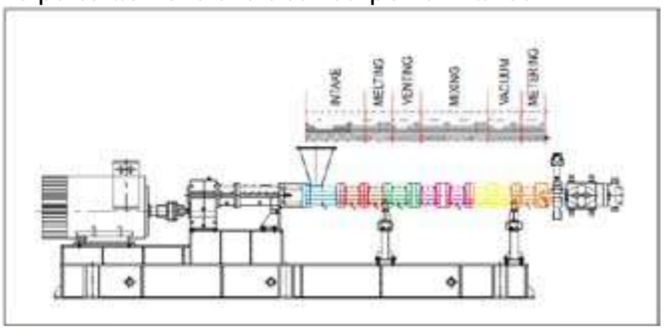
THE HEART OF A TWIN SCREW EXTRUDER IS EPZ

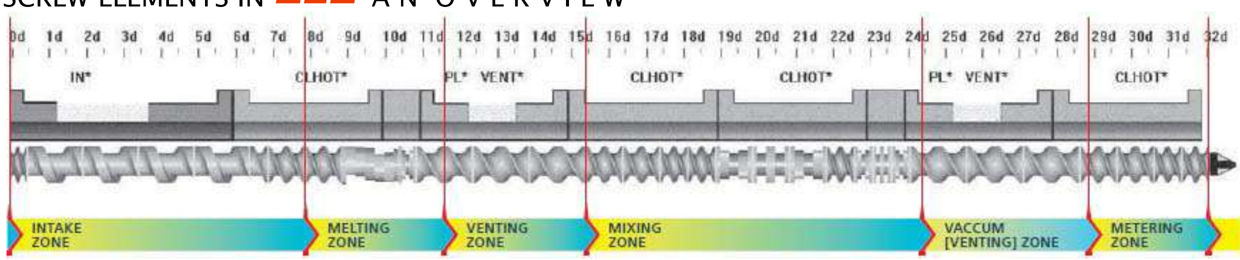
The Extruder Processing Zone (EPZ) is the 'heart' of a Co-rotating Twin-Screw Extruder that helps to achieve the desired performance.



Work done in the Extruder Processing Zone results in the desired quality of compounded material and levels of output in a co-rotating twin-screw extruder. In the EPZ, several actions are carried out on the material as it works its way through the extruder and exits from the die. Depending on the nature of work being carried out, these zones are called Intake, Melting, Atmospheric Venting, Mixing, Vacuum Venting and Metering. Proper configuration with the right choice of elements and barrels optimizes the performance of each zone. Solids conveying in Intake, Softening of Polymer in Melting, Degassing in Venting, Dispersion and Distribution accompanied by Kneading action in Mixing, Discharge control in Metering are the functions of the various zones.

Conveying screws, Kneading Blocks and other Mixing Elements are the working members in each zone. Making the right selection among numerous elements and configuring them in the right order needs understanding of the functional characteristics of each element. This article attempts to throw further light in understanding the zones and characteristics of elements.

CONFIGURATION OF SCREW ELEMENTS IN EPZ A N O V E R V I E W



The adage 'different strokes for different folks' holds good when one attempts to deal with the EPZ (Extruder Processing Zones) of a Co-rotating Twin-Screw Extruder. Within this EPZ area the 'key to success' lies with the exact design of the 'Element and Barrel' Configuration. In the game of Chess, a 'good formation' is important to achieve a winning result, since pieces in isolation cannot perform. This is true in the case of Compounding also. Elements work best in some combinations, and some elements are more powerful than others. Indeed, it is true!

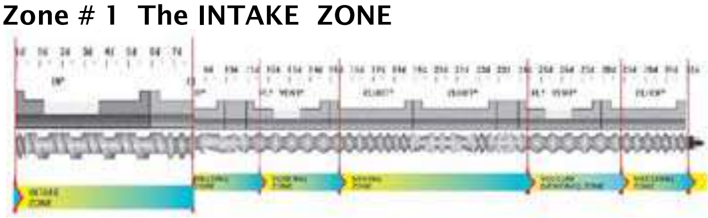
Importantly,

1. The design has to deliver the correct amount of work on the product for melting and mixing.
2. The design should have the capacity to take the product “in” and “out” of the extruder.
3. Lastly, the design should allow gases or volatiles to escape without the product leaking out through Vents.

