Chapter 9

Nozzle Validation

9.1 Introduction

In the previous chapters the physical model and the equations necessary to write an extrusion program to simulate the whipping were described. Moreover, in chapter 7 all the parameters necessary were found thanks to rheological characterization. In order to validate and extend the model, the validation tests were conducted in the laboratory with two different cans filled in Codap, and then, to see how the model was capable of following changes in the working conditions, the effects of both pressure and rheology were studied. The aim of this study was to obtain more physical knowledge about the fluid dynamics, texture and final residue in the can. This last point is, in fact, a very important parameter to commercialise a whipping product, because this must not exceed an exact value.

The model computation gives the values of the variables considered in the model at any instant and the comparison was made by using the data obtained by extrusion trials.

9.2 Numerical Solution

The differential equation system described in the previous chapter 8 (eq.s 8.9-8.11) was solved by a finite element method implemented in the commercial software Comsol Multyphysics ver. 3.2 (Comsol, Sweden). The subdomain was discretized (Figure 9.1) by using an “extra fine” meshing generation with 3821 degrees of freedom; on a 2.8 GHz Intel Pentium Personal Computer, with 2.0 GB of free RAM, the problem solution was reached usually in 45 minutes for all simulations, except when treating sample E3; this emulsion, indeed, is characterised by high viscosity values and, therefore, caused more numerical problems during the analysis of the flow in section area changes. In this case a higher computation time and a lower integration time step were necessary to get the solution.

Owing to numerical difficulties in Multyphysics implementation, to simplify the problem, eq. 8.14-8.16 were solved by assuming a linear trend of Q(t) between the initial value (i.e. at time zero) and the current value at any time, in this way the numerical solution of integrals in eq. 8.14-8.16 was significantly simplified. It was found that this assumption does not significantly affect the final results but simplifies the Multyphysics solution, therefore it was used during all computations.

Two nozzles, N1 and N2, were considered, as stated in chapter 8, and the principal geometric dimensions are transferred in table 9.1 with the typical initial conditions.

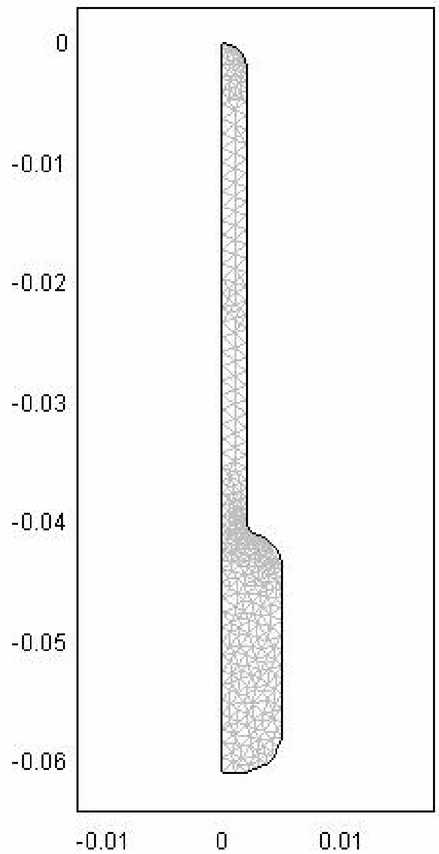

Figure 9. 1 – Subdomain Meshing

Nozzle N1		Nozzle N2		Initial conditions	
Total Length [cm]	6	Total Length [cm]	4	Initial Pressure [kPa]	800
Nozzle diameter [mm]	4	Nozzle diameter [mm]	6	Initial liquid mass [g]	250
Maximum actuator diameter [mm]	10	Maximum actuator diameter [mm]	10	Initial un-dissolved gas mass [g]	2.7

Table 9. 1 - Nozzle dimensions and initial conditions

9.3 Numerical results

As stated at the end of the chapter 7, the emulsion E3, E6 and E7 show a rheological behaviour that seems to be suitable for soft ice cream production, and then they are used to simulate the extrusion process at low temperatures (4, 0, -5°C) to evaluate can working conditions. Moreover, the fluid dynamics of emulsion E5 was simulated to compare the real performance with the simulated, having a can filled by Codap laboratory with nozzle N1 and emulsion E5.

The amount of nitrous oxide dissolved in the cream was calculated with equation 8.5, using the mass of N_2O added to the can and the measured pressure in the can. For the value of the Henry constant Codap internal values were used, depending on the temperature and fat content of the cream.

Can pressure and foam flow rate are shown in the following figures.

