Extrusion: balancing a profile die

• Die design:
  complex due to 3D velocity profiles
polymer flow:
  Temperature dependent viscosity
  Non-newtonian flow
after exiting the die: die swell, cooling, relaxation,…

• Often FE analysis is used
Extrusion: balancing a profile die

General rules in extrusion die design

• No dead spots in flow channel
• Steady increase in velocity along the flow channel
• Assembly and disassembly should be easy
• Land length about 10x land clearance
• Avoid abrupt changes in flow channel geometry
• Use small approach angles
Extrusion: balancing a profile die

U-Profile stack die: exploded view

(1) extruder mounting plate; (2) die adapter plate; (3) transition plate; (4) preland plate; (5) die land plate; (6) die bolt hole; (7) alignment dowel pin hole; (8) thermocouple well;
Extrusion: balancing a profile die

- METHOD 1: Cross flow minimization CFMM
  - materials with no or little memory effect (e.g. PVC)
  - Separate channels up to the die exit
  - Extruded profile = final profile

\[
\Delta P_1 = \Delta P_{2a} + \Delta P_{2b}
\]
Extrusion: balancing a profile die

- **METHOD 2:** adjusting geometry after die exit
  - materials with memory effect
  - Change thickness of thinnest section to match pressure drop in thickest section
  - Calibrators needed to obtain correct profile dimensions
Extrusion: balancing a profile die

Example

HDPE
\( \rho = 900 \text{ kg/m}^3 \)
\( k = 0.1 \text{ W/mK} \)
\( C_p = 2300 \text{ J/kgK} \)
\( T_{\text{melt}} = 220^\circ \text{C} \)
\( T_{\text{solidified}} = 90^\circ \text{C} \)
\( T_{\text{cooling}} = 20^\circ \text{C} \)
\( L_{\text{cooling line}} = 15 \text{m} \)
Die length = 100mm

\[ \tau = m \gamma^n \]
\[ m = 1000 \]
\[ n = 0.5 \]
Extrusion: balancing a profile die

Example

Production speed determined by cooling

\[ t_k = \frac{s^2}{\pi^2 a} \ln \left( \frac{4}{\pi} \left( \frac{T_w - T_{melt}}{T_w - T_{solid}} \right) \right) \]

*with* \( s = 0.003 \) and \( a = \frac{k}{\rho C_p} \)

\( \Rightarrow t_k = 24.4 \text{s} \)

\( \Rightarrow \) Cooling line is 15m long \( \Rightarrow \) 15/24.4s = 0.615m/s
Extrusion: balancing a profile die

Example method 1: Separation

\[ A_1 = 90 \text{mm}^2 \implies Q_1 = 5,538 \times 10^{-5} \text{m}^3/\text{s} \]

\[ A_2 = 94 \text{mm}^2 \implies Q_2 = 6,153 \times 10^{-5} \text{m}^3/\text{s} \]

\[
\Delta P = m \cdot b^{-(2n+1)} \cdot L \cdot \left[ \left( 1 + \frac{1}{2n} \right) \frac{Q}{W} \right]^n
\]

\[
\Delta P_1 = m_1 \cdot b_{1}^{-(2n+1)} \cdot L \cdot \left[ \left( 1 + \frac{1}{2n} \right) \frac{Q_1}{W_1} \right]^n
\]

\[ \Delta P_1 = 270 \times 10^5 Pa \]
Extrusion: balancing a profile die

Example method 1: separation

\[
270 \times 10^5 = m \cdot b_1^{-(2n+1)} \cdot X \cdot \left[ \left( 1 + \frac{1}{2n} \right) \frac{\dot{Q}_2}{W_2} \right]^n
\]

\[+ m \cdot b_2^{-(2n+1)} \cdot (L - X) \cdot \left[ \left( 1 + \frac{1}{2n} \right) \frac{\dot{Q}_2}{W_2} \right]^n\]

\[\Rightarrow X = 0.0513 \text{m}\]
Extrusion: balancing a profile die

Example method 2

\[ \Delta P_1 = m \cdot b_1^{-(2n+1)} \cdot L \cdot \left[ \left( 1 + \frac{1}{2n} \right) \frac{\dot{Q}_1}{W_1} \right]^n \]

\[ \Delta P_1 = 270 \times 10^5 Pa \]

