CHAPTER-2

REVIEW OF LITERATURE

2.1 INTRODUCTION

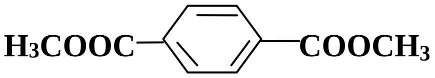
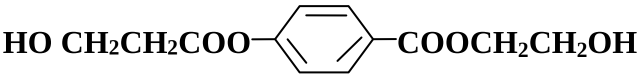
In present work, our aim is to modify existing PET- FDY (fully drawn yarns) line to produce PET mother yarn which is further split into monofilaments; attributing to a huge saving in capital cost without compromising the quality of the product. Modification work is carried out at a facility near, Surat. Thus by modifying quenching system, finish application system & winders at the take-up of our FDY line , we can produce high dpf (denier per filament) FDY yarn popularly known as mother yarns.

As high dpf PET mother yarn is a specific area of PET melt spinning, hence very limited published literature is available (only pamphlets of some machine suppliers are available) about modification details in present PET-FDY lines. Spinners are modifying their running FDY lines to save the cost of a new line for mother yarn. Mother yarn is basically a high dpf FDY yarn; which is further split into PET monofilaments. Hence basic fundamentals of PET FDY in melt spinning process are applicable here. Therefore it is necessary to review in detail theory of melt flow, solidification of melt through quenching, proper and even application of spin finish and winding at take-up in melt spinning process. Presently polyester fiber is one of the most economic & extensively used fibers in the field of the textiles. Due to its low-cost PET fiber (polyester) is replacing other costly fibers like Nylon and Viscose in several fields of the applications.

2.2 CHEMISTRY OF THE PET POLYMER

Polyesters are defined as step growth (or condensation) polymers containing ester units as the essential polymer chain forming a linkage. Presently polyethylene terephthalate (PET) is supposed to be one of the most successful commercial textile fibers. Polyester fibers or largely PET fibers dominate the world synthetic fiber industry. Poly (ethylene terephthalate) (PET) is synthesized by step growth reaction of ethylene glycol with either dimethyl terephthalate (DMT) or purified terephthalic acid (PTA). The chemical structure of monomers and compounds used in PET synthesis is shown below in Table 2.1:

Table.2.1: Raw materials

Raw materials	Abbreviation used	Chemical Structure
Ethylene Glycol	EG	$HOCH_2CH_2OH$
Purified Terephthalic Acid	PTA(TPA)	$HOOC\text{-}C_6H_4\text{-}COOH$
Dimethyl Terephthalate	DMT	
Bis(Hydroxyethyl) Terephthalate	BHET(Also DTG)	
Diethylene Glycol	DEG	$HOCH_2CH_2\text{--}O\text{--}CH_2CH_2OH$

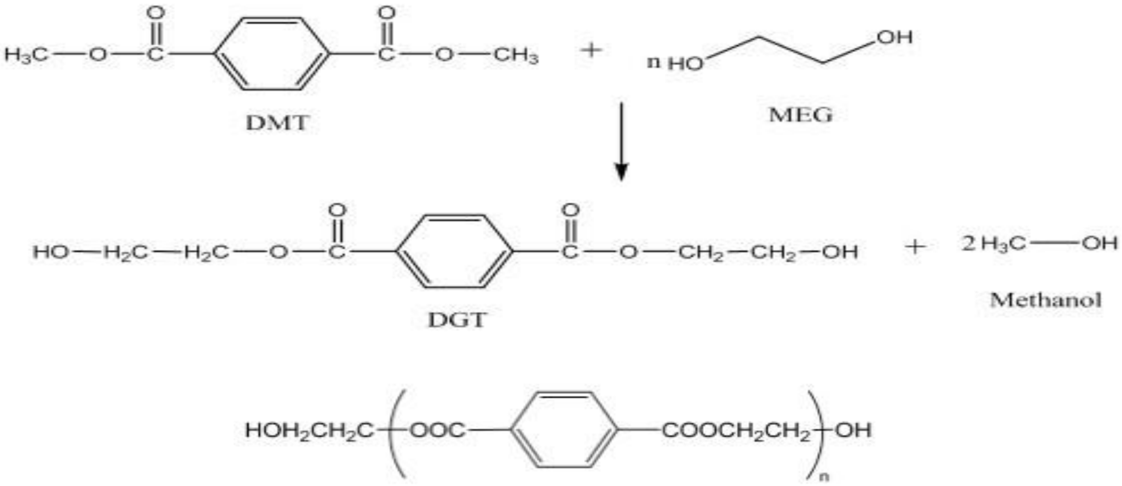
When DMT is used as the monomer, it is known as the DMT process. This DMT process is commercialized first due to the availability of pure DMT earlier. Later the purified terephthalic acid became available and PTA process was introduced. Now both processes are used. The strategy used to synthesize polymeric chains of PET is very different to that used for nylon 66. The ethylene glycol monomer is not a strong enough base to give rise to a salt with the other monomer, terephthalic acid, therefore the route to exact stoichiometry is not available for PET synthesis. Therefore, the synthesis is started with an excess of ethylene glycol and later on removed by evaporation as polymerization proceeds so that ultimately the monomer stoichiometry of 1:1 is achieved.

2.3 SYNTHESIS OF PET POLYMER

The synthesis of PET requires two steps. The first step is known as ester interchange (EI) in DMT route or direct etherification (DE) in PTA route. Both produce a mixture of ethylene glycol esters of terephthalic acids. The second step is polycondensation, which is common for both routes.

First Step of polymerization

1. **DMT route: Ester Interchange (or transesterification) Reaction.[8]**



In the ester interchange (EI) process, an excess of ethylene glycol is reacted with dimethyl terephthalate in the presence of catalysts at temperatures starting from 150°C and slowly increasing to 210°C as shown in reaction. The heat of reaction is ~14 kcal/mol. It is reversible and is driven forward by taking out by-product methanol. This distillation is carried out using fractionating column so that a minimum of ethylene glycol is removed. In practice, the ethylene glycol to DMT ratio of 1.7 – 2 is used so that the temperature at completion does not rise too high.

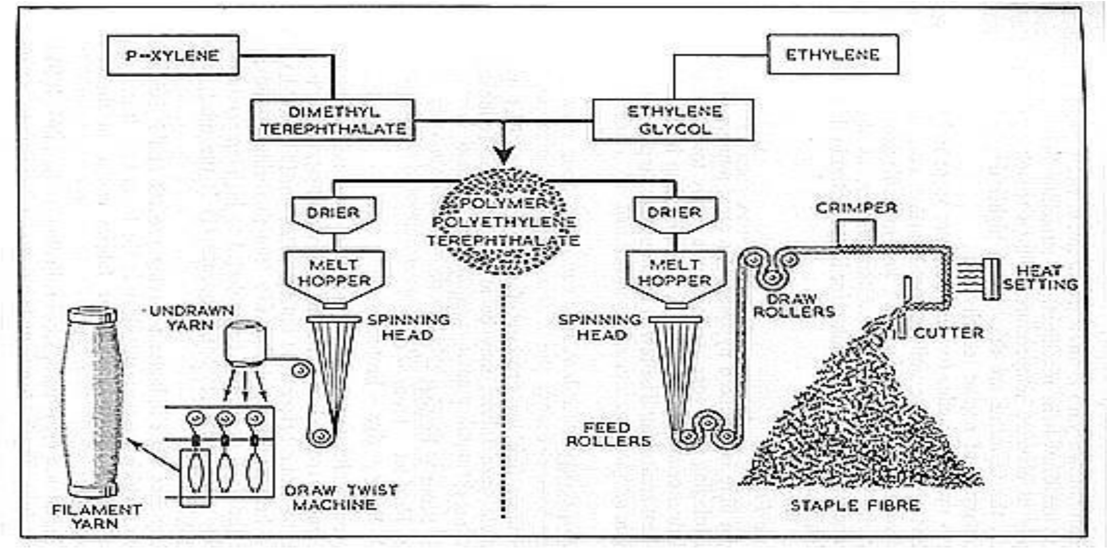


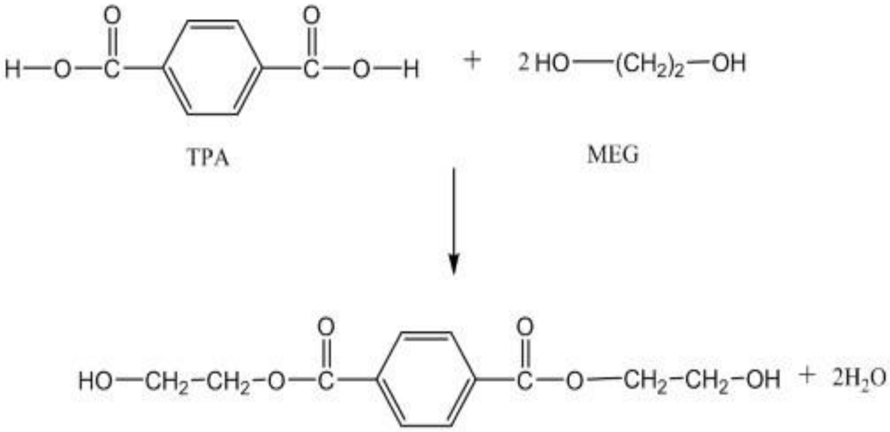
Fig.2.1: PET polymer through DMT route[8]

This pre-poly condensation reaction gives mainly bis(hydroxyethyl) terephthalate known as (BHET).The product also contains some unreacted ethylene glycol together with linear oligoesters of the general formula as shown in structure. The number of repeat units in polymer reaction mixture depends on the ratio of ethylene glycol to DMT. If a number of moles of EG is twice that of DMT, only BHET is obtained. If it is lower than 2 times the DMT, a higher value of n is obtained. This mixture is called prepolymer and is used in the second step known as polycondensation.

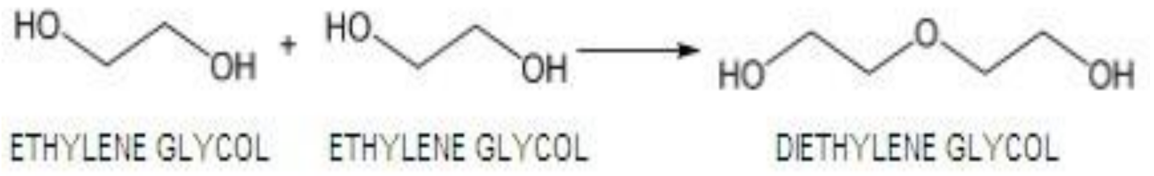
Preferably metallic salts of Cd, Ca, Pb, Zn and Mn are used as a catalyst. Many of these cationic species are also known to catalyze ester interchange and the thermal degradation reaction that occurs at polycondensation step. Since the thermal degradation reaction becomes more competitive at polycondensation conditions, it tends to limit the attainable molecular weight and results in a yellow color in the polymer. Therefore, at the end of transesterification stage, the catalyst must be deactivated by the addition of a sequestering agent such as phosphoric acid and triphenyl phosphate.

2 TPA Route: Direct Esterification Reaction [9]

In the direct esterification process (DE) as shown in reaction, due to the low solubility of terephthalic acid in boiling glycol, it is necessary to raise the reaction temperature and pressure to 240-260 °C and 4 x 10^5Pa, respectively, to obtain an adequate reaction rate.



The reaction is self-catalyzed by the carboxylic acid groups. However, additional catalysts such as stronger acids and esters of titanic acid are also used. The volatile by-product of direct esterification is water, which is distilled out of the reactor to force the reversible reaction towards completion. The catalytic action of acid groups and the high temperature employed during the esterification increases the formation of DEG, DEG formation can be reduced by reducing the EG/TPA ratio during the start of the reaction and by the addition of chemicals which reduce or prevent DEG formation.Therefore an EG/TPA ratio of 1.1 to 1.3 is used and consequently, the initial reaction product is a mixture of linear oligomers of a somewhat higher degree of polymerization (n) than that from ester interchange reaction. A very small amount of a strong base, such as sodium hydroxide or an organic quaternary hydroxide is added as effective catalysts to show reduce DEG formation.



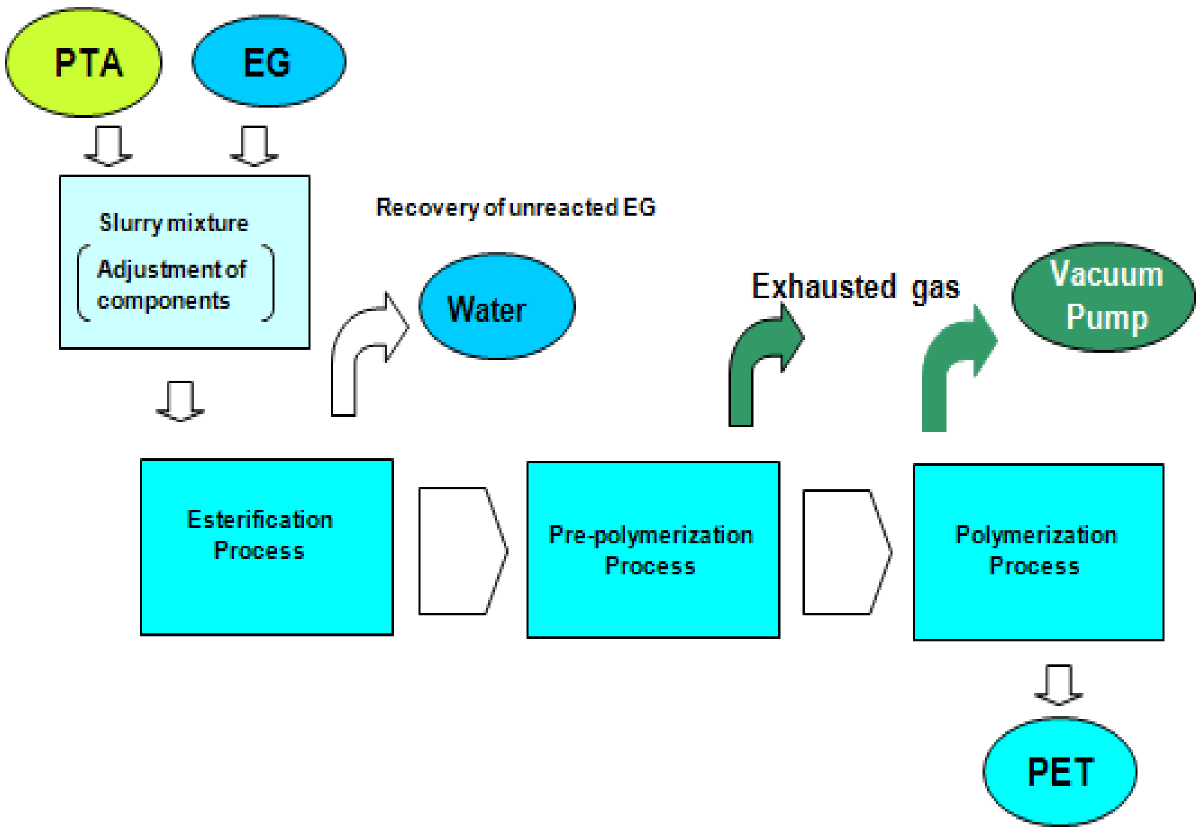


Fig.2.2: Process flowchart [10]

One of the side products of this reaction is the formation as shown in reaction of diethyl glycol (DEG)

The formation of DEG during pre-polycondensation step results in a decrease of the melting point of the polymer obtained from TPA route, and therefore, its melting point is generally lower than that obtained by DMT route. After esterification is complete, a phosphite or phosphate ester may be added to inactivate the basic additive and stabilize the polymer. TPA route has several economic advantages over DMT route, which are given below:

The yield by weight of the polymer obtained from the monomer is higher in PTA route, because, DMT is a diester with two methanol molecules which need to be removed during ester interchange reaction. EG/PTA ratio is much lower in PTA route than EG/DMT ratio used in DMT route, therefore lower amount of EG needs to be removed during the polycondensation step (i.e. 2nd step) to achieve same molecular weight. The cost of PTA is lower than that of DMT

Methanol obtained from ester interchange reaction, needs to be collected, purified by distillation and sold as a byproduct, which makes DMT route more expensive. Therefore, the PTA based production saves 8% of total capital investment and 15 % of feedstock cost.

2.4 MELT SPINNING PROCESS OF PET FIBER

There are mainly three steps involved in melt spinning of polyester:

(1) Melting and extrusion of dried polymer chips,

(2) Quenching of molten polymer below glass transition temperature and then

(3) Winding at take-up

2.4.1Details of the manufacturing process:

Spinning Plant:

The filament spinning plant consists of spinning lines producing Fully Drawn Yarn (FDY) and/or Partially Oriented Yarn (POY) on spinning bobbin.

Section-wise Process Description is as follows.

Chips Handling:

Raw Material Polyester Chips (Polyethylene Terephthalate) are received in bags of 25 /50 / 1000 kg. These bags are opened and charged in chips bin. These Chips will transfer to chips dryer by the pneumatic conveyor.

Chips Drying:

Chips received from the market are having about 0.2 % moisture which needs to be removed before using these in spinning lines. Chips from chips bins are conveyed to chips dryer from the top of the dryer and hot air is supplied from the top. This air picks up moisture from chips and is vented out. These dried chips are then fed to extruders.

Extrusion:

Dried chips from dryer are fed to the extruder from the inlet of the extruder (Barrel &Screw System). Barrel of the extruder is heated by controlled electric heaters. On heating, chips get melted and come out from the outlet of the extruder. In extruder spinning process, the polyester chips are re-melted and converted into the polymer for spinning the yarn which is a physical change and there is no chemical change in the process.

Spinning:

It is described below equipment-wise:

Spinning Equipment:

The spinning beam consists of a manifold or melts distribution block for spinning pumps, the spinning pumps and the spinneret packs with spinnerets. These components are embedded in an insulated set and heated by diphyl vapor, which generated in a diphyl heater. This is closed loop system.

The temperature of diphyl heating beams (280-300 ^{o}C) can be varied in a wide range and once acquired can be controlled in a narrow limit. The feed rate of melt has to be adapted to the parameters of spinning (spun titer take-up). This is achieved by variation of the revolution speed of the spinning pump.

For this purpose, the spinning pump drives are equipped with synchronous inverted motors which are variable in speed. Speed is adjusted and controlled by static frequency modulator. Each spinneret, the pack contains a filter tube made of porous sintered metal through which melt is filtered before entering the spinneret.

Air Quenching Chambers:

After having passed through the spinnerets the polymer melt already in the form of filaments is solidified in the air and passed downwards through the air quenching chambers and the spinning tubes and then wound on bobbins at the take-up machine.

The air quenching chambers are arranged directly below the spinning beams. Each quenching chamber is equipped with a shut-off device and regulator flap for adjusting the air flow. In the very short time during which the filaments are still in the plastic state, they are drawn to several times to their original length, thus reaching a certain molecular orientation of their polymeric structure.

This drawing effect is due to the great difference between the speed of ejection and the speed of the first godet. The orientation, and in general all factors determining the quality of the finished yarn can be influenced by the way in which capillary solidifies. Therefore in the air quenching duct, a current of air with constant speed (0.4-0.6 m/s) and temperature (20-22°C) and in strictly laminar flow is conducted across the thread path, fixing the solidification point of the filaments.

The quench air supplied from an air-conditioning system which is designed to maintain a constant temperature, humidity, and supply pressure. A good speed distribution over the width of the quenching chamber and constant and correct condition of the air together with convenient speed distribution over the length of the quenching chamber are the main factors which determine the quality of the yarn, mainly with regard to its titer uniformity. According to the particulars of the spinning process, the operating conditions can be adjusted in to fix the solidification point of the filaments conveniently.

Spin finish application system:

Each of the freshly spun yarn is separately guided over one specifically shaped ceramic application nozzle and /or moving finish oil roller, which are the parts of the spin finish application system. Hence the yarn is applied with an exact amount of spin finish. This application is important for the proper build-up of spinning bobbins, the behavior during subsequent textile processing and the quality of final yarn. The spin finish application device is installed at the bottom of the quenching chambers. The spin finish is pumped to the application nozzle/oil roller sump by the multiple gear-type metering pumps. The spin finish is an aqueous solution which is prepared in a mixing tank and thereafter transferred to storage tanks and this finish is pumped to the overheads service tanks.

This partially drawn yarn comes on the moving set of hot godet is higher than the first godet and that of the third godet is higher than the second godet. Speed and temperature of the godets are adjusted and controlled so as to get the desired drawing. Each end of the yarn emerging from the godet is guided straight down to the corresponding head of the take-up machine.

Between spinning tube and take-up head, the yarn passes as yarn path control system, consisting of yarn suction nozzles and yarn cutter which are actuated by a yarn break sensor. At the take-heads, the yarn is wound on cylindrical tubes which are fixed on bobbin holders by pneumatically releasable chucks.

The bobbins holders are activated by friction rollers driven by the synchronous inverter motors. Traverse motion is performed by a combination of traversing bi-rotor system. All the motors are fed by static frequency modulators. The take-up heads are designed for take-up speeds up to 6000 m/min. The traverse speed is adjusted according to the take-up speed of approximately 4800-5500 m/min. , besides it is variables within a wide range to avoid the problem of ribbon formation in the packages.The take-up winders are additionally equipped with RFR (Ribbon Free Random – winding) ribbon breaking system. Movements such as lifting and lowering of the sliding carriage, braking of chuck and pushing out bobbins during doffing are performed pneumatically. These bobbins are taken on trolleys which are sent to quality control department. From there these are sent to packing department. In packing, polythene is wrapped on bobbins & these bobbins are packed in corrugated boxes/pallets.

Cleaning of spinneret packs:

Used spinneret packs are disassembled by the help of a dismantling device. The different components of spinneret pack including the spinnerets are cleaned in a cleaning device for packs, pumps, and spinnerets at a temperature of approx, 450.0°C. This device uses a heated bed aluminum oxide fluidized by hot air. In the fluidized bed polymer materials adhering to the metallic parts is burnt off completely. Spinnerets are additionally treated in TEG bath at 280°C & then an ultrasonic cleaning bath with hot demineralized water containing some detergent.