Zone 1	Intake Zone	for introducing the material into the extruder.
Zone 2	Melting Zone	for heating the material and therefore melting the material and achieve partial or total mixing.
Zone 3	Venting Zone	for removing the volatiles & moisture.
Zone 4	Mixing Zone	for ensuring proper mixing.
Zone 5	Vacuum Zone	for completely removing the volatiles & moisture to the required levels.
Zone 6	Metering Zone	for building up the required pressure at the die.

It can be imagined that there are ‘different zones’ (area) inside the extruder performing a series of specific functions1. Like a relay race, each zone passes on the ‘baton’ (the material being processed) to the next zone and until the final stage. Extruder performance measured by energy consumption, quantity and quality of output, largely depends on the design of these processing zones. The effective selection of elements is the first step in design. The right length and combination of elements is the next step. We shall discuss these various zones and outline the element characteristics, its potential use and certain design principles.

Zone # 1 The INTAKE ZONE



The Two popular methods of feeding an extruder are starve-feeding and force-feeding. During force-feeding, a reserve of material is maintained in the hopper of the extruder and material is “positively displaced” or “forced” into the extruder. Starve-feeding is the condition when an extruder is fed at a rate less than the capacity of the screw. The hopper remains empty and functions as a conduit to avoid material from spilling. Starve feeding is the more popular method for feeding due to several advantages that will be discussed later.

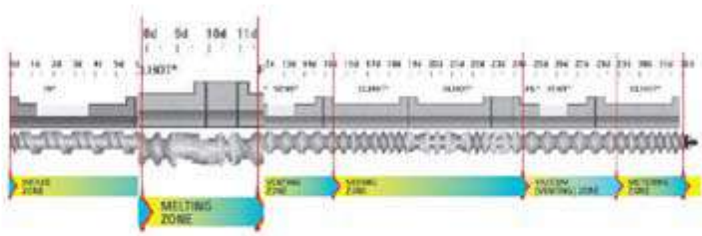
The modular design of the extruder screw assembly provides an option for a wide selection of screw elements for configuring in the 'intake zone'. The popular twin-screw elements2 are Single Flight Element (SFE), Schubkanten Element (SKE), Special Schubkanten Element (SSKE), Normal Right-hand Screw element (RSE), Deep flight SK element (DSK), and the newly invented Single Flight 'V' shaped (SFV) element.

TABLE OF INTAKE ZONE ELEMENTS					
ELEMENTS		CHARACTERISTICS			POTENTIAL USE
NOMENCLATURE	GEOMETRY & PROFILES	CONVEYING EFFICIENCY	FREE VOLUME	TENDENCY TO BREAKUP AND COMPACT	
Single Flight 'V' Element		Highest	Medium	Medium	All Types
Forward Screw Element		Low	Medium	Medium	Pellets
Deep Flight Schubkanten		Low	Highest	Medium	Tri-lobed Force-fed Extruders
Schubkanten Element		High	High	High	Powders, Mix of Powders and Granules
Special Schubkanten Element		Low	Highest	Medium	Bi-lobed Force-fed Extruders
Single Flight Elements		Medium	Low	Low	Alloys & Blends with different melt characterization

Free Volume is the free space for material available in an extruder. This is obtained by removing the space occupied by screw elements inside the 8 shaped barrel. Conveying Efficiency is the ability of the element to move the material forward in the extruder. It is 100%, if all the material moves forward at the completion of each turn of rotation.

Compaction is the removal of air entrapped in the material. For example, knocking or vibrating a vessel containing a powder compacts the material (reduces the volume) while stirring does not. Breaking up results in reduction in particle size or changes the particle morphology.

Zone # 2 The MELTING ZONE



It is common to imagine melting as a phase transformation from Solid to Liquid. In case of polymers, melting is generally associated with reaching the required melt viscosity or melt temperature. It is really that the crystalline polymers undergo some amount of melting while amorphous polymers undergo glass transition. The work that can be carried out depends on the resistance offered to it. As the Polymer melts, the resistance drops as the viscosity reduces. Strong compression aids in the melting of Crystalline Polymers like Polyamides and Polyolefins. Frictional heat generation by shearing forces is sufficient for increasing the temperature of amorphous Polymers like Atactic Polystyrene and Polycarbonate to the required process temperature which is usually above the Glass Transition Temperature.

