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## Analysis of extrusion foaming of polyolefins using isobutane and CO<sub>2</sub>

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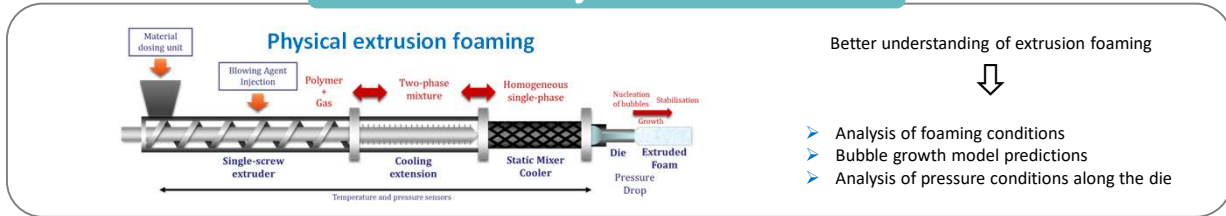
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## Objective



## Materials, foaming conditions

### Two sets of foaming experiments:

#### LDPE grades:

CD0230 and LD0304 from TotalEnergies  
Foaming with 5 and 8 wt% iso-butane

Range of  $T_{melt}$  during foaming: 120 to 100 °C at the die exit

CD0230 and LD0304:  $T_c = 97^\circ\text{C}$  (start 100°C)

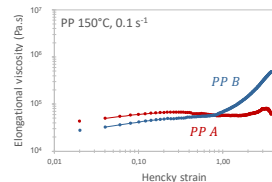
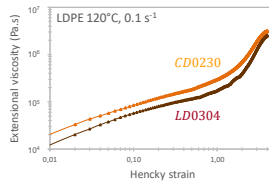
#### PP experimental grades:

PP A (linear chains) and PP B (branched chains) from TotalEnergies  
Foaming with 1 and 2 wt% CO<sub>2</sub>

Range of  $T_{melt}$ : 170 to 130°C at the die exit

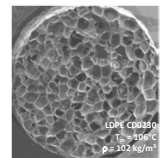
PP A:  $T_c = 97^\circ\text{C}$  (start 105°C), PP B:  $T_c = 104^\circ\text{C}$  (start 110°C)

### Rheological behaviour



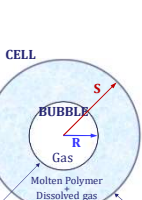
### Foam characterization:

- SEM → Cell density (cells/m<sup>3</sup>)
- Mean bubble size
- Foam density (kg/m<sup>3</sup>)



## Bubble growth modeling

### Model equations and hypotheses [1]



Growth of a gas bubble in a polymer shell containing polymer and dissolved gas

Constant cell density:  $n_{b,0} \rightarrow S_0 = \sqrt[3]{\frac{3}{4\pi n_{b,0}}}$ ,  $R_0 = 1\mu\text{m}$ ,  $c(r,0) = c_0$

Diffusion equation:  $\frac{\partial c}{\partial t} + \frac{R}{r^2} \frac{\partial c}{\partial r} = \frac{D}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial c}{\partial r} \right)$

Bubble growth:  $\frac{d}{dt} (p_g R^3) = 3 D R T \frac{\partial c}{\partial r} \Big|_{r=R}$

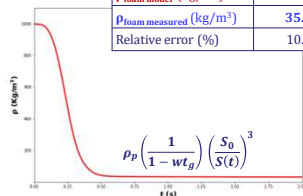
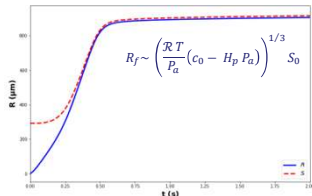
Momentum equation:  $P_g - P_a = \frac{2\gamma}{R} - \tau_{rr}(S) - \frac{2}{3} \int_0^S \dot{\gamma}^2 - \dot{\gamma}_0^2 \frac{\tau_{rr} - \tau_{\theta\theta}}{r^3} dy$

Viscoelastic matrix: Multi-Maxwell or Phan-Thien-Tanner model

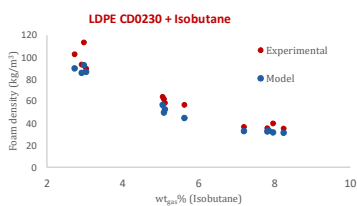
### Bubble growth prediction

CD0230	%wt isobutane	8.23
	$T_{melt}$ (°C)	104
	$n_{b,0}$ (cell/cm <sup>3</sup> )	9500
	$D$ (m <sup>2</sup> /s)	1.23E-09
	$H_p$ (mol/(m <sup>3</sup> Pa))	1.818E-03