The cleaned spinnerets are microscopically checked with the help of spinneret checking device. After checking all cleaned components, the packs are assembled to be reused again. The clean assembled packs are preheated in a preheating furnace/oven kept in the spinning department control room. All control cabinets, switching cabinets and frequency changer of the spinning machines are located in a control room at the same level as take-up room. The control cabinet for spinning beam contains all necessary electrical equipment and instrumentation to fulfill the requirements of the process. Within the controls are temperature recorder/controller for diphyl vapor, temperature recorder of liquid diphyl, pressure and temperature indicator for melt between spinning pump and spinneret, thyristor unit for feeding and control of diphyl heating and other instruments.

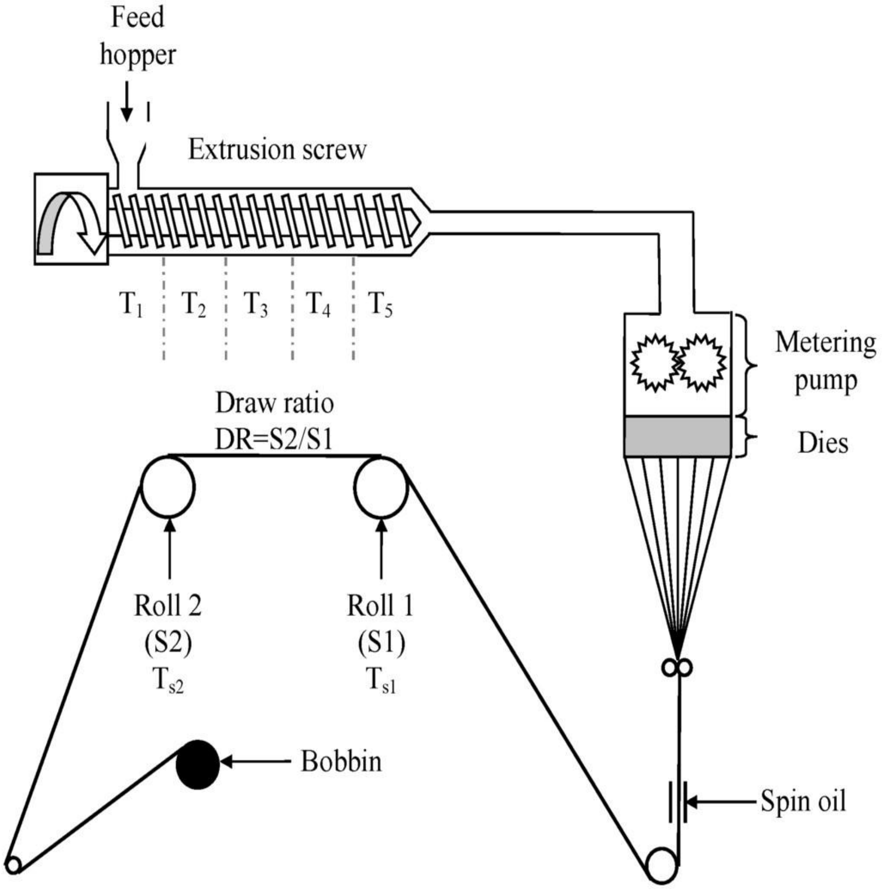


Fig.2.3: Schematic diagram of melt-spinning process[11]

2.5 MELT SPINNING CONCEPTS [12]

Spinnability:-

There are several requirements for a polymer to be spinnable. The polymer should be linear and of reasonably high molecular weight so that connectivity from one chain to another chain may be obtained. The intermolecular forces should be strong and allow reinforcement of developed structure through orientation and crystallization. There are many polymers that are linear and have high molecular weight; however, not all are spinnable into fine filaments.

Requirements for Spinnability:-

Polymers exist as a folded structure in melt/solution form. During spinning, a polymer melt or solution is stretched manifolds in a particular direction to produce a very fine, strong anisotropic entity. This unusually high stretchability of the polymer fluid is possible only if the long polymer chains have the tendency to unfold irreversibly under the application of small spinning force. This is the first requirement.

As the polymer is elongated, its surface area increases and this transformation opposed due to a rise in the surface energy of the system. Additionally, the oriented chains have lower entropy compared to the starting point, where the polymer chains are randomly oriented. However, for this deformation to occur and be stable thermodynamically, the overall Gibb’s free energy of the system must be lowered. This is accomplished by improved cohesion of the oriented chains that leads to stress-induced crystallization. The ability of the polymer chains to crystallize is a necessary condition for the spinning to take place because only crystallization could lower the enthalpy, and therefore, the overall free energy of the system in a spinning process. Crystallization stabilizes the unfolded structure in the new dimension. This is discussed in detail in the next section.

In other words, if a polymer system could not stabilize with the formation of a structure with stronger cohesive energy, it would not remain extended and will fold back to a mass of isotropic fluid as soon necessary energy is available. For example, amorphous polymers, such as styrene, PMMA, atactic PP, and polymer with bulky pendant groups are unable to form a fiber. This is the second requirement.

Other requirements of Spinnability:

Another requirement for spin ability is the ability of the polymer fluid to offer higher resistance to deformation as the fluid is elongated at a faster rate.

This increase in resistance with increasing extension rate helps in stabilizing the elongating structure with a thinner cross-section as it moves down the spinning line. If this does not happen, the thinned cross-section of the spun filament will go into ductile failure under the constant spinning force. The resistance to deformation is a result of relative rates of polymer deformation and relaxation.

If the relaxation rate is faster, the polymer is able to deform without much resistance, while if the rate is slower, the polymer network shows more elasticity. The strain hardening is said to occur when the elastic characteristic of the polymer network starts to dominate. However, the relaxation rate cannot be extremely low. If the relaxation rate is extremely low, it will result in accumulation of elastic energy to a degree that the polymer network hardening becomes excessive. Under this situation, the polymer will be difficult to stretch at the desirable spinning speeds and application of higher spinning force may result in a cohesive failure of the polymeric fluid i.e. breakage of the spinning filament. Therefore, for a polymer to be spin-able, it should have appropriate relaxation time so that it is able to show controlled strain hardening to avoid ductile failure and at the same time avoid cohesive failure.

Melt spinning is a complex process which consists of several phenomena. These may be broadly classified as:

Thermodynamics

Rheology or fluid dynamics

Mechanical force balance or rate of momentum balance

Heat balance

Thermodynamics

For any process to occur spontaneously, it should be thermodynamically supported, otherwise, it will not be stable. In other words, the overall Gibbs free energy of the system must be lowered, or the change in Gibb’s free energy (ΔG) must be negative. Here H is heat and S is entropy.

$$\Delta G=\Delta H-T\Delta S <0$$

During spinning, the polymer chains which are randomly placed in the molten fluid are elongated and oriented in the direction of spinning. This implies that the entropy of the system is forced to be lowered because the spun fiber is a more ordered structure.

For spinning to happen, the spinning system should provide conditions that will induce phase change as soon as the polymer has undergone desirable deformation. This phenomenon is facilitated by rapid cooling of the filament under spinning stresses. The temperature of cooling air, its humidity, and flow rate are some of the spinning parameters that decide the cooling rate and position at which the filament undergoes melt crystallization, and subsequently, solidifies (i.e. achieves glass transition temperature) in the spinning line.

Fluid dynamics

In spinning of thermoplastic polymers, two types of melt flow are observed –first from screw to spinneret that is shear flow and other is extensional flow or elongation flow from the spinneret to winders. To maintain continuity of fluid flow, these regions must be stable. Therefore for efficient spinning process technical person should understand various instabilities of spinning process and try to minimize the same to observe defect free spinning.

Types of instabilities in melt spinning

Basically, two types of instabilities are observed in the extrusion of polymer melt through a spinneret, one is melt fracture and other is die swell. Both of these defects are due to viscoelastic nature of polyester melt. Die swell occurs when polymer melt is forced through the holes of the spinneret and further extruded on the other hand.

Another type of flow instability is also occurring in elongation flow zone from spinneret to winder which is known as draw resonance.

(a) Die swell (Barus effect):-

When polymer melt is extruded through holes of spinneret under high pressure, one part of energy supports the flow of polymer but remaining energy is stored in polymer chains as elastic energy. When molten polymer fluid comes out of the hole, this stored energy comes in the play and polymer chains start relaxing. In this process of relaxation, swelling is observed just below the holes of the spinneret. This phenomenon is called as die swell or Barus Effect. Extradite swell is measured as the ratio of the diameter of the swollen extradite/diameter of the spinneret.

If the die swell is high, it will lead inconsistent spinning performance hence needs to be minimized. High die swell can create a fusion of adjacent melt streams if holes of spinneret are quite close. Since this property is related to elastic nature of polymer melt, so one has to optimize spinning parameters to minimize this phenomenon.

Factors affecting die swell:

The extent of swelling would depend upon the quantity of energy which is stored in polymer melt during its flow from the extruder to the exit of spin box assembly. More the stored energy, more elasticity in the polymer melt and will finally give more die swell effect when melt comes out of spinneret hole.

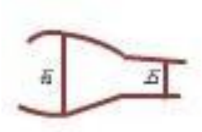


Fig.2.4: Die swell

Therefore if sufficient time is given to polymer melt to relax, the energy could be dispensed through relaxation of polymer chains. The elastic nature of polymer fluid is a manifestation of this stored energy. Die swell can be controlled by reducing the molecular weight of the polymer by putting some additives or by spinning the polymer at a higher temperature. Alternatively, the polymer may be provided more time in the spinneret, so that it has enough time to dissipate the accumulated energy before the actual process of extrusion starts. The design of spinneret plays a very important role to reduce extradite swell. One can reduce down this problem of die swell by keeping the higher length to diameter ratio for a given spinneret. Therefore to spun higher molecular weight polymer, spinners use higher l/d ratio spinnerets so that polymer gets sufficient time to dispense with the accumulated energy and thus controls die swell. It has been found for given polymer, die swell effect is directly related to polydispersity index (PDI).

One can reduce the phenomenon of die swell by reducing deformation rate of molten fluid during spinning. Shear rate can be lowered either by using the higher diameter of spinneret holes for a given polymer throughput or by reducing the rate of flow of polymer from the spinneret.

It is also possible to reduce the die swell effect by keeping higher drawdown in the spinning line i.e. higher tensile force in the spinning zone.

(b) Fracture of the polymer melt

When the flow of melt is not continuous and smooth through the spinneret, it can cause irregularities in spinning and hence causes frequent breakages. It means the rate of shear flow should not exceed a defined critical value. If shear rate is higher than critical shear rate, one cannot maintain the continuity of polymer melt. In a capillary flow, the rate of shear is always maximum at walls and hence the first sign of melt fracture is shown on filament surface. It can be seen in form of distortions at the surface of filaments.

Factors affecting melt fracture

The critical shear rate is one of the most important factors to decide the nature of polymer flow inside the spinneret. For a given set of conditions, faster the relaxation time higher the value of critical shear rate.

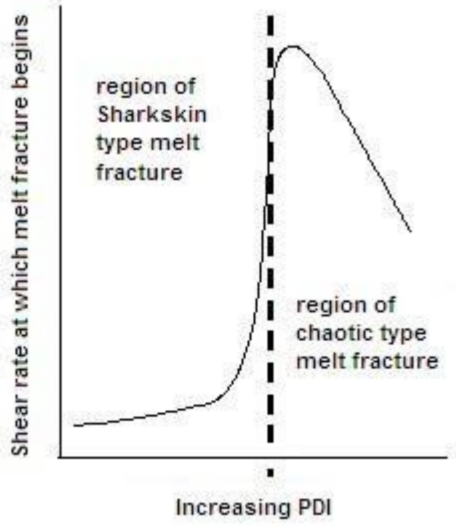
The relaxation time of the polymer decreases with the following parameters:

Increasing temperature of flow

Decreasing molecular weight and its distribution (low PDI)

Presence of plasticizers or additives

The shear rates for the onset of melt fracture are strongly dependent on molecular weight. The critical shear rate of LDPE polymers is found to be proportional to the power of minus 5 to its molecular weight. (Critical shear rate αMw^{-5}). And it is also observed that optimum melt fracture is also related to specific PDI for a given molecular weight. It is clear in fig 2.5 where a relation of the apparent shear rate is plotted against polydispersity index. For lower values of PDI, the shear rate also increases slowly but as is approaches critical value between 8.6 to 9.6, the apparent shear rate increases sharply which is quite good for better extrusion. The nature of melt fracture is of shark skin type up to PDI value 9.6 but above this value shear rate starts decreasing and a wavy typical melt fracture is observed (high amplitude and low frequency). Fig no 2.6 shows nature of melt structure below and above critical PDI. Apart from molecular weight, PDI has a very important role for the onset of melt fracture.



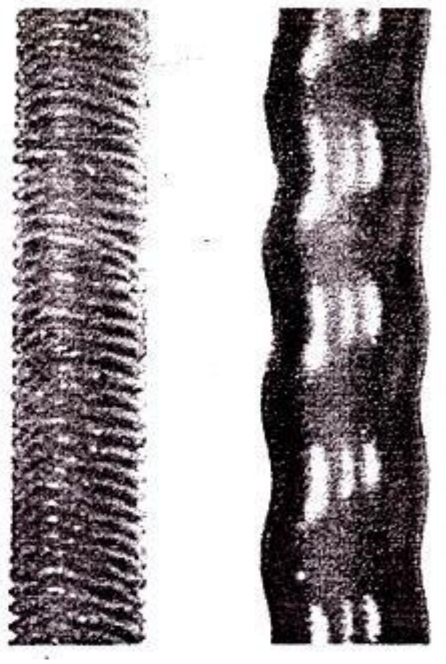


Fig 2.5: Dependence of critical shear rate on polydispersity index (PDI)

Fig 2.6: Typical fractured extradite appearances of polymers

In melt spinning of thermoplastic polymers especially PET, Nylon and LDPE/HDPE flow rate of the polymeric very important and it should not exceed the level higher than critical shear rate. Temperature plays a very important role and is directly related to critical shear rate. This is the reason melt fracture is often observed at the exit of spinneret hole due to the cooling of the bottom surface. It is suggested to use the hot shrouds just below the spinneret to avoid the temperature fall due to cooled quench air.

(c) Draw resonance

This instability occurs in elongation flow region between spinneret and take-up. It has got periodic nature due to recurring oscillations in spinning line and is reflected as thick and thin places along the length of the filament. Despite the constant flow rate and fixed take-up speeds, this type of spinning instability manifests at some critical draw ratio. One can major the effect t of this instability in terms of systematic deviation in filament diameter.

Fig.2.7: Draw resonance

This draw resonance affects the spinning performance and quality of the product. A spinner could produce a filament with a uniform thickness by avoiding this type of instability.

Types of fluids showing draw resonance:

It is observed in both Newtonian and non-Newtonian fluids. It directly depends on polymer properties like molecular weight, molecular weight distribution, the rate of relaxation and structure and polymer etc. This instability also related with spinning parameters like rate of cooling, drawdown, melt temperature and design of spinneret.

Change in material properties can also enhance the onset of draw resonance i.e. viscosity, density, elasticity and thermal capacity. Other disturbances which are responsible for this type of defect in the fiber are due to change in spinning conditions like quench air velocity, humidity, thread temperature and velocity gradient of thread line etc.

Fluctuation in melt throughput and take –up velocity can very well initiate draw resonance. The variation in spinning temperature can cause fluctuation in pressure and viscosity which in turn may change polymer throughput.

Draw resonance can be altered by the change in viscoelasticity of the polymer fluid. But basically, this type of instability is related to the moving streams of liquid. All Newtonian liquids exhibit this instability above critical draw ratio~ 20. Basically, it is a type of hydrodynamic instability.

Any melt spinning process at fixed melt temperature with uniform stress conditions is an example of constant and uniform drawing. Also, in such cases, the velocity gradient is constant. If in a melt spinning process, throughput and winder speed in constant then no diameter variation is observed in spun filaments. Therefore it becomes clear that variation in draw mode is the very cause of draw resonance.

Different types of draw modes in melt spinning:

The local draw can be defined as $\delta/ \delta A (\delta V/\delta X)$ where A is an area of cross section of fiber and V is the velocity of the fiber at a distance X from the spinneret.This will give three draw modes with the conditions:

>0…… (2.1) Uniformizing draw mode

$\delta/\delta A(\delta V/\delta X) \quad =0$……(2.2)Uniform draw mode

>0…… (2.3) Non-Uniformizing draw

In the (2.3) condition smaller cross-section of fiber is drawn more and this gives a necessary condition for draw resonance.

Resonance in Real-time melt spinning:

An alternate expression of draw mode can be obtained by differentiating w.r.t. distance z,

$$\frac{\delta^2 v}{\delta z^2} \left.\right\} \begin{cases} > 0 & \cdots\cdots (2.4) \\ = 0 & \cdots\cdots (2.5) \\ < 0 & \cdots\cdots (2.6) \end{cases}$$

While the $\delta^2V/\delta X^2$ draw mode can be calculated from the velocity gradient of the spin line.It is clear from figure 2.8 that the velocity profile has two distinct regions:

Unstable region (Strain thinning region)

Stable region (Strain thickening region)

In strain thinning region, a thinner section of fiber get stretched more because of more stresses due to less area of cross section(spinning force/area) and thus viscosity get lowered which further enhances stretching of already thin sections. In the stable region, the phenomenon of strain thickening is observed due to cooling and rearrangement of molecular chains (stress induced crystallization and orientation).Therefore higher viscosity at the thinner section and thicker section get extended more thus suppressing the phenomenon of draw resonance.

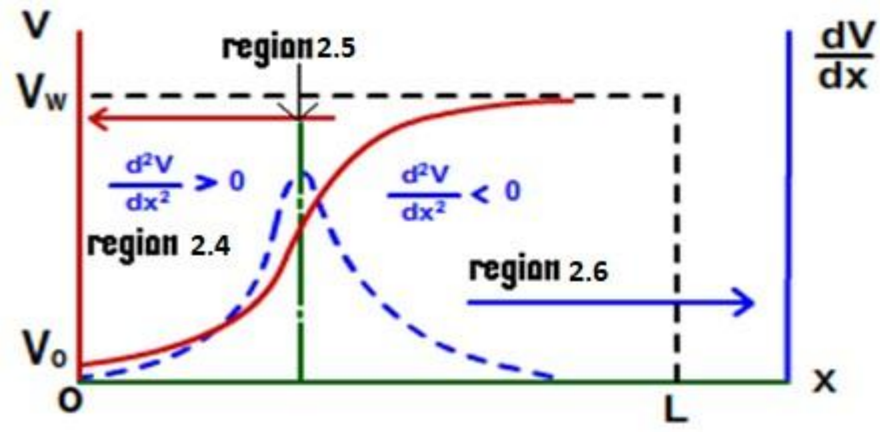


Fig.2.8: Different regions of velocity and velocity gradient observed during melt spinning of fibers

Draw resonance and wave theory:-

The exact waveform of draw resonance in the isothermal spinning of Newtonian fluids can be sought by numerically solving equations of melt spinning in their original, non-linear form. When the draw ratio exceeds 20, solutions of the equation become a limit cycle (sustained oscillation having period and amplitude independent of initial conditions).

In melt spinning, there exists an invisible kinetic wave (throughput wave) derived from the continuity equation, that travels the thread-line distance maintaining constant amplitude and a unique velocity. The fluctuation in throughput results is either an instantaneous increase or decrease in the diameter at the exit of the spinneret hole. This variation (say positive wave) when travels down the line to the winder induces an opposite change in diameter (negative wave) at the start of the spinning line. In order to continue this phenomena, or in other words for draw resonance to establish, two such throughput waves, positive and negative deviations from the mean value, need to travel the spinning distance (from the spinneret to the take-up, T_L) in a single thread-line residence time (T_L, time taken by the fluid to travel from spinneret to the take-up). This is because the throughput passing through the system in one period of draw resonance must be constant.

Factors that affect draw resonance

1. Process variables

This instability directly affects spinning line tension. Disturbances in the melt spinning system travel through the spinning line in the form of waves which ultimately changes the thread line tension then brings about a new disturbance wave which travels towards winders. When this disturbance travels, it again changes the spinning line tension but opposite in nature. Hence, another wave appears and the whole cycle repeats.

So disturbances in the spin line tension directly affects cross-sectional area and any change in the process conditions/parameters reflects instability of spin line which in turn influences spin line tension and ultimately diameter of filament

2. Spin-line Cooling

The overall effect of the disturbance on spin-line area decreases with increasing cooling i.e. increased cooling stabilizes the system thereby reducing draw resonance. Thus, it may be inferred that the stabilizing effect of spin-line cooling depends on tension sensitivity. The reason behind this phenomenon can be stated as that if the spin-line tension is held to its maximum limit, its sensitivity to disturbance tends to be minimum i.e., tension sensitivity decreases with increasing spin-line tension.

Another theory suggests that the thinner portions are cooled more rapidly than the thicker ones and so attain a larger viscosity, thus leading to greater stability. However, the above reasoning for increased stability on cooling holds true only for Newtonian fluids because, in the case of non-Newtonian fluids, the effect of fluid viscosity on the severity of draw resonance depends on the power-law index, as explained earlier.

3. Fluid Elasticity

Stability of the spin-line depends on the Deborah number, particularly the fluid relaxation time, λ. Increasing fluid elasticity increases the value of λ giving rise to a lower critical draw ratio (at which draw resonance occurs) than a fluid having a smaller λ. Thus, it can be concluded that increasing fluid elasticity destabilizes the elongation flow.

