computational domain is a box with the size of 0.15m x 0.15m x 1.3m (see Figure 5). The size of the computational domain is sufficient to contain the tube of packaging material. The tube of packaging material is imported in *FlowVision* using the "moving body" capability as the Abaqus FE mesh. While the computational domain in *FlowVision* is fixed a "moving" body is the way to introduce a moving boundary. During the import phase FlowVision automatically defines the external surface of the FE mesh. All the other parts inside the tube (floater, counter-pressure flange, inlet tube) are imported as CAD geometries and are not included in the Abaqus computational model. The Floater is defined in FlowVision as a rigid "moving body"; its motion is fully controlled by FlowVision.



- **Figure 5. FlowVision FV model.**

The fluid modeled in the simulation corresponds to distilled water. At the beginning of the analysis a portion of the internal space of the tube is already filled with water (see Figure 6).

- **Figure 6. Initial Water Distribution.**

The motion of water is modeled with the Navier-Stokes equations for incompressible fluid. Turbulence and heat transfer processes are not taken into account.

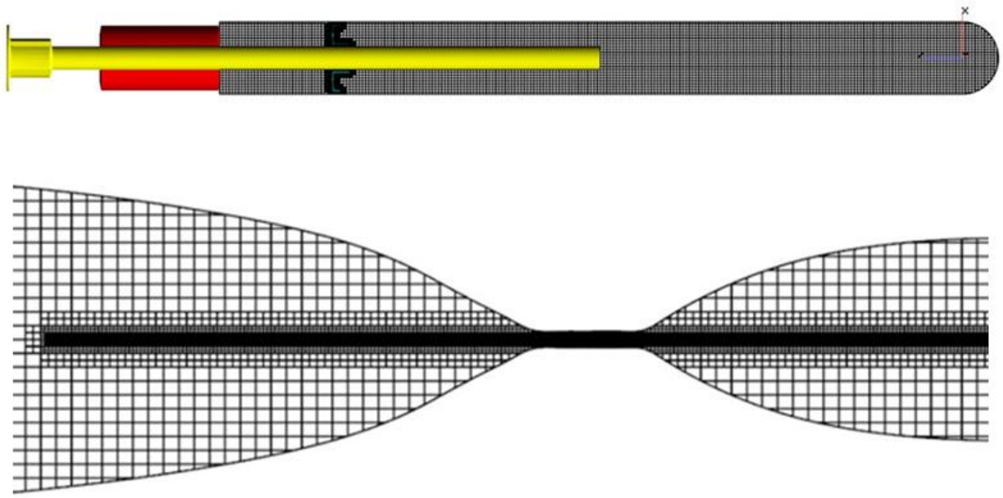
An advanced Volume of Fluid (VOF) method is used to track the water free surface. The air flow can be neglected in the given problem and the gas phase can be substituted by an external atmospheric pressure condition.

Boundary conditions on all parts, including tube of packaging material are of type «Wall». A «Free Outlet» boundary condition is applied on the computational domain boundaries. So, if the internal liquid goes outside the flange or the inlet pipe it is removed from the computational domain. There is an Inlet boundary condition on the inlet pipe's end surface (see Figure 5).

To implement the automatic control of the fluid flow rate at the inflow boundary the *FlowVision* «Formula Editor» is used. The magnitude of the inlet flow rate depends on the measured vertical position (z_F) of the floater's center of mass:

$$Q=f\,(z_F)$$

The CFD initial mesh has approximately 222 500 cells and it is locally refined up to 3 levels, the size of the most refined cells will be 8 times smaller than the size of the initial parent cell (see Figure 7). To limit the computational cost this volumetric adaptation is activated only when the tube's walls come close to each other. The final computational grid has approximately 1 800 000 cells.



