A Practical Approach to Scale-up from Bench-top Twin-screw Extruders

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PRISM Products
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Introduction

1. Twin screw melting and Mixing Process

2. 16mm and 24mm twin screw compounders.

3. Use of Specific Energy Input to predict performance

4. Relationship between screw speed and feed rate and their effect on:
   - Energy Input
   - Residence Time
   - Degree of Fill

5. Scale-up and heat transfer
1. Twin screw melting and Mixing Process

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Simple extrusion – Chinese take-away
TWIN-SCREW MIXING

Material follows a figure '8' path as it is constantly transferred from one screw to the other across the intermesh.

The mixing action is a combination of compression and expansion with smearing effects between screw to screw and screw to barrel wall.

The energy to melt the polymer comes from the mechanical energy of the shafts, (i.e. from the motor).

Inter-particulate friction causes rapid melting, and high shear is imparted during the high viscosity transition from solid to molten phase.
Twin Screw Compounding

- **Feed Rate**: kg/h
- **Power**: kW
- **Screw speed**: rpm
- **Vent**: 
- **Output**: 
- **Heat/Cool**: 
- **Cool**: 

**Diagram Elements**:
- A yellow circle labeled 'P'
- An arrow labeled 'Output'
- An arrow labeled 'Heat/Cool'
- An arrow labeled 'Cool'
- An arrow labeled 'Feed Rate'
- An arrow labeled 'Power'
- An arrow labeled 'Screw speed'
- An arrow labeled 'Vent'
Variables in Twin Screw Processing

Independent variables

- Continuous
- Step change

Primary
- Screw speed
- Feed rate

Secondary
- Barrel temp
- Screw design
- Die design
- Barrel layout

Process parameters
- Shear Rate
- Temperature
- Residence Time

Quality Control parameters
- Dispersion
- Colour
- Degradation

Dependent variables
Twin Screw Torque

Feed Rate, kg/hr

Screw Speed, rpm

Q_{\text{max}}

100\% \text{ Torque}

Low energy configuration

High energy configuration

N. max
Segmented Twin Screw Elements
## Standard Twin Screw Elements

<table>
<thead>
<tr>
<th></th>
<th>CONVEYING</th>
<th>MIXING</th>
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<tbody>
<tr>
<td>Feed Screws</td>
<td>++++++++++</td>
<td>+</td>
</tr>
<tr>
<td>30 deg Forward</td>
<td>+++++</td>
<td>++</td>
</tr>
<tr>
<td>60 deg Forward</td>
<td>+++++</td>
<td>++++++</td>
</tr>
<tr>
<td>90 deg Alternate</td>
<td>zero</td>
<td>+++++++</td>
</tr>
<tr>
<td>60 deg Reverse</td>
<td>- - -</td>
<td>+++++++</td>
</tr>
<tr>
<td>Reverse Feed Screw</td>
<td>- - - - - -</td>
<td>++</td>
</tr>
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Twin Screw Primary Variables

Feed Rate, kg/hr

Screw Speed, rpm

Q_{max}

100% Torque

A → B → C → D → E → F

N. max
Experimental outline

Approx Feedrate
16mm 24mm

Outline

<table>
<thead>
<tr>
<th>RPM</th>
<th>100%</th>
<th>90%</th>
<th>80%</th>
<th>70%</th>
<th>60%</th>
<th>50%</th>
<th>40%</th>
<th>30%</th>
<th>20%</th>
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<tbody>
<tr>
<td>200</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>X</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
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Equipment

1. Twin screw melting and Mixing Process

2. 16mm and 24mm twin screw compounders.

3. Use of Specific Energy Input to predict performance

4. Relationship between screw speed and feed rate and their effect on:
   - Energy Input
   - Residence Time
   - Degree of Fill

5. Scale-up and heat transfer
**Experimental equipment**

PRISM co-rotating twin screw compounders.

<table>
<thead>
<tr>
<th>Model</th>
<th>Screws</th>
<th>Power</th>
<th>RPM</th>
<th>L/D ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eurolab 16</td>
<td>16mm</td>
<td>2.5 kW</td>
<td>1,000</td>
<td>25:1 &amp; 40:1</td>
</tr>
<tr>
<td>TSE 24 HC</td>
<td>24mm</td>
<td>9.0 kW</td>
<td>1,000</td>
<td>28:1 &amp; 40:1</td>
</tr>
</tbody>
</table>
Twin screw configurations 16mm

Eurolab 16 25:1 One and Two stage configuration

Nett Power kW vs RPM

- 3.54 kg/h 2 stage
- 3.54 kg/h 1 stage
- 6.27 kg/h 1 stage
- 6.27 kg/h 2 stage
Twin screw configurations 16mm

16 mm 25:1 L/D

16 mm 40:1 L/D
Twin screw configurations 24mm

24 mm 28:1 L/D

24 mm 40:1 L/D
PRISM Eurolab 16 extruder
PRISM TSE 24 HC extruder
Experimental procedure

Feed Rate, kg/hr

Screw Speed, rpm

100% Torque
Specific Energy Input

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The Specific Energy input is the measure of how motor power is converted into energy in the polymer.

