FST 303

FOOD PROCESS ENGINEERING

- Course code: FST 303
- Course title: Food Process Engineering
- Course credit load: 2

Series 1: Thermophysical Properties of Food

Series outline

- **1.1 Glossary of Thermophysical Properties**
  - 1.1.1 Definition and scope
  - 1.1.2 Key categories of properties
  - 1.1.3 Importance in food processing
- **1.2 Methods of Determination**
  - 1.2.1 Experimental techniques
  - 1.2.2 Instrumentation and measurement tools
  - 1.2.3 Limitations and accuracy considerations
- **1.3 Relevance to Food Processing**
  - 1.3.1 Role in heat transfer and mass transfer
  - 1.3.2 Influence on equipment design and operation
  - 1.3.3 Case examples in thermal processing
- **1.4 Food Composition versus Thermophysical Properties**
  - 1.4.1 Relationship between composition and properties
  - 1.4.2 Variations across food categories
  - 1.4.3 Practical implications for engineers

Introduction

Food processing often involves the transfer of heat and mass, both of which depend heavily on the physical characteristics of the food material. These characteristics, known as **thermophysical properties**, determine how foods respond to heating, cooling, freezing, and drying. For instance, the way milk boils or the way bread bakes is influenced by these properties. By studying them, food engineers can design safer, more efficient, and more consistent processes. This Series therefore provides the foundation for understanding how food behaves under different processing conditions, making it essential for the rest of the course.

The aim of this Series is to equip you with the ability to define, measure, and analyse the thermophysical properties of food, and to evaluate their relevance in food processing operations.

We shall commence this Series by examining the glossary of thermophysical properties, where you will learn their definitions and categories. Next, we will move on to methods of determination, focusing on experimental techniques and measurement tools. Following that, we will explore their relevance to food processing, considering how they affect heat transfer, equipment design, and practical applications. Finally, we will wrap up by analysing the relationship between food composition and thermophysical properties, highlighting variations across food categories and their implications for engineers.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 1.1** define the glossary of thermophysical properties of food,
- **SLO 1.2** explain methods used to determine thermophysical properties,
- **SLO 1.3** analyse the relevance of thermophysical properties in food processing operations, and
- **SLO 1.4** evaluate the relationship between food composition and thermophysical properties.

1.1 Glossary Of Thermophysical Properties

1.1.1 Definition and scope

The term **thermophysical properties** refers to the physical characteristics of food materials that influence how they respond to heat and mass transfer. These include properties such as thermal conductivity, specific heat, density, and viscosity. They are essential because they determine how food behaves during processes like heating, cooling, freezing, and drying. Without accurate knowledge of these properties, engineers cannot design reliable food processing systems.

Fill in the blank: The property that describes how easily heat passes through a food material is called _________.

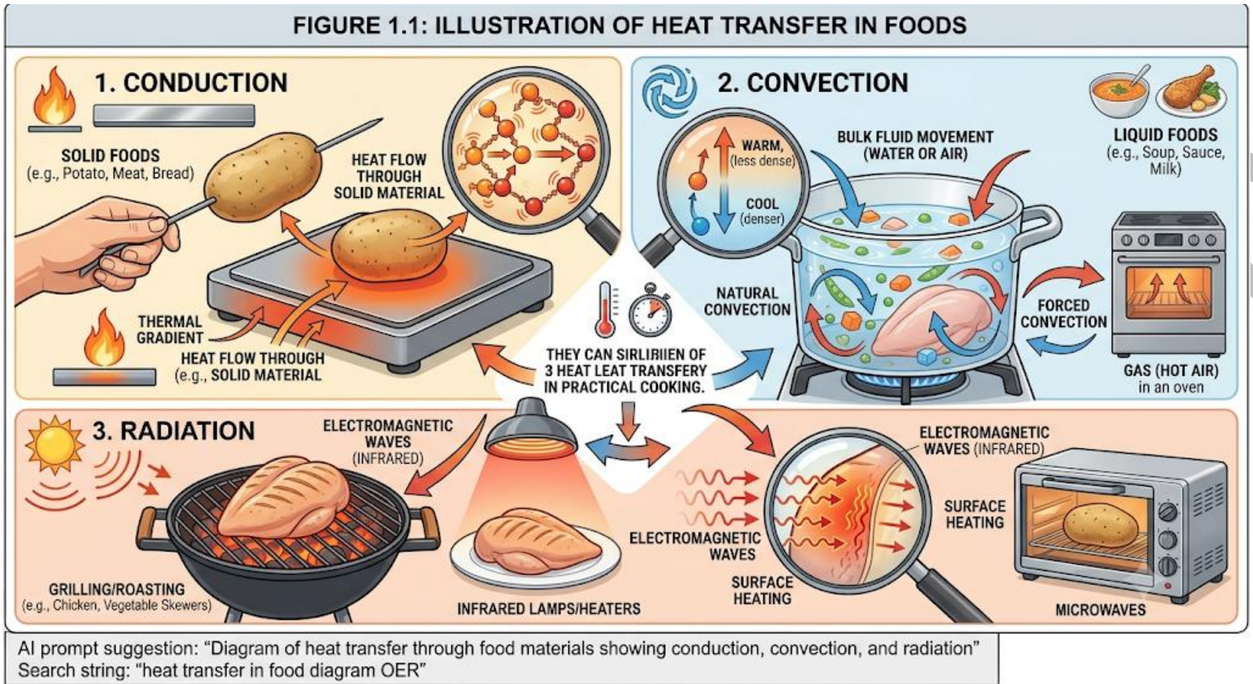


Diagram showing heat transfer through different food materials *Figure 1.1: Illustration of heat transfer in foods*

