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Numerical model of melting, liquid migration and deformation during an ice cream meltdown test

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ABSTRACT

A numerical model was developed which describes the combined phenomena occurring during an ice cream meltdown test which is a test used by ice cream producers to estimate the quality of ice cream. It is based on the measurement of the drip loss and the deformation during melting of an ice cream block placed onto a grid at ambient temperature. This information is related to the ice cream structure and reflects the quality of the product: even partially melted, the ice cream structure should retain the liquid phase and show low deformation. The proposed model takes into account melting, liquid migration inside the ice cream structure (which is considered as an unsaturated porous medium) and deformation. The objective in developing the model is to better understand the mechanisms of the ice cream structure evolution when it is submitted to ambient conditions.

To describe the multiphysics phenomena first, energy equation is solved to describe temperature evolution of the sample. Ice crystal melting was computed by using the enthalpic approach. After partial melting, water movement inside ice cream structure is predicted by Richard's equation. The hydraulic conductivity, the water retention characteristic and the differential moisture capacity are the parameters that control water movement inside the ice cream. Deformation of the partially melted ice cream was described by an elasticity model, Young's modulus being function of the fraction of melted ice. The set of equations was solved using the CFD finite element method implemented in Comsol software. The numerical model was validated with experimental results of temperature, drip loss and deformation. The model allows determining the main parameters, related to product structure, controlling the drip loss.

1. INTRODUCTION

During ice cream process, destabilisation of the fat emulsion occurs as a result of process conditions and mix formula. The whipping and freezing process transform some of the fat in the mix (originally very small $<1\mu\text{m}$) into three dimensional fat aggregates giving a certain microstructure; this phenomena is called fat destabilisation. According to Goff D. & Hartel (2013), fat aggregates play a very important role on the slowness of melting and shape retention during melting. In some cases fat destabilisation is needed, when the product should have some particular structural characteristics, for example in the case of extruded ice cream products. In other words, the process needs to be optimised as a function of the end product (not enough destabilisation would lead to poor shape retention whereas too much destabilisation would lead to the formation of too visible fat aggregates). The ice cream does not collapse although ice melts because water is retained in the microstructure. Fat destabilisation is promoted by several parameters that should be controlled: the total amount of fat and composition of the mix (type of fat, emulsifiers, etc) but also the process conditions such as the speed of the dasher that generates the shearing forces and whipping conditions that generate fat destabilisation.

Ice cream meltdown properties are important for two main reasons (Goff D. & Hartel 2013): melting in the mouth during consumption and meltdown related to storage at warm temperatures. Little work has been done to characterise melting of ice cream or frozen desserts and the relation with the sensory attributes during consumption. The meltdown test or drip-through test has been used by industrial to estimate the microstructure of their products. Normally this test is performed at room temperature. As heat penetrates into the ice cream and ice crystals melt, the water from melted ice dilute the unfrozen mix that drains down through the structure formed by bubbles, fat agglomerates and globules; then the mix diluted leaves the sample through a screen. Some ice cream meltdown collapse and flow totally through the screen. Other ice cream collapse only very slightly, leaving a nearly structure remaining on the screen. The internal structure and

interconnectivity inside the sample influences the ability of the serum to flow inside the structure (Hartel et al (2003), Sofjan and Hartel (2004)).

Very few work in literature deals with modelling multi-physical phenomena during ice cream meltdown. Several interconnected governing phenomena occurs at the same time: heat transfer, phase change, fluid flow through the structure and mechanical phenomena related to the elasticity of the structure formed during freezing. Modelling meltdown coupled multiphysic would allow a better understanding of the microstructure and the process influence on it.

2. MATERIALS AND METHODS

2.1 Mix

Mix of ice cream was prepared under typical conditions, mixing of the ingredients, pasteurization, homogenization and cooling. Then ice cream mix was stored at 5°C for 24 hrs allowing maturation process. The ingredients of the mix are: milk, dry milk, milk fat, sweetening agents, stabiliser and emulsifier. With a Brix of 26°, the milk mix density was about 1130 kg/m³ and its initial freezing point was -2.5°C. Two formulas were considered, containing 6% or 12% of fat.

2.2 Experimental platform

The milk mix was aerated and frozen in a continuous SSHE (WCB® Model MF 50), a schematic representation of which is shown in Fig. 1.

