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NYLON-6: POLYMERIZATION CHEMISTRY, PROPERTIES, AND INDUSTRIAL APPLICATIONS –AN INDUSTRIAL REVIEW

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Abstract:

Nylon-6, a widely used polyamide, stands out among synthetic polyamides as a versatile, high- performance fibre owing to its unique macromolecular structure, balanced physicochemical properties, and broad processability. It is synthesized by the ring-opening polymerization of ε- caprolactam through hydrolysis, polyaddition, and polycondensation under controlled thermal and pressure conditions. The polymerization process is critical in defining the final polymer's characteristics, including molecular weight distribution, residual monomer content, and relative viscosity, which directly influence fiber-forming capability. Advanced process control systems regulating temperature, pressure, level, and flow are indispensable for ensuring stability, reproducibility, and energy efficiency at industrial scale. The structural property relationship of Nylon-6 highlights its superior tensile strength, elasticity, abrasion resistance, dyeability, and thermal stability (Tm ≈ 220°C),with crystallinity levels around 50–55%. Post-polymerization treatments, such as hot washing and solid-state aging, further improve viscosity control and spinnability. Modified formulations with additives or resin blends enhance resistance to heat, solvents, and fire, expanding its range of applications. Due to this combination of mechanical robustness and processability, Nylon-6 is extensively employed in technical textiles (tire cords, carpets, fishing nets, parachutes, and sutures), apparel fabrics, packaging films, and engineering plastics processed via injection molding, extrusion, and blow molding. This Industrial Case study consolidates polymerization principles, control strategies, material properties, and applications of Nylon-6, providing a comprehensive perspective for advancing both research and industrial practices.

***Keywords**:*
Fibre Formation, Melt Spinning Nylon-6, Polymerization and Process control, Technical textiles, Fibre Properties.

1. Introduction

Nylon 6, or polycaprolactam, is a polymer developed by Paul Schlack at IG Farben. [1] The number of atoms present in the polymerization indicates the type of nylon; like, hexamethylene diamine & adipic acid have 6-6 carbon atoms in the final polymeric integration, which is why the final polymer manufactured from these raw materials is called Nylon 6,6. [2] Similarly, the caprolactam forms amino caproic acid, which has 6 carbon atoms in the final polymer hence the polymer formed is called "Nylon 6." [3]

Nylon 6 demonstrates extensive utilization in diverse technical applications attributed to its superior functional characteristics, with global production occurring at substantial scales. The synthesis of Nylon 6 employs ring-opening polymerization methodology, distinguishing it from conventional nylon production processes. [4] During Nylon 6 polymerization process, amide linkages within individual caprolactam molecules undergo scission, generating reactive terminal groups that subsequently form dual covalent bonds, thereby incorporating into the polymeric chain structure. [5], [6], [7]

2. Raw Materials

The monomeric raw material serves as the fundamental precursor in polymer synthesis, wherein Nylon 6 production can utilize aminocaproic acid and its corresponding lactam, though caprolactam remains the predominant monomer for industrial synthesis. Monomeric units establish chemical bonds through intermolecular forces during polymerization. The feedstock employed for nylon-6 chips production comprises caprolactam, a petroleum-derived compound manifesting as hygroscopic white powder in flake or crystalline morphology, characterized by a distinct aromatic profile. This whitish crystalline material is synthesized from cyclohexane precursors. [8], [9], [10]

Cyclohexane → Cyclohexane amine → ε-Caprolactam [NH-(CH2)5-CO] [11], [12]

Caprolactam is obtained as a white, flaky crystalline solid, fully soluble in water and exhibiting a melting point of 68°C–69°C. under controlled ring-opening polymerization conditions typically initiated by H_2O or catalytic NaOH. The lactam itself is derived from cyclohexane and chlorinated hydrocarbon feedstocks. During the polymerization sequence, caprolactam is handled and transferred in its liquefied form at 80°C–85°C. In addition, small proportions of caprolactam are employed as cross-linkers in polyurethane formulations and as intermediates in synthetic lysine manufacture. [2], [13], [14]

2.1 Raw material details [15], [16]

1. White crystalline solid, hygroscopic form, or leaflet form.
2. Molecular formula: C6H11NO
3. Molecular weight: 113.16 g/mol.
4. Density: 1) Water 2) Lactam - 1.02
5. Boiling point: 267°C
6. Melting point: 69°C-70°C

3. Reactions of Polymerization

ε-Caprolactam monomers undergo **controlled ring-opening polymerization** to form Nylon 6. In their pure state, these monomers are **thermally inert** and will not polymerize upon heating alone; initiation requires a **catalyst,** typically **H_2O or NaOH,** in the presence of **acetic acid** as a stabilizer. [17]

The commercial manufacturing process of Nylon 6 for fiber production is based on **a water- catalyzed reaction**. The process is in 3 steps. [18], [19], [20]

i) Ring-opening hydrolysis of caprolactam to aminocaproic acid

$NH\ (C)_5\ CO + H_2O = NH\ (C)_5\ COOH$

Caprolactam is a cyclic amide (a lactam). When demineralized (DM) water is introduced at elevated temperature (~220°C–260°C), nucleophilic attack by water breaks the amide ring, producing 6-aminocaproic acid (ACA). This ring-opening hydrolysis is essential because ACA acts as the reactive species (both amine and carboxyl functional groups are present), which undergoes further polycondensation to form long chains of Nylon-6. [21], [22], [23], [24]

ii) Poly-addition

$NH\ (C)_5\ CO + H\ [\ NH\ (C)_5\ CO]\ n\ OH = H\ [\ NH\ (C)_5\ CO]\ (n+1)\ OH$

The poly-addition step is the chain growth stage in Nylon 6 polymerization, where the reactive species generated in the ring-opening hydrolysis (caprolactam and 6-aminocaproic acid) undergo condensation and chain extension. The polymerization mechanism of Nylon-6 proceeds through nucleophilic attack of the terminal $–NH_2$ group of 6-aminocaproic acid or oligomers on the –COOH group of another molecule, resulting in stepwise chain extension via amide bond formation. This process initially generates dimers, trimers, and tetramers, which gradually propagate into long- chain oligomers and high molecular weight polymers. As the reaction is equilibrium-controlled, water is released as a by-product, and its continuous removal, typically under vacuum or reduced pressure, is essential to shift the equilibrium toward higher degrees of polymerization. At the initial stage, ring-opened caprolactam reacts with aminocaproic acid to form adducts that act as chain initiators, facilitating further propagation into linear Nylon-6 macromolecules. [22], [24], [25] Industrially, the reaction is conducted at elevated temperatures (250°C–280 °C) under autogenous pressure, followed by controlled depressurization and vacuum application to remove water vapors effectively. Reactor design (batch or continuous) and residence time play critical roles in determining the molecular weight distribution, while catalysts or promoters such as phosphoric acid or acetic acid may be employed to accelerate chain extension and stabilize the final polymer characteristics. Here, we get (Caprolactam) + (Amino caproic acid) = (Adduct) [26].