1.1.2 Key categories of properties

The main categories of thermophysical properties include:

- **Thermal conductivity**: the ability of a food material to conduct heat.
- **Specific heat capacity**: the amount of heat required to raise the temperature of a unit mass of food by one degree Celsius.
- **Density**: the mass per unit volume of food, which affects both heat and mass transfer.
- **Viscosity**: the resistance of a fluid food to flow, which influences pumping and mixing operations.

Each of these properties varies depending on the composition of the food, such as its water, fat, protein, and carbohydrate content. For example, foods with high water content generally have higher specific heat values.

Fill in the blank: The resistance of a fluid food to flow is referred to as __________.

Comparison of selected thermophysical properties of common foods *Table 1.1: Typical values of thermophysical properties in foods*

Food Material	Thermal Conductivity (W/m·K)	Specific Heat (kJ/kg·K)	Density (kg/m3)	Viscosity (Pa·s)
Milk (Whole)	~ 0.55 - 0.60	~ 3.85 - 3.95	~ 1028 - 1035	~ 0.0015 - 0.0025
Bread (White)	~ 0.06 - 0.20	~ 2.40 - 2.90	~ 200 - 300	Not applicable (Solid)
Meat (Beef, Lean)	~ 0.40 - 0.55	~ 3.30 - 3.60	~ 1040 - 1080	Not applicable (Solid)

1.1.3 Importance in food processing

Thermophysical properties are crucial in designing and controlling food processing operations. For instance, thermal conductivity determines how quickly heat penetrates canned foods during sterilisation, while viscosity affects the efficiency of pumping tomato paste through pipelines. Engineers must consider these properties to ensure food safety, quality, and energy efficiency.

Fill in the blank: During sterilisation of canned foods, the property that determines how quickly heat penetrates is __________.

Box 1.1: Case study – Tomato paste processing Description: Tomato paste has high viscosity, which requires specialised pumps and careful heat transfer calculations to avoid uneven heating.

Description:	Tomato paste has high viscosity, which requires specialised pumps and careful heat transfer calculations to avoid uneven heating.
Processing Challenges:	* **Flow and Transport:** Because of its thickness, standard pumps may fail. Specialised equipment like rotary lobe pumps or piston pumps are needed to move the paste without damaging it (shearing).
	* **Heat Transfer:** Standard heat exchangers (like plate-and-frame) may plug or lead to burning if the paste moves too slowly. Specialised heat exchangers, such as scraped surface or double-pipe systems, must be used to ensure uniform heating.

	* **Mixing:** Achieving homogeneous mixing becomes difficult with high-viscosity materials, requiring high-torque mixers and carefully designed agitation systems.
Food Engineering Impact:	The entire system must be designed based on non-Newtonian fluid dynamics to maintain product quality and process efficiency.

Pilot questions 1.1

1. Which property describes the amount of heat required to raise the temperature of a unit mass of food by one degree Celsius?
2. What is the term used for the mass per unit volume of food?
3. Which property influences the efficiency of pumping operations in fluid foods?
4. Why are thermophysical properties important in food processing operations?
5. Give one example of how food composition affects thermophysical properties.

1.2 Methods Of Determination

1.2.1 Experimental techniques

To measure **thermophysical properties**, food engineers rely on carefully designed experiments. For example, **thermal conductivity** can be determined using methods such as the line heat source technique, where a heated probe is inserted into the food and the rate of heat transfer is measured. Similarly, **specific heat capacity** is often measured using calorimetry, which involves heating a known mass of food and recording the temperature change. These experiments must be conducted under controlled conditions to ensure accuracy.

Fill in the blank: The method commonly used to measure specific heat capacity in foods is _________.