Prior to use, the sorbet mix was stored in a refrigerated storage tank at 5 °C (1) . During the freezing process, the sorbet mix was supplied into the SSHE by means of a volumetric piston pump (2). Once the sorbet was frozen in the SSHE (3), it flowed down through the outlet pipe of the SSHE (4). A Pt100 probe measured the temperature of the product at the outlet.

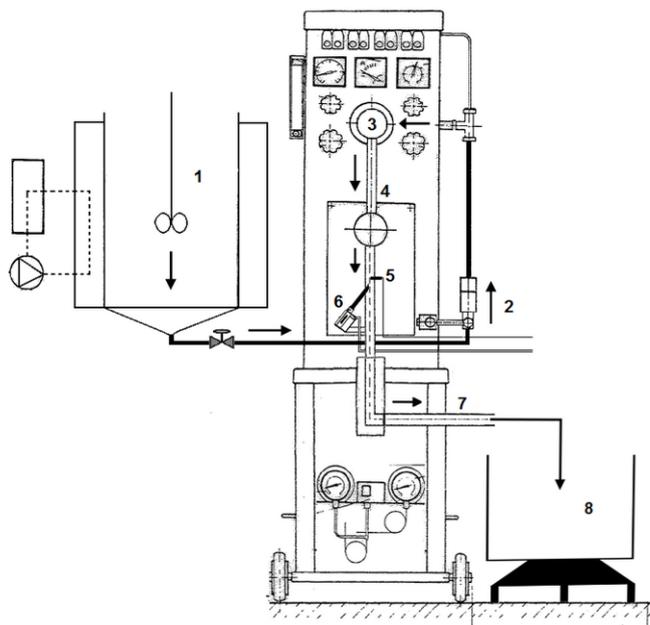


Fig. 1. Schematic representation of the experimental platform. 1. Refrigerated storage tank (200 litres capacity). 2. Volumetric piston pump. 3. Freezer. 4. Outlet pipe. 5. Pt100 probe inserted into the outlet pipe.

The freezer has a variable capacity from 25 to 75 kg/h. The inner diameter of the heat exchange tube of the freezer is 5cm and its length is 40cm (total volume of cylinder 0.785 cm³). Inside the cylinder (figure 1), there is a dasher provided with two scraper blades mounted in a floating manner on the rotor (dasher volume = 0.351cm³). The factory settings allowed the variation of the dasher speed from 200 to 1000 rpm.

Ice cream samples with 75% overrun (volume of gas/ volume of mix) were prepared at two dasher speed: 200 and 1000 rpm.

Samples were obtained from the two formula (fat content 6% or 12%). 500ml pins were filled with ice cream and placed in a freezer at -30°C and stored for the duration of experiments.

2.3 Meltdown Test

Prior to the melting test, ice cream was placed at -20°C for 24 hrs. Conical samples of following dimensions were used: bottom diameter $d_1=9\text{cm}$, top diameter $d_2=8\text{cm}$, height $h=5\text{cm}$. The samples were instrumented with a thermocouple T at the centre of the sample in order to follow temperature evolution during the test. Temperature was recorded by using a datalogger.

Ice cream samples were placed in a temperature controlled room at 20°C where meltdown tests of ice cream have been performed by quantifying and determining the mass that drips from the product through a mesh screen as a function of the time. This way, meltdown curves (plots of melted product versus time) for the different samples have been generated.

Pictures of the samples melting were obtained every 10 minutes to measure the deformation/collapse of the sample vs time. (Figure 2)

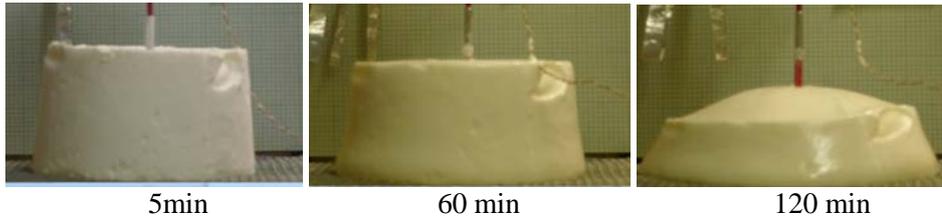


Figure 2 : Pictures of a sample at $t=5\text{min}$, after 60 min and 120 min of melting.