4. Molecular Weight Distribution / Long Chain Branching

Studies reveal that under identical spinning conditions, polymers with a broad MWD show a lower melt strength and lower critical stretch ratio as compared to a narrow MWD polymer. It has also been seen that narrow the MWD, more stable is extensional viscosity up to higher draw ratio. For narrow MWD polymer, critical strain is found on the higher side and this is responsible for spin line stability. Also, polymers with broad MWD are associated with increased extradite swell and ultimately have a detrimental effect on draw resonance.

Polymers with more branching are having more resistance while drawing as compared with linear chain counterparts. This resistance may stabilize the draw resonance but at a cost of good spinnability.

5. Non-Isothermal spinning

Melt Spinning is a non-isothermal process. The temperature of the extruded filament falls rapidly down the spinning line. This increases the apparent viscosity of the polymeric material down the spinning line, and hence, has a stabilizing effect against draw resonance. Since the resistance to flow increases, the polymer does not thin down readily and does not show draw resonance at even much higher drawdown ratios compared to the isothermal case.

Rate of Momentum (force) Balance

The development of stresses inside a spinning filament has a prime effect on both the stability of the spinning process and the development of structure in the spun filament. If the spinning filament develops unstable (variable with time) or excessive stresses, it may develop structural irregularities or break. On the other hand, within a stable force region, the level of stress inside a spinning filament greatly influences the orientation and crystallinity of the as-spun filaments.

The melt spinning process is a steady state process, i.e. it does not change with time. Only when the spinning is conducted under steady state, the properties and structure of the manufactured filaments are consistent along its spun length. The steady-state spinning occurs when the following conditions are met at all times:

$d\zeta(z)/dt = 0$ where $\zeta(z)$ is any dependent process, property or structural variable at distance ‘z’ from the exit of the spinneret. Examples include temperature, viscosity, orientation, crystallinity, density, velocity and rate of extension etc.

Steady state is achieved when all the forces on the filament must be stable and balanced at all points in the spinning line.

Various types of forces act on a spinning filament (Figure 2.9). The first is the total gravitational force (F_{GR}), which acts along the spinning direction and helps in spinning. The second is total surface tension (F_{ST}), which is a resistance against the increase in surface area of the spinning filament and acts against the spinning direction, third is total inertial force (F_{IN}), which is the resistance against the acceleration of the fluid to a higher speed and acts against the spinning, fourth is the total air drag (F_{DG}), which is the resistance offered by the surrounding medium (air) on the moving filament and acts against the spinning direction, and finally, there is net rheological force (F_R ($z = 0$)) generated at the beginning of the spinning line (i.e. at $z = 0$) due to the extension of the fluid as it comes out of the spinneret. This force also works against the spinning direction. In order to overcome these forces, a total external force (F_{EXT} ($z = L$)) has to be applied by the winder on the spinning line.

Therefore, the force balance on the entire filament (Figure 2.9) look like this

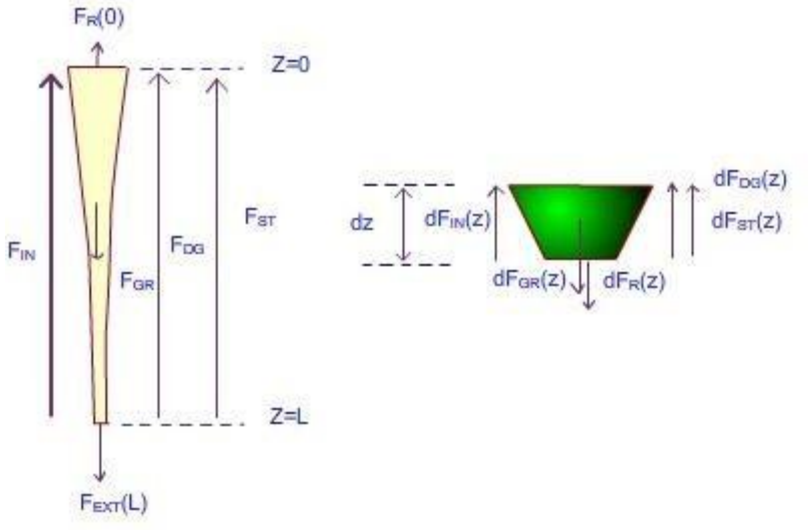


Figure 2.9: Force balance on a spinning filament undergoing extension in spinning zone

$$F_R(0) + F_{ST} + F_{DG} + F_{IN} - F_{GR} = F_{EXT}(z = L)$$

At z = 0, the only contribution is from rheological forces ‘$F_R(0)$.’ Since rheological force at all other places except z=0 is internal to the system, only $F_R(z=0)$ will act on the entire filament at the start of the spinning line.

The external force applied by the winder at z = L is counterbalanced by the internal stresses developed in the filament at z = L. The internal stresses are nothing but rheological stresses (resistance to deformation) at z = L Therefore, the above equation may also be written as:

$$F_R(0) + F_{ST} + F_{DG} + F_{IN} - F_{GR} = F_R(z = L)$$

Total force balance from the spinneret (z = 0) to any point z, can be written as:

$$F_R(z) = F_{EXT}(z) = F_R(0) + F_{ST}(z) + F_{DG}(z) + F_{IN}(z) - F_{GR}(z)$$

The comparative contribution of different forces on the spinning filament with the changing spinning speed is shown in Figure 2.10 for a Newtonian type fluid. The contribution of rheological force in the spinning line is

$F_R(0)$, which has very low magnitude. Its magnitude increases slightly with increasing spinning speed, however, the values are significant in comparison to other forces only at low spinning speeds. As the speed of spinning increases, the F_{IN} and F_{DG} become prominent compared to rheological and gravitational forces. Gravitation and surface tension forces are relatively very low for the spinnable polymers and are usually ignored in modeling and simulation. The development of these stresses during spinning plays a very important role in establishing the spun-fiber structure, which further influences the properties of the final fiber.

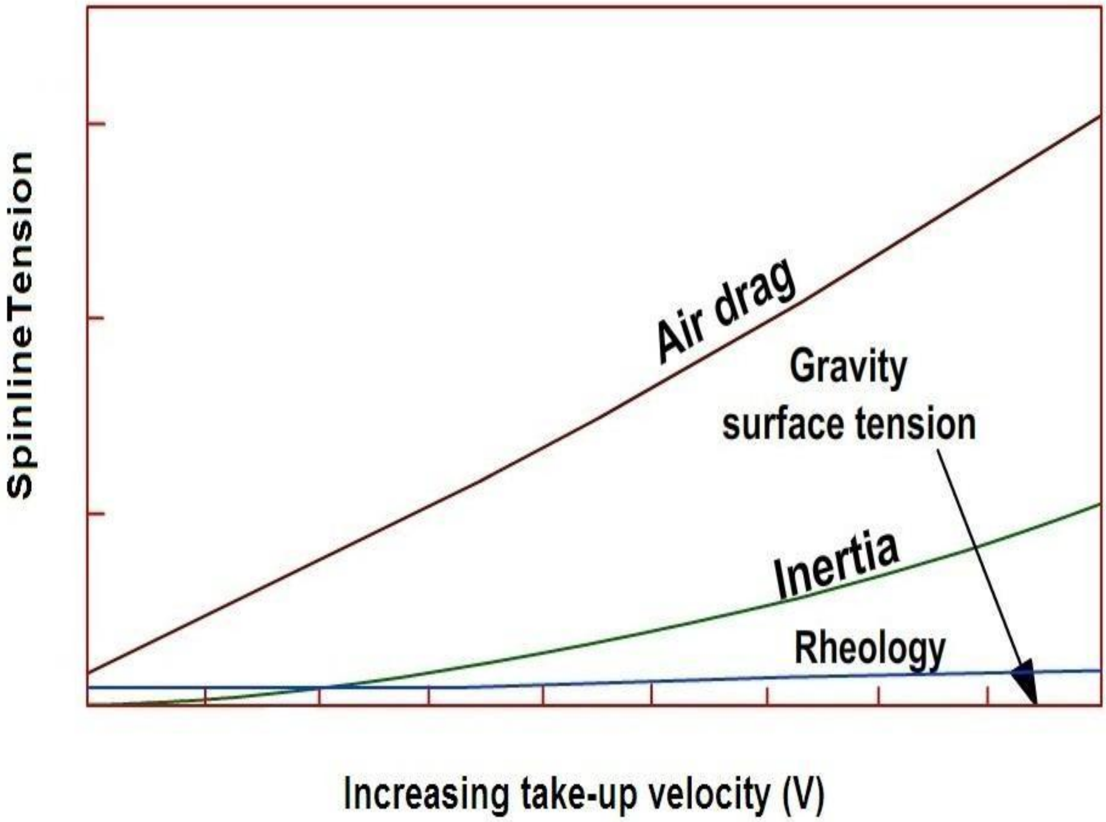


Fig. 2.10 Dependence of various forces on take-up velocity

2.6 MELT SPINNING PROCESS

In melt spinning process of thermoplastic polymers like Nylon, Polyester, PP (polypropylene) etc, and two types of flow of polymer melt is observed **[13].**

1. Shear flow or viscous flow up to spinneret hole
2. Elongation flow after spinneret up to winding stage

2.6.1 Shear flow or viscous flow:

In melt spinning process, polymer flows through elbows, manifold, metering pump, spin pack and finally emerges from the holes of the spinneret. Here nature of the flow is shear type flow because the flowing fluid experiences shearing stresses imparted by various fixed surfaces of melt path up to spinneret. The shear flow plays an important part in spinning starting from the extruder where it helps in mixing and homogenization of the polymer melt, to the spinneret hole where it helps in initiating the process of fiber formation. Therefore, understanding of shear flow is important for any spinner.

What is viscosity? How does it generate in molten polymeric fluid? It is nothing but a resistance against polymer flow which originates because fluid molecules interact with each other in different ways they collide during movement, i.e. physical hindrance, they interact with secondary forces such as ionic, Vander Waals forces, dipole, hydrogen bonding etc. The molten polymer has to overcome these forces in order to move past each other. In polymers which are a bundle of a long chain of a high degree of polymerization which acts as an additional component of resistance that occurs due to these long chains. The long chains get entangled and tend to physically wrap around the other long chains. This entanglement offers very high resistance to the flow. Therefore, the longer the chains, the more resistance it encounters during a flow.

Shear viscosity and molecular weight of the Newtonian polymer are related by following empirical relation:

$$\eta_0 = k\,M^n \text{ ………….. (2.7)}$$

Where η_0 is shear viscosity, k is a constant; n = 1 when the weight average molecular weight (M_w) of the polymer is below a critical molar mass M_c; And n = 3.4 for M_w above the M_c as shown in Figure 2.9. In case of polymer solutions, this critical point is defined by the critical molar concentration for a given polymer.

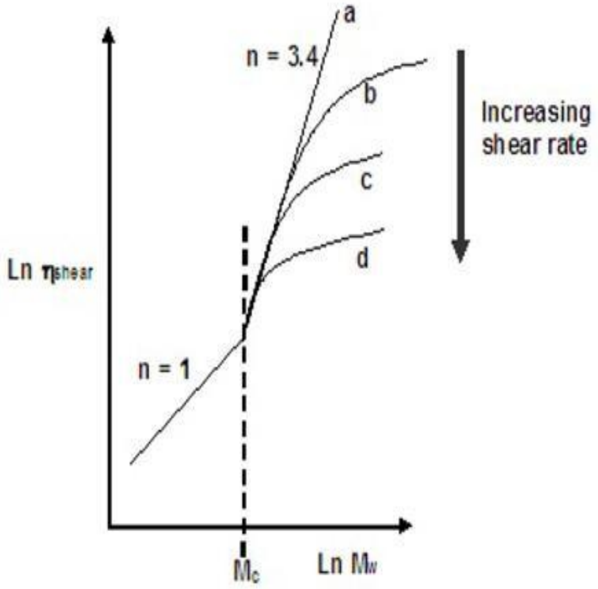


Fig. 2.11: Dependence of Shear Viscosity on Molecular Weight and Shear Rate of a Polymer [13]

Shear viscosity has a significant effect on change in temperature given by following Arrhenius equation:

$$\eta(T) = constant x \exp(E_\eta / RT)$$

Where E_η the activation energy for flow, R is the gas constant and T is a temperature.

Other than molecular weight and temperature, shear viscosity of polymer fluid also depends on important factors like shear rate, time, pressure, molecular weight distribution and molecular branching etc.

Due to these so many factors, the behavior of such polymers is quite complex. To have a better understanding, it may be thought of as a bowl of long and thin worms (a physical model).

Each worm may be considered to be very long as compared to its diameter. It may be imagined that these worms in this bowl cannot move independently because they are all intensely entangled with each other. They can only move their body in parts at a time (equivalent to segmental motion in polymers), and make adjustments at each entanglement (similar to relaxation in polymer chains).

When this bowl of worms is put under a net external force in a particular direction, the entire group of worms will slowly move by wriggling one portion of their body at a time and adjusting (slipping) through various entanglements. If on the other hand, this bunch is pushed out and then released immediately, they will show rubber-like elasticity and will rebind back to nearly the original space and position occupied earlier to the application of external force. However, if they are pulled slowly, while given enough time for adjustment, they will move permanently by a small distance on the application of the comparatively lower level of external force. Also, if the bunches of worms are continuously pulled at a certain rate, they will slowly disentangle with the elapse of time, and the resistance offered by them will get lowered with time. Similar to this model, the viscosity of the polymer fluid is dependent on the rate at which the material is moved (shear rate) and also the time for which it is moved at a certain rate (time dependence). The free space among worms would depend upon their internal energy level (which is reflected by the intensity of mobility of their body parts) and would decide the resistance a group of worms would offer to each other when a force is applied to make them move. This is similar to the case where a lower resistance is experienced by the polymer chains at a higher temperature. Similarly, the presence of short side chains or pendant groups increases free space between two chains, and therefore, would tend to reduce the viscosity of the polymer fluid. Such chains with pendant groups are also stiffer relative to the

Perfectly linear chains and therefore, their critical chain length (i.e. critical molar mass, Mc) at which entanglements take place, is also higher. Therefore, the polymers with side chains are processed able at low temperature. However, if the side chains or branches are long or dense, they may get into entanglements of their own and raise the viscosity.

On the other hand, increasing pressure on a fluid would have an opposite effect on these worms (molecules) and will bring them closer to each other, reducing their free space, and would result in increasing the resistance to flow. We may find this model helpful in understanding the behavior of polymeric fluid under the various situation of fiber spinning.

The above model also explains the inherent elasticity (i.e. tendency to bounce back) that a polymer fluid exhibits along with the viscosity (i.e. tendency to assume new position).

2.6.2 Viscous fluid flow types:

a) Newtonian behavior:

At very low shear rate polymers behave like Newtonian fluids. Newtonian fluids are those where viscosity η is constant at a given temperature and pressure, and stress (τ_{xy}) is proportional to shear rate ($d\gamma/dt$) or velocity gradient (dV_y/dx).

$$\tau_{xy} = -\eta \, d\gamma/dt \qquad (2.8)$$

or

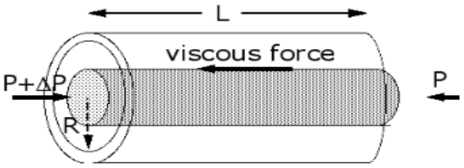
$$\tau_{xy} = -\eta \, dV_y/dx \qquad (2.9)$$

For such a fluid, the velocity profile and flow rate through a cylinder (ignoring its end effects) is given by

$$V_{z|t} = (\Delta P)/4\eta L \, (1-r^2/R^2) \qquad (2.10)$$

b) Derivation of Volumetric flow rate (Q) Poiseuille's Law:

Consider a solid cylinder of fluid, of radius *r* inside a hollow cylindrical pipe of radius *R*.



Let the pressure occurred in the pipe be ΔP, then the driving force:

$$F_{pressure} = \Delta P\left(\pi r^2\right)$$ ……………. (2.11)

The resistance against this flow counterbalances it and is given by length ‘L’ and radius of the fluid ‘r’

$$F_{viscosity} = -\eta\left(2\pi rL\right)\frac{dv}{dr}$$

to … (2.12)

At equilibrium condition of constant speed, where the net force goes

$$F_{pressure} + F_{viscosity} = 0$$

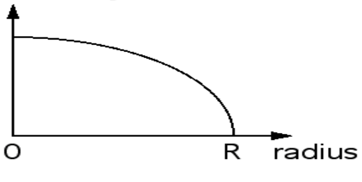
$$\Delta P\left(\pi r^2\right) = \eta\left(2\pi rL\right)\frac{dv}{dr}$$

so

$$\frac{dv}{dr} = \frac{\Delta P\left(\pi r^2\right)}{\eta\left(2\pi rL\right)} = \left(\frac{\Delta P}{2\eta L}\right)\cdot r$$

as . (2.13)

The rate of change of velocity with respect to distance will look like



At the center

- r=0

- $\frac{dv}{dr} = 0$
- V is at its maximum

At the edge

- r=R
- v=0

From the above equation we can have an expression of velocity by integrating and putting the limits:

$$\frac{dv}{dr} = \left(\frac{\Delta P}{2\eta L}\right) \cdot r$$

$$\text{rewriting}$$

$$\int_{v}^{0} dv = \left(\frac{\Delta P}{2\eta L}\right) \cdot \int_{r}^{R} r\,dr$$

$$v(r) = \left(\frac{\Delta P}{4\eta L}\right)\left[R^2 - r^2\right]$$

It comes out in the form of a parabola

Now from continuity equation, the volume flux for the given speed can be given as

$$\frac{dV}{dt} = \int v \bullet dA \qquad \ldots\ldots\ldots\ldots\ldots\ldots$$

(2.14) Putting the velocity and surface area of the moving fluid cylinder:

$$\frac{dV}{dt} = \int v \bullet dA = \int_0^R \left(\frac{\Delta P}{4\eta L}\right)\left[R^2 - r^2\right] \bullet (2\pi r dr)$$

$$= \left(\frac{\pi \cdot \Delta P}{2\eta L}\right)\int_0^R \left(R^2 r - r^3\right)dr$$

$$= \left(\frac{\pi \cdot \Delta P}{2\eta L}\right)\left[\frac{R^4}{2} - \frac{R^4}{4}\right]$$

$$= \frac{\pi \cdot \Delta P \cdot R^4}{8\eta L}$$

Poiseuille's equation **[14]**

$$\frac{dV}{dt} = \frac{\pi \cdot \Delta P \cdot R^4}{8\eta L} \qquad \ldots\ldots\ldots\ldots\ldots \quad (2.15)$$

Volumetric flow rate (Q) = $\pi R^4 \Delta P / 8\eta L$ (Hagen Poiseuille’s law)

Where $V_{z|r}$ is the velocity of fluid in direction z (i.e. cylindrical axis) at a radius ‘r’ and Q is the volumetric flow rate of the fluid flowing through a cylindrical pipe of radius ‘R’ and length ‘L’ under a pressure difference of ΔP applied across the

cylinder length ‘L’.

From above equation, it’s clear that fluid move in parabolic profile,

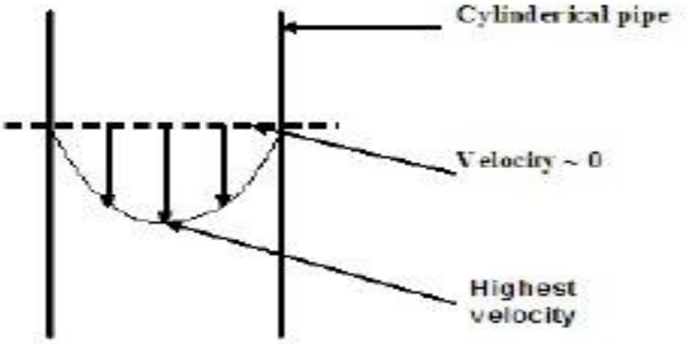


Fig.2.12: Elongation fluid flow [13]

From extruder to spinneret polymer melt flows in confined geometry and nature of the flow is shear / viscous type. When polymer melt comes out from the holes of the spinneret, its flow behavior changes. Now it undergoes elongation flow under axial pull due to high take-up speed.

Molten polymer flows perpendicular to the direction of fluid flow with increasing velocity. This velocity keeps on increasing till winding thus resulting unfolding polymer chain. The linear velocity of filament changes as per velocity gradient (dV_y/dx) throughout the spinning line, the polymer chain tends to uncoil/extend at its ends is caught in different fluid layers traveling at different speeds. There is hardly any gain in orientation in viscous flow due to rotating action included by the shear forces on the fluid.

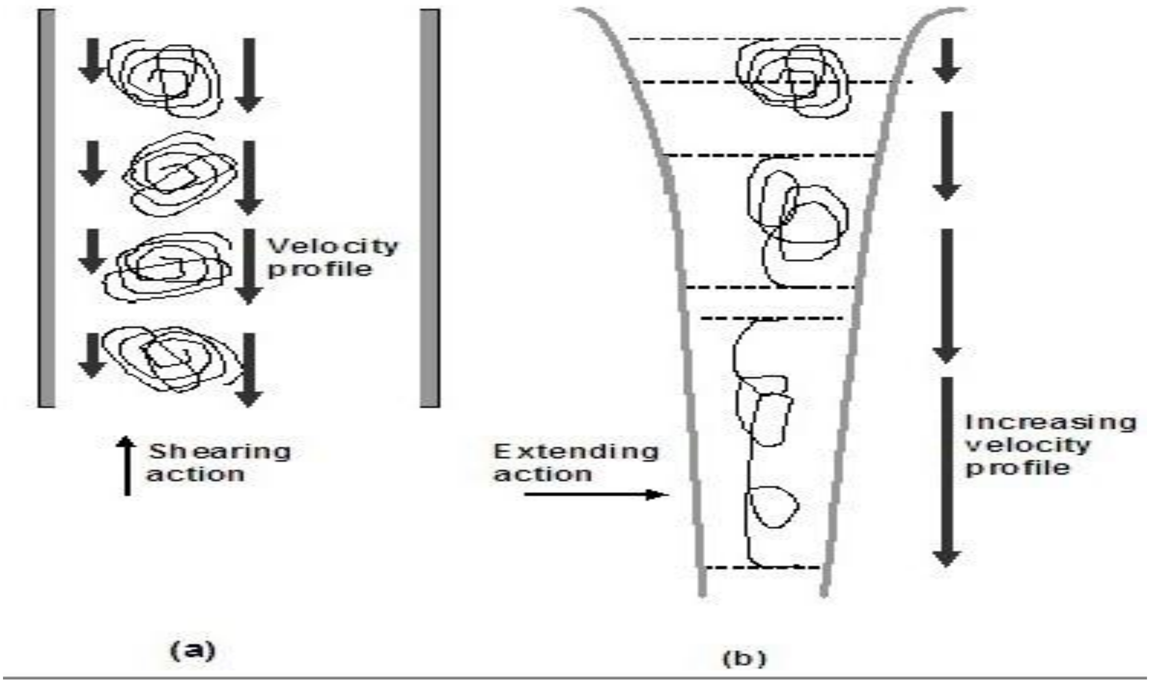


Fig.2.13: Comparison of (a) Shear flow and (b) Elongation flow [15]

This type of flow obeys Hook’s law that is stress is directly proportional to strain:

$$\sigma = \eta_{elog}\, d\varepsilon/dt$$

σ is tensile stress and $d\varepsilon/dt$ is the strain rate or extension rate of the fluid. When, elongation viscosity, is a constant, the fluids are known as Torontonian Fluid. Otherwise it is called non Troutonian fluid.