Figure 1.2: Calorimetry experiment for food samples

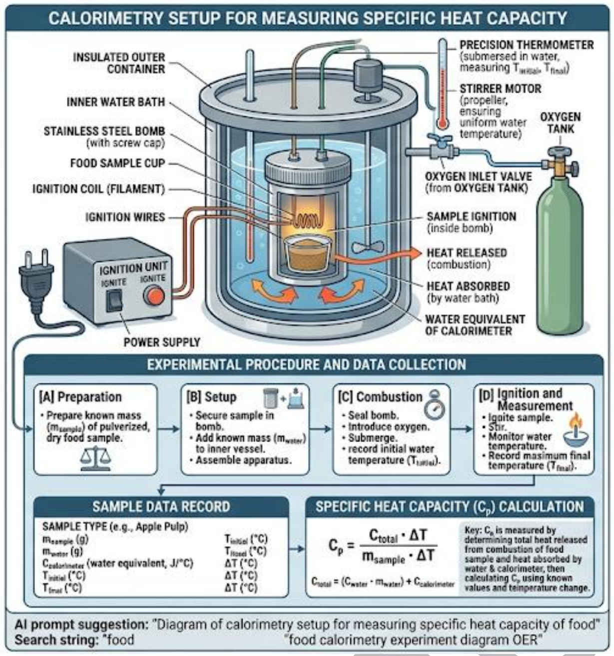


Diagram showing calorimetry setup for measuring specific heat capacity *Figure 1.2: Calorimetry experiment for food samples*

1.2.2 Instrumentation and measurement tools

Accurate measurement of thermophysical properties requires specialised instruments. For instance, a **viscometer** is used to measure viscosity, while a **pycnometer** is employed to determine density. Advanced tools such as differential scanning calorimeters are used to study heat flow in foods during phase changes like melting or freezing. These instruments provide precise data that can be applied in designing food processing equipment.

Fill in the blank: The instrument used to measure viscosity in fluid foods is called a _________.

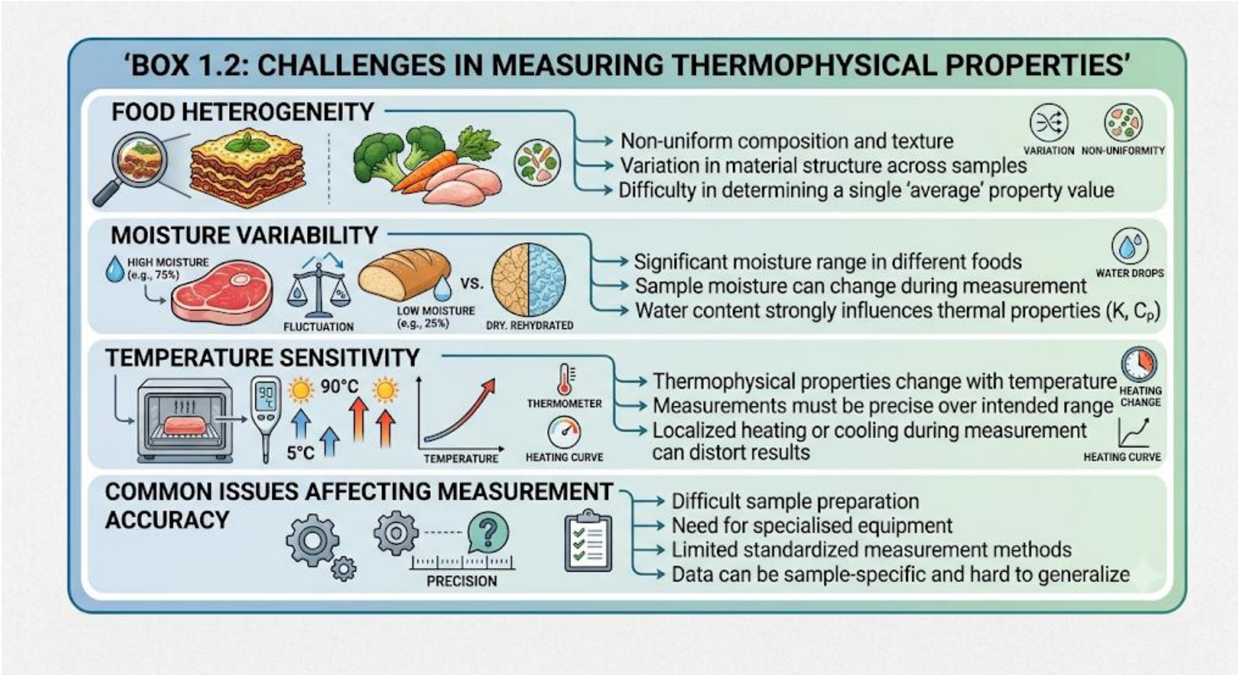
Plate 1.1: Laboratory viscometer for measuring viscosity

] Image of a viscometer used in food laboratories *Plate 1.1: Laboratory viscometer for measuring viscosity*

1.2.3 Limitations and accuracy considerations

While these methods and instruments are effective, they are not without limitations. Food materials are often heterogeneous, meaning their composition varies across samples. This can lead to inconsistencies in measurements. Additionally, temperature and moisture content can significantly affect results. Engineers must therefore interpret data carefully, often repeating experiments to confirm reliability.

Fill in the blank: One major challenge in measuring thermophysical properties of food is its _________ nature.



Box 1.2: Challenges in measuring thermophysical properties Description: Food heterogeneity, moisture variability, and temperature sensitivity are common issues that affect measurement accuracy.

