

1

Equipment Overview

■ 1.1 Process Issues

Efficient melting of polymer pellets or powder is an essential process requirement to obtain a quality product from either single- or twin-screw extruders. An example of an issue associated with poor melting is product surface defects. Tiny unmelted polymer particles, gels, undispersed solid fillers, or additives often contaminate film products when poorly designed screws are used in production [1]. These contamination particles can be caused by the incomplete melting of the resin, especially in bimodal polyolefins [2], or by not having appropriate dispersive mixing elements in the device [3]. A major source of gels in single-screw extruders is screw channels with small radii at the base of the flights; the cause and solution of this issue will be discussed in a later chapter. Another source of gels is contamination during shipping from poorly cleaned railcars to cardboard and trash found in Gaylord boxes. Although not usually a problem when using a twin-screw extruder to melt low-viscosity polymer powders, in single-screw extruders this type of powder can cause a change in the melting mechanism, resulting in unmelted polymer in the extrudate. This issue will be discussed in a later chapter. For either type of extruder, a source of gels in the extruded product is improperly designed extruder-to-die transitions and/or transfer lines where the wall stress is not greater than 20 kPa as the polymer flows [4]. In the twin-screw extruder, an unstable melting process that results in surging can occur. The melt quality can be OK, but obviously not good for any downstream handling for precise profiles, even if a gear pump (GP) is in place. Also, in the single-screw extruder, an improperly designed barrier flighted single screw will melt the polymer but often cause surging at the die due to resin bridging at an improperly designed inlet transition.

■ 1.2 Homogeneous Melt and Composition

For most polymer extrusion processes, the key to economic success is to have an extruder that delivers a polymer melt which is homogeneous, with respect to both composition and temperature, to the forming device, usually a film, strand, or profile die. When developing multiphase polymer melts that often contain suspended solids, the twin-screw extruder is almost always the processing equipment of choice. To accomplish this task, the extruder—which is generally fed with polymer powders or pellets produced by the chemical manufacturer—conveys, “melts”, and mixes the fluid polymer with any other additional required material, such as solid filler, and delivers the mixed homogenized melt to the forming device. For example, Campbell et al. recently investigated the mixing process of fillers ranging from nano- to micron-sized particles. This work has shown mixing in a co-rotating twin screw to be substantially influenced by the polymer rheology [5–7]. In the case of incorporation of solid fillers, up to a 60 volume fraction in the melt, Wetzel et al. found that when the loading exceeds a percolation concentration of about 15% by volume, the structure developed by the filler has a strong influence on the mixing efficiency [8–10]. Therefore, the introduction of fillers, both comingled with the polymer powder or pellets and downstream into the polymer melt via the twin-screw extruder, is an important functional unit operation in the polymer industry. However, in this book the focus will be on developing and delivering homogeneous polymer melts—either from unfilled homopolymers or from previously compounded multicomponent polymer materials, such as particulate, fiber-filled thermoplastics or color concentrates—to the die. The objective of the following chapters will be to provide a detailed compare-and-contrast perspective of the different mechanisms inherent in single-screw and co-rotating twin-screw extruders as they accomplish this task.

■ 1.3 Extruder Mechanical Design Comparison

Before going into detail regarding conveying, melting, and mixing mechanisms associated with the two extruder configurations, it is useful to compare and contrast from a macroscopic perspective many of the design features of these two devices; single-screw extruder: Figure 1.1 [11], co-rotating twin-screw extruder [12]: Figure 1.2.

Single-Screw Extruder

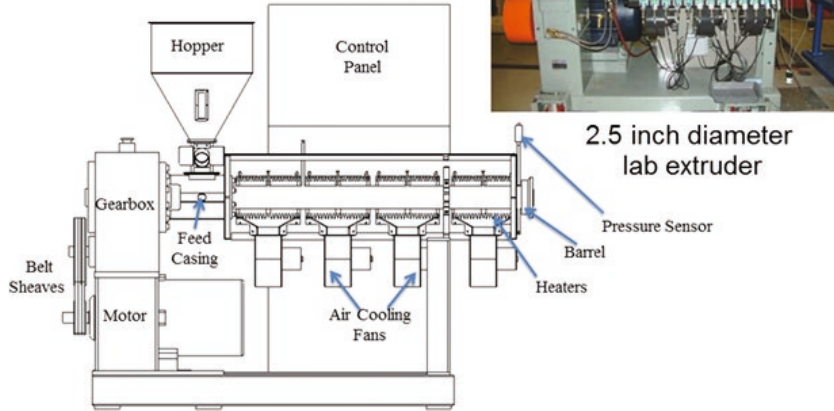


Figure 1.1 Typical single-screw extruder (courtesy of G. A. Campbell and M. A. Spalding, *Analyzing and Troubleshooting Single-Screw Extruders*, 2nd ed., Hanser (2021))