For fluids showing both Newtonian and Torontonian behavior,

$$\eta_{shear} = 1/3\ \eta_{elog}$$

Thermoplastic polymers are not Troutonian, it means for a given stress elongation viscosity changes with the strain rate. At very small strain rate, fluid follow Troutonian behavior i.e. viscosity remains constant. Elongation viscosity increases with increasing in strain rate on higher strain rates. These types of fluid are called “strain thickening fluid” and “strain thinning fluids”. Elongation viscosity normally builds up with laps of time at particular strain rate. To understand elastic behavior one should consider energy dissipated due to chain relaxation versus energy builds up due to elastic effect of polymer fluids. As

Compared to condensation polymers like Polyester and Nylon, elastic built-up of polyolefins are quite high. Generally, the elasticity of polymers is more sensitive to the change in temperature than to changes in strain rates. The following figure shows the effect on elongation viscosity of low-density polyethylene (LDPE) and Nylon-6 with time and strain rates.

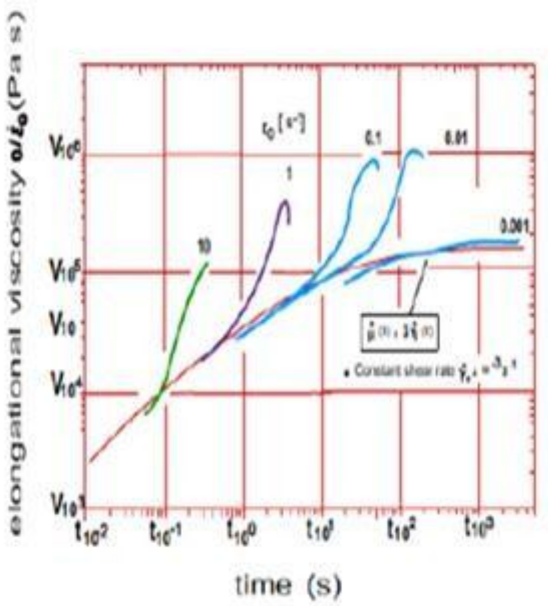


Fig 2.14: Effect of strain rate on change in elongational viscosity with time for LDPE

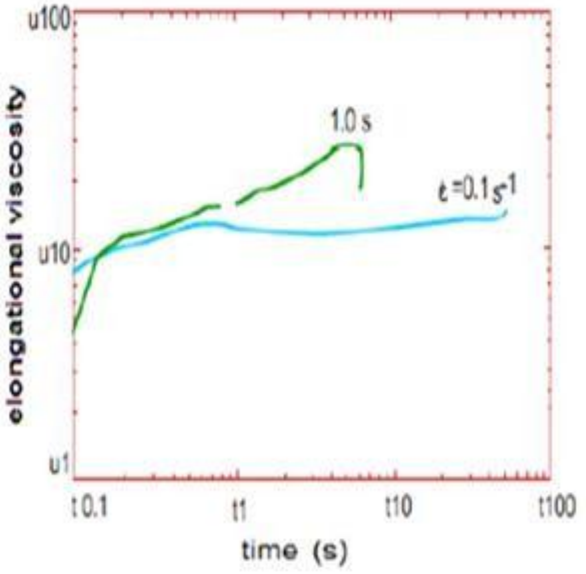


Fig 2.15: Effect of strain rate on change in elongational viscosity with time for nylon-6

2.6.3 Fiber Formation

There are mainly three steps involved in melt spinning of polyester:

(4) Melting and extrusion of dried polymer chips,

(5) Quenching of molten polymer below glass transition temperature and then

(6) Winding at take-up

Quenching is supposed to be the heart of melt spinning process. It is the process in which fiber formation takes place. During quenching axial draw force due to higher take-up speed caused the orientation of molecular chains and slight induced crystallization also. It is the zone responsible for developing physical properties in the continuous filaments.

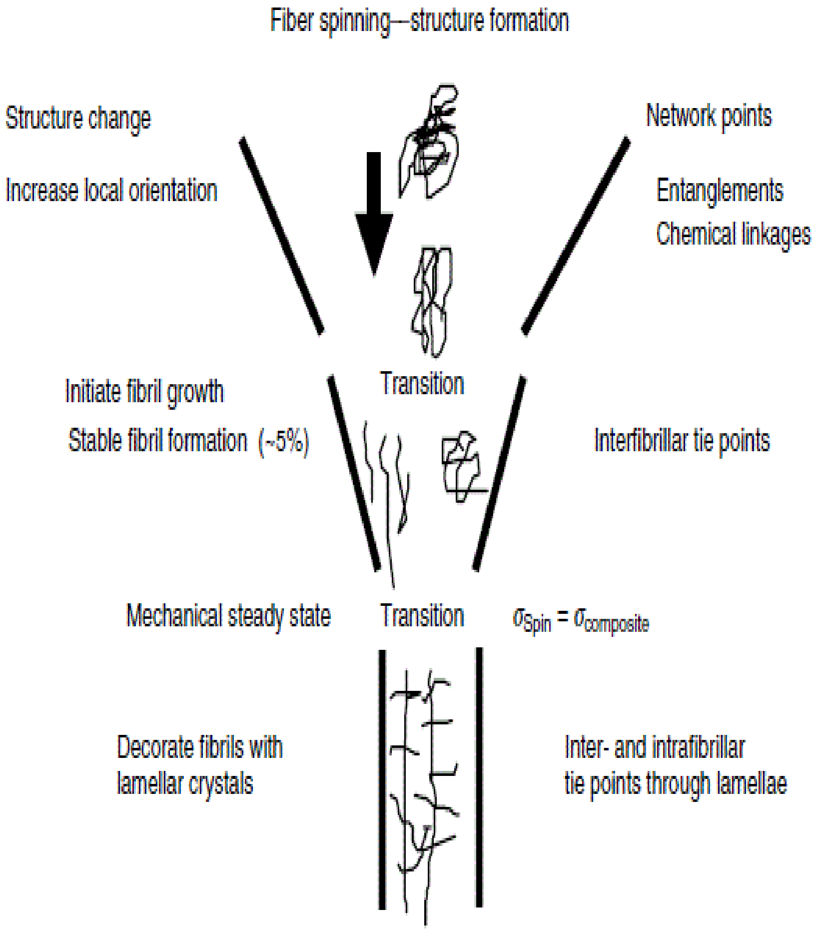


Fig.2.16: Fiber structure formation [16]

In PET melt spinning quenching has a major role. The physical properties of filaments develop just above glass transition temperature (Tg) of PET polymer in spinning line. Quench air quantity requirement is generally supplied by machinery suppliers i.e. M/S Barmag, TMT, DHP, and M/S Beijing Chonglee based on titer plan given by customers.

Generally only quench screen dimensions, quench duct pressure, air velocity and quench air temperature are given by machine suppliers. Actual quench air calculations are not given by them considering it to be a trade secret.

Air quench chambers are means of cooling and solidifying melt-spun filaments bundles coming out from spinneret bores for winding in a few meters distance **[17].** Within this range, the filaments are formed from the liquid phase with very low strength and receive their geometrical properties; the pre-orientation of the macromolecules and other properties such as uniform dyeability, crystallization, elongation, tenacity, Young's modulus, etc. which are subjected to high and consistently rising standard requirements.

2.7 THEORETICAL ASPECTS OF MELT SPINNING AND QUENCHING

2.7.1 Rheological Equations of State [18, 19, 20]

Some polymer behaves like solids at some time and as liquids at other times. But when they are behaving like rubber, then they have the nature of both liquids and solids at the same time. Practically most of the polymers have at some time properties of both elastic solids and viscous liquids. Such materials are termed as viscoelastic. Recently such solid elastic materials having viscous overtones are given the category of viscoelastic solids.

Such materials follow the basic Hook’s law i.e. shear stress is proportional to shear strain under elastic limits.

Stress α Strain

$$\sigma(x) = \mu(x).\frac{d}{dx}v(x) \qquad \text{.............................(2.14)}$$

Where ,

σ(x)= shear stress

$\frac{d}{dx}v(x)$= rate of deformation

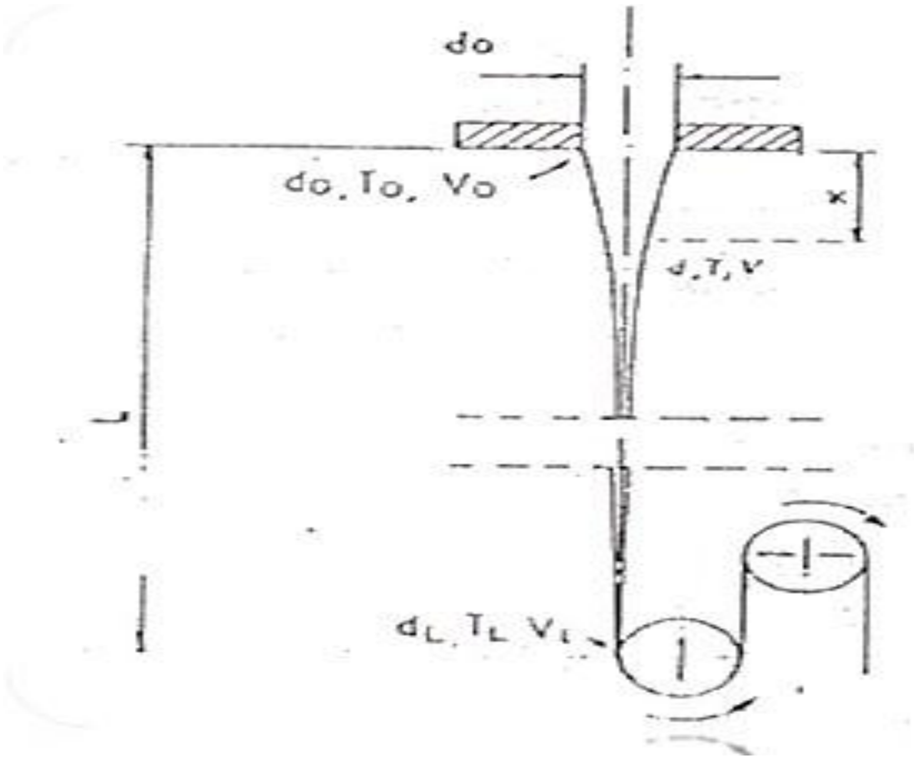


Fig.2.17: Schematic diagram of PET melt spinning [21]

2.7.2 General features of melt spinning

Formation**[21]**of filament after the melt spinning procedure involves preparation of spinning fluid (by melting of a solid fiber-forming material), extrusion of the melt through spinneret’s into a cooling chamber and winding of the resulting filaments onto spools or bobbins (Fig. 2.15) Spinning melt is extruded at constant temperature to constant mass rate, w, which together with the diameter of spinneret orifice, do , and material density, ρ, determines the extrusion velocity V_o The take- up device mounted at distance L, from spinneret gives the filament constant velocity, V_L, related to the average diameter of spun filament, D_L. Along the spinning path, i.e. between the extrusion (X_O) and tack up positions (X_L) the fluid jet is deformed, cooled, solidified and transformed into a filament with a super molecular texture.

Solidification in melt spinning is due exclusively to heat transfer. The rate and cooling process is sometimes controlled by transverse air blow. Materials with very long relaxation times and low spin ability (high-molecular polyolefins) are, often spun into heat cell to reduce the cooling and solidification rates. On the other hand, thick bristles are spun into liquid baths (water) where heat transfer is very rapid.

Spinning velocity, VL, used in melt spinning range from 1000 m/min (thick monofilaments in liquid baths) to several thousand meters/minute through the filament in gases medium. High spinning velocities, the lack of auxiliary materials (solvents, precipitation agents, etc) and the simplicity of spinning apparatus, make melt spinning the most convenient and economic method of fiber manufacture. The only limitation of the method is due to the fiber-forming material which must be fusible and yield thermally stable spinneret melts.

Therefore the condition of continuity in a steady state reads -

$$\rho(x)V(x)\,An(x) = w\ (\text{Constant})\ldots\ldots\ldots\ldots\ldots\ldots(2.17)$$

Where 'A' and 'v' are the cross-section area and average axial velocity of spinning line, and 'ρ' is the material density, all taken at a distance 'x' from the spinneret.

2.7.3 Principal process variables in melt spinning [22]

The process can be characterized quantitatively in terms of several process variables. Three groups of such variables can be distinguished

i. **Primary Variables**

Pre-determined technical parameters acting as a boundary or initial conditions for the dynamic equation (material characteristics, the condition of extrusion, take- up, etc.

ii. **Secondary Variables**

Rated to primary ones by the continuity equation (mentioned above) or similar relationships.

iii. **Resulting Variables**

E.g. Take-up tension or texture of a spun filament determined by primary variables and the kinematics of solidification, phase, and structural transformation, etc.

More important process variables are listed as under:

Primary Variables

Material - Chemical composition, molecular structure, physical behaviour

T_0- Extrusion Temperature

n.,D_0,L_0 - Dimensions and number of spinneret orifices

W - Mass out-flow

L - Length of the spinning path

V_L – Take-up velocity

Cooling conditions - Temperature, T_W, nature, and flow of the the cooling medium, heating cell, etc.

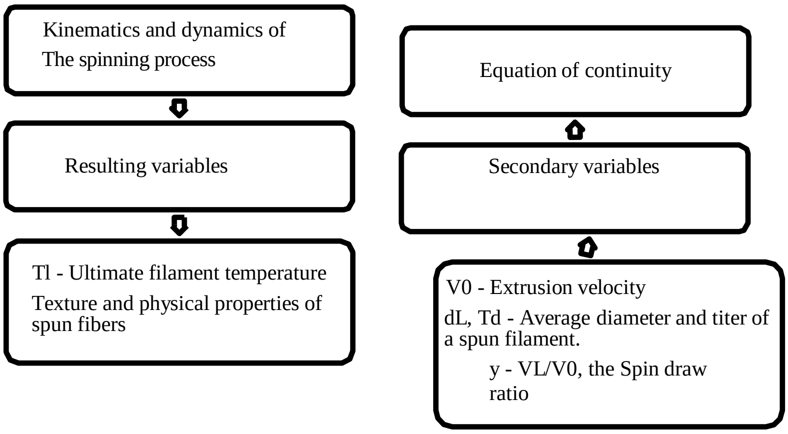


Fig.2.18: Process variables in melt spinning

2.7.4 Quenching of filaments

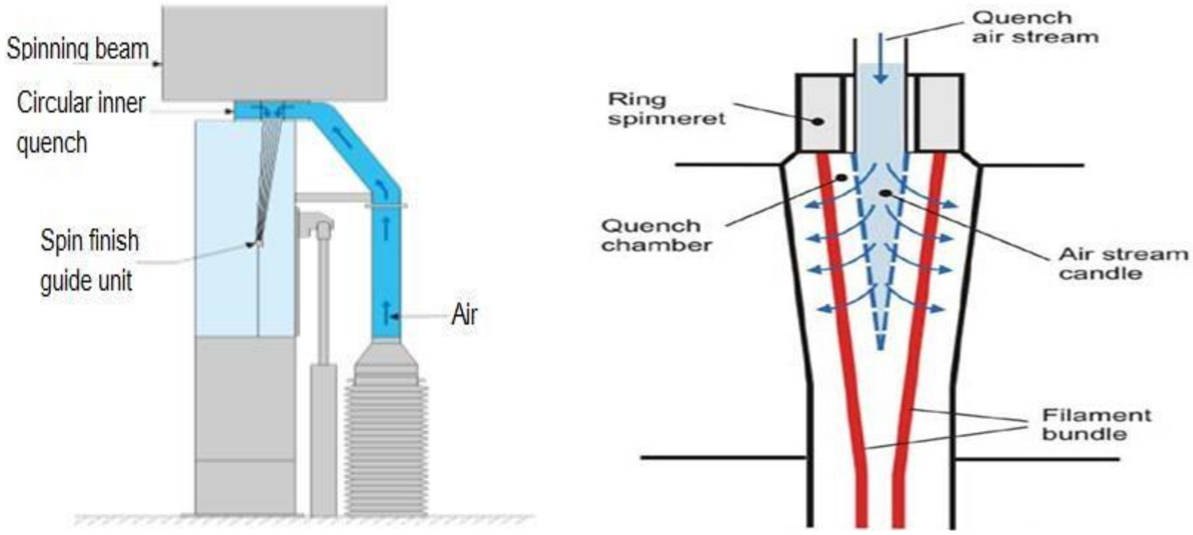
Between the spinneret and the take-up mechanism, the yarn path can be divided into three zones:

- The drawing of the melt from the spinneret hole at a melt temperature t and draw viscosity Ps,
- The draw zone with filament cooling to the solidification temperature and then further to below the glass transition temperature,
- The arrival at the first solid or take-up mechanism where the temperature should be less than the glass transition temperature

2.7.4.1 TYPES OF COOLING WITH QUENCH AIR [23]

Normally the types of cooling are used to quench thermoplastic polymers produced through melt spinning:

i. Cross air flow
ii. Radial air flow (inflow& outflow type) as shown in fig. No 2.19(a & b)



A Fig.2.19: [24] B

A) CIQ (Circular inflow quench) system $^{\textbf{(TMT Machinery Inc.)}}$

B) COQ (Circular outflow quench) system $^{\textbf{(TMT Machinery Inc.)}}$

Most common type is cross quench air flow or traverse flow. But limitation that in this type only 25% of air could be used for the purpose of quenching and rest 75% goes to waste.

Whereas radial quench air type is best suitable to produce staple fibers where the numbers of ends are very high. In this type of air flow utilization of air is up to 70%.

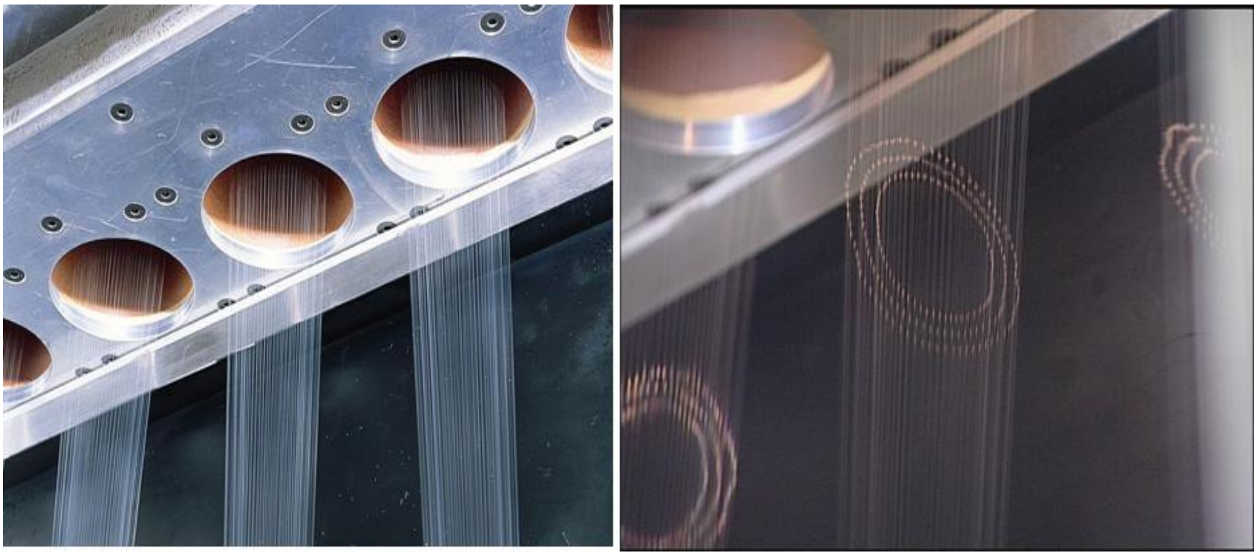
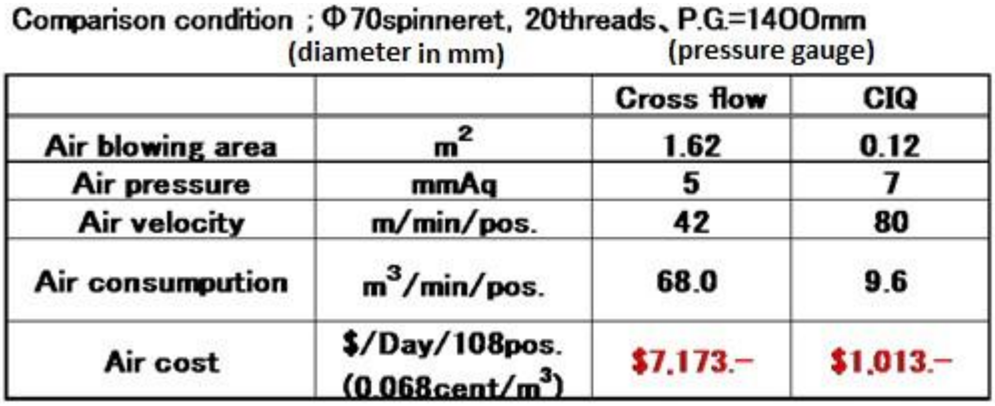


Fig.2.20: 0.3 dpf Multifilament yarn Circular inflow quenching air system (TMT Machinery Inc.)