- **Figure 7. FlowVision Mesh refinement.**

The CFD mesh in FlowVision is built fully automatically using the Subgrid Geometry Resolution Method (SGRM). To take into account the peculiarities of the computational domain shape, the motion of the moving parts etc., the mesh is adapted by using local adaptation techniques. These techniques allow small details to be resolved without large increases of the number of cells. During adaptation each cell is divided into 8 smaller cells. Each division is designated by a level number; the highest level belongs to the smallest cells. The number of levels is unlimited in *FlowVision*.
The “Standard Gap” model is used to calculate forces and fluxes in thin channels between two sides of the deformed tube. The model resolves such channel with calculations made by analytic expression.
The FlowVision time step is automatically defined as the minimum ratio of the size of a cell containing a contact surface or adjacent to a moving body to the absolute value of the velocity of the phase. In our analysis it is equal or close to 1·10-4 s.

3.3 Fluid Structure Interaction model

The co-simulation analysis with Abaqus and FlowVision is based on Abaqus Direct Coupling Interface (DCI) as shown in the Figure below.

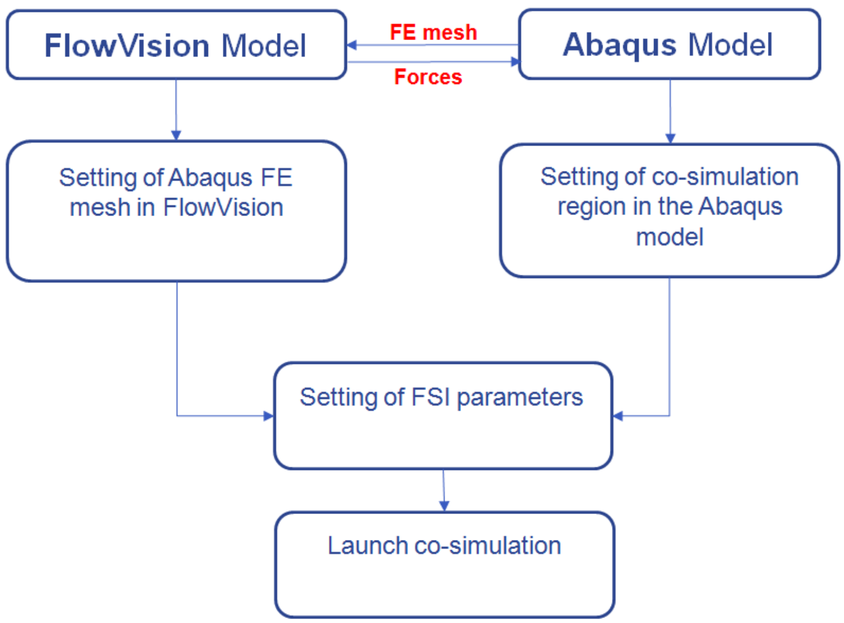


Figure 8. Co-simulation chart.

FlowVision is the master application with Abaqus working in slave mode. At each DCI interaction, FlowVision provides Abaqus with the predicted loadings on each tube's node. These loadings are used by Abaqus to compute the displaced nodal coordinates of tube's mesh, which are returned to FlowVision for the subsequent time step.