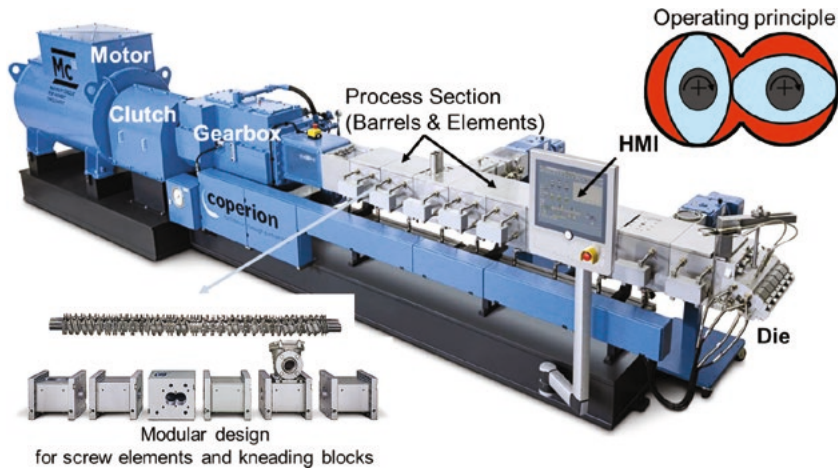


Figure 1.2 Basic layout and main components of the twin-screw extruder with drive power available from 10 kW to 12 MW and rates from 1 kg/h to 100 t/h (courtesy of Coperion Corporation)

Each extruder system consists of a motor, coupling mechanism, gearbox, process section, and shaping device, such as a strand, film, or profile die.

The single-screw extruder has a process section usually constructed from a single piece barrel and a solid screw; see Figure 1.3. The co-rotating twin-screw process

section, as illustrated in the bottom left-hand corner of Figure 1.2, is built up from modular components (both barrels and screw elements). The operating principle of the twin screw, as illustrated in the top right-hand corner of Figure 1.2, is based on two parallel screw shafts where the crest of one screw element wipes the root of the other [13, 14].

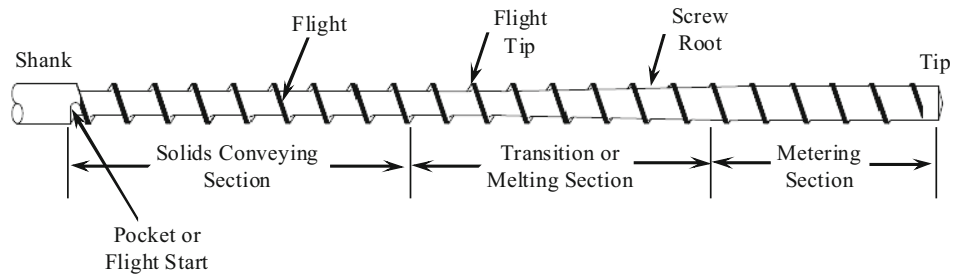
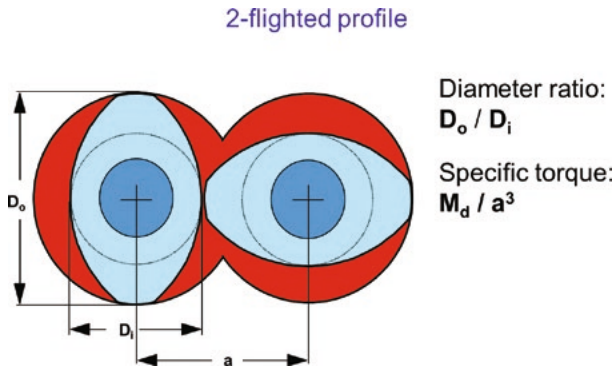


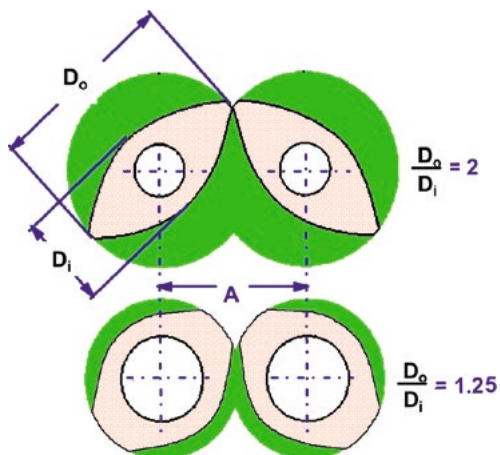
Figure 1.3 Schematic of a typical single-flighted screw (courtesy of G. A. Campbell and M. A. Spalding, *Analyzing and Troubleshooting Single-Screw Extruders*, 2nd ed., Hanser (2021))