By modifying quench air system from cross flow type to circular inflow type. A significant reduction in air quantity is observed and other comparative parameters of quench air are shown in below table 2.2

Table.2.2: Comparison of air consumption with CIQ &Cross flow (TMT Machinery Inc.)



Comparison condition ; Φ70spinneret, 20threads、P.G.=1400mm
(diameter in mm) (pressure gauge)

		Cross flow	CIQ
Air blowing area	m^2	1.62	0.12
Air pressure	mmAq	5	7
Air velocity	m/min/pos.	42	80
Air consumpution	m^3/min/pos.	68.0	9.6
Air cost	$/Day/108pos. (0.068cent/$m^3$)	$7.173.-	$1.013.-

2.7.4.2 Calculation of quench air quantities [25]

equation

Here the conditions according to Fig. 2.21 apply the rheological state

$$\sigma(x) = \mu(x).\frac{d}{dx}v(x)\text{----------} \quad (2.18)$$

and the stability criterion

$$\sigma < \sigma_n = \mu(x)\&\frac{d}{dx}v(x) < \frac{d}{dx}v(x)_{\text{Critical}}\text{--------------------} \quad (2.19)$$

From this follows that a filament can be spun and taken up if it is above the critical titer. This example, especially the catenary curve, is different for every polymer. It is assumed here that $\sigma_n$is proportional to the draw viscosity μ.

This filament with almost no cross stiffness forms in a first approximation catenary with the additional conditions resulting from Fig.2.21. The degree of deviation as caused by cross flowing quench air, the draw-down tension from the spinneret bore must be less than melt tenacity and the final take-off tension SE = S0 + R + 0. Here is R filament in the withdrawn air and G = filament weight between the spinneret and take-off godet.

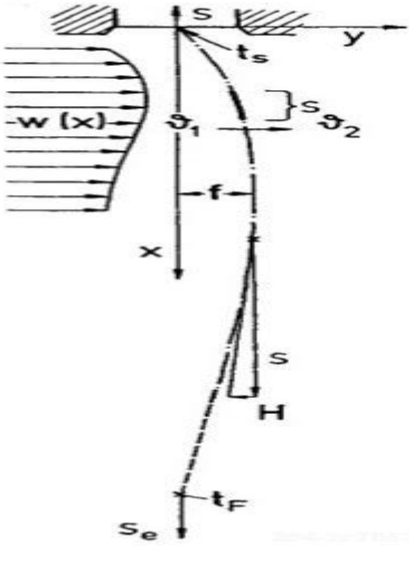


Fig.2.21: Force along the thread path for melt spinning with cross-flow air quench.

For the thermal equilibrium of the following is valid with the nomenclature

$$G_L . C_L . (\theta_2 - \theta_1) = G_s \{c . (T_s - T_F) + S\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.20)$$

S = melt heat, that somewhere in the area of the quench air w(x) becomes free. For the heat transfer from the yarn to the quench air flows:

$$\alpha(\Delta x, x) = \rho d c \frac{T(x) - T(x+\Delta x)}{4\Delta x (T_m - \theta_m)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.21)$$

Evaluation of these formulas are only possible in approximation and is explained in Fig. 2.22 with the help of some measurement

- With the same starting temperature the filament coming from the larger spinneret hole at the same extrusion rate will cool faster due to the larger surface, at this extrusion rate, there is practically no more difference at about 500 mm below the spinneret.

- The same extrusion quantity and take-up speed result in the same finished filament diameter; the spinneret swell increases with decreasing spinneret bores.
- Spinneret swell is lower with air quench than without.
- The air quenched filament cools down faster than the filament without air quench but without any significant difference up to about 300mm below the spinneret Fig 2.22 (1 & 3).

- The heat transfer coefficients at 800m/min take-up speed are on the average (in w/rn2K)

Table.2.3: Cooling of filaments with air and without air [26]

	At 400 mm below the spinneret	at ≥ 600mm
Without air quench(b)	40... 50	200
With air quench (a)	90... 100	300

For other take-up speeds, approximate heat transfer coefficients can be multiplication with (W/W0) °.

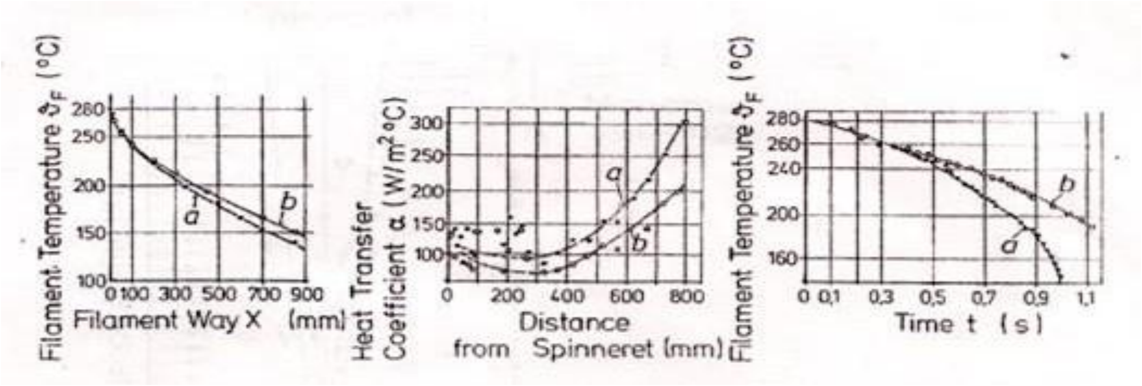


Fig.2.22: 1. Influence of the cross-flowing air cooling on the filament temperature (m=4.5 gm/mm, Ve = 800 mt./minute, spinneret hole dia = 0.9 mm)

2. Heat transfer coefficient a between the cooling air & the filament surface as a function of the distance from the spinneret (a with air, b without air quench)

3. Filament surface temperature as a function of the time after leaving the spinneret hole (data as in 1) [27]

From the mentioned relations the following rough calculation can be deducted:The necessary cold air quantity for quenching a filament bundle within a narrow space on the sides is

$$Q_L\left[\frac{Nm^3}{h}\right]=\frac{C_F(T_S-T_F)+S}{C_L(\theta\ \ -\theta_F)\gamma_L} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2.20)$$

Q_L = Air quantity per time unit in Nm^3/h

G_F= Melt or filament quantity per time unit (kg/h)

γ_L= Specific weight (density) of the air = 1.2 kg/m^3 at 20 °C

T = Polymer temperature [°C] with S for melt, F for filament

θ = Air temperature [°C] with 2 at the lower end and 1 at the beginning of the quench chamber

C_L = 0.25 kcal/kg K (at 20^0, 1 bar)

The cooling air should normally have more than 80 % relative humidity. The yarn temperature to be reached needs to be ‘F < TG (glass transition temperature of the spin mass) minus a minor safety distance. Experience and many spinning trials show that filament breakages increase five to ten fold if the yarn is not below the glass transition temperature before the first contact with solid materials. If this is not possible it is necessary to take the increased number of breaks into account, e.g. for PP.

This results in a first rough formula for the necessary air quantity to cool an uninterrupted filament warp with (T_s — T_F) ≈235 ± 15°C, melt heat S 30 . . . .55 kcal/kg and a specific heat of 0.5 kcal/kg K.

$Q_L in Nm^3$/h/G_F in Kg/h = 270/$\Delta\theta_{L,Permissible}$[^{0}C]

This means that with a permissible increase of the air temperature of 10 K QL/GF becomes 27 Nm^3/kg.

2.7.4.3 Quench air flow around and in a spinning multifilament bundle. [28]

Zone A — cross flowing passing quench air caused by low individual filament speed.

Zone B — Quench air sucked in by a filament bundle.

Zone C — Quench air pressed out of a filament bundle by multifilament convergence.

Zone C/D -Convergence point made for example by an Oiler pins and/or thread guide.

Zone D — Close filament bundle up to the take-up machine.

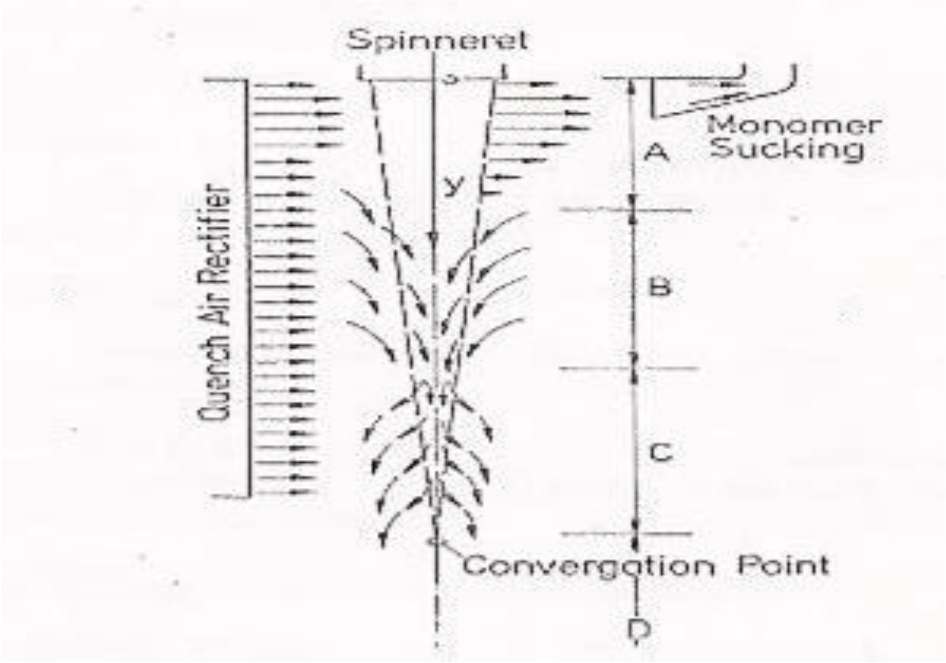


Fig.2.23: Quench air flow

Today, short cooling times are normal for textile yarn, even for nylon-6 carpet yarn with approx 20 dtex POY spin titer, 0.4 s cooling time are possible. Poly-propylene only makes an exception as its inner heat conductivity is much lower than that of PA or PES.

2.8 SPINNING MECHANISM

2.8.1 General view over melt spinning:

Ziabicki, A,**[29]**Falkai, B. Vorn**[30]** and Luckert, H**[31]** have given a very detailed description of the physical process of melt spinning from spinneret to first take-up point. The mathematical treatment of melt spinning process becomes more difficult due to changing the rheological property of highly viscous flow which is actually Viscoelastic in nature important spinning conditions are:

macromolecular chains with a minimum of branches and networks with more than a minimum degree of polymerization.

Sufficient ability of the melted mass to be drawn into filaments, as for example defined by the filament breaking length. The latter depends on the viscosity η and the draft velocity **[31]**. The maximum indicates the optimum spin ability of the material The breaking length L = f ($\mathcal{V}.\eta$) is limited by the melt fracture and the breaking of the filaments [**32**]..Too high a take-up speed and/or too low a viscosity leads to breaking filaments (e.g. due to too thin melt or too high spinning temperatures). Too high molecular weights or viscosity or too fast hardening or coagulation of the outer layer lead to a melt fracture, e.g. melting rupture (=saw toothed appearance).

Reynolds's number of the polymer melt is quite low when it enters the spinneret (in the range of 10^{-7}). This Reynolds's number is in the range of R_e=0.01...0.2 in the spinneret capillaries. This increases after melt exit from the spinneret and got solidified due to cooling by quench air. But just after exiting the capillaries of spinneret the average speed of molten melt is reduced due to spinneret swell (die -swell) by 1.1 to 1.2 times. The uneven velocity distribution inside the spinneret bore is due to the sticking of the solution in a thin area near the wall (range of 0.01... 0.02 mm), and directly upon exiting it changes to a constant speed over the cross-section, and then increases upon cooling from the outside to the inside up to the take-up speed . The flow in the liquid state is described by the elongation viscosity; this is certainly not correct for non-Newtonian liquids, but to date has not been completely investigated.

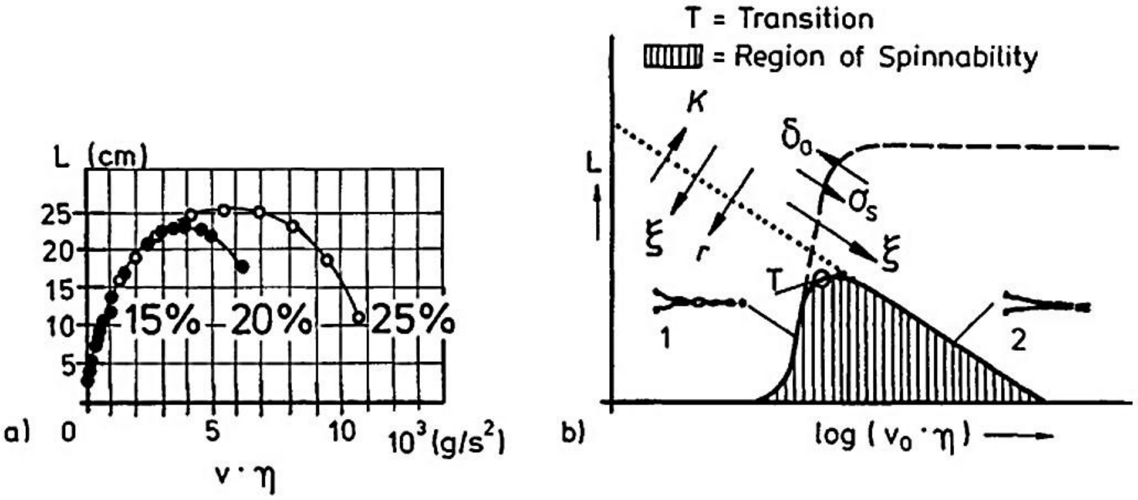


Fig.2.24: a) Maximum length L [cm] of the fluid thread as a function of the extrusion velocity *v* and the shear viscosity .The extradites are differently concentrated solutions of cellulose acetate $[n] = 1.92$ dlg^{-1} in an acetone-water mixture of 85:15 volume-%: results in good spin ability

b) Superposition of theoretical curves of capillary wave failure. (- - - -) and cohesion failure (....) Maximum length of the fluid filament is plotted as a function of the product of extrusion velocity v_0 and shear viscosity η; d_0 = initial diameter; = d $\ln(v/v_o)$/dx = axial deformation gradient; σ_S = surface tension; K = energy of cohesion: τ relaxation time = time for the stress (stored energy) created by a sudden deformation to decay to the (1/e)-part; the arrow shows the direction in which the theoretical curves shift when the indicated parameter increases.

For the common spinning of filaments in the finished range of about 1 to 20dtex (≈0.01 to 0.05 mm diameter) spinnerets of a diameter of 0.05 to 0.25 mm are used for solution spinning, and 0.1 to 0.7mm for melt spinning. The capillary length is L = (1 .... 4) D, in some cases, up to about 10 D. The question concerning the optimum preborn-cylindrical, conical, double conical, hyperbolical-has not yet been determined.

Figure 2.25.a shows what happens inside the filament after exiting the spinneret, and Fig. 2.25.b shows the schematic changes in the filament properties until the material has solidified.

Melt spinning is done for most polymers (PA, PET, PP etc) between 240 and 320 °C, for some special polymers under 200 ^{0}C or between 350 and 450 °C, usually under high pressure (100 to 200 bars) through very thick spinneret plates (= 10mm). In each position x of the thread way the following is valid:

$$\gamma \times F(x) \times v(x) = G = \text{Constant} \ldots\ldots\ldots\ldots (2.23)$$

With γ = density of the polymer (melt or solid), F = filament cross-section, v = filament speed, and G = throughput/bore. For a round filament cross-section $F = d^2\pi/4$ (d = filament diameter) and

$$\cdot\ d(x) = 2\sqrt{G/(\pi.\gamma.v(x)} \ldots\ldots\ldots\ldots (2.24)$$

Table 2.3 shows some general values from operation.

The extrusion velocity = exit velocity from the spinneret v_B[m/min] follows of

$v_B = 4 \times G_B/\pi \times D^2 \times \gamma_{melt}$

with G_B[g/min] filament mass per hole, D [mm] capillary diameter, γ = density of the melt [g/cm^3]; for spinning 167 dtex f 36 PET-POY this will result with D = 0.3 mm, v_{sp} = 3600 m/mm, i = 1.44: v_B= 28.4 m/mm.

This will result in the

Spin draft = take-up speed/extrusion speed = v_{sp}/v_B

In this example, this would be 126.76.

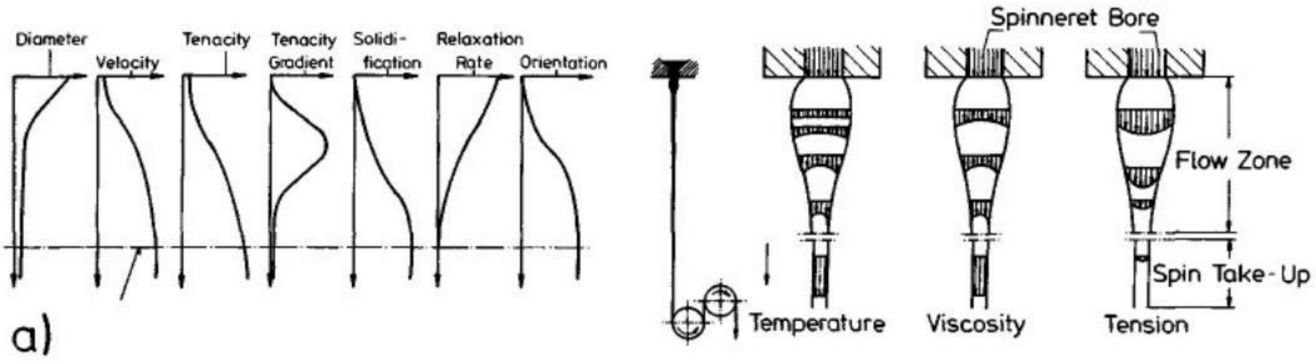
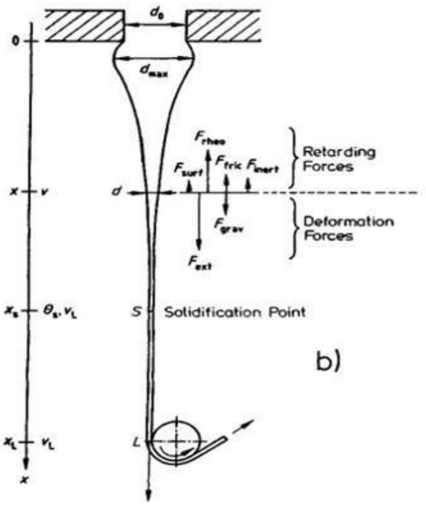


FIG-2.25



d = Filament diameter
d_0 = Spinneret hole diameter
d_{max} = Maximum filament diameter (due to dye swell)
x = Distance from the spinneret
ϑ_S = Solidification temperature
s = Solidification point
L = End of the spin way respectively length
$F_{rheo}(x) = F_{est} + F_{grav}(x) - F_{inert}(x) - F_{frik}(x) - F_{surf}(x)$
with
F_{rheo} = Rheological (viscosity) forces, filament draw force
F_{ext} = External take-up forces (constant along the thread path)
F_{grav} = Gravimetric forces (filament weight below point x)
- for vertical upward spinning F_{grav} becomes negative
- for horizontal spinning F_{grav} becomes 0

F_{inert} = Inertia force (based on acceleration to v_L, the speed at the end of the spin way)
F_{frik} = Friction force between the filament surface and the surrounding spinning medium (e.g., air or water or similar)
F_{surf} = Surface tension (with a tendency to minimize the filament surface by shrinkage)

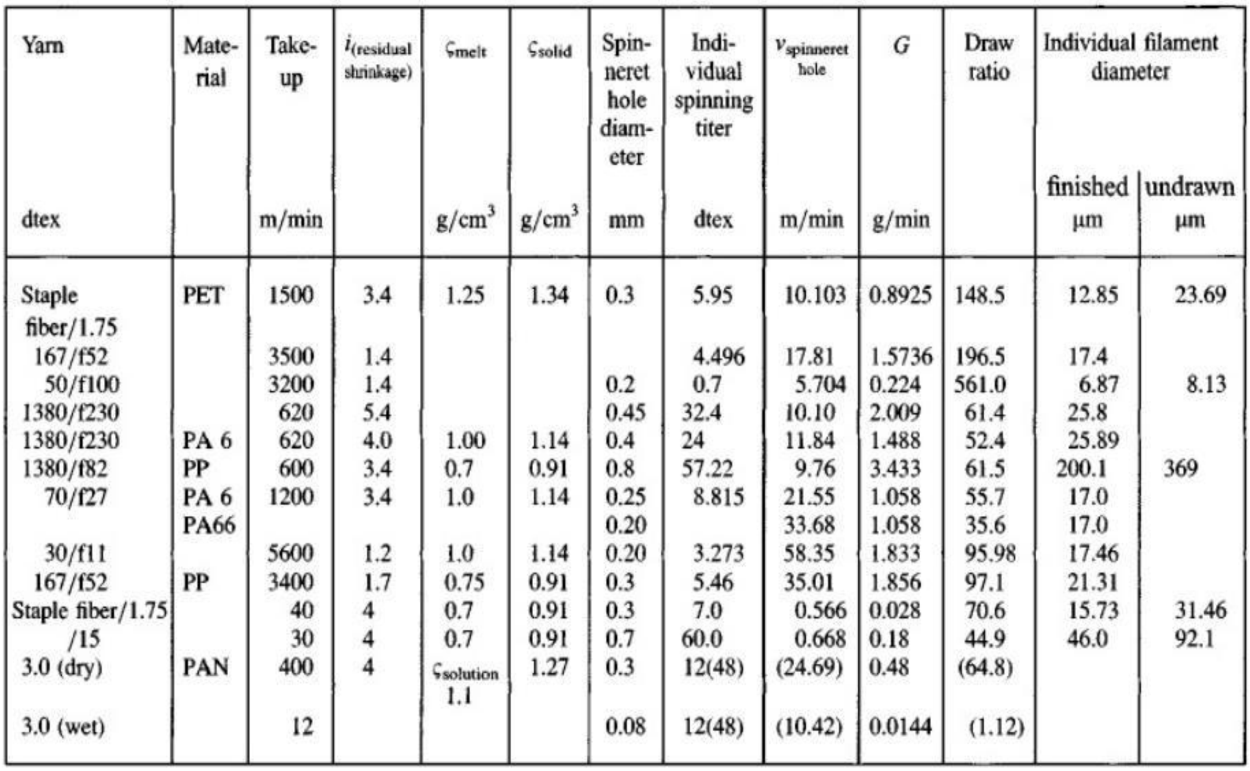
Fig2.25: a) Temperature, viscosity and tension distribution in the polymer stream and schematic curves of different filament situations and properties during the melt spinning process

b) Force equilibrium of the spinning filament (yarn direction downwards)

During melt spinning the following phenomena need to be observed:

In high-pressure extrusion, the melt pressure of usually more than 400 bars between the extruder screw tip, extrusion pump, and extrusion pack is reduced by friction in the extrusion pack to the necessary entrance pressure at the spinneret filter of usually 20 to 60 bar. Specific slots or filters in the extrusion pack are suitable for this. Filters, however, will change the pressure with running time and clog. Due to the shearing force, frictional heat is developed, increasing the melt temperature of PET or PA by 4. . . 4.2 K per 100 bar pressure drop (see Fig. 2.26). Because there are only a few seconds between this increase in temperature to the cooling of the filament, the temperature increase is usually without risk for the polymer. With proper control of the melt flow, one can achieve a uniform heating over the cross-section of the melt and thus an increase of the exit temperature, a decrease of the melt viscosity and an improvement of the spinning conditions, especially for high viscous materials. The spinneret temperature, e.g. of the Dow. vapor, stays at the same level as before the pressure drop.