Motor power minus “no-load” power = $P \ ( \text{kW} )$

Polymer feed rate = $Q \ ( \text{kg/h} )$

Specific energy input = $\frac{P}{Q} = E \ (\text{kWh/kg})$
Scale-up by Specific Energy Input

The Specific Energy value allows a calculation of what motor power is required to process a defined quantity of Material.

Required Polymer Output = \( Q \) (kg/h)

Specific energy input = \( E \) (kWh/kg)

Nett Motor power \( P = Q \times E \) (kW)
Specific Energy in a twin-screw

![Graph showing specific energy in a twin-screw configuration. The graph displays the relationship between specific energy (kW/kg) and feed rate (kg/h) at different speeds (200 rpm, 400 rpm, 600 rpm, 800 rpm, and 1000 rpm). The graph indicates a decrease in specific energy with increasing feed rate and speed.]

Eurolab 16 40:1
Two-stage configuration
Specific Energy in a twin-screw

TSE 24 HC 40:1
Two stage configuration

Nett Specific Energy kWh/kg

Feedrate kg/h

- 200 rpm
- 400 rpm
- 600 rpm
- 800 rpm
- 1000 rpm
Specific Energy in a twin-screw

TSE 24 HC 28:1
Two stage configuration

Feedrate kg/h

Specific Energy kWh/kg

200rpm 400 rpm 600 rpm 800 rpm 1000 rpm
Effect of Screw Speed

TSE 24 HC 40:1
Two stage configuration

Nett Specific Energy
kWh/kg

RPM
0 200 400 600 800 1000

4 kg/h 8 kg/h 12 kg/h 16 kg/h 20 kg/h 30 kg/h 40 kg/h
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Power vs. Screw speed 16mm

Eurolab 16 25:1

Two stage configuration

Nett Power kW vs. Screw Speed rpm

1.45 kg/h, 3.54 kg/h, 4.8 kg/h, 5.8 kg/h, Max Nett Power, 100% Torque
Power vs. Screw speed 16mm

Eurolab 16 40:1
Two stage configuration

Nett Power kW

RPM

1.45 kg/h 3.54 kg/h 4.8 kg/h 5.8 kg/h 100% Torque Max Nett Power
Power vs. Screw speed 24mm 28:1

TSE 24 HC 28:1
Two stage configuration

Nett Power kW

Screw speed rpm

4 kg/h
8 kg/h
16 kg/h
20 kg/h
30 kg/h
100 % Torque
Max Nett Power
Power vs. Screw speed 24mm 40:1

Two stage configuration

Nett Power kW

Screw Speed rpm

4 kg/h  8 kg/h  12 kg/h  16 kg/h
20 kg/h  30 kg/h  100 % Torque  Max Nett Power
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Residence time in a twin-screw

TSE 24 HC 28:1
Two stage configuration

Feedrate kg/h

Residence time secs

- 200 rpm
- 400 rpm
- 600 rpm
- 800 rpm
- 1000 rpm
Residence time in a twin-screw

Residence Time Comparison
16mm 25:1 vs 24mm 28:1
Residence time in a twin-screw
Residence time in a 40:1 twin-screw
Residence time in a 40:1 twin-screw

Residence Time Comparison
16mm 40:1 vs 24mm 40:1
Effect of Barrel length 4 kg/h

TSE 24 HC 28:1 and 40:1
Two stage configuration
4 kg/h

Residence time secs

0 5 10 15 20 25 30 35 40 45 50

1

200 rpm 40

400 rpm 40

600 rpm 40

800 rpm 40

1000 rpm 40

1

200 rpm 28

400 rpm 28

600 rpm 28

800 rpm 28

1000 rpm 28
Effect of Barrel length 8 kg/h

TSE 24 HC 28:1 and 40:1
Two stage configuration
8 kg/h

Residence time secs

0 5 10 15 20 25 30 35 40 45 50

200 rpm 40

200 rpm 28

600 rpm 28

600 rpm 40

400 rpm 40

800 rpm 40

800 rpm 28

1000 rpm 40

1000 rpm 28
Effect of Barrel length 12 kg/h

TSE 24 HC 28:1 and 40:1
Two stage configuration
12 kg/h
Effect of Barrel length 16 kg/h