iii) Polycondensation

$H\ [\ NH\ (C)_5\ CO]\ n\ OH + H\ [\ NH\ (C)5\ CO]\ m\ OH\ = H\ [\ NH\ (C)_5\ CO]\ (n+m)\ OH + OH$

In the polycondensation stage of Nylon-6 synthesis, oligomers undergo stepwise chain extension accompanied by the elimination of water molecules. This reaction is carried out at elevated temperatures, typically between 230°C and 280°C, where the chain-linking rate of oligomers is very high, leading to a rapid increase in chain length.[27] The number of monomer units linked, expressed as the degree of polymerization (DP), is governed primarily by the maintained temperature and the retention time within the reactor. Since polycondensation is an equilibrium- limited process, efficient and continuous removal of water from the system is crucial to drive the reaction toward higher molecular weights. Industrially, this is achieved under vacuum or by applying controlled pressure release. However, due to the equilibrium constraints, not all caprolactam reacts completely, and approximately 8%–12% of residual monomer and low- molecular-weight oligomers remain in the polymer at processing conditions. Importantly, while the equilibrium constant of polyaddition increases with water content, favoring oligomer formation, the equilibrium constant of polycondensation decreases with water content, making the removal of water. Since, it is a decisive factor in achieving high-molecular-weight Nylon-6 with optimal thermal and mechanical properties. [9], [24], [28], [29], [30]

4. Pre-Polymerization Process

The pre-polymerization stage plays a critical role in ensuring the efficient polymerization of lactam by preparing it in a molten state suitable for subsequent reactions. This stage typically consists of a crusher, melter, filtration units, storage tanks, and mixing tanks, which collectively provide uniform feed quality to the polymerization reactors. The melter and filters are employed to melt and purify the lactam, while the storage tank maintains the processed material under controlled conditions before feeding. The mixing tank ensures homogeneity of the molten lactam, enabling consistent polymerization kinetics in later stages. Each tank is equipped with level indicators, temperature monitoring systems, pressure sensors, and designated control points to maintain precise operational conditions. To ensure uninterrupted flow and operational reliability,

A controllable bypass arrangement of pumps is integrated into the system, allowing continuous processing and minimizing downtime. [31], [32], [33]

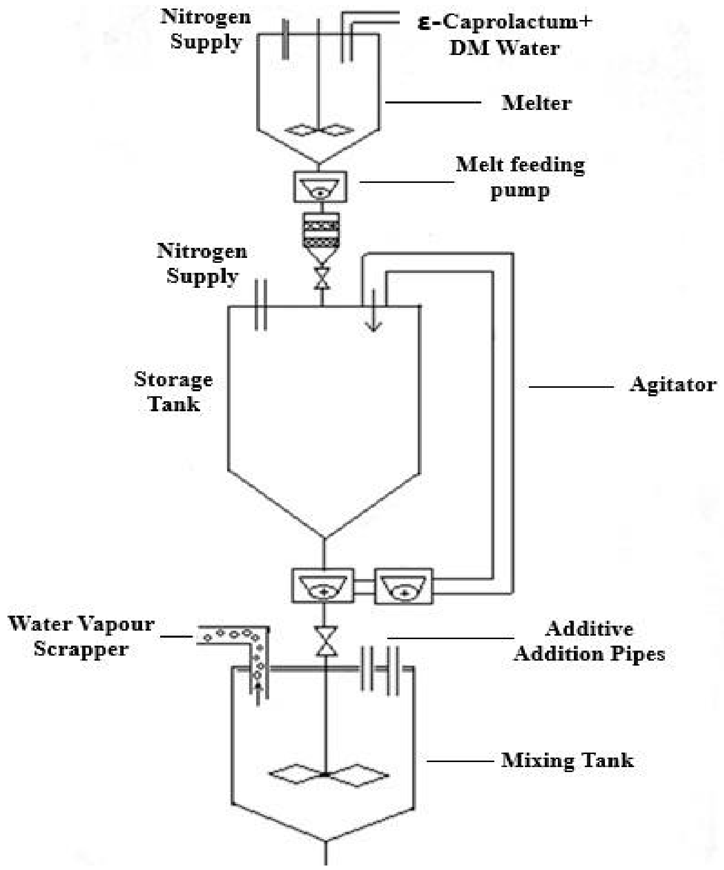

Figure 1: Lactam Preparation Process (Pre-Polymerization Process).

4.1 Melter

Caprolactam is typically processed in flake form after the disintegration of larger lumps through crusher operations. Reduction to smaller particle sizes facilitates efficient melting in the melter. [27], [33] Its key physicochemical properties are summarized in Table 4.1.

Table I: Physicochemical properties of Caprolactam [15], [16], [34], [35]

Property	Value
Molecular weight	113.16 g·mol^{-1}
Density	1.02 g·cm^{-3}
Boiling Point	267°C
Melting Point	69°C

As shown in the figure, in industrial practice, caprolactam flakes are fed into a melter along with distilled mineral (DM) water, where the temperature is maintained at 69°C–70°C by hot steam injection to achieve complete melting. [36] An agitator is employed to ensure homogeneity of the melt, while the reactor atmosphere is kept oxygen-free through continuous nitrogen (N_2) purging to prevent oxidative degradation, which would otherwise compromise polymer quality. The molten lactam is subsequently passed through fine mesh filters (5–10 µm) to remove impurities before being transferred to a storage tank via glass wool–jacketed pipes to minimize heat loss. DM water, added at approximately 1%–5% depending on the targeted polymer properties, serves as the primary catalyst for the ring-opening reaction. Precise control of water content at this stage is critical, as it directly influences both the initiation of polymerization and the final molecular characteristics of Nylon-6. [12], [37]

4.2 Storage Tank

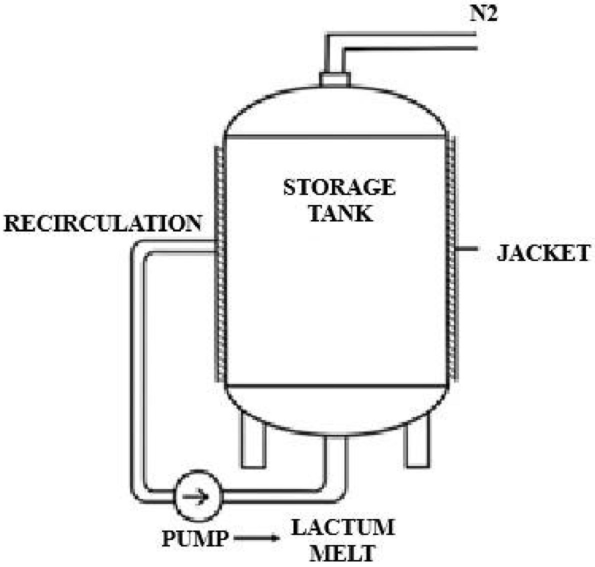

Figure 2: Storage Tank

The storage tank serves as an intermediate reservoir for the lactam melt prior to mixing and subsequent polymerization. Designed with a total capacity of approximately 80–85 tons, it is constructed as a jacketed vessel with hot water circulation and insulated externally with a glass wool sheath to minimize heat loss. The operating temperature is maintained at 90°C–92°C under a nitrogen (N_2) atmosphere to prevent oxidative degradation of the lactam melt. Continuous recirculation using pumps ensures homogeneity, functioning analogously to mechanical stirring.