Both the single screw and the twin screw have similar degrees of freedom with respect to geometry, power transmission, and screw speed [15]; however, the self-wiping criterion places constraints on the overall twin-screw extruder design flexibility. While the single-screw extruder can have multiple different channel depths along the axial length of the screw profile to meet process requirements (Figure 1.3), the cross-sectional geometry of the twin-screw extruder is fixed at a constant channel depth to maintain self-wiping. The twin-screw cross-sectional geometry is defined by three dimensions: screw diameter (either the outer diameter (D_o) or the inner (root) diameter (D_i)), D_o/D_i ratio, and centerline distance (a) between the two screw shafts (Figure 1.4). Once two of the above three criteria are defined, the other one is fixed. For a constant centerline distance, as the D_o/D_i ratio is increased, the extruder D_o increases and the D_i decreases. Therefore, the diameter ratio can be used as a comparative measure of the free cross-sectional area among twin-screw extruders, and thus of the internal free volume per unit length as well. The larger the D_o/D_i ratio, the greater the internal free volume per unit length of the extruder. Therefore, D_o/D_i is a relative measure of the maximum theoretical volumetric throughput capacity of the extruder. However, as is discussed in the next paragraph, D_o/D_i cannot be increased without at some point impacting the power transmission capacity of the screw shaft [14].

**Figure 1.4**

Characteristic dimensions of co-rotating twin screws (courtesy of Coperion Corporation)

D_o/D_i has several additional influences on the extruder design and operating conditions. In addition to being a comparative measure of internal free volume, D_o/D_i defines the average shear rate constant for the extruder geometry. The average shear rate constant is determined by integrating the shear rate as a function of the channel depth over the entire screw profile. The average shear rate of a fully filled channel can then be determined by multiplying this constant by the screw rpm. This average shear rate can be used to compare extruders with different diameter ratios as well as extruders run at different rpm values. For example, as D_o/D_i is increased, the channel depth of the extruder increases and the shear rate constant decreases. Finally, as D_o/D_i increases, the shaft diameter available for power transmission is reduced; see Figure 1.5. This creates a conflicting scenario. An extruder with a small D_o/D_i has reduced free volume, but significant power transmission design capacity. On the other hand, a larger- D_o/D_i extruder has a greater volumetric throughput capacity, but geometric constraints limit the shaft diameter and therefore the power transmission capacity. Consequently, an appropriate balance between required power transmission capability and available free volume must be determined so that neither one is a process-limiting parameter. The ideal situation exists when a process is simultaneously power-limited, and volume-limited.

**Figure 1.5**

Relationship between D_o/D_i ratio and free volume (courtesy of Coperion Corporation)

As an example of the power/volume trade-offs discussed above, Table 1.1 shows the difference in free cross-sectional area, average shear rate, and power/volume ratio expressed as torque capacity/centerline distance cubed (M/a^3) of two currently available co-rotating twin-screw extruders with the same centerline distance but D_o/D_i ratios of 1.55 and 1.80, respectively. As expected, the power/volume ratio of the extruder with the 1.80 D_o/D_i ratio is lower than that of the 1.55 D_o/D_i extruder, due to shaft limitations.

Table 1.1 Impact of D_o/D_i on Free Cross-Sectional Area and Average Shear Rate

Machine Size	D_o/D_i	Free Cross-Sectional Area [cm ²]	Average Shear Rate (300 rpm) [s ⁻¹]	Torque/Centerline ³ (M/a^3) [N·m/cm ³]
ZSK-92	1.55	46.0	100	18.0
ZSK-98	1.80	62.9	60	11.3

While both extruders could be used for similar processing tasks, the processing length, screw configuration, and operating conditions would need to be different. However, when power versus volume is considered, the 1.55 D_o/D_i extruder would be capable of the highest rates for energy-intensive processes such as processing glass-filled nylon, but the 1.80 D_o/D_i extruder would win out for processing low bulk density material not requiring a significant energy input, such as 60% talc-filled PP.

■ 1.4 Extruder Screw Design/Unit Operations Comparison

The single-screw extruder is generally divided into three primary sections/unit operations (Figure 1.3): section 1, solids conveying; section 2, melting/mixing; and section 3, metering. Additional unit operations, such as enhanced melt-mixing and discharge pressurization elements, are often incorporated into the metering section. Much of the mixing, such as dispersion of color concentrates, is accomplished in the melting section of the single screw.

