Plasma Technology for Textiles

Definition of Plasma (2022)

- Plasma is the fourth state of matter that is different from solid, liquid, and gas states.
- Plasma is a highly ionized and electrically conductive gas consisting of proportionately positive ions and free electrons.
- A gas becomes plasma with the addition of high heat and high pressure.
- This ionization process gives plasma its unique properties, including the ability to conduct electricity, respond to electromagnetic fields, and emit light.

Basic Concept of Plasma IMPORTANT

- Plasma technology is based on a simple physical principle.
- At room temperature, some matter exists in a solid state, some are in the form of liquid, and some are in the form of a gaseous state.
- Each matter can also exist in all three states if it is heated to a temperature above room temperature and cooled to below room temperature.

For example,

- Water is in a liquid state at room temperature and atmospheric pressure.
- If water is cooled to below 0°C, much lower than room temperature, it will turn into ice—the solid state of water.
- On the other hand, when water is heated to 100 °C, it turns into its gaseous state—steam (Figure 1).

- Now consider what will happen if the steam is heated to a temperature much higher than 100°C.
- Some water molecules (H_2O) may dissociate into **hydrogen** and **oxygen** atoms. The hydrogen and oxygen atoms may ionize to form positive ions and electrons while the temperature is high enough. **This "ionized" state of water is the fourth state of matter, called the plasma state.**

