Coupling phenomenological model of expansion with mechanical model of starchy products extrusion (Projet AIC 'QualExp' 2013-2015)

Magdalena Kristiawan, Guy G. Della Valle, Kamal Kansou, Amadou Ndiaye

To cite this version:

HAL Id: hal-02798651
https://hal.inrae.fr/hal-02798651
Submitted on 5 Jun 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Magdalena KRISTIAWAN (BIA-MC2)

Problème d’application INCOM : Couplage/Réduction de modèles

Partners

- INRA: M. Kristiawan, K. Kansou, G. Della Valle (BIA); A. Ndiaye (I2M)
- CEMEF: B. Vergnes
- SCC: C. David

Examples of application

- Innovative starchy foods, with modulated shape and digestibility
- Starch based shape memory biopolymers for medical devices
Coupling between expansion and 1D mechanical Ludovic® models

(Logiciel d’Utilisation de DOubleVIls Corotatives)

Starch + MC (% water)

Extruder: Clextral BC 45 & Slit die

Temperature $T_p$ (° C)
Total dissipated energy SME (kJ/kg)

150 rpm

Hopper

Die

« Ludovic®’s output variables at die exit = input of expansion model »

« New Ludovic outputs = macro & cellular structure of foams »
Context: Expansion by extrusion

Acquisition of texture

Deterministic models:
- Unsatisfactory
- Complex ↔ Ludovic®

State diagram

The bubble growth stops at $T_p \geq T_g + 30^\circ C$

$MC = \text{product water content}$

$T_g = \text{glass transition temperature}$

$T_p = \text{product temperature}$

$R = \text{bubble radius}$
**Methods and Resources**

Phenomenological modeling of **bubble growth** in a **viscoelastic** biopolymer matrix in the transition state from rubbery to solid phase.

Macro & micro structure = f (Water%, $T_p$ °C, SME kWh/t, shear & elongational viscosities)

**Approach**

1) **Validation of Ludovic® extrusion simulation** for starchy products
   - Ludovic®’s output variables at die exit = input of expansion model

2) **Collection & Representation of knowledge** (scientific)
   - **Concept map**

3) **Establishment of phenomenological models of expansion**
   - Model validation on more complex starchy products

4) **Relation between anisotropy and cellular structure** (fineness)

5) **Coupling between expansion & Ludovic® models**: INRA & SCC

Séminaire InCoM 1er avril 2015
Output variables

- **Macrostructure** (360 data, maize starches)

  **Volumetric Expansion Index** \((\text{VEI})\)

  \[
  \text{VEI} \approx \frac{\text{melt density}}{\text{foam density}}
  \]

  **Radial Expansion Index** \((\text{SEI})\)

  \[
  \text{SEI} = \frac{\text{foam cross section}}{\text{die cross section}}
  \]

  **Anisotropy Factor** \((\text{AF})\)

  \[
  \text{AF} = \frac{\text{VEI}}{\text{SEI}^{3/2}}
  \]

- **Microstructure**: **Cellular Fineness** \((F)\)

  \[
  F = \sqrt{\frac{250}{\text{MWT}} + \frac{1}{\text{MCS}}}^{2}
  \]

  **MCS** = Mean cell size (mm)

  **MWT** = Mean wall thickness (µm)

  - **AF = 1** (Isotrope)
  - **AF > 1** (Axial)
  - **AF < 1** (Radial)

  **Cell wall thickness distribution**

  - \(F > 1\) : Fine
  - \(F < 1\) : Coarse

  X-ray tomography
  ESRF Grenoble
**Concept map: Phenomenological model of expansion**

**Input variables**
- Temperature $T_p$
- Water content $MC$
- Shear viscosity $\eta(\gamma)$
- Storage modulus $E'(T_g)$

**Output variables**
- Foam density $\rho^*$

**Expansion mechanism**
- Nucleation
- Bubble growth
- Coalescence
- Shrinkage

**Formula**

$$VEI \approx [MC]^x \otimes [T_p]^y \otimes [\eta(\gamma)]^z \otimes [E'(T_g)]^t$$