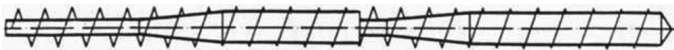


Figure 1.6 Two-stage single-screw profile

Additionally, the three screw sections have separate heater zones on the barrel to provide energy to the screw where required, as seen in Figure 1.1, and to remove energy (providing cooling) when the polymer's viscosity leads to unacceptable high melt temperatures. There are, however, two-stage single-screw designs (Figure 1.6) that have an increased channel depth following the first metering section to allow additional material to be introduced, but this design is usually used to volatilize and remove low molecular weight contaminants such as moisture. The process section for a co-rotating twin-screw compounding line can require the same three primary unit operations, solids conveying, melting/mixing, and metering/conveying, when used for processes that require no compounding of multiple components or other complex processing functions. Such an application is melting nylon pellets for a monofilament spin line. However, more typically, the compounding process can be broken down into unit operations as depicted in Figure 1.7. These are: introduction of the feed material, solids conveying, melting (softening, phase transformation), additive incorporation, mixing (dispersive, distributive), atmospheric venting, mixing, degassing/devolatilization, discharge pressurization, and discharge shaping [16].

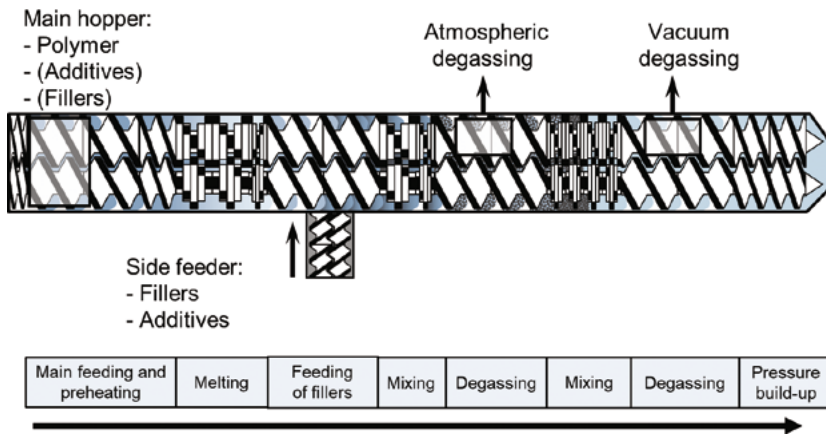


Figure 1.7 Typical co-rotating twin-screw compounding line unit operations (courtesy of Coperion Corporation)

Most single-screw extruders have one of two typical screw designs: single-flighted, Figure 1.3, or barrier screws, Figure 1.8. The barrier flight is undercut from the main flight to allow molten resin to transfer from the solids-conveying channel to the melt channel. The entrance transition to the solids channel of the barrier screw must be carefully designed or the pellets will bridge when they leave the screw feed section.

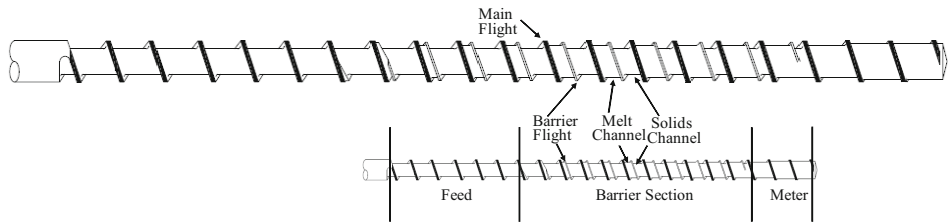


Figure 1.8 Schematic for a barrier melting section (courtesy of G. A. Campbell and M. A. Spalding, *Analyzing and Troubleshooting Single-Screw Extruders*, 2nd ed., Hanser (2021))

As illustrated in Figure 1.3, the single flight consists of a single helix along the length of the shaft. This first section of the screw, the feed zone, is normally flood fed from the hopper and has a deep channel depth to effectively take in and convey the lower bulk density solid feed. The next section, the melting zone, has a decreasing channel depth along the down-channel axial direction to compact and subsequently melt the feedstock. The final section, the metering zone, conveys the melted polymer and generates the required pressure to force the polymer melt through the shaping device attached to the end of the extruder barrel. The pitch, or lead, of this screw is normally constant along the entire length of the screw; however, the pitch may be changed in differing sections of the screw to control the solids feed rate in the feed section or to increase the pressure development in the metering section. The pitch, or lead, is determined by the distance between two consecutive flights along the axial direction of the screw of the same helix and if the pitch/lead is equal to the barrel diameter, the screw is referred to as a square-pitched screw. The screw can have more than one flight (helix or start). Multiple flights are most common in large-diameter screws in the metering sections to enhance pressure development to overcome the back pressure from the die.