[7] For safety and process stability, the tank is never operated at full capacity; although its design capacity is 100%, only 60%–75% of the volume is utilized to provide a buffer zone. From this tank, the lactam + DM water melt is pumped into the mixing unit for further processing. [17], [27], [33], [36]

4.3 Mixing Tank

The mixing tank functions as a crucial unit operation for homogenizing the lactam melt with selected additives prior to polymerization. It is equipped with an agitator to ensure uniform distribution of the melt and additives, which are introduced through a dedicated supply line in precisely controlled proportions. Additives are incorporated to impart specific functional properties to the polymer; for instance, titanium dioxide (TiO_2) is commonly used as a delustering agent, while thermal stabilizers are added to enhance heat resistance during subsequent high- temperature polymerization stages. [27], [33] In addition to mixing, the tank is integrated with a deoxygenation chamber designed to eliminate dissolved oxygen and moisture from the melt. The presence of oxygen in the melt can lead to oxidative degradation of caprolactam, adversely affecting polymer quality. At this stage, the melt typically contains caprolactam, water, and traces of oxygen, which are removed under vacuum conditions. During the deoxygenation process, any vaporized lactam is recovered through condensation to minimize material losses. Following this treatment, the purified lactam melt is transferred via pumping into the vertical kneader (VK) reactor, where the main polymerization reaction takes place. [17], [27], [37], [38], [39]

5. Polymerization process

Polymerization is fundamentally defined as the chemical transformation in which many similar or dissimilar monomer units combine to form a macromolecule. This process may occur with or without the elimination of small molecules such as water and generally involves the formation of covalent linkages, often through carbon–carbon (C–C) bonds or other strong chemical bonds. In the case of Nylon 6, polymerization is achieved via the ring-opening polymerization of ε-caprolactam, which undergoes successive chain growth to yield linear polyamide structures.

For industrial-scale production, Nylon 6 is commonly synthesized using continuous polymerization processes carried out in specialized reactors known as VK reactors, also referred to as the VK tube method.[40] The abbreviation “VK” originates from the German phrase “Verandahs Kontenuerlich,” meaning “continuous,” which reflects the operational principle of this method. The VK reactor is designed to ensure precise control of process conditions such as monomer feed, residence time, and temperature distribution, thereby enabling stable polymer growth and consistent product quality. [39], [41]

The efficiency and degree of conversion in the polymerization process are primarily governed by four critical parameters:

i) **Reactor Level Control:** Maintaining appropriate levels within the reactor chamber ensures steady-state conditions and uniform reaction kinetics.

ii) **Temperature Regulation:** Polymerization is highly temperature-sensitive, and optimal control (typically 250°C–

290°C for Nylon 6) is essential for achieving the desired molecular weight while minimizing side reactions. [42]

iii) Residence Time: Sufficient time must be provided for complete monomer conversion and chain extension, balanced against the need for process continuity.

iv) Agitation/Flow Speed: Controlled flow or mixing promotes homogeneous conditions within the reactor and prevents localized overheating or incomplete conversion. [7], [39], [41]

Additionally, the polymerization step often requires an inert atmosphere (e.g., nitrogen blanket) to prevent oxidative degradation and may incorporate vacuum stages to remove by-products such as water vapor. The combination of these parameters ensures high conversion efficiency, controlled molecular weight distribution, and the production of Nylon 6 with the desired mechanical and thermal properties for end-use applications.

5.1 Polymerization Assembly: VK reactor

The VK reactor serves as the primary polymerizer in the continuous production of Nylon-6 and is specifically designed to maintain precise control over reaction parameters during ring-opening, polyaddition, and polycondensation stages. [39], [40] It is a vertical reactor equipped with pressure sensors, level indicators, temperature monitoring systems, and control points, like the pre- polymerization tanks, but adapted for higher operating severity. An agitator is installed to maintain homogeneity of the lactam melt, while below the mixing zone, a series of baffle plates are stacked in sequence. These perforated plates promote uniform distribution, controlled mixing, and laminar flow throughout the reactor column, thereby minimizing dead zones and ensuring efficient contact between reactants. [41], [43]

To prevent oxidative degradation of lactam, the internal environment of the reactor is maintained under a continuous nitrogen (N_2) atmosphere. Initiation of the reaction is achieved by introducing distilled mineral (DM) water through a dedicated inlet, while at the reactor outlet, a metering pump discharges the final polymer melt through a die plate. This die plate, analogous to a spinneret, enables extrusion of the polymer into strands, and the metering pump regulates the polymer flow rate. Pump capacity is expressed in cubic centimeters per revolution (cc/rev), which is determined by the gear tooth configuration and rotational speed, offering precise flow control. [44]

Thermal management within the VK reactor is achieved through a hot oil circulation system. Specialized thermal oils, such as Dowtherm, are preheated in external heater coils and then circulated through reactor jackets to maintain stable internal temperatures in the range of 250°C– 270°C. This arrangement ensures uniform heating and prevents localized overheating, both of which are essential for consistent polymer quality. The typical retention time of the material within the VK reactor is approximately 5–6 hours, providing sufficient residence time for complete polymerization. [39], [41], [42], [44]