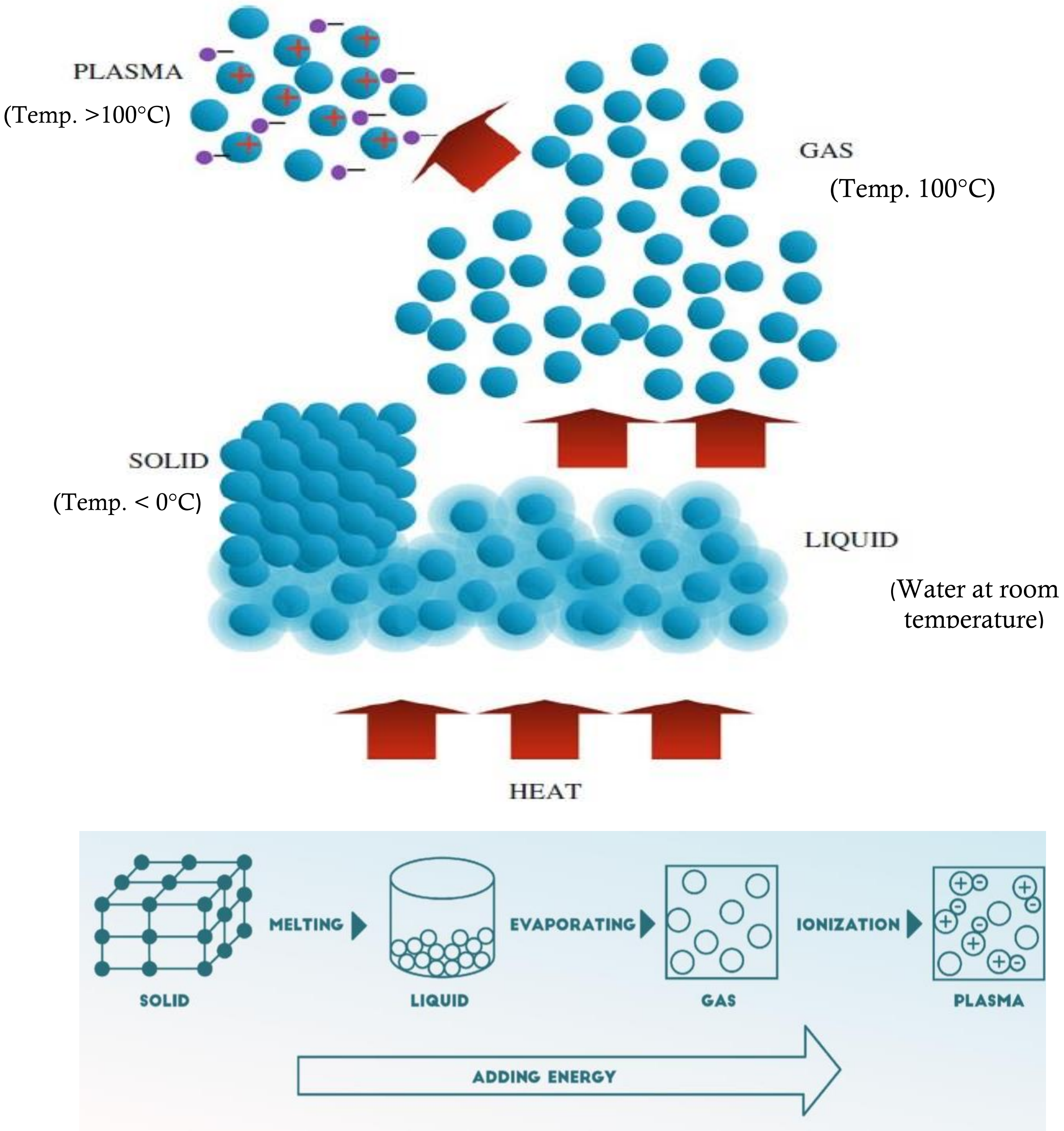

Figure 1: Plasma—the fourth state of matter

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Characteristics of Plasma

1. **Ionization**: Plasma is characterized by a significant fraction of charged particles (ions and electrons) due to the high energy involved.
2. **Conductivity:** Plasma is an excellent conductor of electricity because of the presence of free electrons.
3. **Response to Electromagnetic Fields**: Plasmas can be influenced by electric and magnetic fields, and they can emit radiation in various parts of the electromagnetic spectrum, including visible light, ultraviolet light, and X-rays.
4. **High Temperature:** Plasmas are typically very hot, with temperatures ranging from thousands to millions of degrees Celsius, depending on the specific plasma.
5. **Low Density:** Despite its high temperature, plasma is often less dense than its solid or liquid counterparts.

Classification of Plasma

- High-temperature plasma (about 100 million °C).
- Low-temperature plasma (≈ near 50°C- used for textiles).
- Low-pressure plasma.
- Atmospheric pressure plasma.

Difference Between Atmospheric Pressure and Low Pressure Plasma in Textiles (Shortly):

Atmospheric Pressure Plasma:

Operates at normal atmospheric pressure

No vacuum needed (cost-effective)

Suitable for continuous processing

Less uniform treatment

Low Pressure Plasma:

Operates under vacuum

Requires controlled chamber (costly)

Ensures uniform and deep treatment

Better for precision applications

Application in Textiles (2019)

- Desizing
- Wettability enhancement
- Water /soil repellence
- Dye/print ability
- Shrink resistance

(2022) Importance /Advantages of Plasma Technology/Process

- The electrons in low-temperature plasmas can slice covalent chemical bonds, thereby producing physical and chemical modifications of the surface of the treated substrate without changing the fibre properties.
- No or less chemicals are required; hence, no waste is generated.
- No drying process is required, and hence, no wastewater is generated.
- It ensures Eco-friendly and Sustainable Textiles due to no or less chemicals and no drying process.
- Change in fibre wettability (hydrophilic, hydrophobic properties);
- Increase in dyestuff affinity.
- Improve dye levelling properties.
- Anti-felt finishing in wool.
- High environmental compatibility of the processes.
- The processes can be applied to almost all kinds of fibres.

- Requires extremely short treatment time and low application temperature.
- Therefore, plasma treatment represents an energy-efficient and economical alternative to classical Textile finishing processes.

Different types of Energy are required to generate the plasma

- Low frequency (LF), 50–450 kHz;
- Radio-frequency (RF), 13.56 or 27.12 MHz;
- Microwave (MW), 915 MHz or 2.45 GHz.
- The power required ranges from 10 to 5000 watts, depending on the reactor size and desired treatment.

Gases commonly used for plasma treatment are:

- chemically inert (e.g. helium and argon);
- reactive and non-polymerizable (e.g. ammonia, air and nitrogen);
- reactive and polymerizable (e.g. tetra fluoroethylene, hexamethyl disiloxane)

Differences between Atmospheric Pressure and Low Pressure Plasma

Parameters	Atmospheric pressure plasma	Low pressure plasma
Plasma generation	High tension (1-100kv; 20-40kHz) between dielectric coated electrodes.	Direct current (DC) or high frequency up to microwave range.
Pressure	Atmospheric pressure	Low pressure (0.1 - 1mbar)
Extension of plasma	30 µm (Micro-discharge)	Electrode diameter
Life time	1-10 ns	Permanent
Continuous process control	Simple	Complex

(2022)

Difference between traditional Wet Chemistry and Plasma Process

Parameters	Plasma process	Wet chemistry process
Medium	Treatment by excited gas phase	Water based
Energy	Electricity(Only free electron heated)	Heat (Temperature of entire system must be raised)
Energy consumption	Limited for atmospheric plasma but greater for vacuum plasma	High energy consumption
Temperature	Room Temperature	High Temperature
Water consumption	Negligible	High

Environmental Benefits of Plasma Technology (2020)

- In some cases, increasing adhesion between the Textile and a layer, such as a coating or **glue resulting from plasma pre-treatment, can avoid pre-processing, such as applying a chemical primer or a solvent process.**

- Regarding water pollution, it has to be taken into account that the fluorocarbon resins of the wet processes are all characterized by poor biodegradability and bio-eliminate ability.