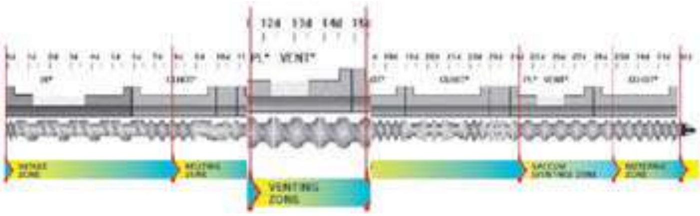
TABLE OF MELTING ZONE ELEMENTS						
ELEMENTS		CHARACTERISTICS				POTENTIAL USE
NOMENCLATURE	GEOMETRY & PROFILES	MELTING ABILITY		DISPERSIVE MIXING ABILITY	SHEAR UNIFORMITY*	
		AMORPHOUS	CRYSTALLINE			
Fractional Kneading Element		Highest	Highest	Highest	High	All types of Melting and Dispersive Mixing
Forward Kneading Element		Low	Medium	Low	Medium	Easy to Melt Crystalline Material
Reverse Kneading Element		Medium	High	Medium	Medium	Crystalline Material
3KB Kneading Elements		High	Highest	High	Medium	Amorphous
Neutral Kneading Elements		Medium	High	High	Low	Not usually recommended for Melting Used for Mixing

Mixing3 that accompanies melting is dispersive in nature. This is due to the high viscosity levels of the melt at the time of melting and as a result of which the high shear stresses opens an opportunity for elongation and break-up.

This melt mixing is achieved by Kneading Elements by the amount of shearing between the tip of the kneading block and the barrel. The intensity of shear experienced by the material will vary depending on the gap it passes through as the Kneading blocks complete a full rotation. In many cases, a hot zone is created due to intense action at certain points.

*Shear Uniformity: Unlike a Single Screw Extruder, a twin-screw extruder has shear planes in all three dimensions. Generally, Shear in the Radial plane and Lateral planes are ignored since they are unique to co-rotating twin-screw extruders. While the longitudinal shear (similar to Single Screw) can reach value of 250 /s, lateral and radial shears can reach 10 or 20 times this value. Importantly, not all parts of the melt will experience the intense localized shear action. The shear uniformity is a term used to characterize this. High uniformity will mean the shear rate in that entire section in all planes will be within a factor of 4. Low uniformity will mean variation of 10 times or more.

Zone # 3 The VENTING ZONE



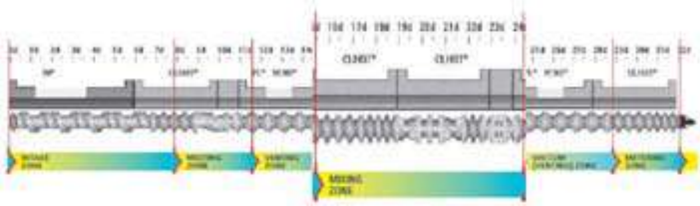
Vents are required to continuously remove air and moisture (or volatiles) during or after the melting stage. Removal of moisture to prevent hydrolysis of condensation polymers such as Nylon and PET is one of the most important requirements. Additionally, down-stream to the venting zone, entrapped air may be pumped into the extruder from a side-feeder that need to be removed in order to increase the capacity of the extruder.



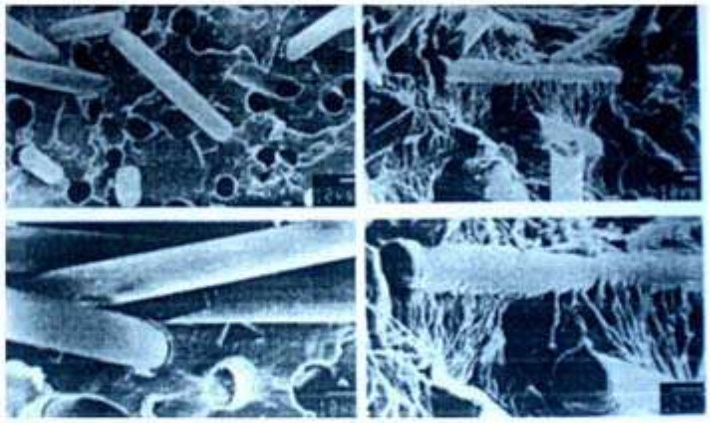
The most important controlling factor affecting the functioning of this zone is the degree of fill (Dof). Dof is the ratio of actual space (volume) occupied by material to the actual free space in that particular section of the extruder. When the Dof is high, material can escape through the vent port. The Dof in an extruder is controlled by the factors such as extruder speed, feed rate, element design and element configuration.. In the case of under-cut elements (SK type elements) actual free volume is increased by 20% compared to the regular constant clearance elements. Lead of the screw elements do not change the free volume but can still reduce the Dof. This is because velocity of the melt in that zone is increased.