⇒ Same pressure drop in second channel

\[ 270 \times 10^5 = m \cdot X^{-(2n+1)} \cdot L \cdot \left[ \left( 1 + \frac{1}{2n} \right) \frac{\dot{Q}_2}{W_2} \right]^n \]

⇒ \( X = 1,355 \text{mm} \)
⇒ Thickness of the thinnest zone = 2,71mm
Extrusion: balancing a profile die

“automatic procedure in VEL software

Desired profile shape

72.7% of cross sectional area

27.3% of cross sectional area

15mm

20mm

2mm

1mm
Extrusion: balancing a profile die

“automatic” procedure in VEL software

Velocity distribution without optimized cross section of the die length

- 93.1% of total MFR
- 6.9% of total MFR

Velocity distribution with optimized cross section of the die length

- 72.7% of total MFR
- 27.3% of total MFR
Extrusion: balancing a profile die

Window profile
Extruder die design

Coextrusion

Material 1 ➔ 2mm ➔ Material 2 ➔ 4mm

50mm Axisymmetric

Die wall, no slip, 200°C

Material 1 = LDPE
Material 2 = PP

viscosity vs. shear rate

KU LEUVEN
Extruder die design

Mass flow rate material 1 = material 2 = 2kg/hr
Extruder die design

Mass flow rate material 1 = material 2 2kg/hr

Interface is calculated
→ Wall thickness at die exit is determined
Extruder die design

Wall thickness at die exit [mm]

Mass flow rate material 2 [kg/hr]

\[
\frac{MFR_1}{MFR_2} = \frac{2}{0.5}
\]

\[
\frac{MFR_1}{MFR_2} = \frac{2}{2}
\]

\[
\frac{MFR_1}{MFR_2} = \frac{2}{8}
\]
Extruder die design

Coextrusion – adding 15kPa yield stress tot material 2
Thermoforming

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Application: thermoforming

• Process description
• Required material properties
• Challenges in thermoforming
Thermoforming: process description

heating

clamping

forming & cooling

demoulding

189
Thermoforming: process description

• Heavy gauge thermoforming (thickness > 1,5mm)

• Thin sheets (packaging applications)
Thermoforming: process description

Heating step:

- crucial for process stability and product quality!

Current approach in industry

- Trial & Error
- Personnel Experience

(results in high scrap volumes and long process start-up times)
Thermoforming: process description

Different heating strategies

- theoretical optimum
Thermoforming: IR heating

- UV radiation
- Visible radiation
- IR radiation

- Treatment of UV-sensitive materials
- Eye supporting functions
- Warmth/heat transport

- 0.7 µm
- 2 µm
- 4 µm
- 10 µm

- 2500°C
- 1200°C
- 700°C
- 500°C

- Halogen heater
- Quartz heater
- Ceramic heater
Thermoforming: IR heating

- Contact free IR heating

  Ceramic heater elements
  300-500K – slow response – IR C – low power
  most used in industry (60%)

  Halogen heater elements
  1700K – fast response – IR A – high power
Thermoforming: IR heating
Temperature measurements

- Thermocouples type K (0-200°C)
  heating of the thermocouple
  heat absorption by the tape?
  slower response

- IR measurement
  emmisivity?
  gloss, colour?
  point measurement vs.
  in plane temperature distribution
Temperature measurements
Illustration of infrared transparency

Test setup
Temperature measurements
Illustration of infrared transparency

Material type
1mm PP (Ceramic)  1mm PS (Ceramic)

- More transparency for Polypropylene (Idem for halogen heaters)
Temperature measurements
Illustration of infrared transparency

Material type
1mm PP (Halogen)

1mm PS (Halogen)