- Therefore, plasma technology can achieve substantial environmental benefits regarding reduced discharge.

Biodegradation and its steps

- Degradation is a process of breaking down a material into its fundamental elements by a physical, chemical or biochemical process which should be irreversible.

(2021,22)

- **Biodegradation** is a natural process by which organic substances are broken down into simpler compounds through the action of microorganisms such as bacteria, fungi, and other enzymes. These microorganisms feed on the organic material as a source of energy and nutrients, and as a result, they transform complex organic molecules into simpler, more stable substances.

  Biodegradation of a material takes place in three steps (2020)

  i. **Bio-deterioration ·**

  ii. **Bio-fragmentation ·**

  iii. **Assimilation.**

- **Bio-deterioration** of materials is a combined result of many degradative factors like **mechanical degradation, thermal degradation and degradation due to the presence of moisture, oxygen, ultraviolet light and environmental pollutants.**
  Due to the result of these mentioned factors, a huge amount of microorganisms stick onto the surface of materials.
- **Bio-fragmentation, is a natural process in which larger organic materials, such as dead plants and animals, are broken down into smaller pieces such as oligomers, dimers and monomers by biological organisms and physical forces.**
- Microorganisms produce new biomass and various metabolites using energy, and simple gaseous molecules and mineral salts are released into the environment in the last step of **assimilation.**

Types of Bio-degradation

- There are two types of Biodegradation, **aerobic and anaerobic**.

- **When material is biodegraded in the presence of oxygen, it is called aerobic Biodegradation, and if without oxygen, then anaerobic Biodegradation.**

- For a material to be completely biodegraded, it must be converted into **carbon dioxide, water and minerals**, and the intermediate products should contain.

- Aerobic and anaerobic processes of degradation can be represented by equations 1 and 2, where Cpolymer represents either a polymer or a fragment that is considered to be composed only of carbon, hydrogen and oxygen.

Aerobic biodegradation (2019,21)

Aerobic biodegradation refers to the process by which microorganisms, such as bacteria and fungi, break down organic substances in the presence of oxygen. This natural process results in the transformation of complex organic compounds into simpler end products such as carbon dioxide (CO_2), water (H_2O), biomass, and other inorganic substances.

- Aerobic biodegradation

$$C_{polymer} + O_2 \rightarrow CO_2 + H_2O + C_{residue} + C_{biomass} + Salts \qquad \text{Equation 1}$$

Key Features of Aerobic Biodegradation:

1. **Presence of Oxygen**: Oxygen is essential for the metabolic activities of aerobic microorganisms, which use it as an electron acceptor to break down organic matter.
2. **Microorganisms Involved**: Various bacteria (e.g., *Pseudomonas*, *Bacillus*) and fungi (e.g., *Aspergillus*, *Penicillium*) play a role in this process.
3. **End Products**: The primary products are CO_2, water, and microbial biomass.
4. **Applications**:
    - **Wastewater Treatment**: Aerobic biodegradation is a key mechanism in activated sludge systems and other biological wastewater treatment processes.
    - **Composting**: Organic waste, such as food scraps and yard debris, is aerobically degraded to produce compost.
    - **Environmental Remediation**: Aerobic biodegradation is used to clean up pollutants, such as hydrocarbons in soil and water (bioremediation).

Importance:

- Aerobic biodegradation is a critical component of the natural carbon cycle and plays a significant role in reducing environmental pollution by converting waste into harmless or useful byproducts.
- It is also more efficient and faster than anaerobic biodegradation due to the higher energy yield provided by oxygen.

When Cpolymers are completely converted into gaseous products and salts, then the Biodegradation is completed.

Anaerobic biodegradation (2019,21)

Anaerobic biodegradation is the process by which microorganisms, such as bacteria and archaea, break down organic substances in the absence of oxygen. This natural process results in the production of simpler compounds such as methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S), and other organic acids.