3. MODEL DESCRIPTION

A numerical model was developed to describe the multiphysics phenomena occurring during an ice cream meltdown test. A number of assumptions were considered:

- Ice cream is considered as a porous structure constituted by fat, proteins and air bubbles filled with an aqueous sucrose solution which is more or less frozen.
- Ice melting occurs over a temperature range from T_{f0} (onset melting temperature) to T_{f1} (onset freezing temperature) and concerns the freezable water mass fraction in the mix: ω_f . The external temperature T_a is constant and a uniform heat transfer coefficient h is applied.
- Liquid flow through the sample (dripping) follows Richard's equation. The retention model of van Genuchten (1980) was considered for the effective saturation S_e , the specific moisture capacity C_m and the relative permeability k_r in function of the pressure head $H_p=p/(\rho_l g)$. The hydraulic permeability (κ) depends on the ice fraction which in turn depends on temperature and the liquid viscosity (μ_l) depends on the temperature and the sucrose concentration of the residual solution which depends on ice fraction. For κ/μ_l , a sigmoid function varying from $(\kappa/\mu_l)_0$ below T_{f0} to $(\kappa/\mu_l)_1$ above T_{f1} was used. The initial internal pressure head is zero (saturated state). The external pressure head (lower and lateral side of the sample) varies from 0 below T_{f0} to H_{p1} above T_{f1} .
- Deformation of the ice cream during melting is represented by a linear isotropic elasticity model. Young's modulus decreases with temperature from E_0 below T_{f0} to E_1 above T_{f1} . There is no stress on the upper and lateral surfaces. No displacement is assumed at the bottom. The small deformation approximation is used as a first approach even if rather large deformations are expected. Deformation is not taken into account in the heat and flow equations.

The set of equations to be solved is the following

Energy equation

$$\rho C_{p,\text{app}} \frac{\partial T}{\partial t} = \vec{\nabla} \cdot (\kappa \vec{\nabla} T) \text{ with } C_{p,\text{app}} = C_p + \frac{\omega_f \Delta H_f}{T_{f1} - T_{f0}} \text{ if } T_{f0} < T < T_{f1}; C_{p,\text{app}} = C_p \text{ if not}$$

Flow equations (Richard's equation)

$$\frac{C_m}{\rho_l g} \frac{\partial H_p}{\partial t} = \vec{\nabla} \cdot \left(\frac{\kappa}{\mu_l} k_r \vec{\nabla} (H_p + z) \right) \text{ where } \frac{\kappa}{\mu_l} \text{ is a sigmoid function of } T$$

$$\text{if } H_p < 0: \theta = \theta_r + S_e(\theta_s - \theta_r); S_e = \left[1 + |\alpha H_p|^{1/(1-m)}\right]^{-m};$$

$$C_m = \frac{\alpha m}{1-m}(\theta_s - \theta_r)S_e^{1/m}(1 - S_e^{1/m})^m; k_r = S_e^p \left[1 - (1 - S_e^{1/m})^m\right]^2$$

$$\text{if } H_p \geq 0: \theta = \theta_s; S_e = 1; C_m = 0; k_r = 1$$

where θ is the volume of liquid per porous medium volume, θ_r its residual value and θ_s the total porosity.

Mechanical Equation

$$\rho \frac{\partial^2 \bar{X}}{\partial t^2} = \bar{\nabla} \cdot \bar{\sigma} + \rho \bar{g} \quad \text{where } \bar{\sigma} = \frac{E}{2(1+\nu)} \left[\bar{\nabla} \bar{X} + (\bar{\nabla} \bar{X})^t + \frac{2}{1-2\nu} (\bar{\nabla} \cdot \bar{X}) \bar{I} \right]$$

and E is a sigmoid function of T

Following table summarizes the parameter values

T_{f0}	T_{f1}	T_a	h	ρ	C_p	k	ω_f	ρ_l		
-10	-2.6	20	10	600	2000	0.6	0.6	1000		
°C	°C	°C	$W \cdot m^{-2} \cdot K^{-1}$	$kg \cdot m^{-3}$	$J \cdot kg^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$		$kg \cdot m^{-3}$		
$(\kappa/\mu_l)_0$	$(\kappa/\mu_l)_1$	m	p	α	θ_s	θ_r	H_{p1}	E_0	E_1	ν
10^{-10}	10^{-9}	1/2	1/2	1	0.5	0	-1.2	10^5	250	0.5
$m^3 \cdot s \cdot kg^{-1}$	$m^3 \cdot s \cdot kg^{-1}$			m			m	Pa	Pa	

These equations (completed by the adequate initial and boundary conditions) were solved with the finite element method implemented in the Comsol software.