Table.2.4: Example of yarn at different take-up speeds



Yarn	Material	Take-up	$i_{(residual\ shrinkage)}$	ς_{melt}	ς_{solid}	Spinneret hole diameter	Individual spinning titer	$v_{spinneret\ hole}$	G	Draw ratio	Individual filament diameter	
											finished	undrawn
dtex		m/min		g/cm³	g/cm³	mm	dtex	m/min	g/min		µm	µm
Staple fiber/1.75	PET	1500	3.4	1.25	1.34	0.3	5.95	10.103	0.8925	148.5	12.85	23.69
167/f52		3500	1.4				4.496	17.81	1.5736	196.5	17.4	
50/f100		3200	1.4			0.2	0.7	5.704	0.224	561.0	6.87	8.13
1380/f230		620	5.4			0.45	32.4	10.10	2.009	61.4	25.8	
1380/f230	PA 6	620	4.0	1.00	1.14	0.4	24	11.84	1.488	52.4	25.89	
1380/f82	PP	600	3.4	0.7	0.91	0.8	57.22	9.76	3.433	61.5	200.1	369
70/f27	PA 6	1200	3.4	1.0	1.14	0.25	8.815	21.55	1.058	55.7	17.0	
	PA66					0.20		33.68	1.058	35.6	17.0	
30/f11		5600	1.2	1.0	1.14	0.20	3.273	58.35	1.833	95.98	17.46	
167/f52	PP	3400	1.7	0.75	0.91	0.3	5.46	35.01	1.856	97.1	21.31	
Staple fiber/1.75		40	4	0.7	0.91	0.3	7.0	0.566	0.028	70.6	15.73	31.46
/15		30	4	0.7	0.91	0.7	60.0	0.668	0.18	44.9	46.0	92.1
3.0 (dry)	PAN	400	4	$\varsigma_{solution}$ 1.1	1.27	0.3	12(48)	(24.69)	0.48	(64.8)		
3.0 (wet)		12				0.08	12(48)	(10.42)	0.0144	(1.12)		

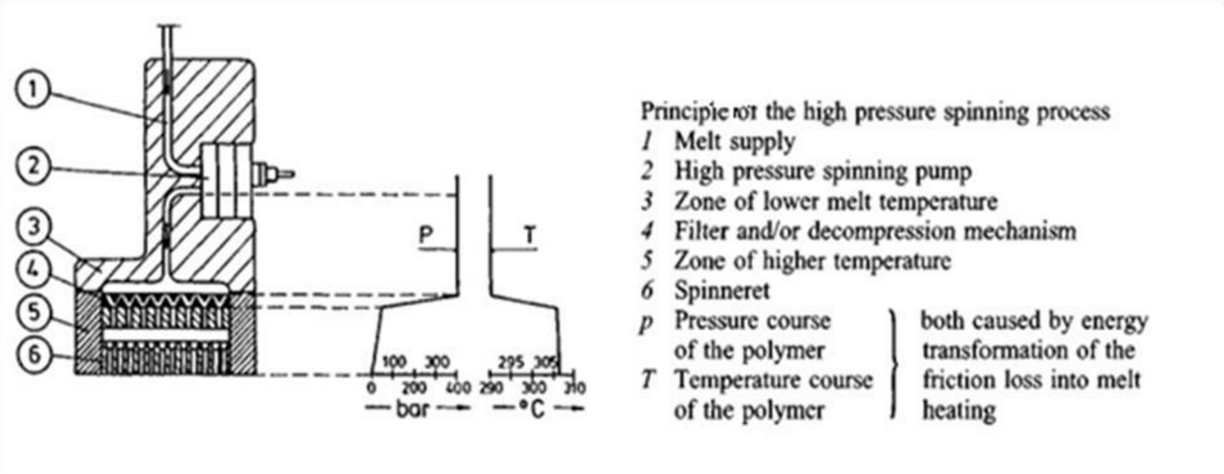


Fig.2.26: Principle of high-pressure spinning process

Delayed cooling under the spinneret with a hot shroud (Fig. 2.27) or by blowing hot gas to the filament: This avoids the risk of too fast cooling of the filament surface and too high pre-orientation. This will result in a lower take-up tension and lower pre-orientation and therefore in better draw ability and higher final tenacity.

Delayed cooling with a heater after the cooling zone: Here the filament temperature is increased after the filaments pass the cold air zone with the help of a hot air stream. The yarn speed in the air quench is first reduced and increases to the full POY take-up speed after leaving the hot air tube. The final stretch takes place in the hot air tube, resulting for example for PET in a final tenacity of 35 cN/tex at 4000 m/mn, which is not possible without the hot air tube until 6000 m/min (Fig. 2.28). These filaments can often be used as the final product.

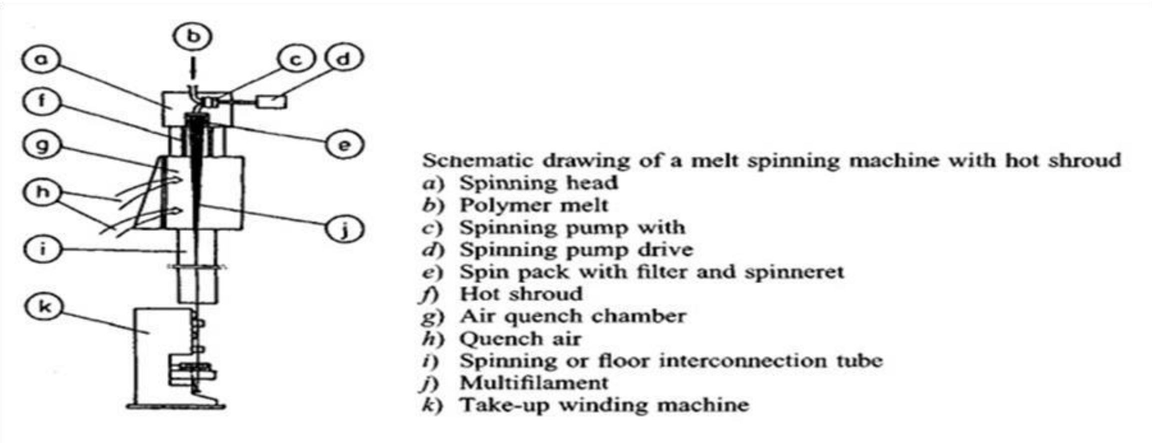


Fig 2.27 Schematic drawing of a melt spinning with hot shroud

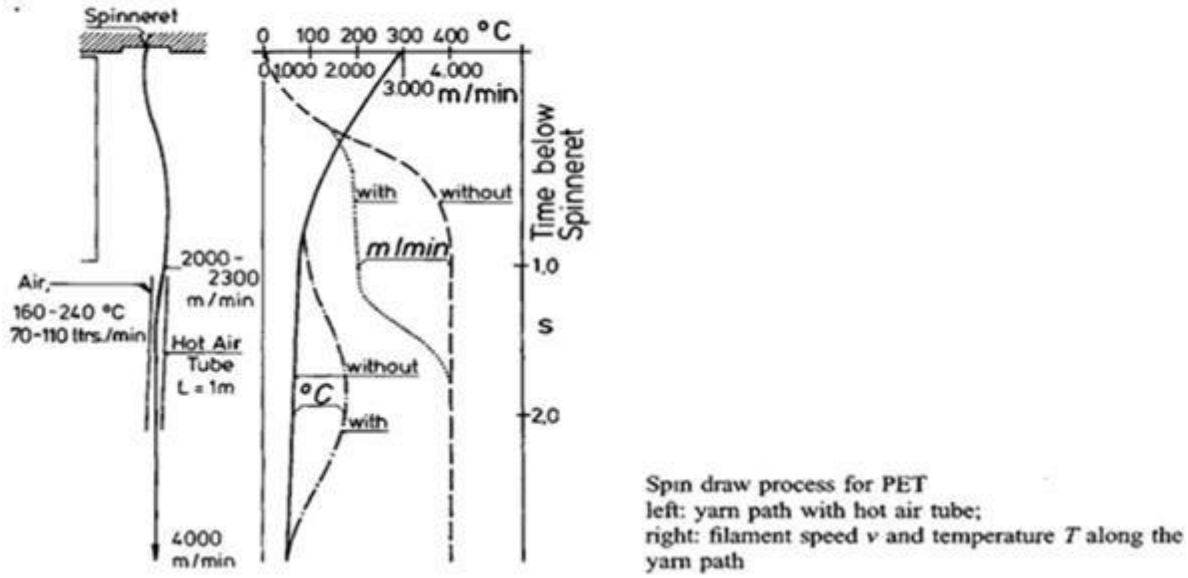


Fig.2.28: Spin draw process for PET [34]

2.9 SPIN FINISH APPLICATION SYSTEMS

It is very much required to apply spin finish to make the yarn more moist, more pliable and antistatic. In addition, there is the possibility of reducing the air friction component of yarn tension by converging the filaments as close to the spinneret as possible. If the spin finish applied at spinning is not sufficiently durable, finish is again applied once or twice more during further processing, possibly after washing off the original spin finish. The tendency is, however, to make the spin finish suitable and stable for all further processing stages. In the case of PET POY for draw texturizing, e.g., the finish must be able to withstand temperatures up to 240 °C, must not decompose and must remain on the yarn in sufficient quantity. For this reason, possibly more finish must be applied at spinning than remains in the end product.

For PET- POY normally percentage spin finish is kept o.352 to 0.45 w/w%, based on dry yarn, while staple tow requires up to 4% if washing occurs downstream. Finish is applied as a 10... .25% solution or emulsion in distilled water. To avoid layering or separation of spin finish components continuous stirring or circulation is required. Finish damaged by oxidation cannot be re-used.

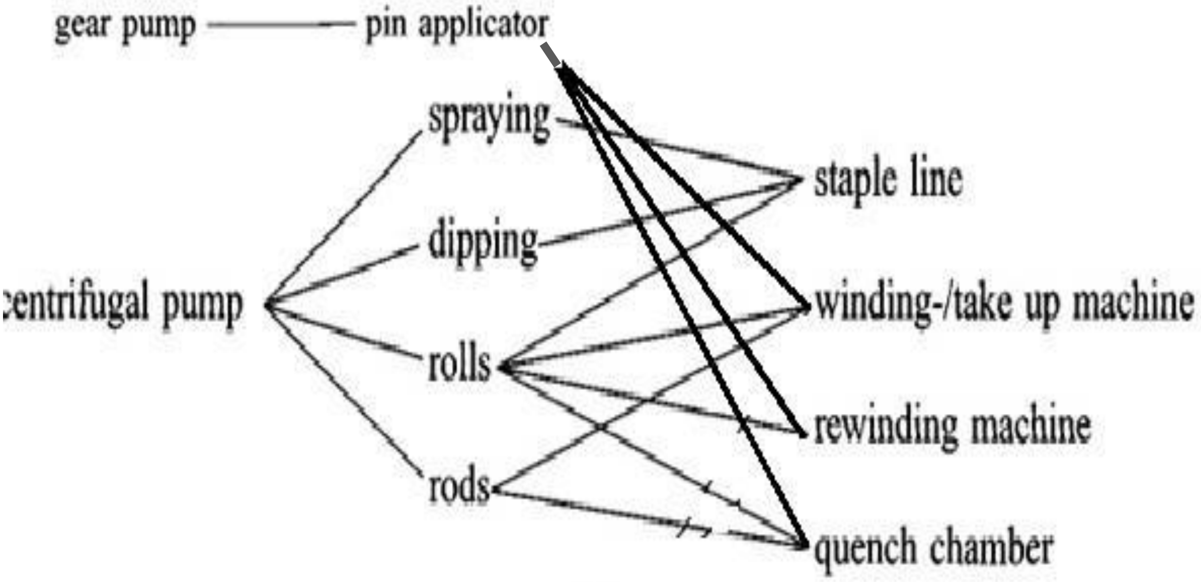


Fig 2.29: Different types of spin finish application system

Above are five different methods of applying spin finished for four different production positions: Normally spin finish level of 0.6 to 0.8 w/w% based on dry yarn, taking into account losses in further processing.

- When the yarn contacts the finish (particularly in POY spinning), one observes that the finish is explosively atomized and is taken up by the room air as an aerosol. This finish-contaminated air must be cleaned by washing and/or catalytic combustion.

- Losses during the hot drawing of yam or tow by evaporation, decomposition or washing.
- Drying out losses.

As more finish is again applied at further processing, the spin finish material balance, from beginning up to finished goods, is fairly complicated, and is not evident to the spinner; one should, therefore, limit oneself to optimizing the spin finish level up to the winding stage, and possibly the next processing stage.

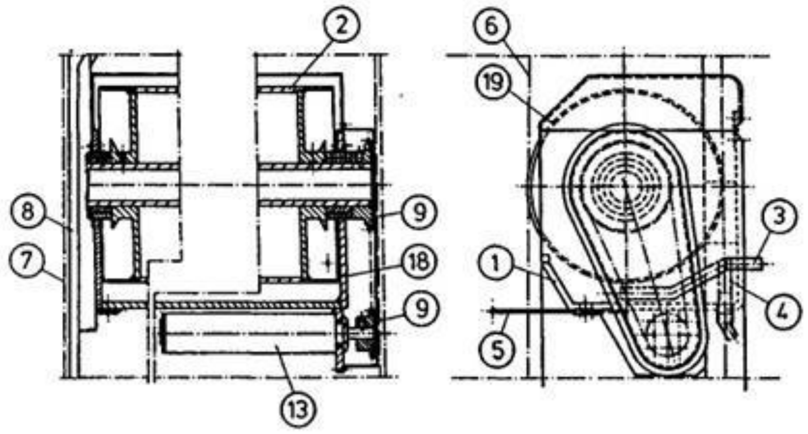
2.9.1 Roll application system

This is the oldest finish application system and is still used today particularly for wide tows and for speeds below 1800 m/mm. Roll application can be fitted at the inlet to the take-up machine, at the bottom of the quench chamber or at tow processing.

The kiss (lick) rollers**[35]** have a diameter between 120-180 mm and width is kept maximum tow width +50mm. Normally speed of finish roller is kept between 5 to 9 rev/minute.

The bottom of the rotating roll dips into a shallow tray, which has an inlet in one corner and an adjustable level overflow in the opposite corner. When built into a spinning machine, a yarn guide (10 to 20 mm) and the tip of the spin finish tray protrude beyond the face of the machine.

The spin finish supply can be held in a sufficiently large machine tank. The submersible centrifugal pump is used to supply spin finished from the tank to the tray via polyethylene tubing, the excess finish returning via similar tubing of larger diameter to the tank, where it is filtered.



Spin finish lick roll for installation in the quench chamber [24]

1 Spin finish trough
2 Spin finish roll
3 Spin finish inlet pipe
4 Adjustable overflow
5 Yarn-retaining guide
6 Yarn warp (band)
7 Quench chamber sidewall
8 Support rods
9 Chain drive
13 Drive motor
18 Bearing housing = side wall to (1)
19 Hinged cover

Fig.2.30: Spin finish lick roll installation in the quench chamber

To run avoid range of titer or product, two sets of rolls are recommended. Upper roll is for wetting and second roll is for spin finished application. To maintain a ratio of moisture/spin finish, changing the speed of one or the other roll is recommended, not the percentage spin finish concentration.

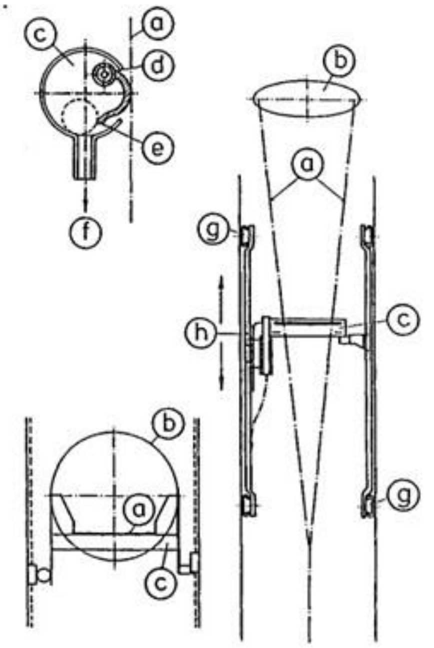
2.9.2 Rod (Bar) application system

Rod is a plasma coated stainless steel tube of the same length as of kiss roll width, having a row of equally closely spaced holes for spin finish outlet above the point where yarn comes in contact of the rod.

Finish supply system is same as roll application system **[36].**

2.9.3 Spray application system

Atomizing jets are used to spray spin finish from the above onto a running tow. Centrifugal pump is used to deliver spin finish to spray jets. This spray system is seldom used alone but is often used above a finish roll when the latter cannot transfer sufficient finish, as, e.g., before staple tow take-up in cans. Normally a centrifugal pump delivers the finish to the spray jets.



Spin finish applicator rod
a) Yarn path
b) Spinneret
c) Spin finish applicator rod
d) Spin finish applicator delivery pipe having slits or drilled holes
e) Spin finish overflow collector
f) Overflow pipe
g) Slide rails (for height adjustment)
h) Carrier rods
Comment: The spin finish applicator tube (*c* to *e*) can also be curved, e.g., round

Fig 2.31 Spin finish applicator rod

2.9.4 Dipping bath application system

Dipping baths can either have 2 or 3 silicone rubber coated calendar rolls running in a heated finish trough or 1 to 5 dipping rolls running in a finish pan, both followed by nips to squeeze out the excessive finish.

2.9.5 Pin Application system (Metered Spin Finish)

Geared spin finish pumps are used to supply emulsion to each thread through the finish applicator (pin). Spin finish losses can be compensated by a slightly increased pump speed to give required finish level to the yarn. The finish applicator is placed either in quench cabinet (where yarn temperature is below the polymer glass transition temperature) or at top of take-up machine.

A sample calculation, using metered spin finish, is given for a 6-fold PET POY yarn of 83.3 . . .167dtex final (125. . .250 dtex spin), spin at 3500 m/min and Dress Materials with 1% finish oil on yarn using a 20% aqueous emulsion:

Spun titer × m/min × % oil on yarn/concentration = g/min emulsion pick up

Spin finish pump size, cm^3/r = g/min emulsion pick up at 8. . .65 r/min

This gives 2.19.. . 4.38 g/min 27.4. . . 54.8 r/min for a 0.08 cm3/r pump. A 6-chamber pump is required.