TSE 24 HC 28:1 and 40:1
Two stage configuration
16 kg/h

Residence time secs

0 5 10 15 20 25 30 35 40 45 50

1000 rpm 40
800 rpm 40
600 rpm 40
400 rpm 40
1000 rpm 28
800 rpm 28
600 rpm 28
400 rpm 28
Effect of Barrel length 20 kg/h

TSE 24 HC 28:1 and 40:1 Two stage configuration 20 kg/h
Effect of Barrel length 30 kg/h

- TSE 24 HC 28:1 and 40:1
- Two stage configuration
- 30 kg/h

Residence time secs

- 1000 rpm 40
- 800 rpm 40
- 600 rpm 40
- 1000 rpm 28
- 800 rpm 28
- 600 rpm 28
Introduction

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Degree of Fill

It is possible to calculate the degree of fill in the barrel, from knowledge of the extruder free volume, residence time, feed rate and melt density of the product.

\[
\text{Feed rate in grammes/minute} = F \\
\text{Residence Time in minutes} = T \\
\text{Product Density in grammes/ml} = D \\
\text{Extruder free Volume in ml} = V
\]

\[
\text{Degree of fill in } \% = \frac{F \times T}{D \times V} \%
\]
Effect of Barrel length 4 kg/h

TSE 24 HC 28:1 and 40:1
Two stage configuration
4 kg/h

Screw Speed
1 2 3 4 5

0% 10% 20% 30% 40% 50%

Degree of fill

1.45 kg/h 40
1.45 kg/h 28

1.45 kg/h 40
1.45 kg/h 28

1.45 kg/h 40
1.45 kg/h 28

1.45 kg/h 40
1.45 kg/h 28
Effect of Barrel length 8 kg/h

TSE 24 HC 28:1 and 40:1
Two stage configuration
8 kg/h

Degree of fill

Feedsetting

8 kg/h 40
8 kg/h 28

8 kg/h 40
8 kg/h 28

8 kg/h 40
8 kg/h 28

8 kg/h 40
8 kg/h 28
Effect of Barrel length 12 kg/h

TSE 24 HC 28:1 and 40:1
Two stage configuration 12 kg/h

Screw speed

Degree of fill

0% 10% 20% 30% 40% 50%
Effect of Barrel length 16 kg/h

TSE 24 HC 28:1 and 40:1
Two stage configuration
16 kg/h

Degree of fill

Screw Speed

0% 10% 20% 30% 40% 50%

16 kg/h 40
16 kg/h 28
16 kg/h 40
16 kg/h 28
16 kg/h 40
16 kg/h 28
Effect of Barrel length 20 kg/h

TSE 24 HC 28:1 and 40:1
Two stage configuration 20 kg/h
Effect of Barrel length 30 kg/h

TSE 24 HC 28:1 and 40:1
Two stage configuration
30 kg/h
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Process Scale-up

16mm Laboratory extruder
5 kg/h

48mm Production extruder
150 kg/h
Surface Areas and Volumes

D = 16mm

L = D = 16mm

Surface area = \( \pi D^2 \)

\( \text{mm}^2 \)

= 256

(1)

Volume = \( \frac{1}{4} \pi D^2 L \)

\( \text{mm}^3 \)

= 1,024

(1)

Area/Volume = 1/D

= 0.0625 mm\(^{-1} \)

(1.5)

D = 24mm

L = D = 24mm

Surface area = \( \pi D^2 \)

\( \text{mm}^2 \)

= 576

(2.25)

Volume = \( \frac{1}{4} \pi D^2 L \)

\( \text{mm}^3 \)

= 3,456

(3.375)

Area/Volume = 1/D

= 0.04167 mm\(^{-1} \)

(1)
Adiabatic Operation

1. Set extruder barrel temperatures to match melting point of polymers to be processed.

2. Begin extrusion, and monitor temperatures within the extruder, or at the discharge.

3. Align barrel temperatures to match the measured melt temperatures.

4. If temperature level exceeds desired limits, modify process conditions of screw speed and feed rate.

5. If temperatures are still outside the limits, consider changes to the screw configuration.
Summary

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   - Residence Time
   - Degree of Fill

5. Scale-up and heat transfer
Ancillary Equipment
Conclusions

1. Measuring Specific Energy Input on a laboratory scale extruder allows prediction of performance of a production extruder, operating under similar conditions of screw speed and residence time.

2. At a fixed feed-rate, increasing screw speed will increase product specific energy and temperature, because of increased shear rate.

3. At a fixed screw speed, increasing feed-rate will reduce product specific energy and temperature, because of reduced residence time.

4. Increasing the L/D of an extruder will increase specific energy input, and residence time, even if the extra length is only conveying screws.

5. Operating a twin screw extruder adiabatically will avoid scale-up problems from differences in heat transfer.
Acknowledgements

Wells Plastics in Stone for donation of the polymer used in the experiments

Jim McLatchie for assistance in collecting the data during the tests
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