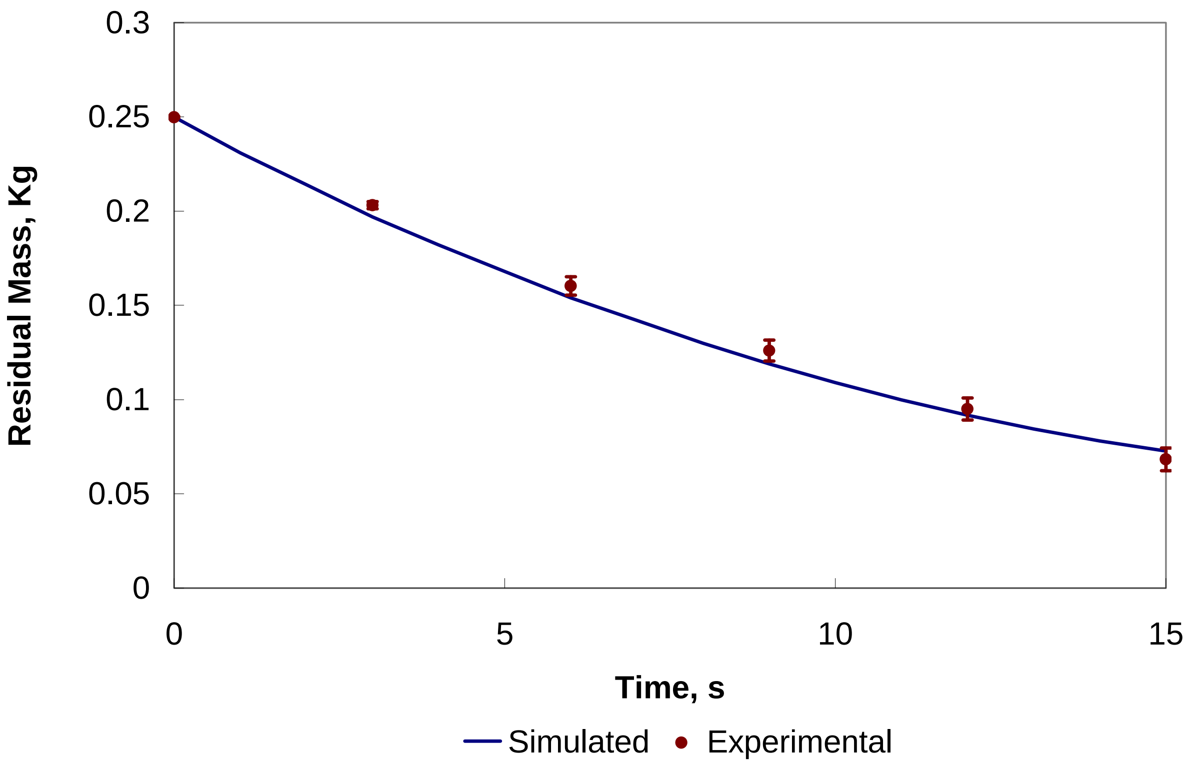

Figure 9. 2 – Residual mass trend for emulsion E5 at -5°C.

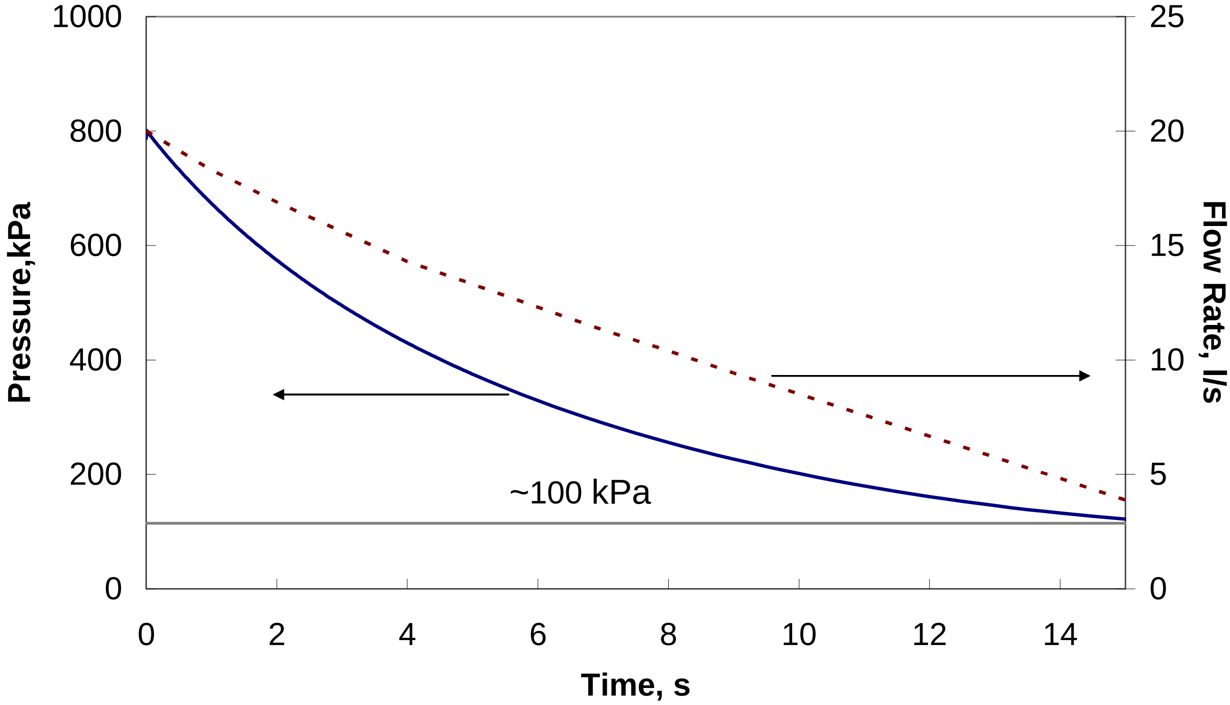

Figure 9. 3 – Simulated pressure and flow rate trend for emulsion E5 at -5°C.