Metered spin finish application

a) Closed execution, *b*) Open execution

- *1* Dosed spin finish
- *2* Ceramic applicator ("oiler")
- *3* Adjustable angle of inclination
- *4* Oiler rentention pin
- *5* Retention block
- *6* Spin finish overflow
- *7* Spin finish overflow collector
- *8* Adjustable yarn guide
- *9* Locking latch for carrier assembly
- *10* Protective covering
- *11* Yarn guide cover plate
- *12* Carrier rod
- *13* Vertical carrier rod

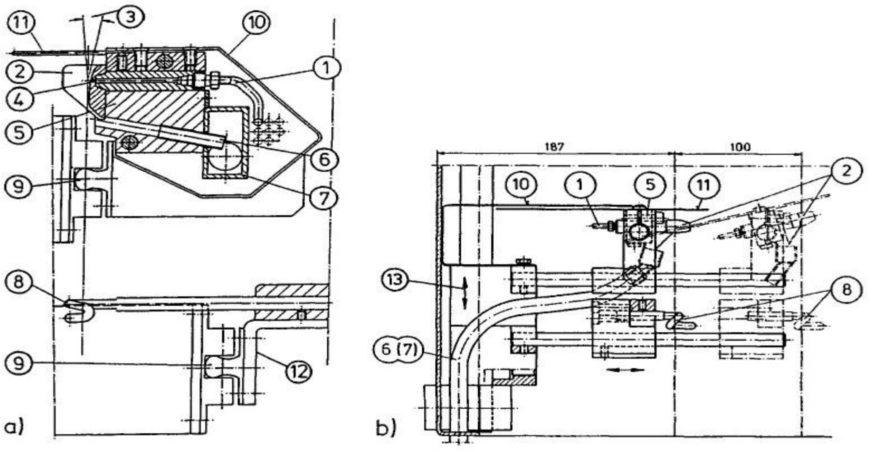
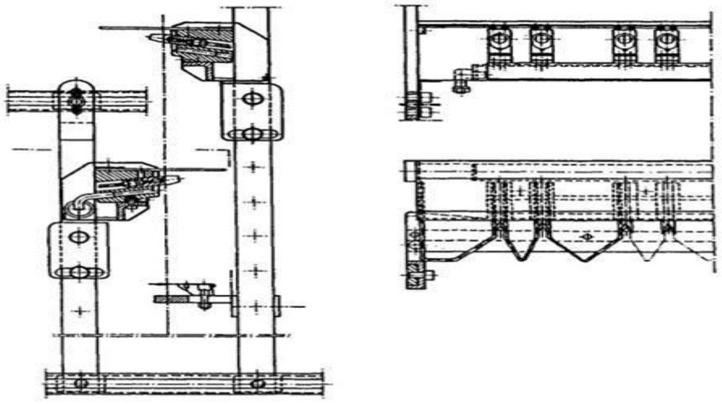


Fig.2.32 Metered spin finish application shows the detailed construction of a metered spin finish system

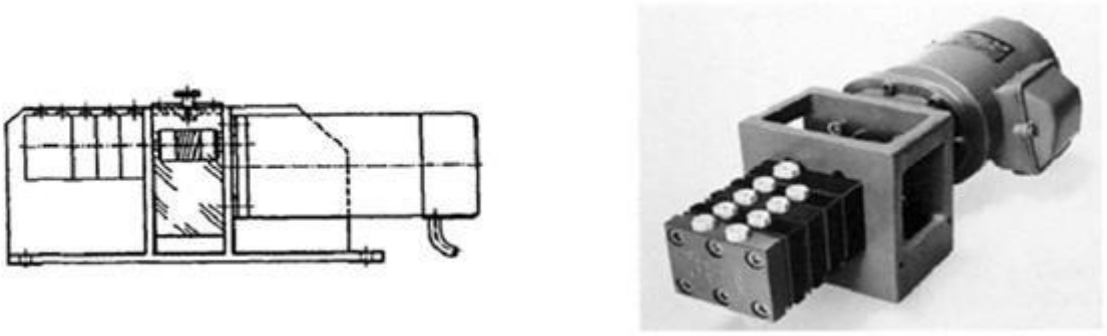
As the spin finish cover is an important factor in yarn quality and uniform run ability, the flow rate to each applicator is often monitored and displayed on a scanner. The applicator carriage (5) has a quick- latching device (9) to enable it to be swung aside or moved out of position when throwing down at the start of spinning. Metered spin finish has a uniformity of around ±7%. The distance between the oiler and the spinneret must be adjustable, as a short free length of yarn above the convergence point is favorable for good Uster values, as well as conferring low yam tension. In PET POY spinning, a convergence distance of 400 mm suffices for 0.5 dtex final dpf, 600...800 mm for 1.5. ..2.5dpf. 1200. . .1300 mm for 5 dpf and 1700 mm for 10 dpf



Double-sided metered spin finish application in the quench chamber. This is used particularly for large yarn bundles and for microfilament yarns, and is adjustable in height. It is fitted with yarn guides and thread-up guides

Fig.2.33 Double-sided metered spin finish application in the quench chamber

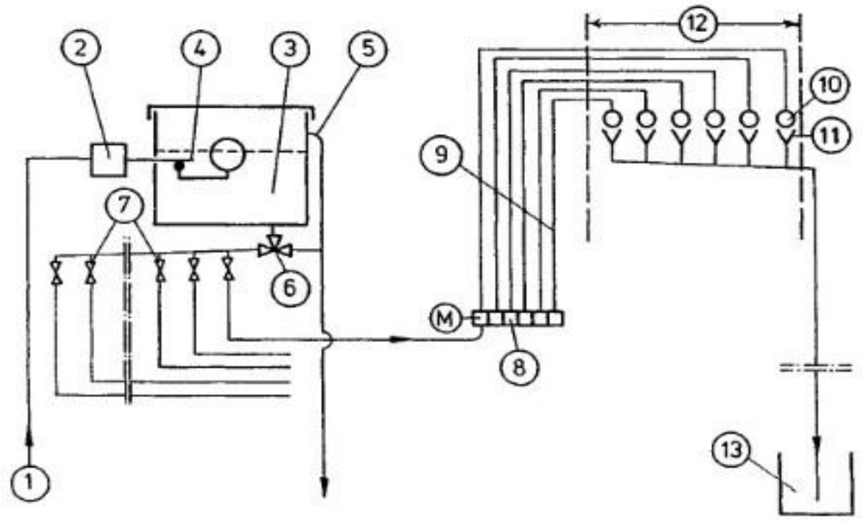
Figure 2.33 shows a double-sided applicator [**37**], used for microfilaments of the high count and for thick multifilament bundles. Threading up through the applicators is facilitated by a matte hard chromed wire guide.[**38, 39, 40**]



Spin finish pump assembly for many yarn ends, fitted with gear tooth pumps a small, geared reluctance motor of 40 . . . 60 W to give 8 . . . 60 rev/min

Fig.2.34: Spin finish pump assembly

Similar applicators with individual inlets can also be fitted at the yarn inlet to take-up machines .Figure 2.34 shows a spin finish pump assembly, together with the drive. The 2 to 12 chamber pump is bolted onto the housing and joined, via a flexible coupling, to a geared motor bolted on from the other side of the housing; the system runs at 10.. .80 r/min and has a maximum power of 60 W. A static frequency inverter powers all the finish pumps in a spinning machine. The earlier, often used



Metered spin finish application system, from spin finish mixing tank (1) through machine spin finish tank (3) to spin finish applicators (10, 11)

1 from vessel (8, 11)
2 Filter ≤ 5 μm
4 Float valve (in 6.31)
5 Overflow = return flow to (5)
6 Three-way valve for drainage, and for
7 Inlet to individual spin finish pumps
8 Spin finish pumps
9 PE tubing
12 Spin finish applicator block
11 Spin finish return (after a yarn break; not re-usable)
13 Spin finish waste collector drum

Fig.2.35: Metered spin finish application system

Similar applicators with individual inlets can also be fitted at the yarn inlet to take-up machines. Figure 2.34 shows a spin finish pump assembly, together with the drive. The 2 to 12 chamber pump is bolted onto the housing and joined, via a flexible coupling, to a reluctance geared motor bolted on from the other side of the housing; the system runs at 10.. .80 r/min and has a maximum power of 60 W. A static frequency inverter powers all the finish pumps in a spinning machine.

2.10 VISCOSITY

The viscosity of any fluid shows its resistance when subjected to deformation. Crudely one can say more the thickness, more the viscosity of the fluid. Honey is “thick”, having higher viscosity while water is “thin”, having lower viscosity. In a simple language, if a shear stress is applied to any fluid, less viscous fluid deforms easily and can be said to have higher fluidity **[41]**. Therefore it is a measure of fluid resistance against flow due to internal friction of the fluid layers. Practically all fluids offer resistance against the flow and are viscous. If a fluid offers no resistance to flow than it is an ideal fluid or inviscid fluid. Properties of flow of matter are studied under the science “Rheology”.

2.10.1 Dynamic (shear) Viscosity

It expresses resistance of fluid against the shear flow, where adjacent layers move parallel to each other with different speeds. It is commonly represented by Greek letter μ (mu) **[42, 43, 44]**, among mechanical/ chemical engineers. However Greek letter η (eta) is also used by physicists, chemists, and IUPAC **[45]**. The SI unit of shear viscosity is Pa.s (Pascal-second) or N.s/m^2 or Kg/m.s . If a shear stress of 1 Pa is applied to a fluid having a viscosity of 1 pascal second when placed between two plates then it will move a distance equal to the thickness of the layer in 1 sec.

In CGS system, the physical unit of dynamic viscosity is “poise” (P)**[46]** given after Jean Louis Mary Poiseuille. Commonly it is used in centipoise (cp). The viscosity of water at 20^{0}C is 1.0020 centipoise (cp).

1 P = 0.1 Pa·s,

1 cP = 1 mPa·s= 0.001 Pa·s.

2.10.2 Kinematic Viscosity

It is given by the ratio of dynamic viscosity (μ) to the density (ρ) of the fluid and represented by the Greek letter ν (nu).

$\nu = \mu/\rho$

The SI unit of Kinematic viscosity is m^2/s. in CGS system the unit of ν is stokes (st.) named after G. G. Stokes.

$1 \text{ st} = 1 \text{ cm}^2.\text{s}^{-1} = 10^{-4} \text{ m}^2.\text{s}^{-1}$

$1 \text{ cst} = 1 \text{ mm}^2.\text{s}^{-1} = 10^{-6} \text{ m}^2.\text{s}^{-1}$

The kinematic viscosity of water at 20^0C is about 1 cst.

Fluidity

Fluidity is reciprocal of viscosity and is given by $\Phi = 1/\mu$. It is measured in reciprocal poise (cm.s/gm). It is also called the *rhe*. It is not used in common language of an engineer.

2.10.3 Properties and behavior

When a force is applied to any fluid it moves, but layers of fluids move at different velocities and viscosity of fluid arises due to the shear stress between the layers of the fluid. Let us assume a homogeneous fluid is separated between two plates of area A and distance between the plates is 'y'. Suppose the lower plate is fixed and force F is applied to the upper plate which causes it to move with a velocity 'u', then,

$F \alpha A$ (applied force is proportional to the area)

$F \alpha u/y$ (applied force is proportional to the velocity gradient in the fluid)

Or, $F \alpha Au/y$

Or, F = μ Au/y

Hence μ (mu) is the constant of proportionality and is called the dynamic viscosity of the fluid

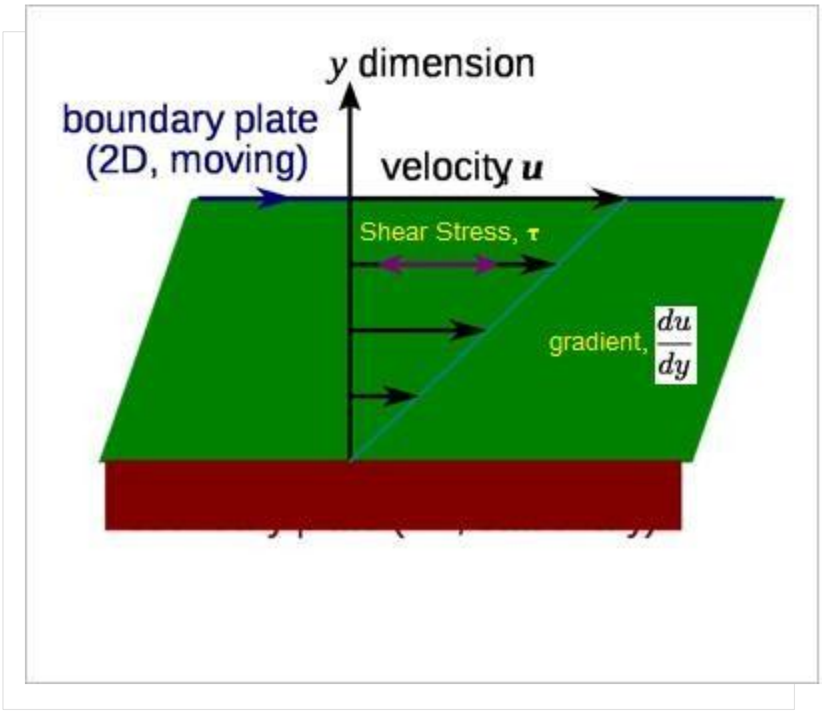


Fig: 2.36 Laminar shear of fluid between two plates.

Friction between the fluid and the moving boundaries causes the fluid to shear. The force required for this action is a measure of the fluid's viscosity. This type of flow is known as a Couette flow.

Shear stress is force per unit area and can be written as τ = F/A.

Isaac Newton expressed this in a differential form. So for a uniform flow shear stress is proportional to shear strain or the velocity gradient between the fluids in the direction perpendicular to the layers.

τ = μ du/dy

Hence a relation between shear stress and shear strain can be derived. The rate of shear deformation u/y can be derived as shear velocity du/dy.

As per known physicist, J.C. Maxwell viscosity is nothing but analogous to elasticity in solids where deformation opposes shear stress in solids and in the case of fluids, shear stress is opposed by the rate of deformation.

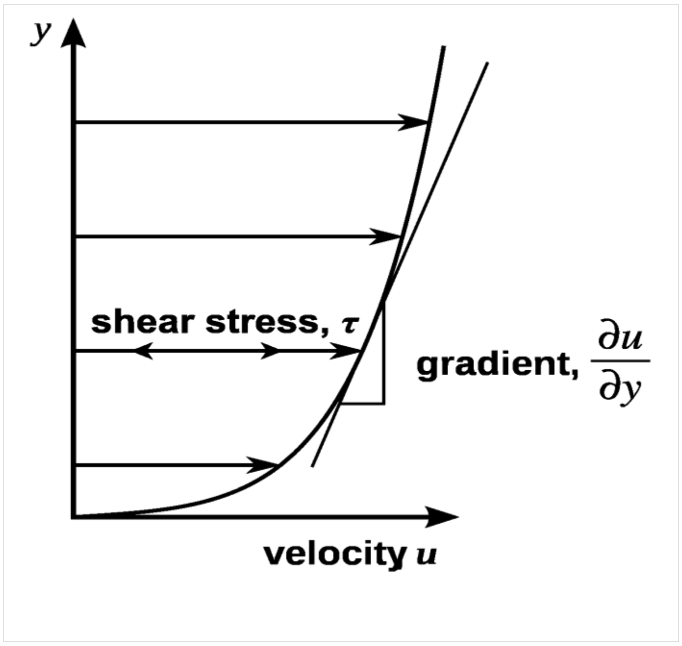


Fig 2.37 Stress-Strain curve

Laminar shear, the non-constant gradient, is a result of the geometry the fluid is flowing through.

2.10.4 Types of viscosity [47]

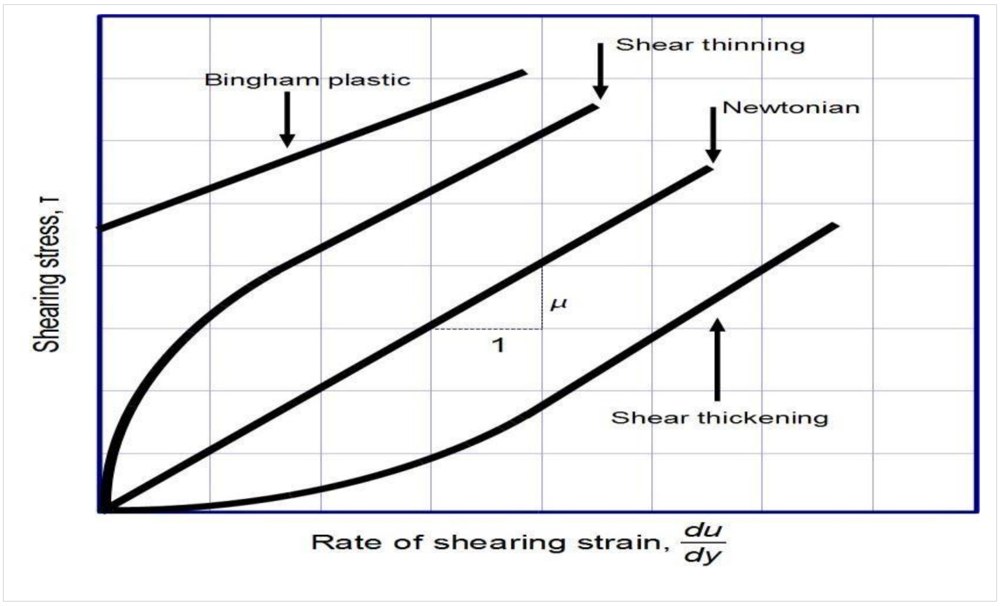


Fig.2.38: Forms of viscosity

"Shear stress is directly proportional to the rate of shear" (Newton's law of viscosity) is not a fundamental law. It holds good for some materials and fails in others. Non-Newtonian fluids do not follow this linear relationship and behave otherwise. Following are the different forms

Newtonian fluids: such as water and other gases which have a linear relationship and have a constant viscosity.

Shear thickening fluids: materials that thicken when agitated or worked are called shear thickening fluids

Shear-thinning fluids: some gel or pastes behave like a fluid when worked and then settle into a solid state when at rest.

Shear thinning can be classified into three fluids:

A material that has a viscosity which decreases under shear rate but stays constant over time is said to be pseudo plastic.

A material that has a viscosity which decreases under shear stress and continues to decrease with time is said to be “thicksotropic”.

When the transition from high viscosity to low viscosity takes place only after the shear stress some minimum value, the material is known as “Bingham plastic”.

There are some fluids when subjected to a magnetic field its apparent viscosity increases greatly to the point of becoming a viscoelastic solid.

2.10.5 Viscosity coefficients

Viscosity coefficients can be defined in two ways:-

1) Dynamic viscosity: - It is also known as absolute or shear viscosity. SI unit is Pa.s, other units are poise or centipoise.

   1 p = 100 cp

   It is represented by Greek symbol η (eta).

2) Kinematic viscosity: - It is given by the ratio of the dynamic viscosity of the fluid to its density. SI unit of kinematic viscosity is m^2/s. Its CGS unit is cm^2/s or stokes. It describes the behavior of flow of a substance under earth’s gravity.

Viscosity a tensorial quantity can be decomposed in different ways into independent components. The most usual decomposition is the following viscosity coefficients:

It is simply called viscosity. It is the reaction of the fluid when applied by a shear stress. It is given as a ratio of shear stress and rate of shear or change in velocity.

Volume viscosity: - It is also bulk viscosity or second viscosity. It is more significant when fluid is compressed. Examples are the propagation of sound and shock waves.

Extensional viscosity: - It is a combination of shear and volume viscosity. It explains how a fluid reacts when it gets elongated. For example, water has a dynamic shear viscosity at room temperature of about 1.0 x 10^{-3}Pa.s and motor oil of about 250 x 10^{-3}Pa.s.

2.10.6 Intrinsic viscosity

Intrinsic viscosity (η) measures the contribution of solute to the viscosity of the solution (η_0). Whereas inherent viscosity is given as the ratio of the natural logarithm of relative viscosity to the mass concentration of the polymer.

$$[\eta] = \lim_{\phi \to 0} \frac{\eta - \eta_0}{\eta_0 \emptyset}$$

η_0 = viscosity of solvent in the absence of the solute.

Φ = volume fraction of the solute in the solution.

The intrinsic viscosity of any fluid is a dimensionless number.

As per Albert Einstein, the intrinsic viscosity of a polymer solution at infinite dilution equals 5/2 when the solute particles are rigid spheres.

In normal practice Φ i.e. solute mass concentration is given as c = g/dL, therefore the unit of η (I.V.) will become deciliters per gram (dL/g)

2.10.7 Viscosity measurement

Measurement of viscosity of fluids is carried out by using various rheometers and viscometers. Rheometers are normally used to measure viscosities of fluids which do not have fixed viscosity and thus it requires various parameters to set and measure. While measuring viscosity, one has to control the temperature of fluid quite closely especially in the case of lubricants which are very sensitive to temperature. Viscosity values of such lubricants can even double in a temperature difference of just 5^0C.

In Newtonian fluids, shear stress is directly proportional to shear strain and thus viscosity is constant over a wide range of shear rates. While in the case of non-Newtonian fluids it is not a single number as here shear stress is differently correlated with shear rates.

Generally, in the paint industry, Zahn cup is used to measure the efflux time and the same is communicated to the users which can convert it to kinematic viscosities.

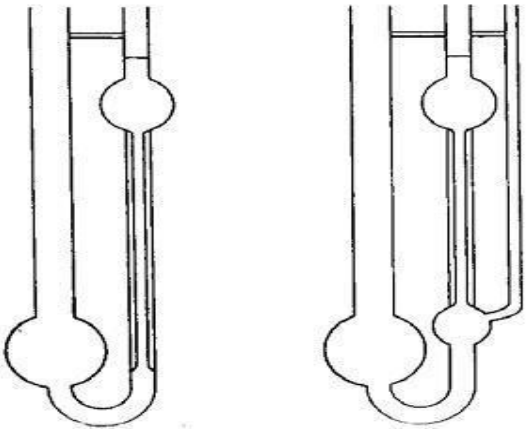
While developing oil and gas wells normally apparent viscosity is calculated and it helps in maintaining parameters of drilling fluids to meet required standards.

Viscometric studies of polymeric fluids are very simple in respect of experimental approach and apparatus needed and hence, widely practiced.

Capillary viscometers are used to measure the viscosities of dilute solutions. Most common viscometers used in polymer industry are Ostwald type and Ubbelohde type shown in the figure. In ubbelohde type viscometer, measurement of flow time is not depending on the volume of solvent and solutions in the viscometers. One can change the dilution of solution within the viscometer. Both the viscometers are provided with thermostat strictly maintaining the temperature within ±0.1^0C. Relative viscosity is calculated by taking the ratio of the efflux time of solution to the efflux time of pure solvent. By plotting the values in the graph and then extrapolating the same to infinite concentration ($c \rightarrow 0$) to obtain I.V. (η).