• More transparency for Polypropylene (Idem for halogen heaters)
Temperature measurements
Illustration of infrared transparency

Material thickness
1mm PP (Ceramic)  3mm PP (Ceramic)

- Increasing thickness lowers transparency (Idem for halogen heaters)
Temperature measurements
Illustration of infrared transparency

Heating element
1mm PP (Ceramic)

1mm PP (Halogen)
Temperature measurements

Technical variations

Emissivity setting

![Graph showing the relationship between Emissivity setting and Thermocouple temperature. The x-axis represents the Emissivity setting (0.96, 0.94, 0.92, 0.9) and the y-axis represents the temperature (89°C to 97°C). The graph shows an increase in temperature with an increase in Emissivity setting. The red line indicates the Thermocouple temperature.]
Reflections
Measurement angle
Temperature measurements

Silicon measuring sheet

- Multiple silicone and bonding layers with a total thickness of 4mm

- 15 embedded thermocouples divided over 3 layers, 5 thermocouples on defined locations per layer
Results

• Halogen heating one-sided
Through thickness results

- 30% - 190s
- 50% - 100s
- 70% - 80s
- 100% - 60s

~ Top side
~ Bottom side

One sided heating
Through thickness results

~ Top side
~ Centre of the plate
~ Bottom side

One sided heating
Through thickness results

~ Top side
~ Centre of the plate
~ Bottom side

One sided heating
Heating power influence
Time to reach target temperature
Heating power influence
Temperature difference at maximum temperature

![Bar chart showing temperature gradient at different power levels](chart.png)
Thermoforming: modelling

• Based on finite difference method
  1D heat transfer ~ heating of a volume located in the centre of the sheet
Thermoforming:

Different efforts in recent years

FD- heating model in 1D

1D heating parameter optimization

FD-heating model in 3D with link to machine heating elements

Identifying challenges in existing software

Linking sheet thickness variations to temperature variations
Thermoforming: material description

**KBKZ model**

\[ \tau = \int_{-\infty}^{t} m\left(t - t'\right) h\left(I_1, I_2\right) C^{-1}\left(t'\right) dt', \]

- \(m = \) time memory function
- \(h = \) damping function
- \(C = \) Right cauchy-Green deformation tensor
- \(C^{-1} = \) Finger strain tensor

Testing is done at IKT Stuttgart
Thermoforming: simulation

Ø1200mm, H=480mm
Thermoforming: simulation
Thermoforming: simulation

- Critical venting areas analysis
Thermoforming: simulation

<table>
<thead>
<tr>
<th>referentie</th>
<th>simulatie 1</th>
<th>simulatie 2</th>
<th>simulatie 3</th>
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<tbody>
<tr>
<td>A [°C]</td>
<td>180</td>
<td>200</td>
<td>180</td>
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<tr>
<td>B [°C]</td>
<td>180</td>
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<td>160</td>
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<tr>
<td>C [°C]</td>
<td>180</td>
<td>160</td>
<td>140</td>
</tr>
</tbody>
</table>
Thermoforming: simulation

Vormtemperatuur - zoneverdeling - langsrichting
plaatdikte in functie van lengte


25/10/2017
Thermoforming: simulation

Vormtemperatuur - zoneverdeling - hoek onderaan bad
plaatdikte in functie van lengte

25/10/2017
Concluding remarks

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Concluding remarks

• Viscosity measurements
Concluding remarks

- Injection moulding

→ Without shear thinning, injection moulding would not be possible!

→ Large pressures, large forces

→ Highly non-isothermal flow
Concluding remarks

• Polymer extrusion

→ Extruder simulations require detailed information on screw design, material, friction coefficients ??

→ Balance a profile die carefully!
Concluding remarks

• Thermoforming

→ Take wall thickness variations into account in a structural analysis

→ Challenges: polymer sheet quality
  improved heating strategies
  material characterisation
Introduction to Non-Newtonian Fluid Mechanics and Industrial Applications

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https://iiw.kuleuven.be/onderzoek/propolis