4. RESULTS AND DISCUSSION

Figure 3 present the simulated temperature field at three different instants. It shows also the deformation of the sample. Globally, heat penetrates progressively toward the centre, the frozen part remains stiff whereas the partially melted zone is submitted to deformation and dripping.

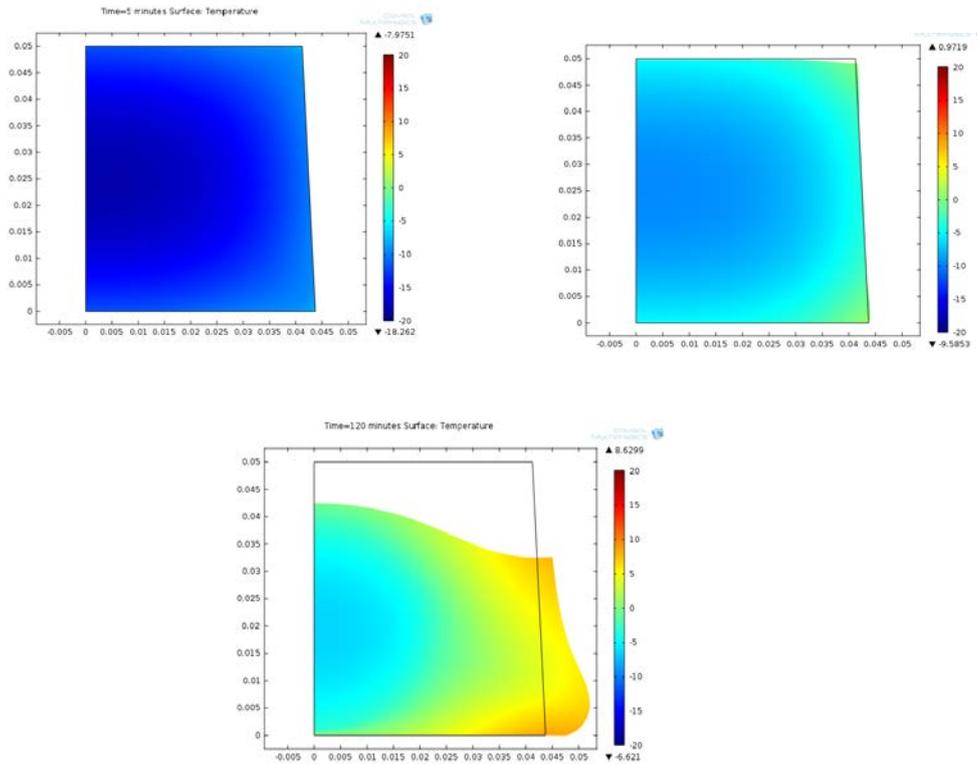


Figure 3: Deformation and temperature field after 5min, one hour and two hours.

Figure 4 shown below, presents the temperature evolution at the centre of the sample. It appears, both for experimental and simulated evolutions, that temperature rises relatively quickly up to about -10°C , then it increases slowly because of the melting of freezable water. Above about -2°C , temperature again rises rapidly tending toward the ambient temperature. The experimental evolution is smoother than the predicted one. This could be explained by the fact that the sensor remained at the same height (2.5 cm) whereas the 'centre' of the sample goes down.