The co-simulation parameters in the step module of the input file are defined as shown in the Figure below:

```
*CO-SIMULATION, PROGRAM=DIRECT, NAME=FV, CONTROLS=COSIM_CONTROLS
*CO-SIMULATION REGION, IMPORT
DC-surface, CF
*CO-SIMULATION REGION, EXPORT
DC-surface, COORD
*CO-SIMULATION CONTROLS, NAME=COSIM_CONTROLS, TIME INCREMENTATION=SUBCYCLE, TIME MARKS=YES
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Figure 9. Co-simulation keywords.

Abaqus allows sub-cycling during the coupling time step.
An explicit coupling procedure is applied for the time stepping algorithm. The exchanged data are the forces computed by FlowVision at the nodes of the FE mesh, and the node displacement computed by Abaqus. The exchange time period (FSI time step) is based on the value of the CFD explicit time step (min h/V over the entire CFD domain: h- cell size, V – fluid speed).
As practice shows, for the fast simulation processes, like the dynamic analysis of our tube deformation is, the best choice of FSI time step is 1 or 2 CFD explicit steps.
The FSI time step is started by Abaqus and uses loadings from the previous FSI time step, as shown in Figure 10. FlowVision receives new node coordinates and calculates new loadings.

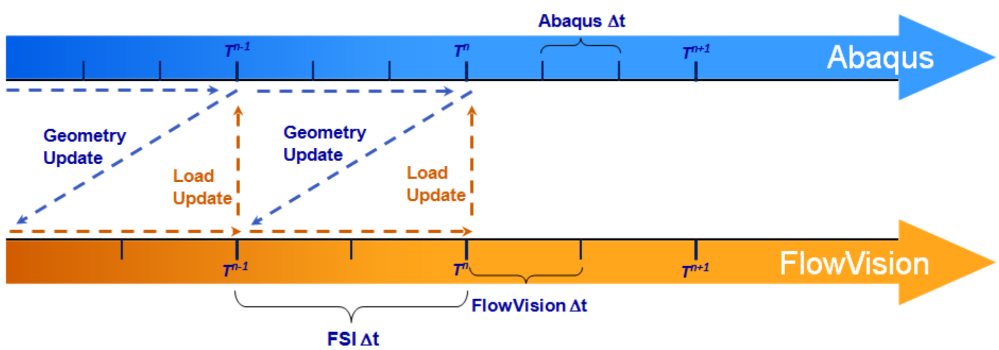

Figure 10. Coupling scheme.

4. Results

The results presented in this paragraph are referred to the case of constant fluid flow rate throw the inlet pipe; this means that there is no feedback through the floater's position on the filling process. In these filling conditions the floater moves up until it achieves its maximum upper position which is about 0.05m of relative displacement from the initial position (see Figure 11). The mentioned upper position is reached when the jaws have almost completely closed a package. At this point since the floater can't move up further the water starts to fill the volume above the floater. This event has a negative influence on the shape of the formed packages, so a controlled fluid flow rate at the inlet is very important for the quality of the forming process and will be taken into account in our next investigations.

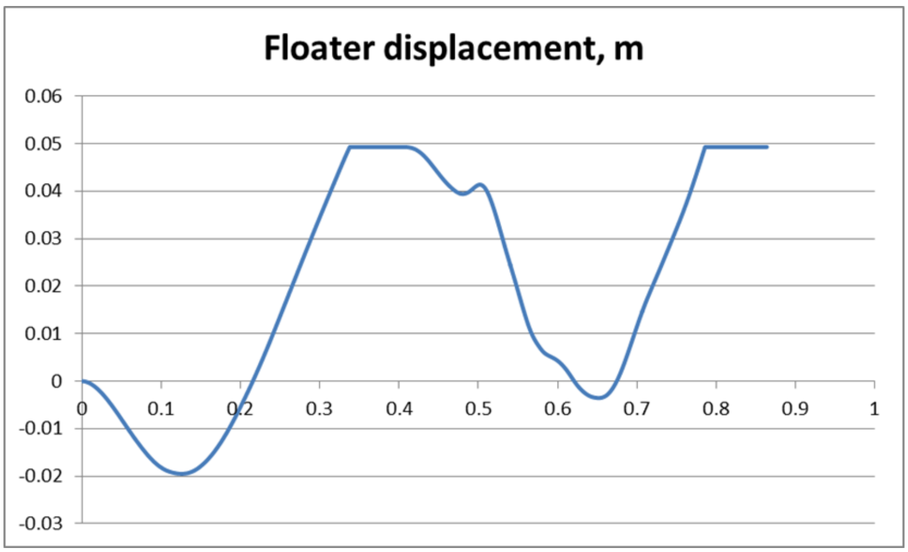

Figure 11. Floater displacement