For the twin screw, elements are often constructed with a single, double, or triple helix; see Figure 1.9. So far, no commercial twin screw has incorporated more than the triple helix design. Figure 1.10 illustrates a two-flighted (helix) geometry. As shown, the pitch is the distance between the first and the third crest. The proper definition is that pitch is equal to the axial distance traveled when tracing the crest over 360 degrees.

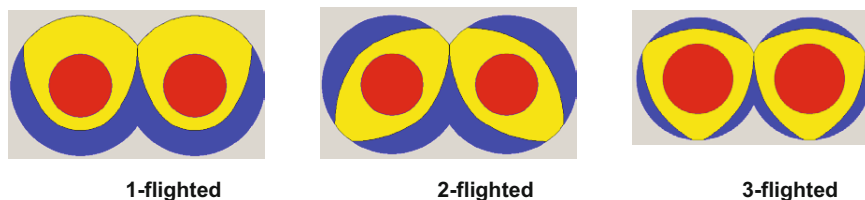


Figure 1.9 Examples of twin-screw single-, double-, and triple-flighted cross-section geometry (courtesy of Coperion Corporation)

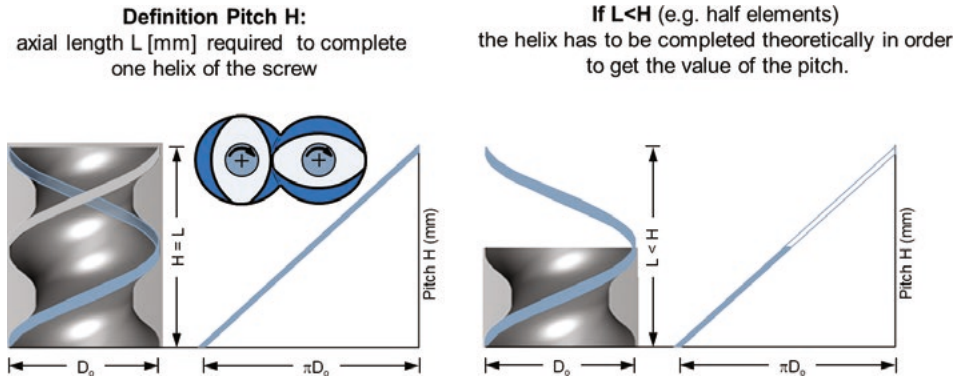


Figure 1.10 Pitch defined for the two-flighted twin-screw profile (courtesy of Coperion Corporation)

For many polymers, this barrier screw design (Figure 1.8) has a higher melting rate than the basic screw design because the solid bed is kept closer to the moving surfaces of the screw, thus producing more dissipative energy to enhance melting. As discussed in detail in Campbell and Spalding [11], in the solids-conveying section, plastic materials, usually in the form of pellets or powders, are flood fed continuously through a hopper into the extruder. Then, the polymer moves down-channel, pushed by the rotating flights of the screw. Because of heat conduction through the barrel wall and mechanical friction, the solid polymers are heated and softened first at the polymer barrel interface after the solid bed is compacted. As soon as the temperature of the solid polymer reaches its melting point (for crystalline polymers) or softening point (for amorphous polymers), a viscous polymer melt is formed in the so-called delay zone, that is, before the section of the screw where the core/root is increasing in diameter. The detailed theory of how the melt encapsulates the solid bed will be presented in a later chapter. Most of the bed heating is viscous dissipation caused by the shearing action in the film due to the relative motion of the screw surfaces and the solid bed motion relative to the stationary barrel. This energy is then conducted into the solids, melting crystalline resins and softening amorphous resins to the point that they will flow in the shear field next to the barrel. In the melt-conveying (metering) section, polymer melt is “pressurized” and readied to be pumped through the die. For a single-screw extruder with a properly designed screw geometry, the metering section is the rate-controlling part of the screw and the transition and feed sections must be properly designed to complement the dynamics in the metering section.

Co-rotating twin-screw extruder screw configurations, as pointed out previously, are constructed from modular component elements assembled in a specific sequence to implement the unit operations required to accomplish the process task. Figure 1.11 illustrates a barrel and screw configuration sequence for homopoly-

mer powder to pellet conversion. In general, there are two types of elements: conveying elements, whose primary function is to transport material in the down-channel direction, and kneading blocks, whose function is to impose a “stress” on the material to perform some energy-intensive task such as melting, dispersion, or homogenization. Figure 1.12 displays several types of conveying elements (top row) and kneading blocks (bottom row).