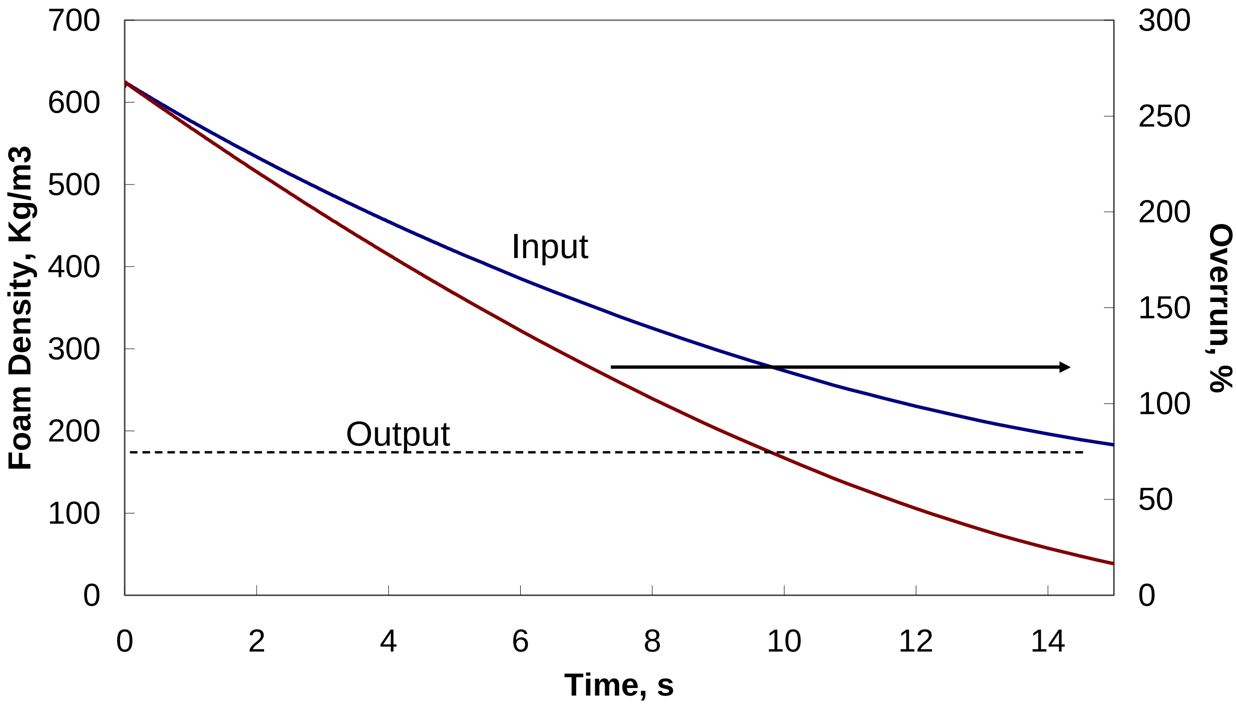

Figure 9. 4 - – Simulated foam density and overrun for emulsion E5 at -5°C.

The principal system variables are plotted as time functions, for sample E5 at -5°C for nozzle N1, it can be seen that after 15 s the internal pressure is almost the same as the external one (120 kPa) and flow rate goes fast to zero, meaning that no cream can come out from the tin.

This numerical result was confirmed by practical experiments performed on a commercial can, having nozzle N1 and filled with sample E5, in the same amount used for simulations; the can was stored for 24h at -5°C to ensure that all samples were at the correct temperature and the extruded foam was continuously weighted by a precision balance (B2002-S, Mettler Toledo, Germany). Experimental results, in terms of residual mass as time function, are compared in figure 9.2 with simulated data, even though only a few points can be obtained during the experiments, it can be seen that a good agreement is found. In addition it is worth noticing that at the end of the experiments a liquid product, not aerated, was withdrawn from the can, confirming that the residual gas inside the can was insufficient to promote flow and aeration.

Figure 9.3 shows the pressure profile inside the can and demonstrates that flow is possible up to 150 kPa even if with low overrun (figure 9.4).

In order to test the model sensitivity and the better emulsion for the purpose, simulations were carried out using nozzle N1 and emulsions E3, E6 and E7. Figure 9.5 shows the residual mass inside the can and, according to rheological trend, the emulsion E3 has a residual mass higher than the others. The trend is also confirmed by the pressure profile from which it is clear that E3 stops the flow at ~200 kPa, because the driving force is not enough due to the high viscosity.

For the purpose it is important to evaluate the overrun due to the mass of gas dissolved in the cream, the shaking, rheological and fluid dynamic conditions, like type of nozzle. Thus, the overrun was calculated using the following equation:

$$Overrun\% = \frac{\rho_0 - \rho_f}{\rho_f} \cdot 100 \tag{9.1}$$

where ρ_0 denotes the density of cream, and ρ_w that of whipped cream [Jakubczyk E., 2005]. The overrun as a function of extrusion time is plotted in figure 9.7. It can be seen that the emulsions E6 and E7 give a better overrun than mix E3 and that at the end of the extrusion process the overrun is nearly negligible as is the case with the experiments.