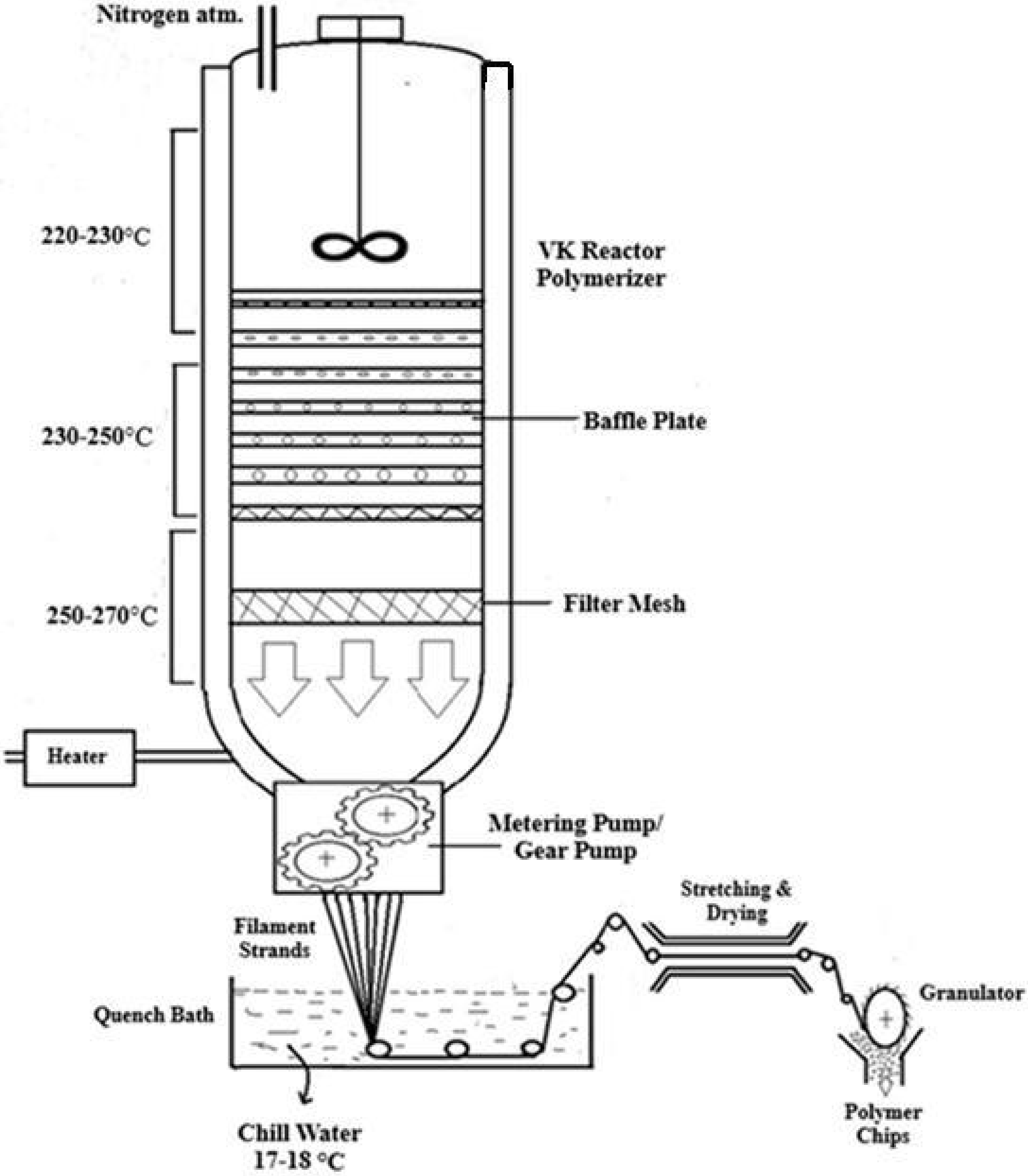

Figure 3: VK reactor – Polymerization assembly of Nylon 6.

Functionally, the VK reactor operates as a staged system encompassing three sequential reaction zones: **(i) the ring-opening stage,** where ε-caprolactam undergoes hydrolytic cleavage to yield aminocaproic acid; **(ii) the polyaddition stage,** where stepwise chain growth occurs through the formation of oligomers; and **(iii) the polycondensation stage**, where high-molecular-weight Nylon-6 chains are formed with the elimination of water as a by-product. This configuration, coupled with precise process control, enables the production of Nylon-6 with well-defined molecular weight distribution and superior thermal and mechanical performance. [23], [24], [30], [39], [41], [45]

5.2 Ring opening stage

$NH\ (C)_5\ CO + O \quad = \quad NH\ (C)_5\ COOH$

The ring-opening stage represents the initiation step in the polymerization of caprolactam. This reaction is triggered by the addition of distilled mineral (DM) water, which acts as a hydrolyzing agent to convert caprolactam into amino caproic acid, the primary reactive intermediate for further chain growth. The process begins only at elevated temperatures, typically in the range of 230– 270°C, where sufficient thermal energy is available to break the lactam ring structure.

At this stage, partial chain extension also occurs as a result of the availability of $-NH_2$ and $-COOH$ groups, enabling limited oligomer formation in parallel with ring-opening hydrolysis. However, the principal objective of this stage is to ensure efficient ring cleavage, which sets the basis for subsequent polyaddition and polycondensation reactions. [36], [41]

The reactor conditions are carefully controlled to avoid water accumulation. A substantial amount of surplus water is generated as the hydrolysis progresses, which exits from the top of the reactor in vapor form. This vapor stream is directed into a condenser, where it is cooled and condensed. The condensate often contains traces of vaporized lactam, which can be recovered and recycled back into the system to improve process efficiency. [7], [38]

For the start-up of fresh polymerization cycles, DM water is introduced from the top of the reactor in a regulated manner to initiate hydrolysis. The amount of DM water added is a critical process parameter, as it strongly influences the equilibrium between ring-opening and subsequent polymerization stages. Maintaining an oxygen-free (N_2) atmosphere during this stage is equally important to prevent oxidative degradation of lactam, which would otherwise reduce polymer quality. [23], [30], [41], [46]

5.3 Poly-Addition reaction stage

$NH\ (C)_5\ CO + H\ [\ NH\ (C)_5\ CO]\ n\ OH = H\ [\ NH\ (C)_5\ CO]\ (n+1)\ OH$

The polyaddition stage follows ring-opening and is characterized as an endothermic process, requiring continuous heat input to sustain the reaction. In this stage, the reactive $–NH_2$ (amino) and –COOH (carboxyl) groups of the hydrolyzed caprolactam intermediates undergo condensation- type linkages, resulting in stepwise chain extension. Initially, monomers couple to form dimers, which subsequently extend to trimers, tetramers, and higher oligomers. [24], [30]

The key feature of this stage is that the reaction primarily involves sequential addition without significant by-product removal, which limits the degree of polymerization. As a result, the polymer chains formed at this point are relatively short, generally extending only up to pentamers or hexamers. Although the chain length achieved is modest, this stage is essential as it prepares stable oligomeric precursors that later undergo substantial chain growth in the polycondensation stage. The efficiency of polyaddition strongly depends on maintaining adequate thermal conditions and uniform mixing inside the reactor. Careful control of temperature is critical, as insufficient heating can result in incomplete oligomerization, whereas overheating may promote degradation or side reactions. Reactor designs such as VK-tube polymerizers employ baffle plates and staged heating zones to ensure laminar flow, efficient mixing, and controlled oligomer formation. [7], [27], [39], [47]

In summary, the polyaddition reaction stage establishes the foundational oligomeric structures necessary for further chain extension. While the degree of polymerization remains relatively low at this point, the proper execution of this stage ensures a smooth transition into the polycondensation stage, where high-molecular-weight Nylon 6 is ultimately achieved Polyaddition has an endothermic reaction in which heat is added to the reaction. [17], [27] During a polyaddition reaction, monomers are linked and converted into dimers, tetramers, and so on. An increase in chain length takes place by an addition reaction (by $-NH_2$ and -COOH). The reaction only extends monomer to dimer to trimer and oligomer conversion in polyaddition. The degree of polymerization achieved here is at an exceptionally low extent, up to a pentamer or hexamer. [24], [38]

5.4 Poly-condensation stage

$H\ [NH\ (C)_5\ CO]\ n\ OH + H\ [NH\ (C)5\ CO]\ mOH\ =\ H\ [NH\ (C)_5\ CO]\ (n+m)\ OH + OH$

The polycondensation stage is the final and most critical step in Nylon-6 synthesis, where short- chain oligomers such as dimers, trimers, pentamers, and hexamers undergo extensive chain linking to form high-molecular-weight polymers. Unlike the preceding polyaddition step, this stage is an exothermic process, releasing heat as the condensation reactions progress. The reaction occurs under controlled conditions of atmospheric pressure and elevated temperatures, typically in the range of 250°C–270°C, which promote equilibrium-driven polymer growth. [12], [45]