Pilot questions 1.2

1. Which technique is commonly used to measure thermal conductivity in foods?
2. What is the name of the instrument used to measure density in food samples?
3. Which advanced tool is used to study heat flow during phase changes in foods?
4. Why is food heterogeneity a challenge in measuring thermophysical properties?
5. How can engineers improve the reliability of measurements in food experiments?

1.3 Relevance To Food Processing

1.3.1 Role in heat transfer and mass transfer

The **relevance of thermophysical properties** lies in their direct influence on how foods undergo heat and mass transfer during processing. For example, **thermal conductivity** determines how quickly heat penetrates into canned foods during sterilisation, while **specific heat capacity** affects the amount of energy required to raise the temperature of frozen vegetables. These properties are therefore critical in ensuring food safety and quality.

Fill in the blank: The property that influences the amount of energy required to raise the temperature of food is _________.

Figure 1.3: Heat transfer in canned food processing

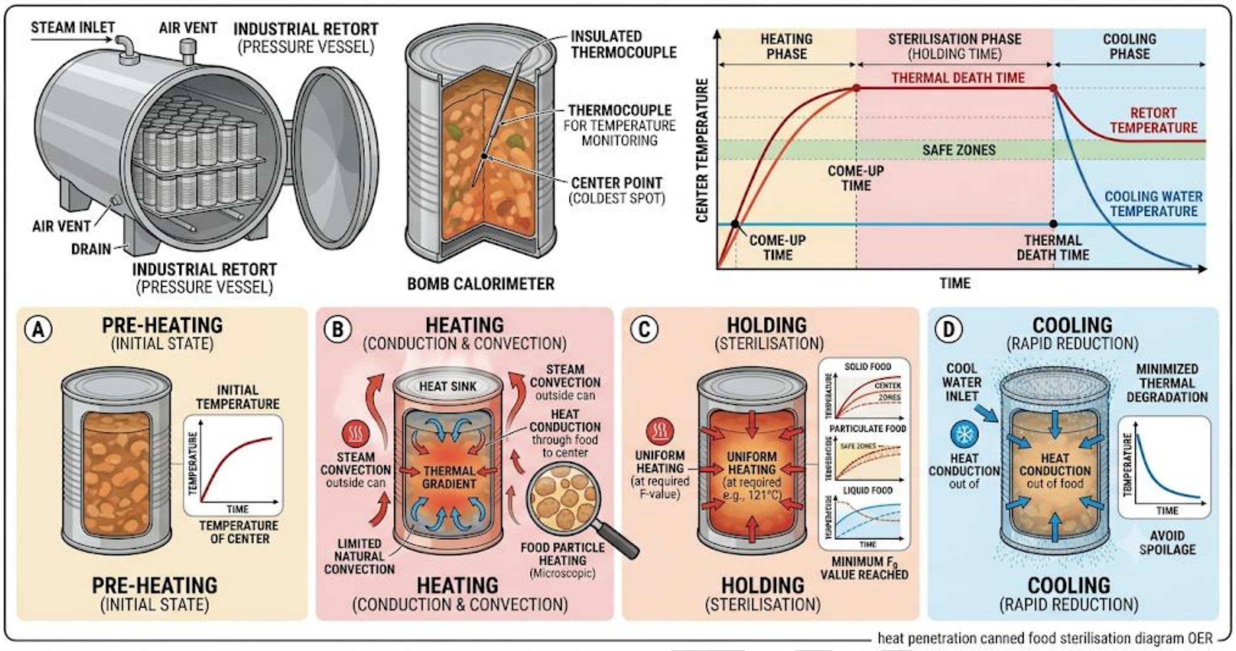


Diagram showing heat penetration in canned food during sterilisation *Figure 1.3: Heat transfer in canned food processing*

1.3.2 Influence on equipment design and operation

Food processing equipment must be designed with thermophysical properties in mind. For instance, high-viscosity foods such as sauces require pumps with greater power, while foods with low thermal conductivity need longer heating times in retorts. Engineers use property data to select appropriate equipment, optimise energy use, and maintain product quality.