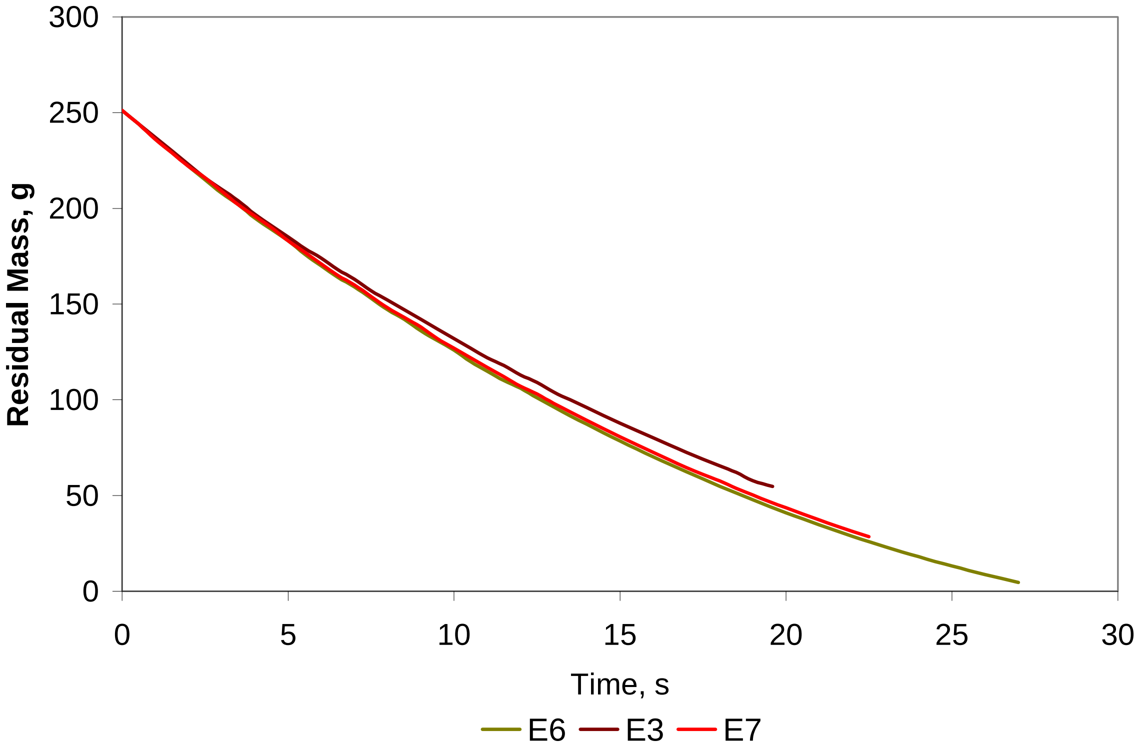

Figure 9. 5 – Simulated residual mass for different sample, -5°C, Nozzle N1.

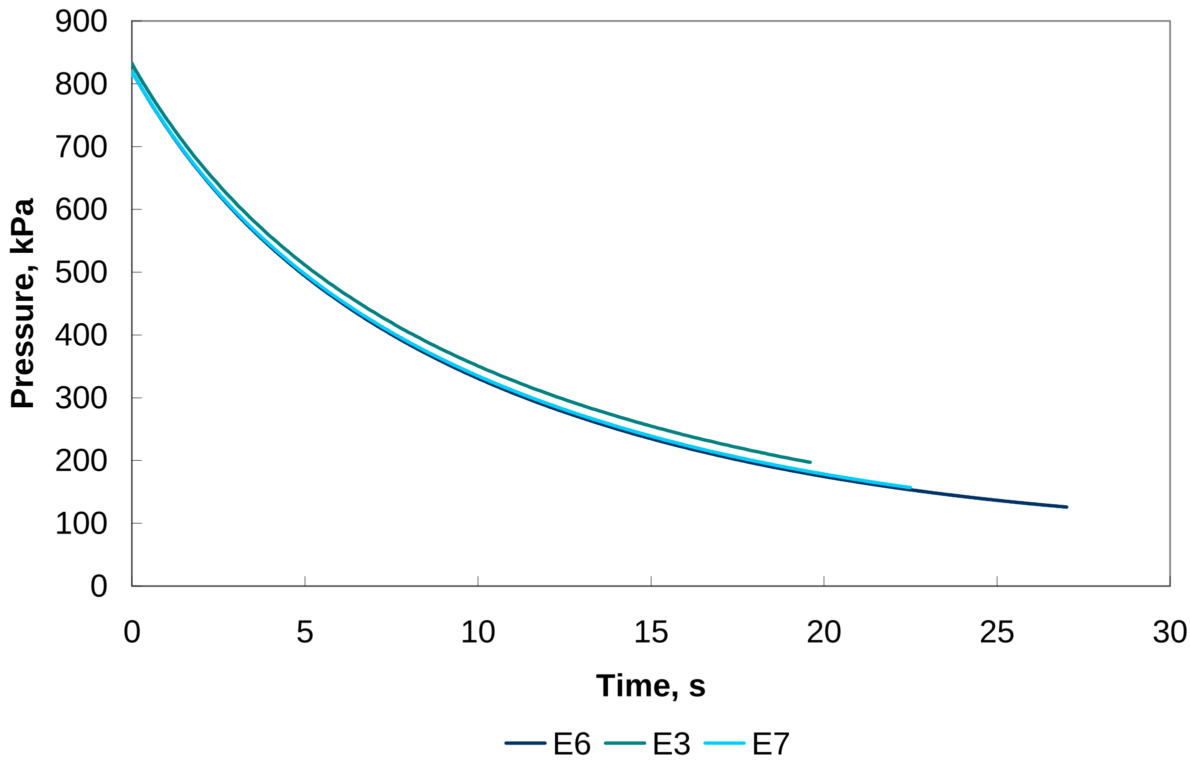

Figure 9. 6 - Simulated pressure profile for different sample, -5°C, Nozzle N1.