During this stage, water is generated as a by-product of amide bond formation. Continuous removal of water vapor from the system is crucial because the equilibrium constant of polycondensation decreases with increasing water content. If water is not effectively removed, the forward reaction slows, and polymer chains fail to achieve the desired degree of polymerization. Industrially, water vapor is withdrawn through top outlets and condensed externally, while nitrogen blanketing prevents oxidative side reactions. [3], [11], [34]

Despite optimized conditions, caprolactam does not completely convert to polymer. A residual fraction, typically 8%–12% unreacted lactam and low-molecular-weight oligomers, remains within the polymer matrix under equilibrium conditions at 230°C–280°C. These residuals are tolerated within specific limits, though post-polymerization extraction or finishing steps are sometimes employed to reduce them further, particularly when high-purity Nylon-6 is required for fiber spinning or engineering applications. [31], [48]

Overall, the polycondensation stage governs the final molecular weight distribution, crystallinity, and mechanical performance of Nylon-6. Reactor design, residence time, and efficiency of water removal are therefore critical operational factors that determine polymer quality and suitability for downstream processing. [49]

5.5 Extrusion & Granulation

The extrusion and granulation stages serve as the transition from polymer melt to processable solid chips, which are subsequently used for fiber spinning or other downstream applications. The process begins with the spin block assembly, which includes spin packs, metering pumps, and downstream quenching and cutting systems. [7], [50], [51], [52]

5.5.1 Spin Block Assembly

A standard spin block consists of four spin packs connected to two precision metering pumps, with each pump supplying two spin packs. [51], [53]

a) Spin Pack:

The spin pack is a critical assembly comprising a series of graded filter meshes (typically four layers of varying micron sizes) and a spinneret plate. [53], [54] The filters eliminate impurities such as dust, unmelted chips, or silica particles, thereby preventing spinneret clogging and ensuring filament uniformity. The spinneret itself contains micron-sized capillaries through which the polymer melt is extruded. The denier of the resulting filaments depends on both the metering pump discharge rate and the spinneret hole dimensions. Furthermore, the number of filaments in the yarn corresponds to the number of spinneret holes, which can be tailored depending on the desired denier specifications for multifilament yarns. [53]

b) Metering Pump:

The metering pump is a gear-type precision pump that regulates the flow of polymer melt through the spin pack under uniform pressure and at a constant rate. It plays a decisive role in filament properties, as the pump speed directly influences filament denier and melt throughput. Stable operation of the metering pump ensures consistency in yarn quality and prevents surges or interruptions in extrusion. [52], [55], [56]

5.5.2 Extrusion and Quenching

The polymer melt, filtered and metered through the spin pack assembly, is extruded as continuous multifilament strands. These hot strands are immediately passed through a quench bath containing chilled water maintained at 13°C–18°C. Rapid cooling induces solidification (coagulation) of the polymer strands, thereby preserving their dimensional stability. The solidified strands are subsequently collected and continuously drawn by a take-up roller system to maintain uniform tension before being conveyed to the granulator. [57], [58], [59], [60]

5.5.3 Granulation Process

The granulator converts the continuous solidified strands into polymer chips (granules) suitable for downstream melting and extrusion processes. It consists of a rotary cutter operating against a stationary knife, with the rotary speed typically maintained in the range of 5000–7000 rpm. The cutter speed determines the chip size, which directly influences processing performance. [61], [62]

5.5.4 Effect of Chip Size

Chip dimensions exhibit an inverse relationship with cutter velocity parameters. The determination of optimal sizing is contingent upon extruder design specifications and operational requirements within the spinning process. Appropriate sizing at the extruder inlet is essential for facilitating adequate thermal transfer mechanisms and achieving melt characteristics that conform to specified properties, thereby enabling enhanced spinning process performance. [63]

Larger Chips reduced heat transfer efficiency between chips results in incomplete melting during subsequent extrusion. This leads to higher melt viscosity and potential spin pack choking, thereby disrupting continuous spinning. [61], [63]

Smaller Chips excessive heat transfer can cause thermal degradation of the polymer, producing frequent filament breaks and compromising yarn quality.

Figure 4: Nylon 6 Chips

Thus, chip size optimization is a critical control parameter. It is carefully adjusted according to the design of the extruder and maintained consistently by regulating the cutter speed of the granulator. The concept of chips per gram (CPG) is often employed to quantify and control chip dimensions, ensuring reproducibility in processing and end-product quality. [61], [63], [64]

6. Post-polymerization process

The post-polymerization stage is essential for refining polymer chips into a form suitable for high- performance fiber and filament production. It primarily involves hot washing and thermal aging of the polymer chips to remove unreacted species, improve chain uniformity, and optimize molecular weight characteristics. [64], [65], [66]

6.1 Hot Washing

After extrusion and granulation, the polymer chips contain approximately 4%–5% residual caprolactam monomer and low-degree-of-polymerization (DP) oligomers. Although the bulk of lactam (~94%–96%) is converted into polymer during the main polymerization stage, these unreacted monomers coat the chip surface and can adversely affect fiber spinning performance and final yarn quality. [67]

The hot washing process employs water at elevated temperatures to selectively leach out unreacted lactam and low-DP oligomers. This step reduces the monomer content on chip surfaces to below 0.5–1.0 wt%, which is the industrially accepted range for high-quality fiber production. Efficient washing not only enhances fiber spinnability but also prevents issues such as filament breakage, dyeability inconsistencies, and inferior mechanical properties in the final product. [61], [62], [63]

6.2 Thermal Aging

Following washing, chips are subjected to thermal aging in confined tanks maintained at elevated temperatures of 180°C–200°C under controlled conditions. During this stage, small amounts of additives may be introduced to impart desired processing or performance characteristics. Common additives include TiO_2 (as a delustering agent) and thermal stabilizers, which improve surface properties, reduce filament sheen, and enhance thermal resistance during subsequent high- temperature processing. [17], [65]

The key purpose of aging is to promote solid-state chain extension, which increases the Relative Viscosity (RV) of the chips. RV serves as an indirect but highly reliable measure of the degree of polymerization (DP) in Nylon 6, since direct DP measurement is impractical. Generally, the RV of freshly polymerized chips ranges from 2.3 to 2.7 cP, but through controlled aging, this value can be increased to 3.6–3.8 cP, corresponding to higher chain length and improved molecular uniformity. Achieving the target RV is crucial, as it directly governs the spinnability, tensile strength, and thermal stability of the final yarns and fabrics. [11], [27], [63], [66]

6.3 Process Control Considerations

Precise control of temperature, residence time, and oxygen exclusion during aging is essential. Excessive temperature or prolonged aging may lead to chain scission and degradation, while insufficient aging results in underdeveloped polymer chains with poor performance characteristics. Thus, optimization of washing and aging processes ensures that Nylon 6 chips achieve the desired balance between purity, molecular weight, and viscosity, ultimately defining their suitability for downstream applications such as textile fibers, engineering plastics, or films. [61], [65], [67]

6.4 Effect of Post-Polymerization Processes on Nylon 6 Chips

Table II: Effect of Post-Polymerization Processes on Nylon 6 Chips. [66], [67], [68].