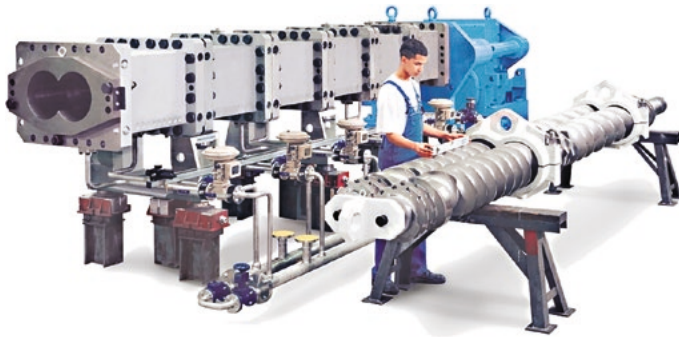


Figure 1.11 Barrel and screw configuration sequence for homopolymer powder to pellet conversion (courtesy of Coperion Corporation)



Figure 1.12 Basic elements of the twin-screw compounder; top row: conveying elements, bottom row: kneading blocks (courtesy of Coperion Corporation)

Twin-screw conveying elements are inherently different from the conveying geometry of the single screw. Single-screw extruders screws typically have a constant pitch, but a depth that varies from the feed intake zone (deep) to the metering discharge zone (shallow); see Figure 1.3. On the other hand, twin-screw extruder conveying elements maintain a constant channel depth, but vary the pitch. Standard screw bushings are constructed with pitches ranging from approximately $0.5 D$ to $2.0 D$, where D is the machine diameter; see Figure 1.13. Large-pitch elements ($1.5 D$ to $2.0 D$) might typically be used in feed or devolatilization areas of

the extruder. Medium-pitch elements (approximately $1.0 D$) are used to transport material between unit operations (i. e., feeding, mixing, and vacuum devolatilization). Narrow-pitch elements ($0.5 D$ to $0.7 D$) are used in areas where compaction of material and 100% fill is desired, such as to build melt pressure before kneading blocks or the die. Up to approximately $2.5 D$, a greater element pitch results in increased down-channel material conveying. This results in a decrease in residence time, degree of fill, as well as a narrower residence time distribution. However, while there is an increased drag flow capacity associated with a greater pitch, there is also an increased sensitivity to pressure flow. That is, as the pitch of an element is increased, the drag flow conveys material in the down-channel direction at a faster rate. However, if there is a restrictive force placed in the flow path, the greater-pitch element is less effective in building up the pressure necessary to push material past the restriction [17]. See Section 6.5.3 for a more detailed discussion. Reverse pitch elements are used to generate back pressure and therefore create sections of 100% fill which, for example, can be used to separate unit operations or totally fill a mixing section.

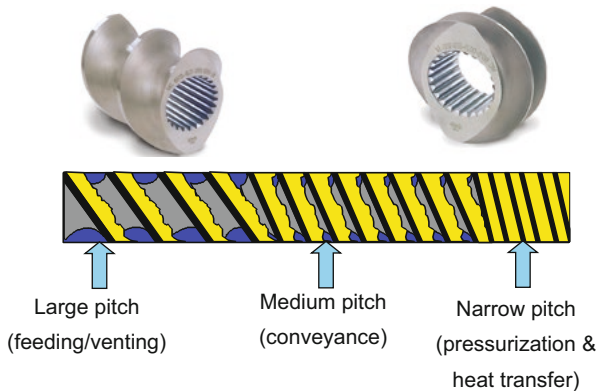


Figure 1.13 Typical utilization for large ($\sim 1.5\text{--}2.0 \times$ screw diameter), medium ($\sim 1.0 \times$ screw diameter), and narrow ($\sim 2/3 \times$ screw diameter) pitch conveying elements (courtesy of Coperion Corporation)

The basic building blocks for mixing in the co-rotating, intermeshing-type twin-screw extruder are kneading blocks and special mixing bushings. Special bushings include slotted elements, toothed mixing elements and blister rings, or the self-wiping equivalent element [18–22]. Standard conveying-type screw bushings are also used in certain circumstances.