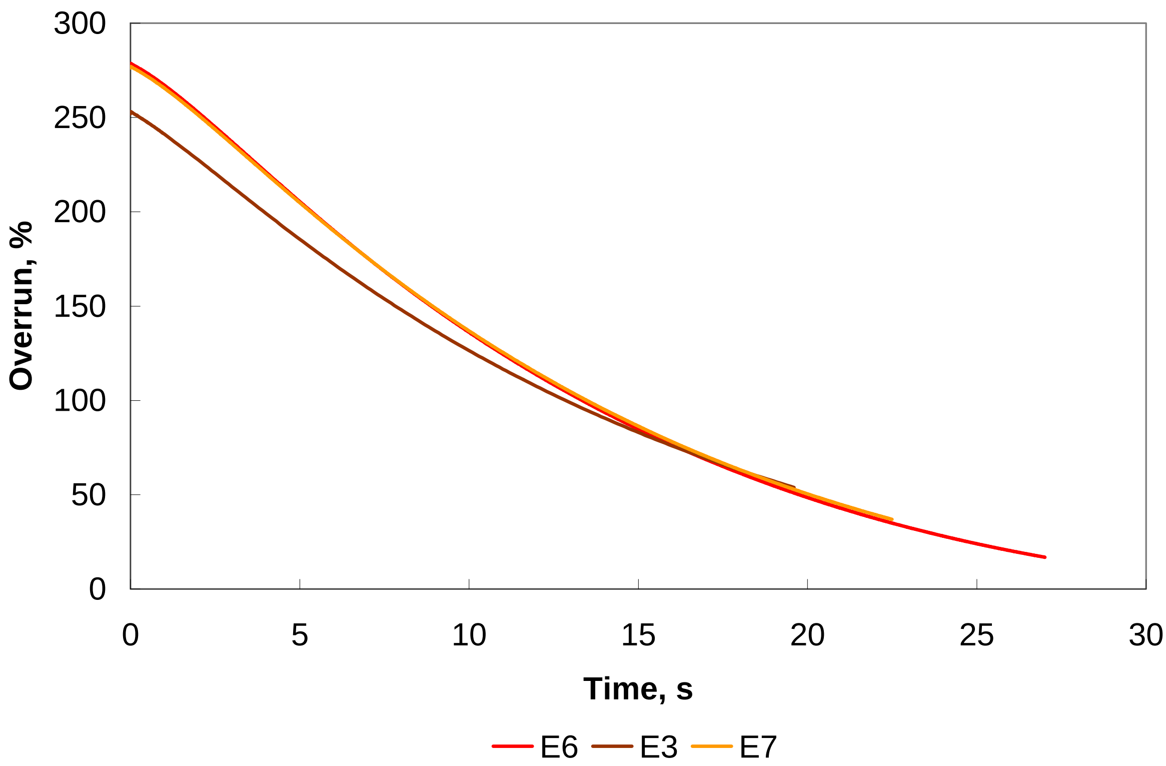

Figure 9. 7 – Simulated overrun versus extrusion time for different sample, -5°C, Nozzle N1.

The same simulations were performed using a nozzle N2 in order to test the model sensitivity and the possible advantages obtained by changing geometry. For the emulsion E7 the simulated profile was compared with the experimental profiles obtained from the extruding can filled by Codap with E7. Experimental results, in terms of residual mass as time function, are compared in figure 9.8 with simulated data, even though only a few points can be obtained during experiments, it can be seen that a good agreement is found, except for the last point. Probably the difference is due to the difficulty in the experimental measures caused by short extrusion time. Finally, the effect of the pressure was considered, for a different emulsion E7, at typical working conditions, i.e. T=-5°C.
Simulations carried out for different emulsions, at -5°C, were put in figure 9.9 as residual mass vs. time. The trends of emulsion E6 and E7 do not show any significant difference (see residual mass plot in Figure 9.9), whereas the residual mass of E3 is 4.7 times higher than E6 and E7. This is due to the dependence of extrusion on viscosity; numerical results confirm that E3 is not the right emulsion for the purpose, since it shows major residual mass and lower overrun (see figure 9.10) than others.

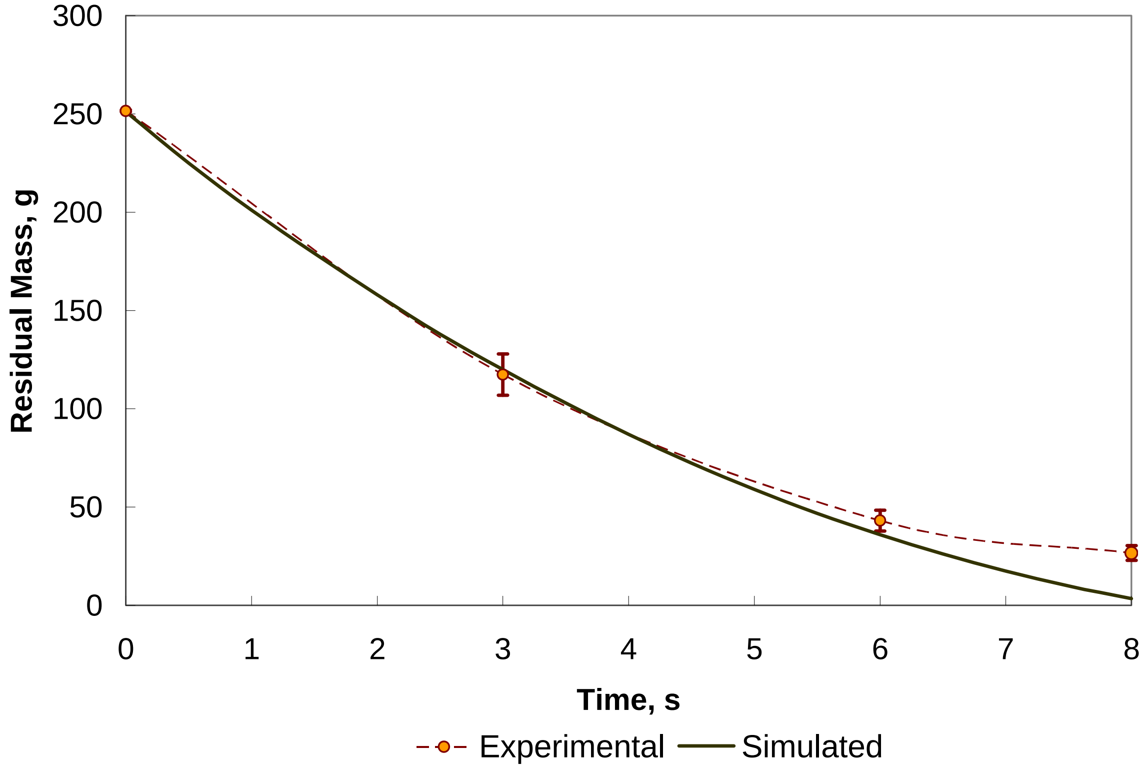

Figure 9. 8 - Residual mass trend for emulsion E7 at -5°C.