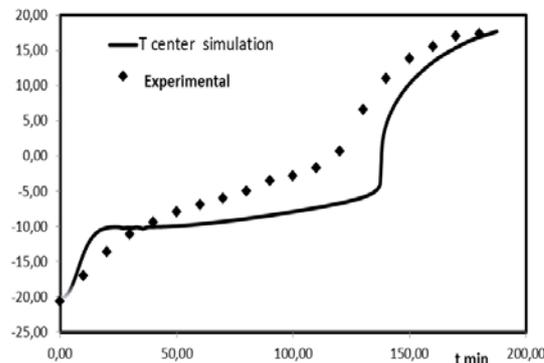


Fig.4. Measured and simulated temperature evolutions at the centre of the ice cream sample during meltdown

Figure 5 presents the drip loss. After 3 hours (180 min), the mass loss is about 55 g for both experimental and simulated values. But the simulated evolution does not agree with the measured one. The predicted drip loss occurs earlier and more suddenly. It has to be mentioned that the model parameters were not precisely adjusted in this preliminary work. The maximal permeability value should certainly be lowered and the temperature range of permeability increase seems to be not exactly the same as the range of ice melting.

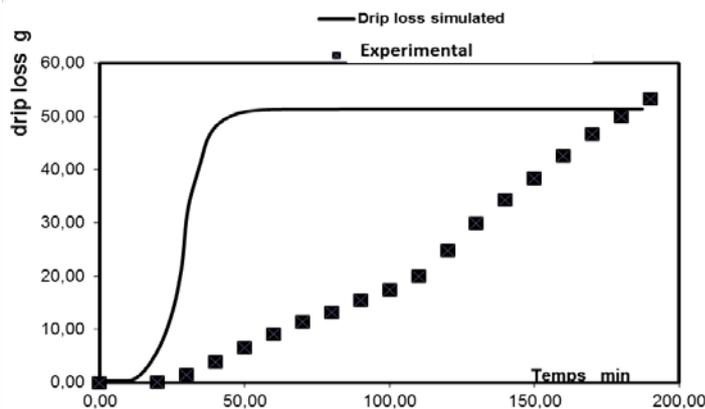


Fig. 5. Measured and simulated drip loss

Figure 6 presents the height decrease of the sample. After 3 hours, the experimental and the predicted height reductions are around half of the initial value (50 mm). The same kind of remarks as for drip loss applies here concerning the difference between the measured and simulated evolutions: the predicted height decreases later and more abruptly. The function relating the elasticity modulus to the temperature should certainly be modified.

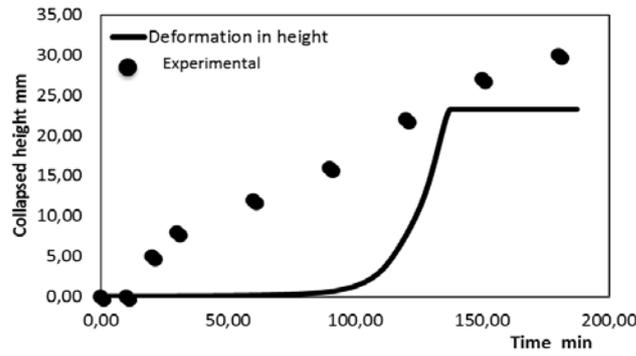


Fig.6 Height decrease (at the symmetry axis) of the ice cream sample during meltdown test: experimental versus simulated results

5. CONCLUSION

A model coupling heat transfer, phase change, drip loss and deformation during the melting of a sample of ice cream was developed by using a number of simplification assumptions. With a first set of parameters, it was able to predict the core temperature evolution, the drip loss and the deformation after 3 hours of melting. Further parameter adjustment is necessary to better fit the drip loss and deformation evolutions. The model could also be improved by using a large deformation ALE (Arbitrary Lagrangian Eulerian) approach.

NOMENCLATURE

C_p = Specific Heat ($J\ kg^{-1}\ K^{-1}$)	α = Water retention parameter (m^{-1})
C_m = Specific moisture capacity (m^{-1})	μ = Viscosity ($Pa\cdot s$)
E = Elasticity (Young's) modulus (Pa)	ν = Poisson's coefficient
G = Gravity acceleration ($m\ s^{-2}$)	ρ = Product density ($kg\ m^{-3}$)
H_p = Pressure Head (m)	ρ_l = Liquid density ($kg\ m^{-3}$)
H = Heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)	σ = Stress tensor (Pa)
K = Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	ω_f = Freezable water mass fraction
k_r = Relative permeability	κ = Hydraulic permeability (m^2)
S = Saturation	θ = Volume fraction of liquid
T = Temperature (K or $^{\circ}C$)	θ_s = Total porosity
T = Time (s)	
X = Displacement (m)	

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