Stage	Monomer Content (%)	Relative Viscosity, cP (RV)	Degree of Polymerization (DP)	Observation
After Polymerization (Before Washing)	4–5 (residual caprolactam + low-DP oligomers)	2.3 – 2.7	Low (short oligomers, incomplete chain extension)	High residual monomer affects fiber quality, making it unsuitable for spinning.
After Hot Washing	2 ≤ 0.5 – 1.0	2.5 – 2.8	Moderate	Removal of residual lactam improves purity and chip quality, which is essential for spinnability.
After Aging	≤ 0.5 – 1.0	3.6 – 3.8	High (extended chain length, solid-state polymerization)	RV increase indicates higher DP; chips attain stability and properties suitable for high-quality fiber production.

7. Control system parameter

The continuous polymerization of Nylon-6 is a multi-step process involving ring-opening hydrolysis, polyaddition, and polycondensation under strict thermal and pressure conditions. Polymer quality is solely defined by molecular weight distribution, residual monomer content, and viscosity, which is highly sensitive to process fluctuations. Hence, advanced control systems are essential for stable and reproducible reactor operation. Temperature, pressure, level, and flow controls ensure proper kinetics, equilibrium, residence time, and feed accuracy, while monitoring systems track viscosity, monomer levels, and safety interlocks. Integrated feedback and instrumentation are vital to consistently achieve desired properties, energy efficiency, and defect- free production on an industrial scale. [42]

7.1 Key Control Systems in Industrial Nylon-6 Reactors

Efficient polymerization of Nylon-6 requires precise monitoring and control of multiple parameters within the reactor system. The major control loops typically implemented in industrial reactors are described below:

7.1.1 Temperature Control System

Temperature regulation is critical for ring-opening, polyaddition, and polycondensation stages. Multiple thermocouples or RTDs are placed at different zones (top, middle, and bottom) to monitor gradients. Heat is supplied via thermal oil jackets, internal coils, or steam heating, while cooling is achieved through condensers or controlled water injections. Closed-loop PID controllers regulate heating media and jacket flows to maintain 230°C–270°C, ensuring polymer conversion and preventing thermal degradation. [42], [69], [70]

7.1.2 Pressure Control System

Pressure is maintained differently across stages: elevated in pre-polymerization zones and sub- atmospheric in vapor-stripping sections. Pressure sensors, transmitters, and safety relief valves are installed in vapor exits and condenser lines. Control valves, vacuum pumps, or steam ejectors regulate vapor partial pressure to enable caprolactam stripping without destabilizing equilibrium. Maintaining appropriate balance of pressure is essential for both product quality and safety [71], [72], [73].

7.1.3 Level Control System

Liquid holdup levels within the reactor directly influence residence time and conversion. High- temperature molten polymer requires non-intrusive sensing (gamma-ray or differential pressure transmitters). Feedback loops control discharge pump speed or valve opening to maintain ~30% liquid level, ensuring steady polymer withdrawal and preventing vapor entrainment [74].

7.1.4 Flow Control System

Accurate metering of the feeds the caprolactam, water, catalysts, and stripping steam—is essential. Mass or volumetric flow meters coupled with control valves/pumps regulate input ratios and residence time. Uniform steam distribution prevents channeling, while flow controllers manage heating and cooling media. Precise flow control is also necessary for discharging highly viscous polymer melts [75], [76].

7.1.5 Other Monitoring & Advanced Controls

Online measurement of viscosity (via agitator torque), residual monomer concentration, and oligomer content helps predict molecular weight and quality. Safety systems (over-temperature, over-pressure trips) and advanced process controls (e.g., model predictive control, MPC) further optimize stability and efficiency. Controlling residual caprolactam below 0.5%–1% is a critical quality metric [77], [78].

Table III: Key Control System in Industrial Nylon 6 Reactor.

Control System	Purpose / Function	Typical Sensors & Actuators	Challenges/Key Points	References
Temperature Control	Maintain required temperatures for ring-opening, polyaddition, and polycondensation; prevent degradation and freezing.	Thermocouples, RTDs, heating oil jackets, steam coils, condensers, and PID controllers.	Heat load varies with exothermic/endothermic reactions; avoid gradients and thermal degradation.	[42], [69], [70]
Pressure Control	Regulate reactor pressures (elevated for pre-polymerization, reduced for stripping); ensure vapor removal and safety.	Pressure sensors, control valves, vacuum pumps/steam ejectors, and relief valves.	Leakage, vapor condensation, equilibrium stability, and safety risks from overpressure.	[71], [72], [73]
Level Control	Maintain liquid hold-up for residence time and steady discharge; prevent overflow or vapor carryover.	Gamma-ray or differential pressure level sensors, discharge pumps, and automated feedback loops.	Sensor durability at high temperature, viscosity effects, and avoiding oscillations.	[74]
Flow Control	Control feed ratios (caprolactam, water, catalysts, steam); regulate heating/cooling media and polymer discharge.	Flow meters (mass/volumetric), pumps, control valves, and steam distributors.	Uniform steam distribution, viscous flow metering, and phase-change control.	[77], [78]
Other Controls/ Monitoring	Monitor viscosity, residual monomer, and oligomer levels; safety shutdowns; and advanced controls (MPC).	Torque sensors, online viscosity probes, monomer analyzers, and alarms.	Accurate sampling, response delays, and controlling residual monomer <1%.	[75], [76]

8. Melt Spinning

After post-polymerization, the fully dried Nylon-6 chips are converted into continuous filaments using the melt-spinning process, which is the most widely employed method for synthetic fiber production due to its simplicity and efficiency. [52][65], [79]

8.1 Polymer Melting and Extrusion

The chips are first fed into a spinning hopper, where they are heated to 250°C–290°C using an electrically controlled heater system. At this temperature range, Nylon-6 transitions into a stable molten state without significant thermal degradation.