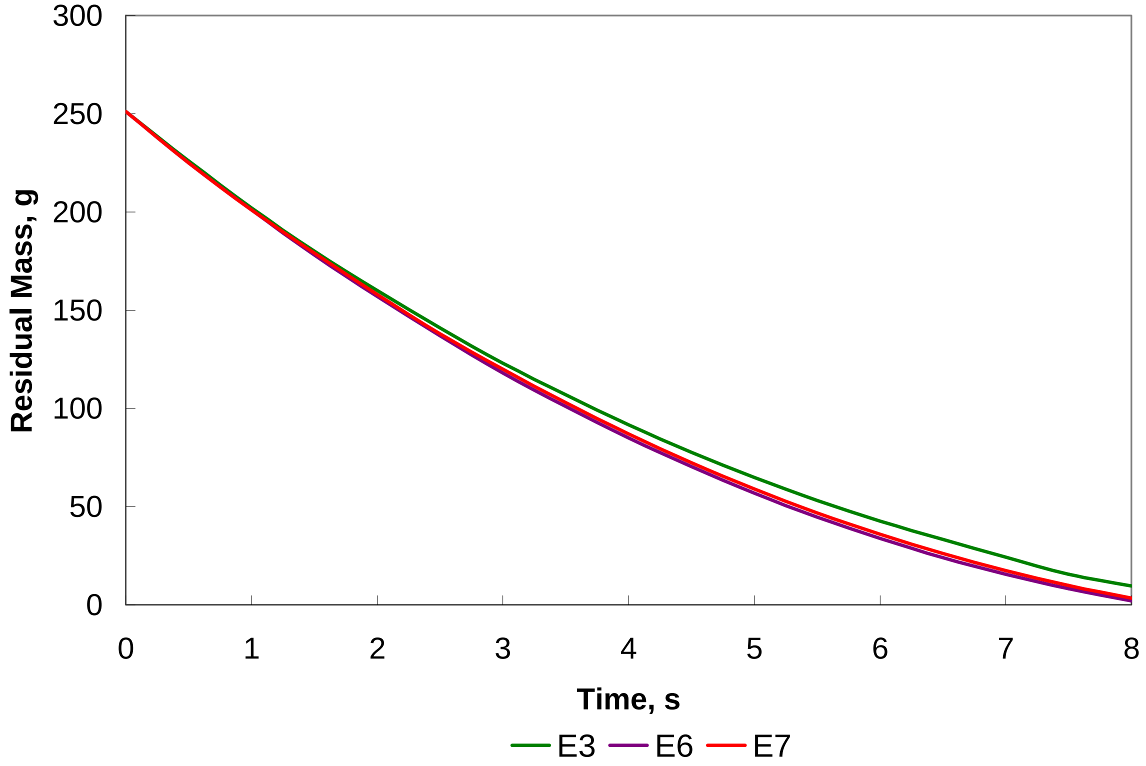

Figure 9. 9 - Simulated residual mass for different sample, -5°C, Nozzle N2.

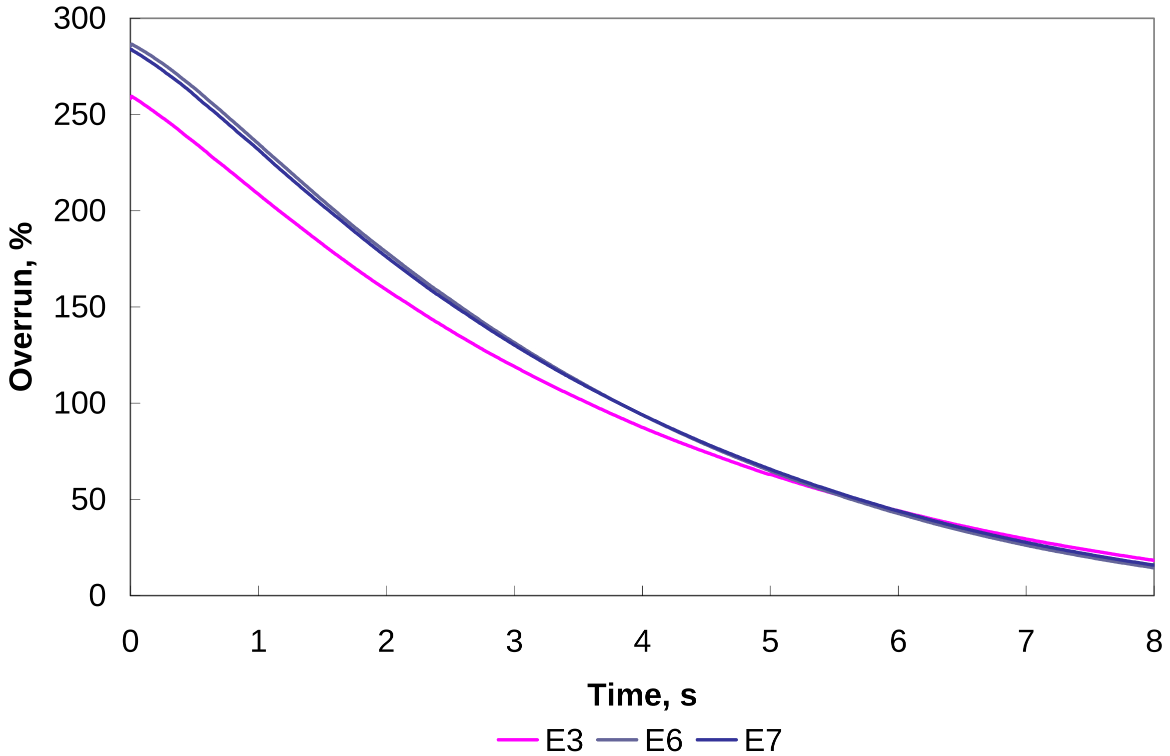

Figure 9. 10 - Simulated overrun versus extrusion time for different sample, -5°C, Nozzle N2.