Weight average molecular weight (M_w) is found out with the help of Mark-Houwink equation:

$$[\eta] = KM^a_w$$ **[48]**



(a) (b)

Fig 2.39: Types of viscometers

(a) Ostwald–type and (b) Ubbelohde–type Capillary Viscometers (CourtsyTata Mcgraw)

2.11 FABRIC TESTING

PET Monofilament produced out of mother yarn 240/12 after splitting is sold as 20/1 PET monofilament after splitting or it is sold directly as it is in the market. Several types of fabrics are made through weaving and knitting process as per the end user.

Different samples of all varieties of fabrics are collected from the Surat market and detailed analysis of the same is carried out and the sample details are given in **Annexure - 2.**

2.11.1Tensile strength [49]

- For woven fabrics if it is required to check strength of the fabric in a specified direction then Tensile strength is measured.
- When a tear is applied on surface of a fabric, Tearing Strength is measured.
- For non-Woven and knitted fabrics, force application is in all direction hence Bursting Strength is measured.

BURSTING STRENGTH OF FABRICS

Tensile strength tests are generally used for woven fabrics where there are definite warp and weft directions in which the strength can be measured.

Certain fabrics such as knitted materials and nonwovens do not have such distinct directions where the strength is at a maximum.

Bursting strength is an alternative method of measuring strength in which the material is stressed in all directions.

- When a fabric fails during the bursting strength test, it does so across the direction which has the lowest breaking extension.
- Bursting strength is measured in units of pressure.
- The usual way is to measure the increase in height of diaphragm during the test and then to inflate the diaphragm to the same height without the specimen present.
- The pressure required to inflate the diaphragm is then deducted from the pressure measured at the point of failure of the sample.

MEASUREMENT OF BURSTING STRENGTH OF FABRICS

- Diaphragm Bursting Strength Test.
- For fabrics having a limited extension.
- Ball Bursting Strength Test.

Fabrics having more extension that cannot be checked by diaphragm bursting

Principle:

"According to the British Standards, the fabric to be tested is clamped over a rubber diaphragm by means of an annular (ring-shaped) clamping ring and a constant increasing fluid pressure is applied to the underside of the diaphragm until the specimen bursts. The operating fluid may be liquid or a gas".

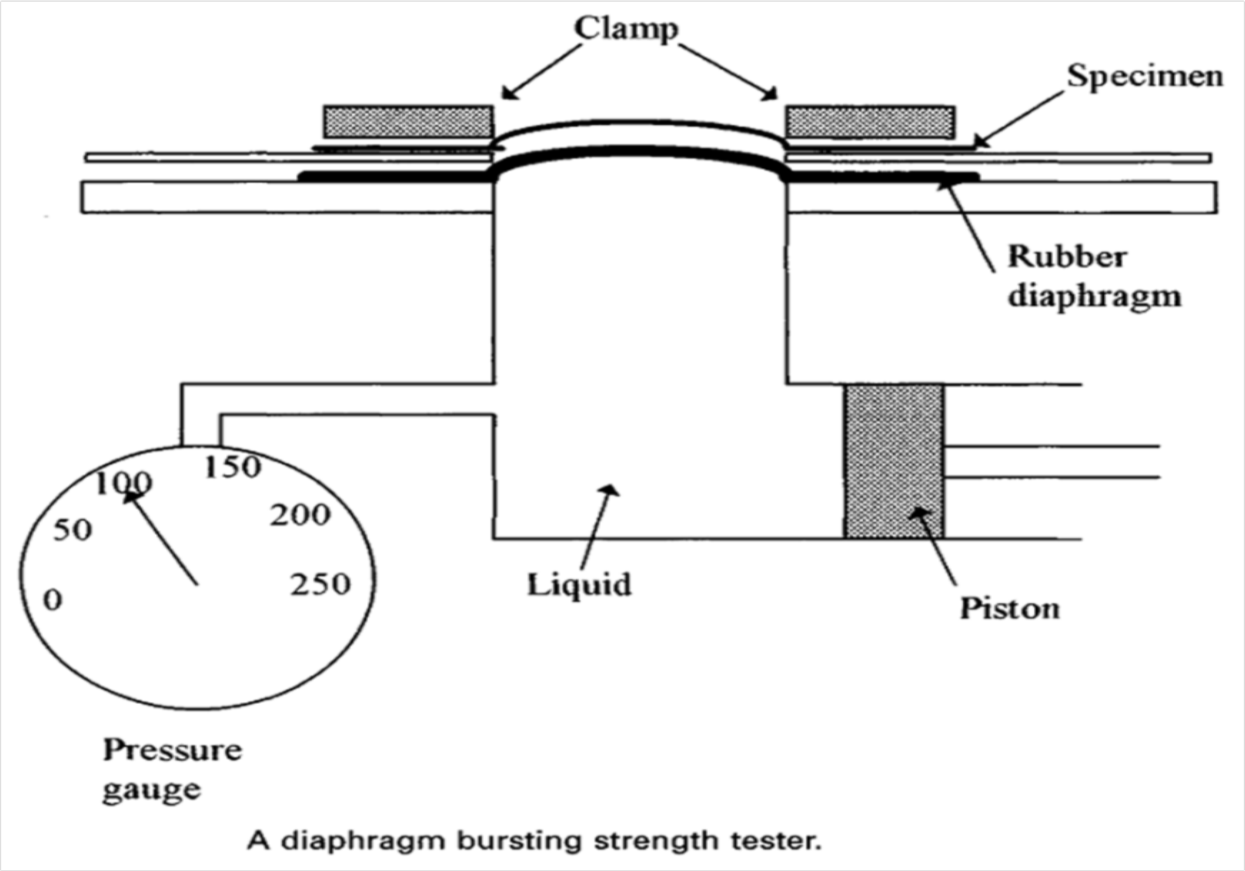


Fig 2.40 A diaphragm bursting strength tester

Sampling:

- 10 samples are taken
- Sample size = 30 mm or 113 mm (two different sizes are in use for different specifications and results)
- The sample with larger diameter fails at a lower pressure; however, there is no direct comparison of the results obtained from the different sizes.

Procedure:

- Sample is clamped over rubber diaphragm
- The fluid pressure is increased at such a rate that the sample bursts within 20+_ 3 seconds

- Extension of diaphragm is recorded and another test is carried out for the same extension, without the sample present
- The pressure to do the above activity is noted and then deducted from the earlier reading
- The following measurements are reported:
    1. Mean bursting strength in kNm^{-2}
    2. Mean bursting distension in mm
- The disadvantage of the diaphragm type bursting test is the limit to the extension that can be given to the sample owing to the fact that the rubber diaphragm has to stretch to the same amount. Knitted fabrics, for which the method is intended, often have a very high extension.

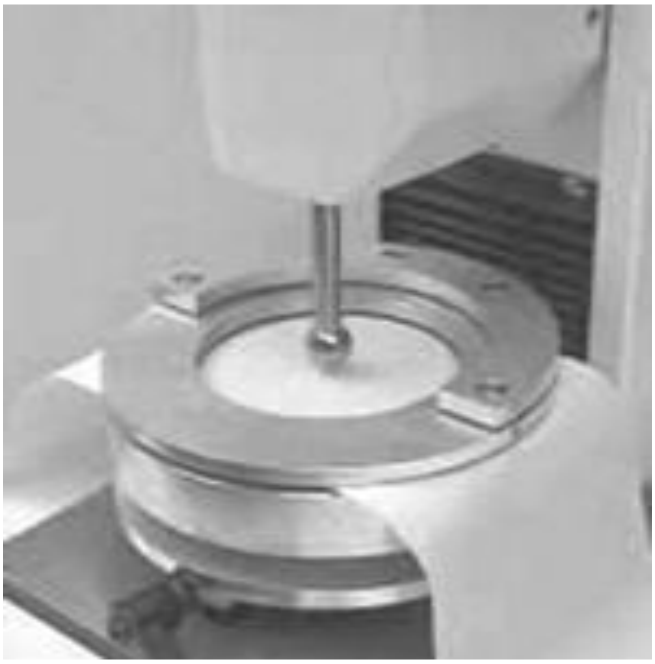


Fig 2.41 Ball bursting strength testing machine

2.11.2 BALL BURSTING STRENGTH TESTING

Sampling and Specifications:

* According to US Standard:

* Steel ball having diameter 1 inch (25.4 mm) with a clamp of diameter 1.75 in (44.45 mm)

* Speed of ball = 12 in/min (305 mm/min)

- Steel ball is an attachment which is used in the tensile mode on a standard tensile strength testing machine
- There are not a British Standards for the ball bursting strength of knitted fabrics, although a standard does exist for coated fabrics:
- steel ball having diameter 25.2 mm with a clamp of diameter 45 mm Speed of ball = 5 mm/sec

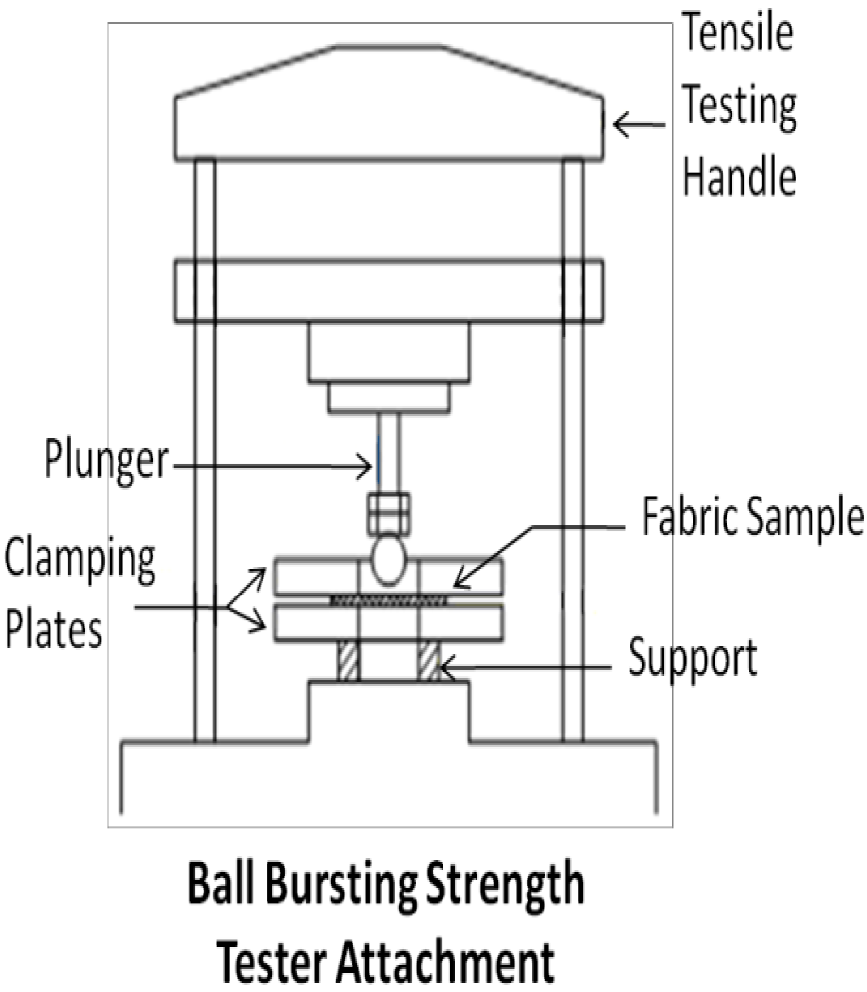


Fig 2.42 Ball bursting strength tester attachment

Procedure:

- Test is carried out using an attachment on a standard tensile testing machine
- In the test, the steel ball is pushed through the stretched fabric and the force required to do so is recorded

Advantage:

This test can be carried out on a standard universal strength tester with a suitable attachment

There is no limit to the extension of fabric as in the case diaphragm test

FABRIC TENSILE STRENGTH

Fabric tensile strength depends upon

Raw materials:
Yarn strength (twist: more twist for more strength)
Fabric construction (*weave*: the plane wave is stronger than floats-satin, sateen which is weaker, *Density:* low density causes weave slippage which results in seam slippage).
The finish applied (resin finish improves weave slippage).
Adverse of “finishing” process.

Measurement of fabric tensile strength

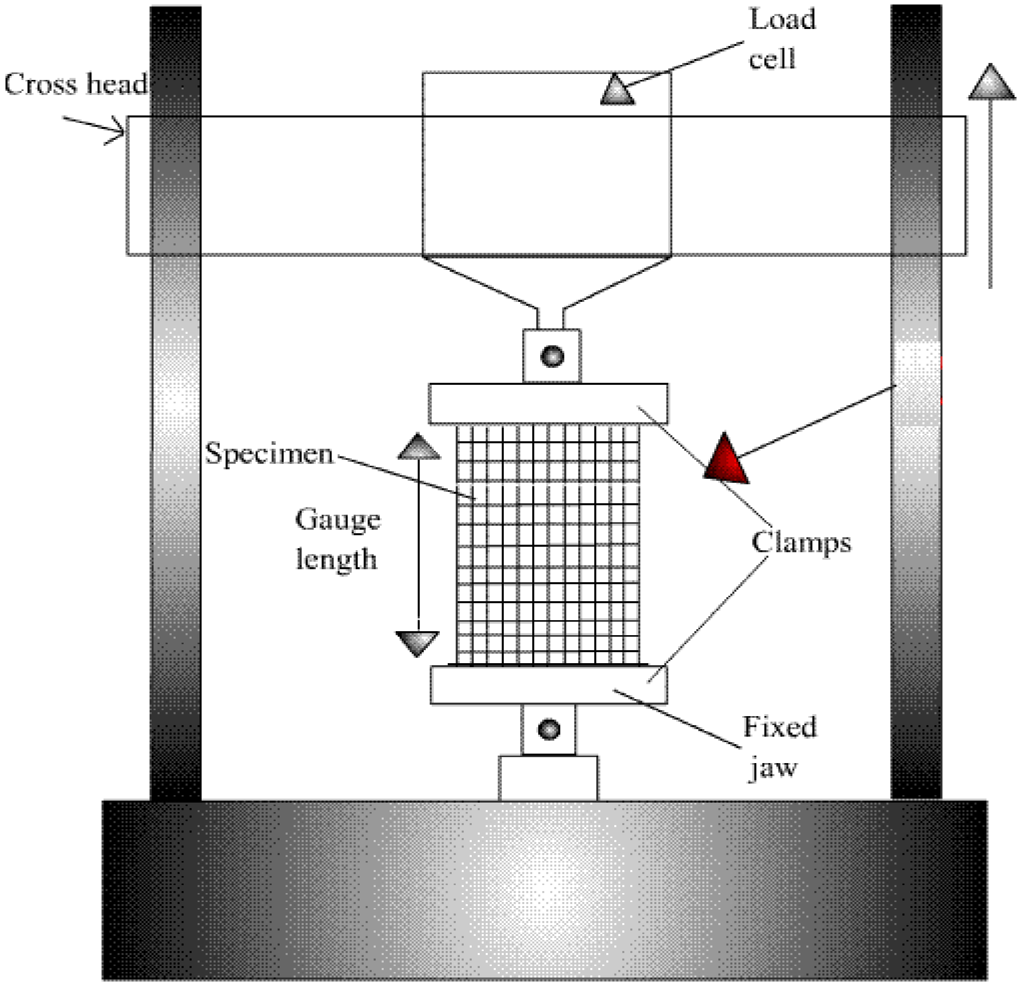
1. **Strip Test: (British) BS 2576:**

In this method, a fabric strip is extended to its breaking point by a suitable mechanical means which can record the breaking load and extension.

Five fabric samples both in warp and weft direction are prepared with each not containing the same longitudinal threads.

Samples are prepared 60mm x 300mm and then frayed to get 50mm wide specimen.

The rate of extension is set to 50mm/min and gauge length is 200mm. pretension is 1% of the probable breaking load.



The apparatus for a fabric tensile test

Fig 2.43 Fabric tensile tester (before breakage)

Any breaks that occur within 5mm of the jaws or at loads substantially less than the average should be rejected.

The mean breaking force and mean extension % of initial length are reported.

Samples are cut (60mm x 300mm) parallel to warp/weft.

Frayed the threads from both sides of the width to bring down to 50mm wide.

For heavily milled fabrics, no fraying is done (50mm x 300mm).

2. **Grab Test: (U.S) ASTM D1682:**

The grab test uses jaw faces which are considerably narrower than the fabric, so avoiding the need to fray the fabric to the width and hence making it a simpler and quicker test to carry out.

The sample used is 100mm x 150mm jaws are 25mm square which stress only the central 25mm of the fabric.

A line is drawn 37.5mm from the edge of fabric to assist it in clamping so the same set of threads are clamped in both jaws.

The gauge length is 75mm and speed is adjusted so that the sample is broken in 20±3s.

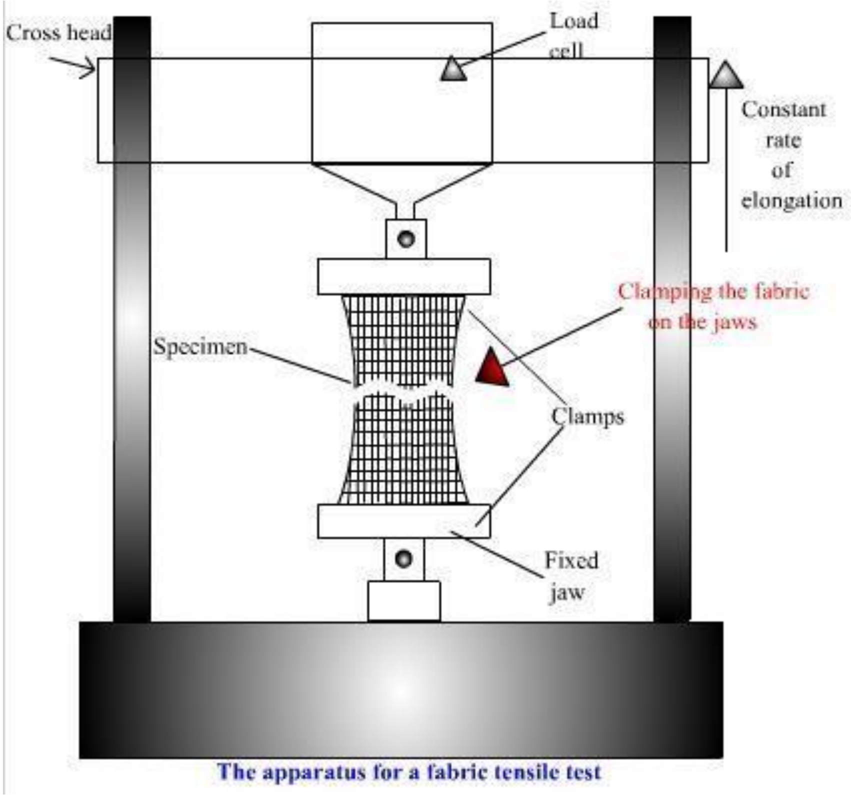


Fig 2.44 Fabric tensile tester (after breakage)

In this test, there is a certain amount of assistance from yarns adjacent to the central stressed area so that the strength measured is higher than for a 25mm frayed strip test.

Fundamentally different from strip test.

Jaw faces are considerably narrower than fabric. No need to fray the fabric.

Simpler and quicker method.

3. USTER TENSORAPID (CRE Principle):

For tensile testing of single and ply yarn.

Testing of slivers, leas and fabrics is also possible.

Force measurements up to 1000N without exchanging the force transducer.

- The *clamping force*, the yarn tensioners and the suction-off of the yarn can be programmed.
    - All numerical and graphical results are displayed on a video screen. (Histogram, L-E curve, tables, etc.)

- Package creel for the automatic measurement up to 20 packages.
- Calling-up of test parameters of frequently tested yarn types from the memory (up to 40).
- *Pneumatically-actuated yarn clamps*; the clamp pressure is programmable.
- Electronic elongation measurement.
- Test speed – Continuously adjustable between 50 and 5000mm/min.
- Test length.

---->With the horizontal position of clamps, continuously adjustable between 200 and 1000mm.

---->With the vertical position of clamps, continuously adjustable between 100 and 1000mm.

Self-test - Automatic calibration check for accuracy through inspection.

2.12 LITERATURE GAP AND SCOPE OF THE STUDY

2.12.1 Literature Gap

Melt spinning is one of the most important techniques for the production of synthetic thermoplastic fibers to produce PET monofilaments through splitting process; a spinner has to produce heavy denier like 240/12 and 300/10 PET FDY which is known as Mother Yarn/Parent Yarn. And these yarns are split into 20/1 and 30/1 PET monofilament.

Basically it is a very specific segment of melt spinning and as such no published literature is available to modify normal FDY line to produce parent/mother yarn from the same spinning line. However, new spinning lines are being supplied by machine manufacturers like TMT and BARMAG, but are quite costly i.e. 15/16 crores for a 24 positions spinning line.

Therefore, a spinner has to modify existing FDY line for appropriate quenching, even and thorough spin finish application on each filament surface and proper winding to facilitate smooth splitting operation. All modifications are based on fundamental concepts of melt spinning process. Various spinners are trying to modify its FDY lines to produce mother/parent yarn but keeping the things in close premises.

2.12.2 Scope of the study

Machine manufacturers TMT (Japan) and BARMAG (Germany) are supplying new spinning lines for PET mother yarn 240/12 and 300/10. But the cost of the machines are around 15-16 crores per spinning lines of 24 positions. Therefore if modification of this line is carried out without compromising quality of the product i.e., 20/1 and 30/1 PET monofilament, then it will be a techno commercial feasible solution. But as per literature survey no such published work is available regarding modification of these lines. Therefore this modification work is taken in this study.