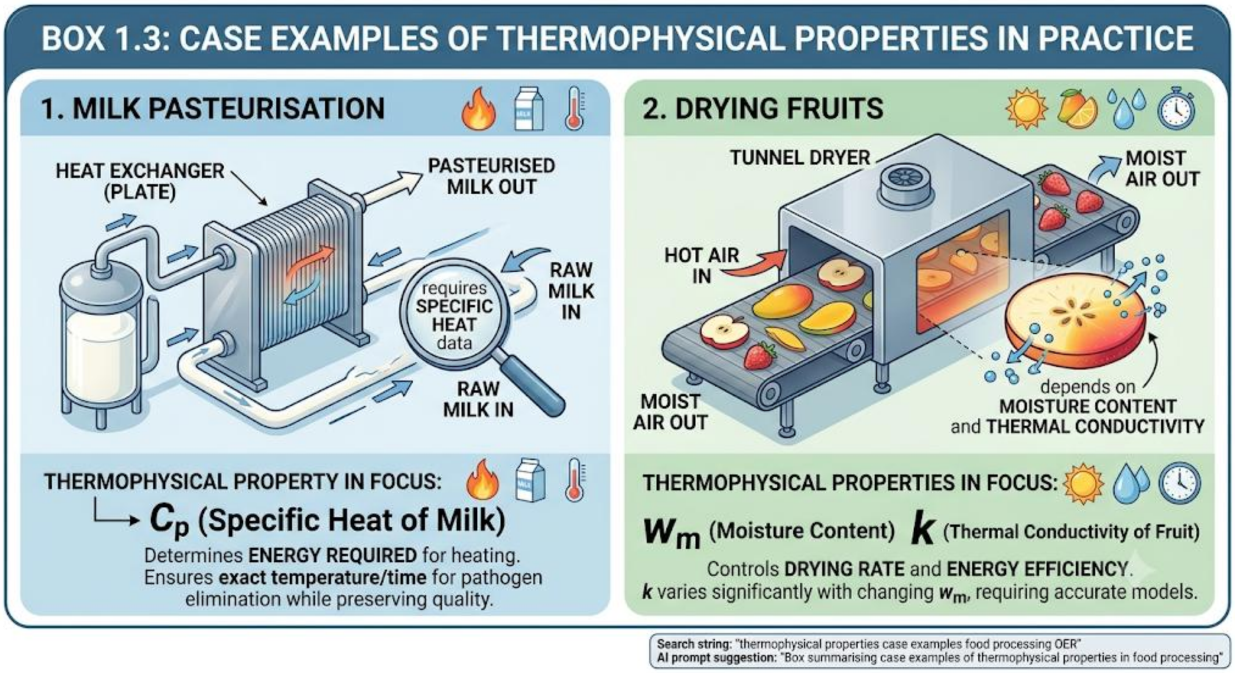
Fill in the blank: Foods with low thermal conductivity require _________ heating times in retorts.

Image of a food retort used in thermal processing *Plate 1.2: Retort equipment for sterilising packaged foods*

1.3.3 Case examples in thermal processing

Practical examples highlight the importance of thermophysical properties. In pasteurisation of milk, accurate knowledge of specific heat ensures uniform heating without scorching. In drying operations, moisture content and thermal conductivity determine drying rates and energy efficiency. These examples show how property data is applied in everyday food engineering practice.

Fill in the blank: During pasteurisation of milk, accurate knowledge of __________ ensures uniform heating without scorching.



Box 1.3: Case examples of thermophysical properties in practice Description: Milk pasteurisation requires specific heat data, while drying fruits depends on moisture content and thermal conductivity.

Pilot questions 1.3

1. Which property determines how quickly heat penetrates into canned foods?
2. Why must engineers consider viscosity when designing pumps for sauces?
3. What type of foods require longer heating times in retorts?
4. How does specific heat capacity affect pasteurisation of milk?
5. Give one example of how moisture content influences drying operations.

1.4 Food Composition Versus Thermophysical Properties

1.4.1 Relationship between composition and properties

The **composition of food** refers to the proportion of water, carbohydrates, proteins, fats, and minerals present in a product. These components strongly influence thermophysical properties. For example, foods with high water content generally have higher **specific heat capacity**, meaning they require more energy to heat. Conversely, foods rich in fat tend to have lower thermal conductivity, which slows down heat transfer. Recognising these relationships allows engineers to predict how different foods will behave during processing.

Fill in the blank: Foods with high water content usually have __________ specific heat capacity.