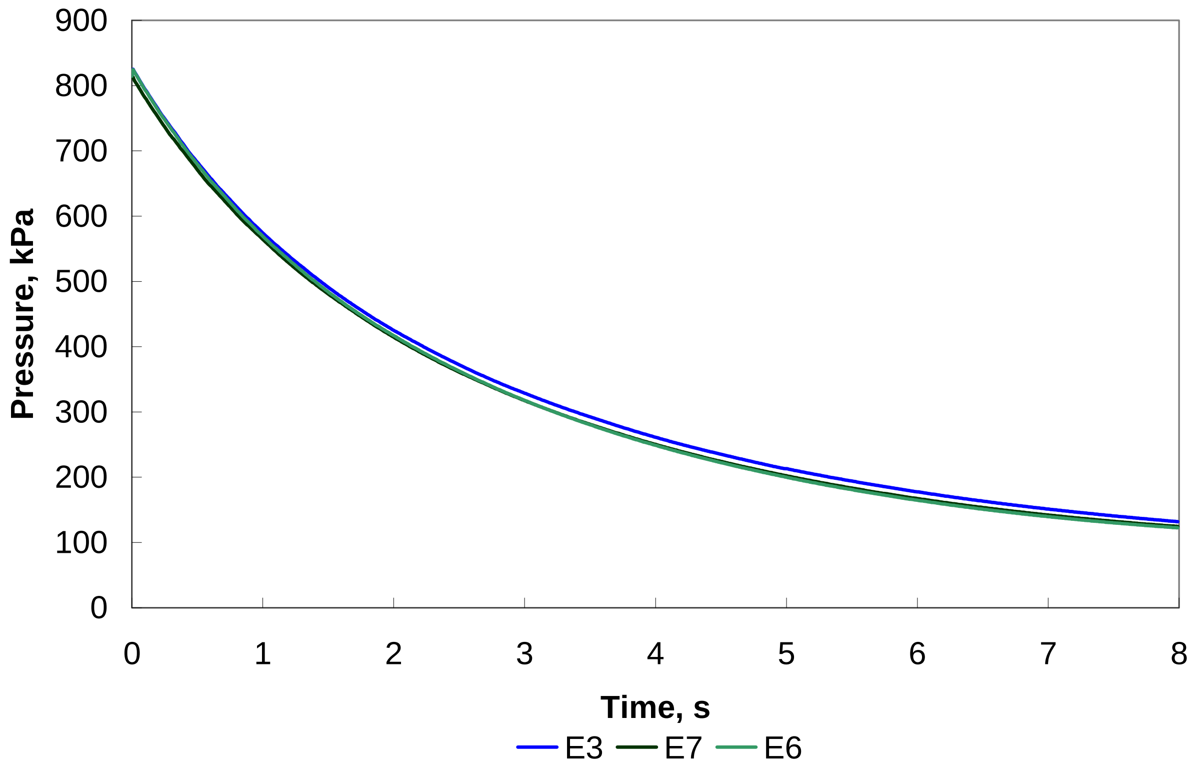

Figure 9. 11 - Simulated pressure profile for different sample, -5°C, Nozzle N2.

Pressure inside the can was changed in a range typically adopted for instant whipped cream (400÷800 kPa) and simulations were performed at 400 kPa, 600 kPa, 800 kPa for sample E7; results in terms of pressure inside the can as a time function (figure 9.12) show a reduction in emptying time at 400 kPa (5 s) whilst at different conditions no significant variations are found.