Just as screw bushings are characterized by pitch (i.e., flight angle), kneading blocks can be characterized by individual disc length (width), Figure 1.14, and stagger angle between successive discs, Figure 1.15. Kneading blocks introduce both a distributive and a dispersive mixing component into the system. The rela-

Index

A

abrasive filler 104
accelerated wear 108
active apex 106
actual deformation mechanism 140
adiabatic temperature rise 145
advancing flight 72
agglomerates 112
agglomeration 111
angular velocity 149
axial pressure 101

B

back mixing 193
baker's fold 207
barrel 127
barrel rotation 147, 149, 151, 154
Barr Fluxion 189
barrier flight 7
barrier melting sections 88
barrier screw 9
barrier section 90
bed breakup 184, 185
bi-lobe discs 58
Bingham model 22
Bingham plastic 19
boundary conditions 142
breakup 88, 92
broader RTD 194
broad RTD 191
bulk density 38, 78, 80

C

capillary rheometers 31
Carreau model 32
Cartesian coordinate 51, 127, 138
channel depths 4
channel height 85
channel width 49, 85
chaotic mixers 177, 207
chaotic mixing 179
coefficient of friction 79, 80
compacted material 118
compatibility 202
component elements 9
compounding efficiency 196
compounding line 102
compounding screw 159
compressive action 106
compressive modulus 38
cone and plate 29
constant pressure head 131
contaminant 177
continuous mixers 56
control volume 152
conveying angle 79
conveying efficiency 78, 79
conveying elements 10, 14, 100, 116, 166, 170
core 137
core rotation 131
corkscrew-type mixing tip 206
co-rotating 57, 156
co-rotating twin-screw 83, 163
counter-rotating 55

critical molecular weight 24
cross-channel 76
Cross model 32
crystalline polymers 120
cylindrical structure 127

D

deep-channel 141
deep channel screws 139
deformation 17, 102, 106
devolatilization 10
dilatant materials 19
Dirac-function 177
discharge backup 167
discharge pressure 164, 167
discrete element 71
disc width 192, 193, 197, 170
dispersive characteristics 113
dispersive mixing 1, 199
dissipate energy 17
dissipation 64, 87, 104, 145, 149
dissipation energy 86
dissipation rate 22
distributive mixing 193
distributive task 199
 D_o/D_i 122
downstream feeding 199
drag flow 75, 133, 137, 158 159
drag flow capacity 166
dynamic mixers 189, 191

E

elastic 18
elements 60
encapsulated 103, 104
energy balance 153
energy consumption 163
energy dissipation 134, 135, 152
enthalpy curve 98, 99
Erdmenger 59, 61
Erdmenger profile 57
Eulerian frame 137
external heaters 122

extruder system 3
extrusion model 46

F

fiber 199
fiber bundles 200
figure 8 pattern 77
filled polymers 19
filler 197
filler addition 198
film thickness 181
fixed boundary problem 140
flattened 63
flight 47, 127
flight clearance 181
flight corners 180
flight undercut 89
flood fed 15
flood point 80
fluid incorporation 202
fluidization 78
forwarding kneading blocks 108,
116
Fourier series 178
four melt films 85, 89
frame change 138
frame-indifferent 140
free helix 177
free helix extruder 129
friction 108
frictional coefficient 76
friction factor 74
fully melted polymer 195

G

gear pump 160, 167
gel contamination 188
gels 1, 178
geometric parameters 48
glass and plastic barrels 128
glass length 199
glass strand breakage 114
glass transition 18

governing equations 141
granules 100

H

heat capacity 40
heat conduction 9
heat generation 106
heat removal 123
heat transfer 15, 135, 136, 153
helical channel 127
helix 137
helix angle 49
high distributive mixing 201
higher-pitch 164
higher temperature rise 149
highly filled 197
highly instrumented extruder 182
high melt temperatures 7
high shear rate 31
high-speed 62
high-torque 62, 63
high viscosities 188
homogeneous polymer melts 2

I

inhomogeneous melting 103
intense back mixing 197
intense melting-section 195
intermeshing geometry 57
irreversible deformation 101

K

KB and TME 200
Kenics™ KM Mixer 208
kneading block performance 171
kneading blocks 11, 98, 100, 108, 110,
119, 169, 170, 192

L

laboratory frame 140
laboratory reference frame 137, 139

Lagrangian frame 139
Lagrangian reference frame 137
lateral stress coefficient 73
lateral stress ratio 39, 71
letdown ratios 184
low aspect ratio fillers 198
low pumping efficiency 163
low-viscosity additives 203