The extruder consists of screws on it and incorporates five distinct heating zones and the barrel of the extruder assembly is coated from inside with silicone gel with magnesium dioxide. The function of the extruder is to melt the chips while simultaneously transferring them at a constant rate from one end to the other. The Fig.5 explains the arrangements in a single-screw extruder. [64], [65]

It contains 5 heating zones with a gradual increase in the temperature. It is heated by the induction heaters, whereas it is blanketed by Dowtherm oil vapors. [52]

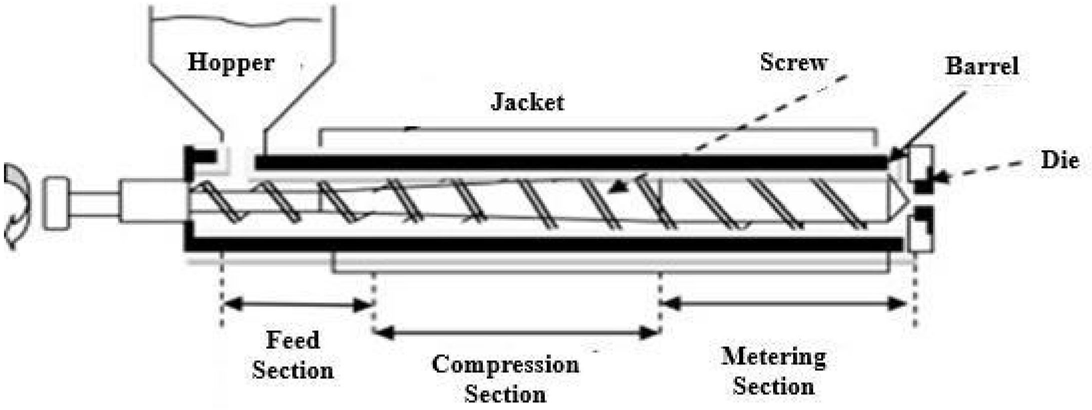

Figure 5: Extruder Arrangement [80]

i) Temperatures - 270°C, 275°C, 275°C, 275°C, 285°C (±5°C) tolerance for all.
ii) Extruder speed - 70 RPM
iii) Pressure - 14.9 Mpa

To further prevent oxidative decomposition, the polymer melt is maintained under an inert nitrogen atmosphere throughout the spinning line. The molten polymer is conveyed at a controlled rate by a screw extruder, ensuring uniform flow and pressure before entering the metering system. [52], [64]

8.1.1 Spin Pack Assembly

The melt is passed through a spin pack, consisting of multiple layers of metal gauze filters followed by precision-engineered spinnerets. The filters remove residual particulates, ensuring melt purity and preventing nozzle clogging, while the spinneret orifices define the filament count and individual filament denier. The combination of metering pump delivery rate and spinneret hole diameter controls the final yarn linear density. [51], [53], [60], [65]

8.1.2 Filament Formation and Quenching

As the polymer melt exits the spinneret, it forms fine continuous streams that rapidly cool and begin to solidify. Controlled quenching air at 16°C–18°C is directed transversely across the filament bundle, inducing solidification by heat exchange. This stage is critical for defining the morphology of the semicrystalline polymer; too rapid quenching may induce voids, while too slow cooling leads to thick filaments with poor uniformity. [57], [60], [65]

8.1.3 Drawing and Orientation

The as-spun filaments (termed as-spun yarn) are weak, amorphous, and highly extensible. To impart mechanical strength, crystallinity, and dimensional stability, the yarn is subjected to a hot drawing process. Multiple godet rollers operating at progressively higher surface speeds stretch the filaments to approximately 4 times to their original length, above the glass transition temperature (Tg ≈ 47°C) but below the melting point. [64] Drawing aligns the molecular chains along the fiber axis, significantly improving tenacity, modulus, and birefringence, while reducing elongation at break. [60], [64], [65]

8.1.4 Godet rollers for Drawing-in of yarn

There are 7 godet rollers used in spinning for the drawing of nylon yarn. Each godet roller has a different speed, temperature and a different number of wraps over it, which is governed by the denier requirements. [65] The number of wraps for improving the dwell time over the godet roller that helps to improve the drawing of yarn. [60], [64]

Figure 6: Godet Assembly

Table IV: Godet settings for Nylon 6

Godet roller	Temperature	No. of wraps
1	Room temperature	3
2	50°C	4
3	100°C	4
4	160°C	4
5	215°C	8
6	100°C	4
7	Room temperature	-

∗*Total Draw Ratio – 4.5-5.5*

8.1.5 Spin-finish Application

After drawing, a spin finish (1%–2% aqueous emulsion of lubricants, antistatic agents, and emulsifiers) is applied to the filament bundle. The spin finish serves multiple purposes: (i) (i) reducing electrostatic charge buildup, (ii) lowering inter-fiber friction, and (iii) improving cohesion and processability during subsequent winding, weaving, or knitting operations. [70], [81]

8.1.6 Take-up and Winding

Finally, the filaments are wound onto bobbins or cheeses in the take-up unit at a speed of 1000– 1500 m/min, depending on the desired yarn characteristics. The winding speed, coupled with the draw ratio, determines the degree of molecular orientation and hence the final fiber properties. Higher take-up speeds generally increase orientation but may also reduce elongation and cause filament breakage if not optimized. [81], [82]

8.1.7 Air Guides

In the melt spinning and drawing line of nylon yarn, air guides play a critical role in modifying the filament bundle structure and enhancing its processability and mechanical properties. In the present configuration, two air guides are strategically positioned as one between the 4th and 5th godet rollers and another after the 7th godet roller. Each serves a distinct purpose in filament handling and yarn quality improvement. [81]

a) First Air Guide (Position: between 4th and 5th godet roller)

The primary function of this guide is filament separation and opening. At this stage, compressed air (0.6 bar) is directed to partially individualize the filaments, thereby preventing filament sticking and ensuring uniform distribution.

This opening of filaments is essential for efficient and uniform application of spin-finish oil, which improves antistatic properties, lubrication, and cohesion during downstream processes such as winding, weaving, or knitting. [82]

Proper spin finish application also prevents yarn damage, reduces filament breaks, and ensures better fiber-to-fiber interaction in subsequent textile operations. [81]

b) Second Air Guide (Position: after 7th godet roller)

This air guide functions as an interlacing or intermingling jet. The compressed air at ~0.3 bar creates localized turbulence, which entangles filaments intermittently, forming discrete knots or entanglement points (typically 5–6 knots per meter of yarn).

These spot entanglements act as binding points, holding the multifilament bundle together without the need for twisting. This enhances yarn cohesion, improves mechanical strength, and prevents filament slippage during handling and processing.

Interlacing is particularly important for high-speed weaving or knitting, where filament separation may lead to processing faults, uneven appearance, or fabric defects. [81], [82]

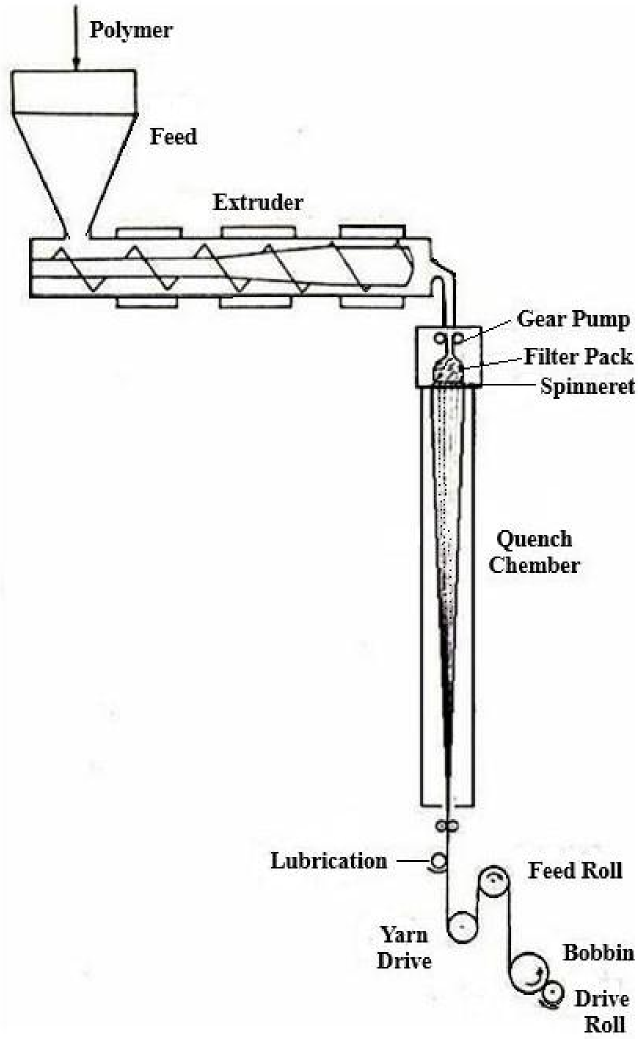

Fig. 7 Melt spinning. [83]