The pressure distribution at t= 0.86 s is shown in Figure 12. At this instant the first “normal” package is formed (excluding the package close to the tube’s end). The highest pressure is inside the almost closed package and it is interesting to note that the pressure just above the package is sensibly smaller. This overpressure inside the package is explained by the work of the jaws that squeeze the tube of packaging material and force the fluid to move from the package to the volume above. This motion is hampered by the decreased gap enforced by the jaws.

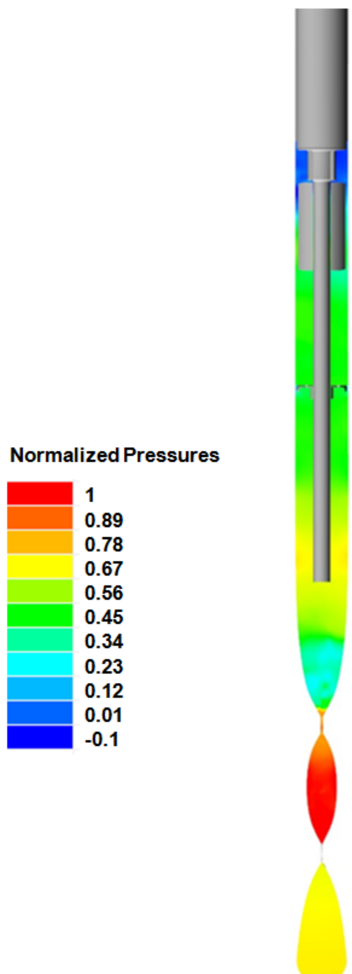

Figure 12. Fluid pressures contour plot

The speed of the jaws directly influence the pressures experienced by the packaging material and thus might be responsible of defects like tears or wrinkles.
The scalar velocity distribution at the same time is shown in Figure 13. The inflow of the fluid from the inlet pipe can clearly be observed. Immediately after that a package is completely closed there is a residual speed on the fluid inside that will result in pressures fluctuations. If the average pressure inside the package is comparable with this fluctuations it will result in a badly formed package with an inaccurate fluid content. Thus from one hand the residual pressure inside the package must be small to avoid damaging the package while on the other hand it must be big to get the proper shape and the desired fluid content.

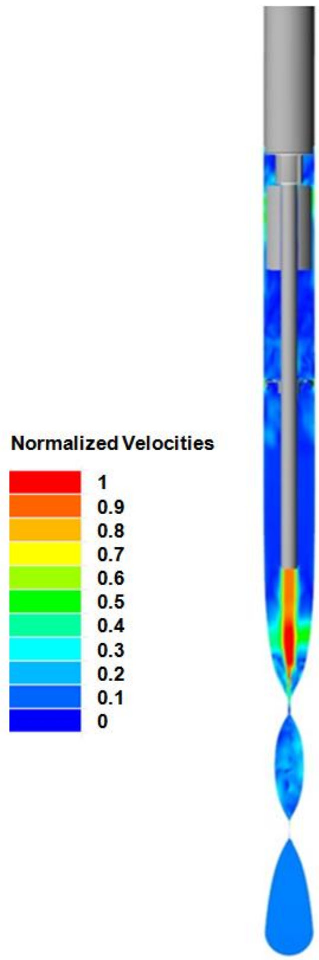

Figure 13. Fluid velocities contour plot

Figure 14. Fluid velocities vector plot

5. Conclusions

We explored a new methodology for the simulation of Tetra Pak pouch forming system.
The methodology is based on solving a fluid-structure interaction problem considering the complex interaction of all the mechanical parts of the forming system with the flexible tube of packaging material and with the liquid product. This methodology involves a two-way coupling between the FEA code Abaqus/Explicit and the CFD finite-volume code FlowVision, based on the Direct Coupling Interface between the two codes. This methodology allows an accurate investigation of different factors (profile of motion of the jaws, design of the counter-pressure flange, inlet flow rate) on the quality of the forming process, reducing the risk of damaged packages and increasing the filling accuracy.

6. References

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