The behavior of the material at the processing temperature can be slippery, Viscous, Watery, and Clumpy. A different flow characteristics is expected at an open vent depending on the material. The handling of these different materials involves specialized vent inserts in the barrel vent opening. Generally, there are three types of inserts used. The open type is used for watery material. The fully closed type is used for viscous material. A partially closed type is used for clumpy material. Slippery material and materials that show a transition in viscosity due to addition of additives and fillers may also be run with partially closed type inserts.

Zone # 4 The MIXING ZONE



Mixing is an essential function in an Extruder. The Goal of the mixing process in an extruder is to increase the uniformity of the composition. Mixing or the lack of it results from the work done in the extruder that causes ingredients (usually immiscible) to experience forces of shear, elongation or compression, bending, erosion and impact. Shear and extensional flow are the two common types of flow in a co-rotating twin-screw extruder. Extensional flow can occur as a result of building up of pressure or during its release.

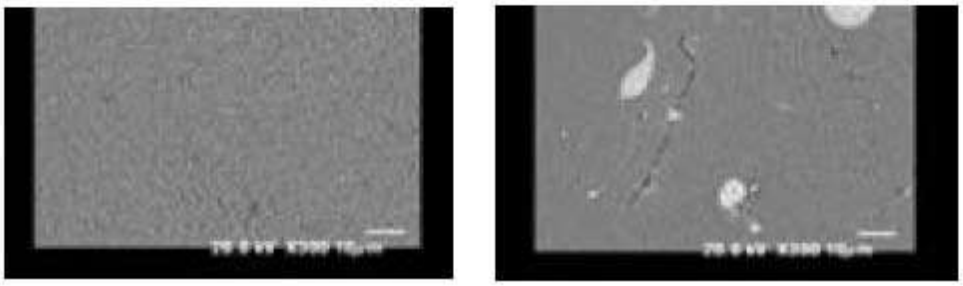


(Fig. A) SEM Images of Poor Wetting (Left) and Good Wetting (Right)
(Source: Sascha Englich, Master's Thesis U. Chemnitz,
Research carried out at STEER Engineering Bangalore)