M

Maddock Mixer 189
Maddock-style mixers 188
material characteristics 163
material compaction 101
material flow 76
mathematical analysis 132
maximum capacity 163
Maxwell fluid 37
mechanical energy 102
melt density 43, 52
melt film 180
melting 1, 99, 103
melting dynamics 83
melting energy 86
melting mechanisms 99, 100
melting-mixing performance 183
melting pressure 109, 120
melting process 180
melting progression 118
melting rate 84
melting section 98, 102, 104
melting temperature 115
melting zone 8
melt/mixing quality 114
melt pump 160
melt viscosity 115
metering section 47, 50, 186
metering zone 8
mixing 177
mixing devices 188
mixing mechanism 181
mixing mechanisms 2
modular 196
modular co-rotating 61

Moffatt eddies 178, 179
mono-lobe 58
motor power 122
moving boundary 127
moving boundary problem 140
multiple-flighted 46

N

narrow-pitch 14
neutral kneading-block 169
new material surfaces 75
Newtonian 32, 145, 32
Newtonian fluid 133, 194
no melt pool 94
normal stress ratio 71
numerical simulations 136

O

one-dimensional melting 93, 97
operating principle 54
optimal discharge section 168
optimal discharge zone 163
oscillation mode 30

P

partially filled 158
partial melt 113
passive apex 106
pellet feed 45
percolation model 23, 26
plasticating extruders 45
plastic energy dissipation 101
plug-flow mode 76
polymer flow 161
polymeric filler 25
polymer melting 98
powder 100
power-law 19, 25, 32
premature melting 103
pressure buildup 164, 165, 167, 169
pressure drop 148
pressure flow 51, 133, 134, 148, 160

pressure generation 169
pressure gradient 53, 120
pressure peak 117
pressure probes 106
pressure rise 169
pressurization 14
process interactions 99
process temperature 159
product quality 102, 165
pseudoplastic 18, 20
pulls solids forward 88
pumping efficiency 163, 166, 167
pushing flight 64

Q

Q/N 101, 115, 120

R

rate-limiting step 50
rate of feed 72
rate/rpm 80
reactive extrusion 60
recirculation flow 205
reduced-diameter elements 109
reference frame 139
residence time 77, 119, 136, 177,
203
residence time distribution 191
restrictive elements 102, 119, 170
restrictive kneading block 112
restrictive screw bushing 108
retention of fiber length 200
reverse flow 194
reverse pitch 11
reverse pitch elements 197
Reynolds bearing 96
rheology 17
ROSS® Mixer 211
rotational flow component 51

S

scale-up 122
screw configuration 6, 98, 122
screw curvature 134
screw, elements 8
screw pitch 166
screw pumped 149
screw rotation 50, 133, 141, 147, 149, 155
screw rotation analysis 50, 142
screw rotation mechanism 85
screw rotation theory 137, 185
screw rpm 163
screws intermesh 75
screw speed 165
self-cleaning 60
self-wiping 201
semi-crystalline 18
shape factors 54
shear rate 21, 27, 53, 159
shear stress 34, 186
shear-thinning 18, 20
shear viscosity 17, 31, 53, 86
short-circuiting 193
simulations 151
single-flight 46, 166
single-screw 45, 83, 103
single-screw extruders 71, 191
single-screw melting 84
single-screw mixing 177
SME 205
SMX™ Static Mixer 210
solid bed 92
solid bed breaks up 182
solid density 43
solid polymer fragments 183
solids-conveying 73, 78
solids-conveying theory 74
solids flow 77
solids-to-fluid 13
solids transport 75
specific energy 159
specific mechanical energy 98, 122, 160, 203

stagger angle 192, 192, 197, 170
starve fed 15
static mixers 208
stationary 127
stress 29, 37

T

tangential stresses 71
temperature calculation 152
temperature dynamics 65
temperature functions 34
temperature increase 28
temperature profile 101
temperature rise 147, 159
thermal conductivity 42
thermal gradient 205
thin striation 181
three basic twin-screw 54
three-lobe 100
three-lobe kneading blocks 110, 113, 170
throughput rate 163, 165
TME or ZME 196
traditional extruder 130
trailing flight 72
transition section 47
transition zone 13
trigonometric relationship 143
Twente Mixing Ring 189
twin-screw 103, 156
twin-screw compounder 99, 157
twin-screw extruders 54, 191
twin-screw “stuffer” 60
two-lobe 100

U

undulation 111
uniform pressure 111
unit operations 157, 192
unmelt 119
unmelted solid 184
unwound 63
unwrapped 127

V

velocities 127
viscoelastic 18
viscoelastic fluid 194
viscoelastic properties 36
viscoelastic response 35
viscosity 14, 164
viscosity differential 202
viscosity increases 167
viscous 18
viscous dissipation 21, 100
volume fraction 199
volumetric drag capacity 158

W

wide-disc 112

Y

y thickness 86

Z

ZME elements 195, 200, 201