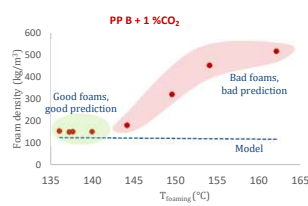
$\rho_{ppolymer}$ (kg/m <sup>3</sup> )	922
$\rho_{foam model}$ (kg/m <sup>3</sup> )	31.6
$\rho_{foam measured}$ (kg/m <sup>3</sup> )	35.4
Relative error (%)	10.7



### Foam density → comparison between model predictions and experiments

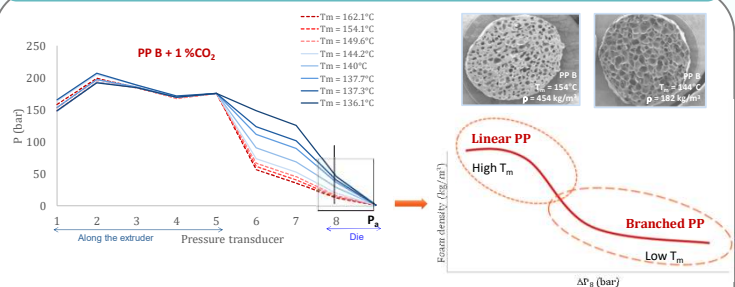


Low density foams → Well predicted by the bubble growth model



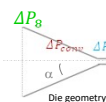
Different densities of PP foams: → Analysis of pressure drop in the die

## Analysis of pressure drop in the die



### Why analysing ΔP in the die ?

Pressure drop in the die = responsible for the foam formation (nucleation + growth)



$$\Delta P_{cis} = \Delta P_{conv} + \Delta P_{cap}$$

$$\Delta P_{conv} = \frac{2KL_c}{3m(R_0 - R_1)} \left( \frac{3m+1}{m} \frac{Q}{\pi} \right)^m \left[ \frac{1}{R_1^{3m}} - \frac{1}{R_0^{3m}} \right]$$

$$\Delta P_{cap} = 2KL_f \left( \frac{3m+1}{m} \frac{Q}{\pi} \right)^m \frac{1}{R_1^{(1+3m)}}$$

If  $\Delta P_B > \Delta P_{cis} \Rightarrow$  Additional contribution:  $\Delta P_{el} = \Delta P_B - \Delta P_{cis}$  (Eq. 1)

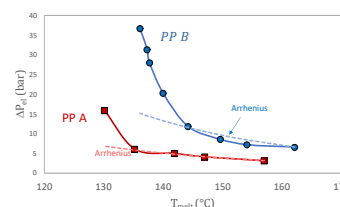
### Steps :

- Calculation of  $\Delta P_{cis}$  ✓
- Comparison with  $\Delta P_B$  ✓  
If  $\Delta P_B > \Delta P_{cis} \Rightarrow$  calculation  $\Delta P_{el} = \Delta P_B - \Delta P_{cis}$  (Eq. 1)
- If viscoelastic effect,  
→  $\Delta P_{el}$  variation with T should follow an Arrhenius law
- If  $\Delta P_{el}(T) >$  Arrhenius law  
→ Crystallization at the origin of  $\Delta P_{el}$  excess  
→ Calculation of  $\eta_{el}$  (Eq. 2)  
→ Estimation of a crystallized fraction  $\phi$  (Eq. 3)

$$\eta_{el} = \frac{\pi \Delta P_{el} (1 - \cos \alpha)}{Q \sin^3 \alpha} \frac{R_0^2 R_1^2}{(R_1 + R_0) \left( \ln \frac{R_1}{R_0} \right)}$$

$$\eta_{susp} = \eta_{matrix} \left[ 1 - \frac{\phi}{B} \right]^{-2}$$

B = 0,54 for spherulites [4]



- Existence of an additional contribution ( $\Delta P_{el}$ ) in the die
- Low  $\Delta P_{el} = f(T)$  (higher T) follow an Arrhenius dependence
- The presence of a crystalline state in the die could explain the pressure drop excess and help in some cases the foaming process

### References:

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