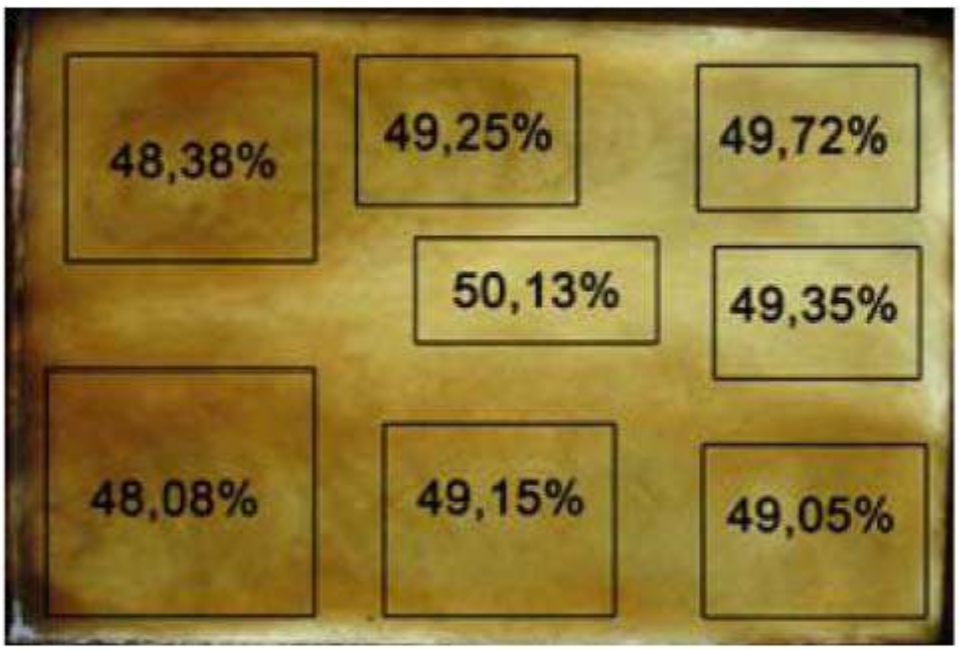
Kneading

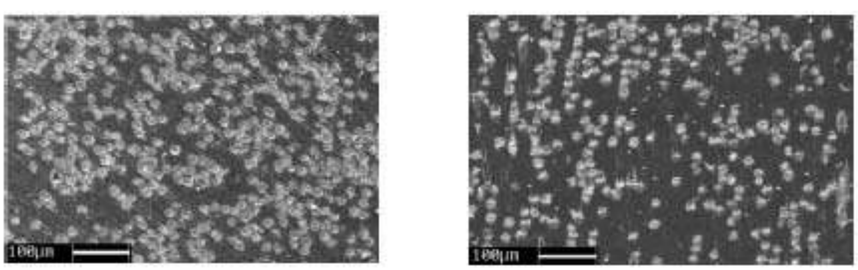
Mixing is complete only if 'wetting' is achieved and the term "kneading" refers to the action in the extruder that causes wetting. Achieving a chemical union (wetting) of two or more components is an important objective of the compounding process. Complete wetting or 100% wet state can be defined as the state of a "foreign" or an immiscible particle which is completely surrounded by the fluid molecules (melt) that have penetrated / bonded to it due to the forces of attraction. Wetting can be "Natural" but facilitated by the use of wetting agents like wax or it can be "Forced" by the use of a coupling agent since wetting depends upon the magnitude of affinity that exists between the particle and the melt. In the SEM image of glass fiber in Polypropylene (PP) showing poor wetting, (Fig. A) it is clear that the individual fiber are completely surrounded by PP. However, this did not result in any kind of chemical union. However, the pictures showing good wetting, the glass fibers are not only surrounded but also coupled with PP. A coupling agent is necessary since the glass fiber does not have natural affinity for PP.

A kneading action that comprises of folding, pressing, and stretching as in the case of 'dough kneading by hand' can be performed in a co-rotating twin-screw extruder. However, due to limitations in understanding the nature of work carried out in an extruder, kneading action as a result of shearing action is the predominant way to create wetting. This type of action results in wasteful energy input without useful mixing. Use of Fractional Elements (US Patent 6783270) in the form of kneading blocks can result in higher wetting action due to inherent design advantages such as uniformity of shear, increased elongational mixing ability without sacrificing the cleaning action. If kneading blocks have to be avoided, continuous mixing elements with Erdmenger profile or Sakagami profile (SMAP elements) are highly effective in creating the right circumstances for wetting. The difference between the design that employs kneading blocks and continuous mixing elements is in the dispersive nature of the two types. Dispersion and Distribution are two important terms that are constantly encountered while discussing Mixing. Mixing is a broad term that comprises of both chemical as well as physical action. In terms of physical action, mixing can be broadly classified as "Dispersive" or "Distributive".



(Fig. B) Images of Good Dispersion (Left) and Poor Dispersion (Right) with TiO_2
(Source: E. I. Dupont)





SEM Images of Fibers not uniformly spatially distributed.
(Source: Sascha Englich, Master's Thesis U. Chemnitz,
Research carried out at STEER Engineering Bangalore)