FIGURE 1.4: INFLUENCE OF FOOD COMPOSITION ON THERMOPHYSICAL PROPERTIES

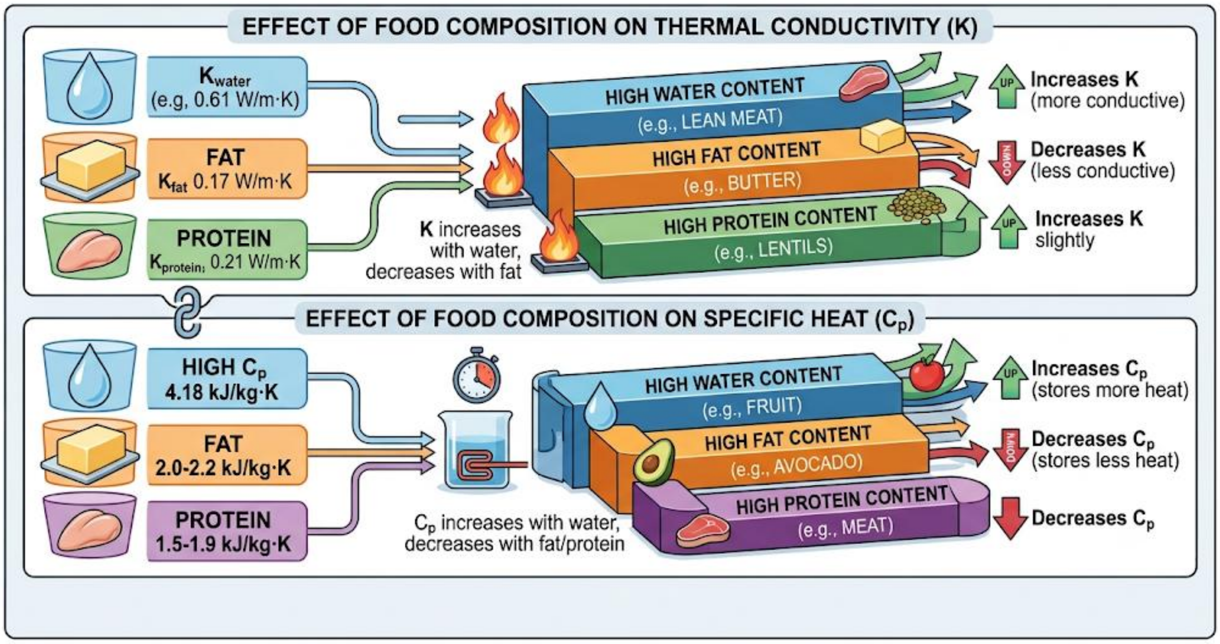


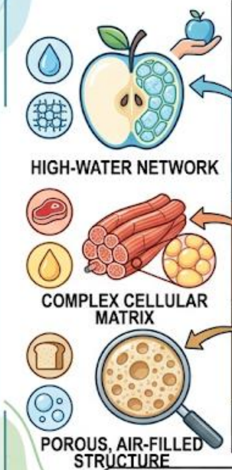
Diagram showing the effect of food composition on thermal conductivity and specific heat *Figure 1.4: Influence of food composition on thermophysical properties*

1.4.2 Variations across food categories

Different food categories exhibit distinct thermophysical behaviours. For instance, fruits and vegetables, which are high in moisture, heat up quickly but require more energy overall. Meat products, with higher protein and fat content, show slower heat penetration. Starchy foods such as bread have unique properties due to their porous structure, which affects both heat and mass transfer. These variations must be considered when designing processes for diverse food types.

Fill in the blank: Meat products show slower heat penetration because of their high _________ and fat content.

Table 1.2: Variations in thermophysical properties of fruits, meat, and bread



Food Category	Description	Examples	Thermal Conductivity (k) [W/(m·K)]	Specific Heat (C_p) [kJ/(kg·K)]	Density (ρ) [kg/m³]	
FRUITS	High-moisture, plant-based structure	Apple, Mango	~0.4 - 0.6	~3.6 - 4.1	~1000 - 1100	High 'k' and 'C_p' due to water content.
MEAT	Cellular matrix, protein & fat	Beef (lean)	~0.4 - 0.5	~3.3 - 3.7	~1040 - 1080	Variables 'k', 'C_p' depend on fat-protein ratio.
BREAD	Porous structure, air pockets	White Bread	~0.06 - 0.2	~2.4 - 2.9	~200 - 300	Low 'k', 'C_p', 'ρ' due to air air gaps.

NOTE: Values are typical ranges; subject to composition & temperature.

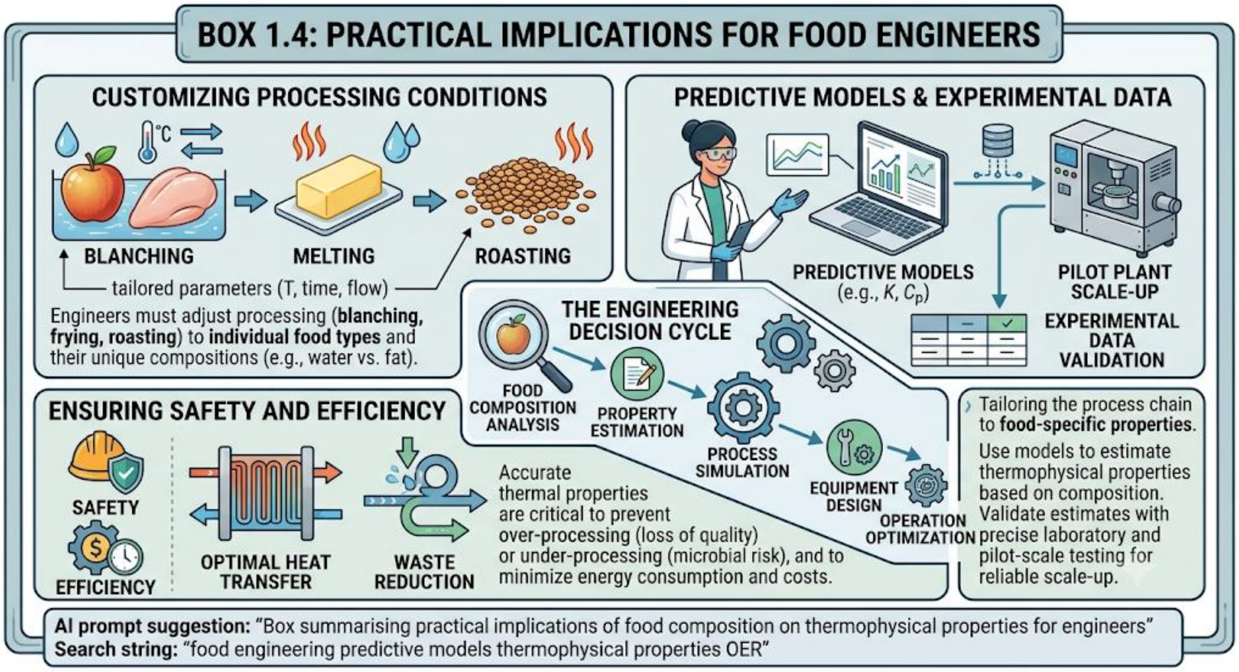
AI prompt suggestion: "Table comparing thermal conductivity, specific heat, and density of fruits, meat, and bread"
Search string: "*thermophysical properties food categories comparison OER*"