9.0 Physical, Thermal, and Chemical Properties of Nylon 6

Table V: Physical, Thermal, and Chemical Properties of Nylon 6

Property	Value/Range	Property	Value/Range
Density of fiber	~1.14 g/cm³ [84],[85]	**Molecular weight (monomer)**	113.16 g/mol [86]
Moisture regains (65% RH)	3.0-5.0% [87][88]	**Degree of polymerization**	200-300 units [86]
Tenacity (dry)	4.0-7.0 g/denier [84][88]	**Birefringence**	0.060 [85]
Tenacity (wet)	3.0-6.0 g/denier [84][88]	**Abrasion resistance**	Excellent [84],[88]
Elongation (%)	17-45% [84],[89]	**Effect of Sunlight**	Weakened by prolonged exposure [84],[89]
Elastic recovery (2% ext.)	~100% [84]	**Effect of microorganisms**	Non-biodegradable, resistant to fungi/mildew [88],[89]

Tensile modulus	18-23 g/denier [84],[85]	**Recycling**	Possible via depolymerization [88]
Melting temperature (Tm)	213-220 °C [84],[86]	**Acid resistance**	Weak acids: moderate effect; strong acids: hydrolysis [86]
Glass transition temperature (Tg)	30-40 °C [87],[86]	**Alkali resistance**	Good [86]
Decomposition temperature	~315 °C [86],[85]	**Organic solvents resistance**	Resistant to benzene, chloroform, acetone, ethers [86]
Limiting Oxygen Index (LOI)	21-22% [85,[86],[85]	**Solubility**	Dissolves in phenol, cresol, strong mineral acids. [85]
Shrinkage in boiling water	<9% [84][88]	**Oxidizing agents**	Stable, can be bleached [88]
Crystallinity	50-55% [86]	**Dyeability**	Good with acid & basic dyes (due to polar groups) [85]

10.0 Applications and End-Use Significance of Nylon-6

Nylon-6 has emerged as one of the most versatile polyamides, finding applications across technical textiles, consumer textiles, engineering plastics, packaging, and specialty fields. Its performance is governed by controlled polymerization parameters such as molecular weight, viscosity, crystallinity, and residual monomer content, which are achieved through integrated temperature, pressure, flow, and level control systems in industrial reactors**.**

Figure 8: Applications and End-Use Significance of Nylon-6

10.1 Technical Textiles:

Nylon-6 is extensively used in tire cords, conveyor belts, and carpet fabrics, where high tenacity, fatigue resistance, and dimensional stability are crucial. Controlled viscosity and molecular weight distribution ensures spinnability and mechanical durability. [90]

10.2 Marine and Outdoor Applications:

Nylon-6 fibers are applied in fishing nets, ropes, strings, and swimwear, owing to their high tensile strength, abrasion resistance, and low water absorption. Proper process control ensures consistent fiber properties, essential for heavy-duty marine performance. [91]

10.3 Military & Safety Textiles:

Nylon-6 is widely used in parachutes, ballistic vests, and flak jackets, where lightweight toughness and controlled crystallinity are required. Reactor temperature and pressure regulation directly influence the chain structure, which determines impact resistance. [92]

10.4 Biomedical Applications:

Sterile Nylon-6 surgical sutures benefit from high tensile strength, flexibility, and a controlled degradation rate. Polymer purity, achieved via advanced stripping and residual monomer control, is critical for biocompatibility. [93]

10.5 Textile & Apparel:

Nylon-6 finds use in dresses, undergarments, ties, sportswear, and tapestry due to its softness, dye affinity, and wrinkle resistance. Flow and level controls during melt polymerization ensure consistent melt properties, enabling uniform filament production. [94]

10.6 Engineering Plastics:

Nylon-6 is one of the most important engineering thermoplastics, used in molded goods, automotive parts, furniture, sliders, door handles, hangers, and gears. Processing routes include injection molding, extrusion, blow molding, monomer casting, and coatings. Reactor control of viscosity and molecular weight enables compatibility with fillers and additives for tailored performance. [95], [96]

10.7 Advanced Property Modifications:

By incorporating additives and copolymers, Nylon-6 can be tailored for oil and solvent resistance, toughness, creep resistance, low friction, fire retardancy, and thermal stability. Process control is crucial to ensure the homogeneous distribution of these modifiers. [92], [94]

10.8 Packaging Films & Sheets:

Nylon-6 is widely used in food packaging films for its oxygen barrier properties, transparency, and mechanical toughness. Low residual monomer content, achieved through pressure/vacuum control, is critical to minimize extractables and ensure safety in contact applications. [97], [98]

11. Conclusion & Perspective

Nylon-6 remains one of the most important synthetic polyamides, combining strength, toughness, thermal stability, and chemical resistance with remarkable processing versatility. Its production, based on the ring-opening polymerization of ε-caprolactam, is highly sensitive to catalysts, reaction temperature, and pressure, all of which determine molecular weight, crystallinity, and viscosity. Careful control of downstream operations including extrusion, quenching, granulation, and spin-block metering ensures stable feedstock properties and uniform fiber spinnability, while minimizing residual monomer content.

Applications of Nylon-6 span technical textiles, engineering plastics, packaging films, biomedical devices, and protective gear. Its performance across these diverse domains is supported by fine- tuned processing routes such as injection molding, extrusion, and melt spinning. Recent advances in copolymerization, nanofiller incorporation, and reactive extrusion have further extended Nylon- 6's property spectrum to include enhanced flame retardancy, barrier properties, and creep resistance.

Looking forward, two major directions define the future of Nylon-6. First, sustainability: the transition toward bio-based caprolactam, energy-efficient polymerization methods, and closed- loop recycling are essential to address environmental concerns and regulatory challenges. Second, advanced applications: developments in electrospinning, additive manufacturing, and nanocomposite engineering are expected to push Nylon-6 into next-generation markets including aerospace components, smart textiles, and biomedical scaffolds. Nylon-6 combines a strong industrial legacy with evolving scientific relevance. Its adaptability, coupled with advances in processing and sustainable chemistry, ensures that Nylon-6 will continue to play a pivotal role in both established and emerging high-performance applications.

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