Dispersive Mixing

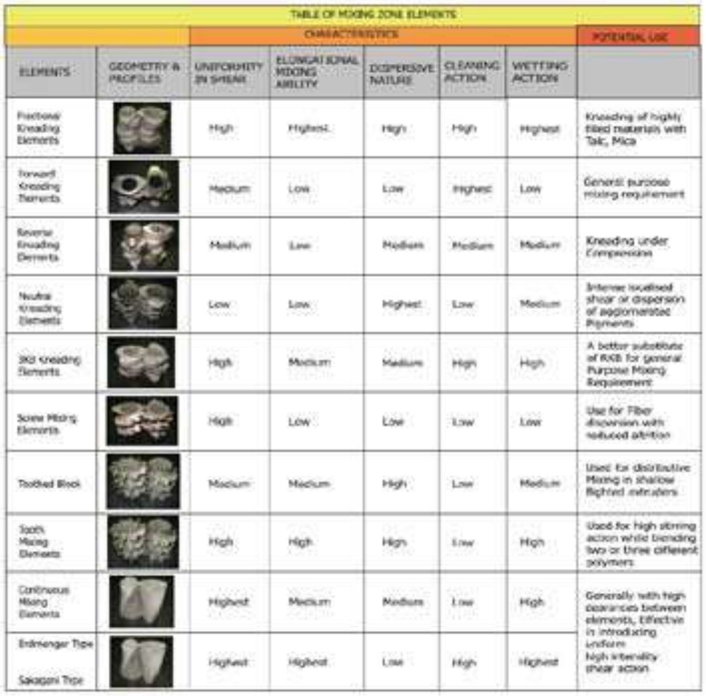


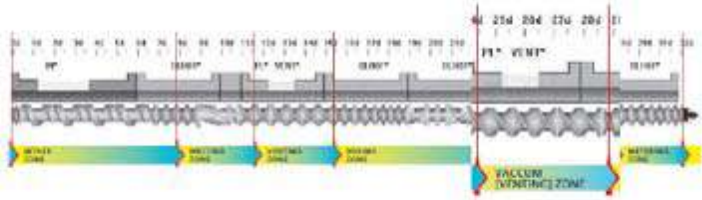
TABLE OF MIXING ZONE ELEMENTS							
		CHARACTERISTICS					POTENTIAL USE
ELEMENTS	GEOMETRY & PROFILES	UNIFORMITY IN SHEAR	ELONGATIONAL MIXING ABILITY	DISPERSIVE NATURE	CLEANING ACTION	WETTING ACTION	
Fractional Kneading Elements		High	Highest	High	High	Highest	Kneading of highly filled materials with Talc, Mica
Forward Kneading Elements		Medium	Low	Low	Highest	Low	General purpose mixing requirement
Reverse Kneading Elements		Medium	Low	Medium	Medium	Medium	Kneading under Compression
Neutral Kneading Elements		Low	Low	Highest	Low	Medium	Intense localised shear or dispersion of agglomerated Pigments
3K3 Kneading Elements		High	Medium	Medium	High	High	A better substitute of RKB for general Purpose Mixing Requirement
Screw Mixing Elements		High	Low	Low	Low	Low	Use for Fiber dispersion with reduced attrition
Toothed Block		Medium	Medium	High	Low	Medium	Used for distributive Mixing in shallow flighted extruders
Tooth Mixing Elements		High	High	High	Low	High	Used for high stirring action while blending two or three different polymers
Continuous Mixing Elements		Highest	Medium	Medium	Low	High	Generally with high clearances between elements, Effective in introducing uniform high intensity shear action
Erdmenger Type / Sakagami Type		Highest	Highest	Low	High	Highest	

Stresses of shear and elongational origin brings about dispersion of the massive agglomerated particle in the melt polymer matrix by separating individual units or grains or crystals. The lowering of the cohesive strength (strength of bond between the same type of particles) of the agglomerate (usually a pigment) is a factor resulting in better dispersion. Mixing at the time of melting improves dispersion as result of high shear stresses during the high viscosity phase of the material. However, with certain material such as TiO2 and Carbon black, this approach can result in a severe issue called re-agglomeration. During the time of melting in an extruder, the material is subjected to high levels of pressure. The particles that have not been completely surrounded by the wetting agent or melt have a chance to bond together and "sinter". One of the SEM pictures show TiO2 particles of 200 nm (Fig. B) fully dispersed in the polymer matrix. In the other picture, agglomerated particle of bigger than 10 microns are seen although such particles were not present prior to the extrusion.

Distributive Mixing

Distributive mixing is defined as the uniform spatial rearrangement of fibers or other dispersed materials in the base polymer matrix. In most applications, especially the ones with fibers, some form of dispersion and forced wetting of fibers brought about by kneading elements precedes distribution of fibers. If necessary, a distributive mixing zone with appropriate elements are configured towards the end of the Extruder Processing Zone (**EPZ**) and in some case outside the extruder using a static mixer. The most common distributive mixing requirement is in the uniform distribution of different length fibers in the melt since fibers may be full dispersed and wet without uniform spatial distribution. Otherwise, distributive mixing is commonly confused with Kneading.