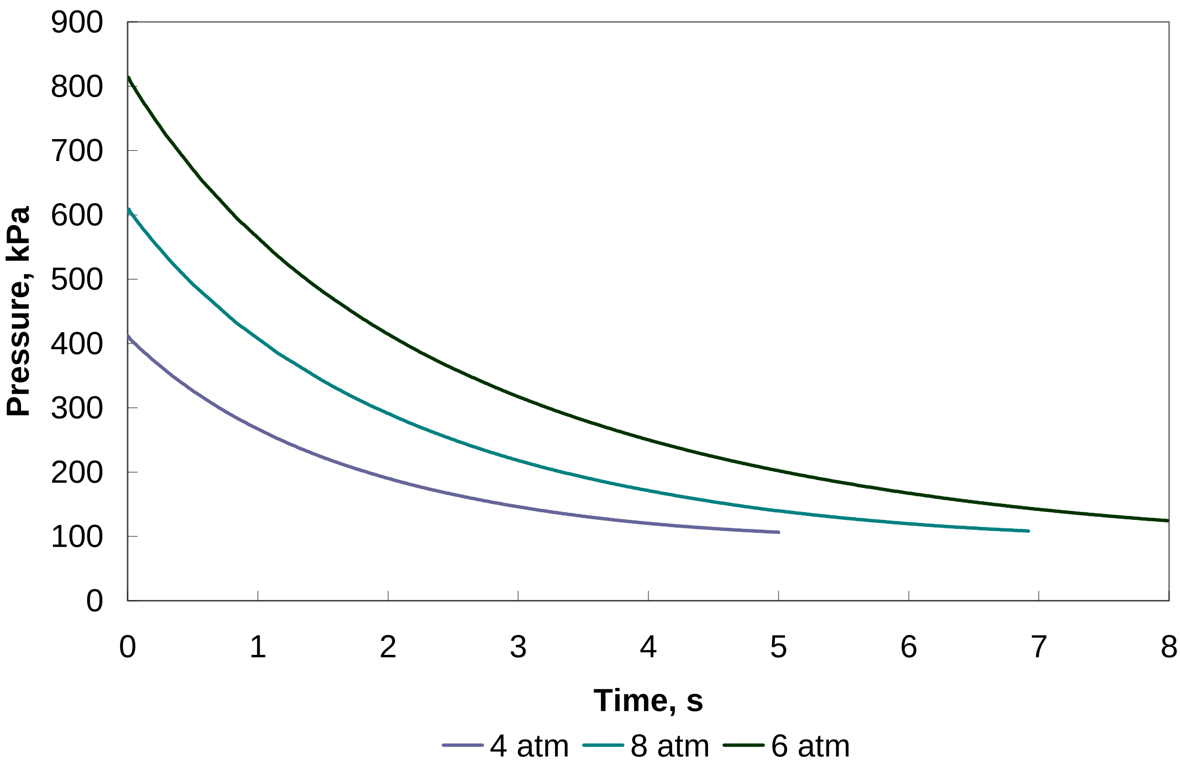

Figure 9. 12 - Simulated pressure profile for sample E7 at -5°C for different initial pressure, Nozzle N2.

When residual masses are considered (Figure 9.13) great differences are found between 800 kPa, 600 kPa and 400 kPa. The amount of residual liquid (45% of the initial mass for sample at 400kPa) is very large and not acceptable for industrial applications (maximum accepted value for residual liquid is approximately 20% of the initial mass).

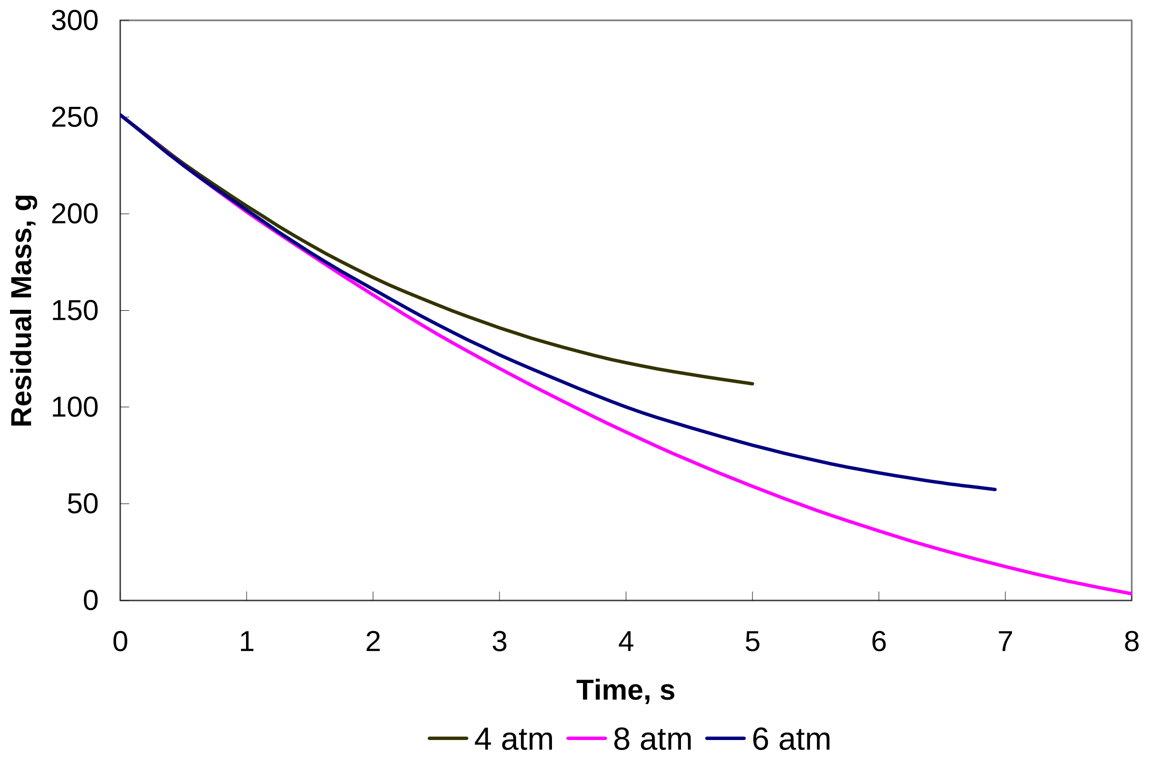

Figure 9. 13 - Simulated residual mass for sample E7 at -5°C for Nozzle N2 at three different starting pressures..

9.4 Conclusions

The fluid dynamic behaviour of the foams, made by liquid emulsion and entrapped N_2O cell, was described by the continuity and the momentum balance equations, by evaluating the pressure inside the can, overrun and residual liquid mass as a function of time. A pseudo-homogeneous approach was used and although relatively simple, the model proved capable of describing emulsion fluid dynamics, and obtained results showed a good agreement with experimental data.

The model was used to evaluate the effects of pressure and the right emulsion formulation for the purpose. The model was solved by finite element methods and can be used, even if very simple, as a tool for applications on an industrial scales.

Interesting results are found by changing nozzle geometry, it can be seen that, at -5°C by using nozzle N2, samples E3, E6 and E7 exhibit sharp changes in liquid mass inside the can, therefore a very fast foam extrusion is obtained with a low emptying time; then the residual mass for sample E3 goes down using nozzle N2 instead of N1. This is probably due to the larger diameter of N2, compared to N1, that reduces the pressure drops and makes the flow too fast.

It is worth noticing that sample E3 in nozzle N2 gives a performance similar to samples E6 and E7 in nozzle N1, owing to the different rheological properties. The model, therefore, can be used to design the geometry and the most proper operating conditions for the single emulsion in order to ensure a good performance of the product; on the other hand is also possible to select the best emulsion to be used inside a specific nozzle.

9.5 References

- Vuozzo D, Codap Internal report, 2005.
- Jakubczyk, E., Niranjan K., Transient development of whipped cream properties, Journal of Food Engineering 77 pp. 79-83, 2006.