Comparison of thermophysical properties across food categories *Table 1.2: Variations in thermophysical properties of fruits, meat, and bread*

1.4.3 Practical implications for engineers

For food engineers, the practical implication is that no single set of property values can be applied universally. Each food product must be studied individually, and its composition analysed to determine accurate property values. This ensures that heating, cooling, drying, and freezing operations are efficient and safe. Engineers often use predictive models that incorporate composition data to estimate thermophysical properties for new or modified food products.

Fill in the blank: Engineers often use __________ models to estimate thermophysical properties of new food products.



Box 1.4: Practical implications for food engineers Description: Engineers must tailor processing conditions to each food type, using predictive models and experimental data to ensure safety and efficiency.

Pilot questions 1.4

1. Which food component generally increases specific heat capacity?
2. Why do meat products show slower heat penetration compared to fruits?
3. How does the porous structure of bread affect thermophysical properties?
4. Why must engineers study each food product individually before applying property values?
5. What type of models are used to estimate thermophysical properties of new food products?

Series Summary

This Series has introduced you to the thermophysical properties of food, which are fundamental to understanding how foods behave during processing. We began by defining and categorising these properties, then examined the methods used to determine them through experiments and instruments. Following that, we explored their relevance to food processing, highlighting their role in heat transfer, equipment design, and practical case examples. Finally, we analysed how food composition influences these properties, noting variations across categories and their implications for engineers.

By completing this Series, you should now be able to define the glossary of thermophysical properties, explain the methods of determination, analyse their relevance in food processing, and evaluate the relationship between food composition and thermophysical properties. These skills directly align with the Series Learning Outcomes and provide a strong foundation for subsequent topics in food process engineering.

Glossary of Terms

- **Calorimetry**: A technique used to measure the specific heat capacity of food by recording temperature changes after heating.
- **Density**: The mass per unit volume of food, which affects both heat and mass transfer.
- **Pycnometer**: An instrument used to measure the density of food samples.
- **Specific heat capacity**: The amount of heat required to raise the temperature of a unit mass of food by one degree Celsius.
- **Thermal conductivity**: The ability of a food material to conduct heat.
- **Thermophysical properties**: Physical characteristics of food that influence heat and mass transfer during processing.
- **Viscometer**: An instrument used to measure the viscosity of fluid foods.
- **Viscosity**: The resistance of a fluid food to flow, which influences pumping and mixing operations.

Concept Check Questions [Series 1]

Objective questions

1. Which property determines how quickly heat penetrates into canned foods? (Linked to SLO 1.3)
2. What instrument is used to measure viscosity in fluid foods? (Linked to SLO 1.2)
3. Foods with high water content generally have higher __________. (Linked to SLO 1.4)

Short-answer questions

4. Define thermal conductivity and explain its importance in food processing. (Linked to SLO 1.1)
5. Why is food heterogeneity a challenge in measuring thermophysical properties? (Linked to SLO 1.2)

Long-answer questions

6. Analyse how thermophysical properties influence equipment design and operation, giving at least two examples. (Linked to SLO 1.3)
    - *Basic response*: Discuss viscosity in pumping and thermal conductivity in retorts.

- *Value-added response*: Include additional examples such as specific heat in pasteurisation and density in freezing operations.

7. Evaluate the relationship between food composition and thermophysical properties, using fruits, meat, and bread as examples. (Linked to SLO 1.4)
   - *Basic response*: Explain how water, protein, and porous structures affect properties.
   - *Value-added response*: Extend discussion to predictive modelling and implications for new product development.