Zone # 5 The VACUUM ZONE



Vacuum vents in the barrels are provided in an extruder for removal of gases effectively in a continuous manner at lower than atmospheric pressure. This degassing helps to conserve the quality of the melt that is affected by the presence of monomers, solvents, moisture and other volatiles. These generally separate from the melt only at those low to high vacuum conditions. Further, the elements used in this zone should expose the material by continuously thinning the melt for effective degassing. This task of smearing the melt on the barrel surface by thinning for degassing is efficiently exhibited by the long forwarding screw elements or SK type Elements.

*Applications involve

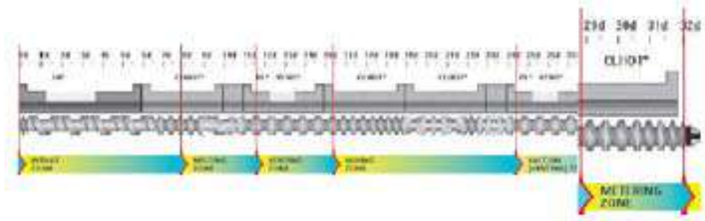
- Removal of monomers and oligomers in the production of polymers (PS, HDPE, PP etc).
- Removal of residual carried fluid in Emulsion and Suspension polymerization (PS, PVC)
- Removal of Solvent and Un-reacted monomers in Solution Polymerization (HDPE)
- Removal of Volatile bonding agents particularly with Glass Fiber reinforced polymers.
- Removal of Reaction products like Water and Methanol etc from condensation Polymerization.
- Removal of water from hygroscopic polymers (Ex ABS, PMMA, PA, PC, SAN, PU, Polysulfone, CA, PPO, etc)
- Removal of Volatile Components in compounding of polymers with additives and other ingredients.

A melt seal is the most vital requirement for removal of moisture and entrapped air from the melt during compounding at lower than atmospheric pressure. Adequate lengths of Vent opening and Vent hood design that maximizes the pressure gradient inside the extruder further facilitate this process. Melt seal is achieved by simply ensuring that prior to starting of the vent zone and just after its completion the melt completely fills up (degree of fill = 1). Usually a reverse lead element will ensure build up of a sufficient wall of material behind it. However, depending on the nature of work, adequate melt seal may have to be built up to avoid frequent breaking of seal resulting in poor devolatilization. At least "1D" length of the melt seal may be required while running high vacuum with thin melts.

Apart from this, the same issues encountered in the Venting zone to prevent melt from raising and filling the vent opening is even more acute here. The best remedy for this situation is the use of a Side-feeder (a.k.a side-stuffer) with proper seal in the gearbox end of the screw to allow a vacuum pump to be connected to it.

* Reference - Principles of Extrusion, Dr. Chris Rauwendaal

Zone # 6 The METERING ZONE



This Zone is also called the pumping zone in an extruder. The compounded polymer melt is transported towards the die by drag flow caused by the rotating action of the screws. Screws with higher degrees of fill with shorter leads are optimum for this zone for creating the pumping effect. The required pressure is based on the die design - see below.

$P=(2L\tau)/R$ Where $\tau=\mu\gamma^\circ$ And $\gamma^\circ=4Q/(\pi R^3)$

[τ = Shear Stress (MPa-N/mm^2), L=Length of the zone (mm)
π =3.14159(Constant), R=Die Radius (mm)
Q=Volumetric Flow Rate (mm^3/s), γ°=Shear rate (/s)]

This zone pumps the homogeneous compounded melt at constant temperature and pressure. The performance of the optimally designed screws is conserved only if the excessive cooling in this zone is avoided.

Metering forms the final processing zone in an Extruder. The function of this zone is to build the required pressure for filtration of foreign particles (if called for) and at the die for a continuous streamlined output. The nature of equipments placed after the metering zone such as Screen Changers, Breaker Plates, Die heads and Die Plates would be dealt in detail in a future article.

CONCLUSION

A good compound is the result of the right chemistry coupled with the right extrusion technology. This is all about putting the right kind of work - always a result of optimally configured screw design. Optimal configuration has the right elements in the right place for the right application and process parameters. Functional understanding of the potential characteristics of each element is the starting point for undertaking this task. Every Characterization table forms the quick reference guide for formation of configuration for different applications. Future articles will focus on the effects of combining different elements, the role of process parameters and the effect of clearances / geometry in processing.

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