**Séminaire InCoM 1er avril 2015**
General expansion model:  \[ SEI = \alpha \cdot \left( \frac{\eta}{\eta_0} \right)^n \]  

\[ = b_0 \left( \frac{MC}{MC_0} \right)^{b_1} \left( \frac{Tp}{Tp_0} \right)^{b_2} \left( \frac{SME}{SME_0} \right)^{b_3} \left( E'/E'_0 \right)^{b_4} \left( \frac{h}{h_d} \right)^{b_5} \]

\[ n = b_6 + \left( \frac{MC}{MC_0} \right)^{b_7} + \left( \frac{Tp}{Tp_0} \right)^{b_8} + \left( \frac{SME}{SME_0} \right)^{b_9} + \left( E'/E'_0 \right)^{b_{10}} + \left( \frac{h}{h_d} \right)^{b_{11}} \]

\[ R^2 \text{ adj} = R^2 = 0.78; \; ddl = 348 \]

Significativity of model parameters

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>( b_0 )</th>
<th>constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_1 )</td>
<td>MC water</td>
<td>---</td>
</tr>
<tr>
<td>( b_2 )</td>
<td>( T_p ) °C</td>
<td>-</td>
</tr>
<tr>
<td>( b_3 )</td>
<td>SME</td>
<td>-</td>
</tr>
<tr>
<td>( b_4 )</td>
<td>( E'(T_g) )</td>
<td>++</td>
</tr>
<tr>
<td>( b_5 )</td>
<td>( h/h_d )</td>
<td>+</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( n )</th>
<th>( b_6 )</th>
<th>constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_7 )</td>
<td>MC water</td>
<td>-</td>
</tr>
<tr>
<td>( b_8 )</td>
<td>( T_p ) °C</td>
<td>-</td>
</tr>
<tr>
<td>( b_9 )</td>
<td>SME</td>
<td>n.s.</td>
</tr>
<tr>
<td>( b_{10} )</td>
<td>( E'(T_g) )</td>
<td>n.s.</td>
</tr>
<tr>
<td>( b_{11} )</td>
<td>( h/h_d )</td>
<td>n.s.</td>
</tr>
</tbody>
</table>

--- or +++ = most significant

Computing the effect of water content on \( SEI \)

R2 adj = R2 = 0.78; ddl = 348

**Amylose 0.47, \( T_p \) ≈ 165 °C, SME 200 kWh/t

General expansion model:  \[ SEI = \alpha \cdot \left( \frac{\eta}{\eta_0} \right)^n \]  

\[ E' = \text{storage modulus} \]
Model validation

Application of expansion model to experimental data from literatures (including Rheological behavior*) of wheat flour with bran (Robin et al., 2011)

*Difficult to find in the literature
Anisotropy & cellular structure: from macro to micro-scale

Mapping of Anisotropy & Cellular structure
Experimental Data from Babin et al. (2007)

Variations of Anisotropy Factor (macrostructure) and Cellular Fineness (microstructure)

The higher AF, the finer the cellular structure.

Axial expansion (LEI) is more favorable to finer cells.

LEI = VEI / SEI

$SEI^{0.5}$

MCS in mm & MWT in µm

$MCS = 0.74$

$MWT = 80$

$MCS = 3.36$

$MWT = 595$

Fine ($F > 1$)

Coarse ($F < 1$)

Finesse (Micro-structure)

$R^2 = 0.82$
Conclusions

- A robust model for starch expansion by extrusion has been established, thanks to the integration of scientific knowledge and experimental data
- Cell fineness was modeled from computed anisotropy factor, providing a link between micro and macroscopic scales

Ongoing & Perspective

- Coupling mechanical model of extrusion (Ludovic®) with phenomenological model of expansion
  - The new Ludovic®’s outputs: Macro and cellular structures of foams
- Extending the domain of application of the model and the software
Dissemination

Articles

Modeling of starchy melts expansion by extrusion (A review).
Trends in Food Sci. & Tech (*submitted*).
A phenomenological model of starch expansion by extrusion.
Rhéologie (*accepted*); Food & Bioprocess Tech. (*in prep.*)

Congress

Annual European Rheology Conference (*AERC*), April 2014, Karlsruhe. *Poster.*
Annual European Rheology Conference (*AERC*), April 2015, Nantes. *Oral.*
International Congress on Engineering and Food (*ICEF*), June 2015, Québec. *Poster.*

Symposium

Thank you for your attention

Discussion....