- Anaerobic biodegradation

$$C_{polymer} \rightarrow CO_2 + CH_4 + H_2O + C_{residue} + C_{biomass} + Salts \qquad \text{Equation 2}$$

Key Features of Anaerobic Biodegradation:

1. **Absence of Oxygen**: Anaerobic microorganisms utilize alternative electron acceptors (e.g., nitrate, sulfate, carbon dioxide) instead of oxygen for their metabolic activities.
2. **Microorganisms Involved**: Common groups include:
    - Hydrolytic bacteria: Break down complex organic matter into simpler molecules.
    - Acidogenic bacteria: Convert these molecules into organic acids, alcohols, and hydrogen.
    - Methanogens: Specialized archaea that produce methane from these intermediates.
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3. **End Products**: Methane, carbon dioxide, ammonia, hydrogen sulfide, and organic acids.
4. **Applications**:
    - **Biogas Production**: Anaerobic digestion is used to convert organic waste (e.g., food waste, agricultural residues) into biogas (methane and CO_2), which can be used as a renewable energy source.
    - **Wastewater Treatment**: Anaerobic processes treat high-strength industrial wastewater and sludge, reducing waste volume and recovering energy.
    - **Landfills**: Organic matter decomposes anaerobically in landfill environments, producing landfill gas.

Comparison to Aerobic Biodegradation: (2019,21)

- **Energy Yield**: Anaerobic biodegradation is slower and produces less energy per molecule of substrate compared to aerobic biodegradation.
- **Byproducts**: It generates methane, a potent greenhouse gas, but this can be captured and used as an energy source.
- **Conditions**: Occurs in oxygen-deprived environments, such as sediments, wetlands, or sealed digesters.

Factors Affecting the Biodegradation

Biodegradation, the natural process by which organic substances are broken down by microorganisms into simpler compounds, can be influenced by a variety of factors.

Type of Organic Material: The composition and nature of the organic material being biodegraded play a significant role. Some organic compounds are more readily biodegradable than others.

Microorganisms: The presence and activity of specific microorganisms capable of degrading the target organic material are crucial. Different microorganisms have different enzymatic capabilities, and their effectiveness in breaking down specific compounds varies.

Environmental Conditions: Environmental factors such as **temperature, pH, moisture content, oxygen availability, and nutrient levels** can significantly influence biodegradation. Microorganisms have optimal conditions for activity, and deviations from these conditions can slow down or halt the process.

Nutrient Availability: Adequate nutrient levels, particularly nitrogen and phosphorus, are essential for microbial growth and metabolism. If the organic material lacks these nutrients, the biodegradation process may be limited.

Toxic Substances: The presence of toxic chemicals in the organic material can inhibit or even kill the microorganisms responsible for biodegradation. Contaminants can include heavy metals, pesticides, and certain industrial chemicals.

Physical Structure: The physical characteristics of the material, such as its size, surface area, and accessibility to microorganisms, can affect biodegradation. Smaller particles and increased surface area may enhance microbial activity.

Time: Biodegradation is often a time-dependent process. Some compounds may biodegrade quickly, while others may take much longer. The rate of biodegradation can vary from days to years or even centuries, depending on the material and conditions.

Microbial Activity

- Our environment is surrounded by a countless number of microorganisms, so nothing in this world is free from the influence of microorganisms.
- However the effect of microorganisms could be pleasant or destructive.
- In most cases, the microorganisms cause problems in the service and life of materials.
- A very simple reason for this is that the microorganisms are also living things, and they require food for their survival, which they get from the materials on which they live in, resulting in degrading them.
- A bio destructor source is required for a material to be biodegraded. The source, microorganisms are present in the atmosphere and the soil as well.

- In fact, soil is very rich in microorganisms, and its layer from 5 to 15 cm deep is most saturated with microorganisms, and one gram of soil contains up to 108 microorganisms.

Steps of Degradation by Microorganism (2019)

- Microorganisms attack any fibre or material surface according to the following steps:

i. Microorganisms stick onto the surface of a material either by adhesion or aggregation
ii. Spread of attached microbial cells
iii. Production of enzymes
iv. Biodegradation of material
v. Reduction of the degree of polymerization of the material polymers
vi. Production of degradable products

Biodegradation of Cellulosic Textile Substrates

- The degradation rate of cellulose and cellulosic textile substrates mostly depends on the microorganisms used.
- Bacteria and fungi are the two main groups of microorganisms responsible for the enzymatic degradation of cellulose.
- In the presence of bacteria, the degradation of the cellulose fabrics proceeds from the surface towards the inside. After the revival of the

cuticle, the organisms penetrate through the secondary wall into a lumen in the presence of fungi.

- The primary function of the enzymes is to decrease the degree of polymerization, damaging the fibres' structure and the fibres' loss of their strength.
- The cellulose degradation rate is directly related to its degree of crystallinity.
- Hence, amorphous cellulose having less degree of crystallinity is more susceptible to enzymatic degradation than a crystalline one.
- The degradation rate also depends on other parameters like degree of orientation, substitution, and presence of non-cellulosic substances.