Answers to Pilot Questions [Series 1]

Part 1.1

1. Specific heat capacity
2. Density
3. Viscosity
4. They are crucial for designing and controlling food processing operations
5. Water content affects specific heat

Part 1.2

1. Line heat source technique
2. Pycnometer
3. Differential scanning calorimeter
4. Food heterogeneity
5. By repeating experiments and controlling conditions

Part 1.3

1. Thermal conductivity
2. Because high viscosity requires greater pumping power
3. Foods with low thermal conductivity
4. It ensures uniform heating without scorching
5. Moisture content affects drying rates

Part 1.4

1. Water

2. Protein
3. It affects heat and mass transfer due to porosity
4. Because each food has unique composition and properties
5. Predictive models

References and Attributions [Series 1]

- Figures, Plates, Tables, and Boxes were created as placeholders with suggested AI prompts for later generation.
- *Figure 1.1*: Heat transfer in foods. Suggested AI prompt: “Diagram of heat transfer through food materials showing conduction, convection, and radiation.”
- *Table 1.1*: Typical values of thermophysical properties in foods. Suggested AI prompt: “Table showing thermal conductivity, specific heat, density, and viscosity of milk, bread, and meat.”
- *Box 1.1*: Case study – Tomato paste processing. Suggested AI prompt: “Case study box on tomato paste viscosity and processing challenges.”
- *Figure 1.2*: Calorimetry experiment for food samples. Suggested AI prompt: “Diagram of calorimetry setup for measuring specific heat capacity of food.”
- *Plate 1.1*: Laboratory viscometer. Suggested AI prompt: “Photograph of viscometer used in food science laboratory.”
- *Box 1.2*: Challenges in measuring thermophysical properties. Suggested AI prompt: “Box summarising challenges in measuring thermophysical properties of food.”
- *Figure 1.3*: Heat transfer in canned food processing. Suggested AI prompt: “Diagram of heat penetration in canned food during sterilisation.”
- *Plate 1.2*: Retort equipment. Suggested AI prompt: “Photograph of industrial food retort equipment.”
- *Box 1.3*: Case examples of thermophysical properties in practice. Suggested AI prompt: “Box summarising case examples of thermophysical properties in food processing.”
- *Figure 1.4*: Influence of food composition. Suggested AI prompt: “Diagram showing how water, fat, and protein content affect thermal conductivity and specific heat in foods.”
- *Table 1.2*: Variations in thermophysical properties of fruits, meat, and bread. Suggested AI prompt: “Table comparing thermal conductivity, specific heat, and density of fruits, meat, and bread.”
- *Box 1.4*: Practical implications for food engineers. Suggested AI prompt: “Box summarising practical implications of food composition on thermophysical properties for engineers.”

All suggested search strings point to Open Educational Resources (OER) for sourcing illustrations.

Series 2: Thermal Processing Principles

Series outline

- **2.1 Retort Processing And Controls**
    - 2.1.1 Principles of retort processing
    - 2.1.2 Control parameters and monitoring
    - 2.1.3 Applications in food preservation
- **2.2 Thermal Death Time Equivalent**
    - 2.2.1 Concept of microbial inactivation
    - 2.2.2 Calculation of thermal death time
    - 2.2.3 Practical examples in food safety
- **2.3 Calculation Of D, Z, And Q10 Values**
    - 2.3.1 Definition of D-value
    - 2.3.2 Definition of Z-value
    - 2.3.3 Definition of Q10 value
    - 2.3.4 Worked examples and applications
- **2.4 Relevance Of Thermal Treatments**
    - 2.4.1 Importance in food safety
    - 2.4.2 Impact on nutritional quality
    - 2.4.3 Industrial applications

Introduction

Thermal processing is one of the most important methods used to ensure food safety and extend shelf life. By applying controlled heat, harmful microorganisms are destroyed and food quality is preserved. From canned vegetables to pasteurised milk, thermal processing principles underpin many everyday products. This Series will help you appreciate how scientific calculations and engineering controls make these processes reliable and effective.

The aim of this Series is to equip you with the knowledge and skills to explain the principles of thermal processing, calculate microbial inactivation parameters, and evaluate the relevance of thermal treatments in food safety and quality.

We shall commence this Series by examining retort processing and its control mechanisms. Next, we will explore the concept of thermal death time and how it is applied to microbial inactivation. Following that, we will study the calculation of D, Z, and Q10 values, supported by worked examples. Finally, we will conclude by considering the broader relevance of thermal treatments, including their impact on food safety, nutritional quality, and industrial applications.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 2.1** explain the principles of retort processing and identify key control parameters,
- **SLO 2.2** define thermal death time and demonstrate how it is calculated for microbial inactivation,
- **SLO 2.3** calculate D, Z, and Q10 values and apply them to food processing scenarios, and
- **SLO 2.4** evaluate the relevance of thermal treatments in terms of food safety, nutritional quality, and industrial applications.

2.1 Retort Processing And Controls

2.1.1 Principles of retort processing

Retort processing is a thermal preservation method where sealed food containers are subjected to high temperatures under pressure. The aim is to destroy harmful microorganisms and enzymes, thereby extending shelf life and ensuring safety. The process typically involves heating foods to temperatures above 100°C in pressurised vessels called retorts. This method is widely used for canned foods, soups, and ready-to-eat meals.

Fill in the blank: Retort processing involves heating sealed food containers to temperatures above _________ °C.

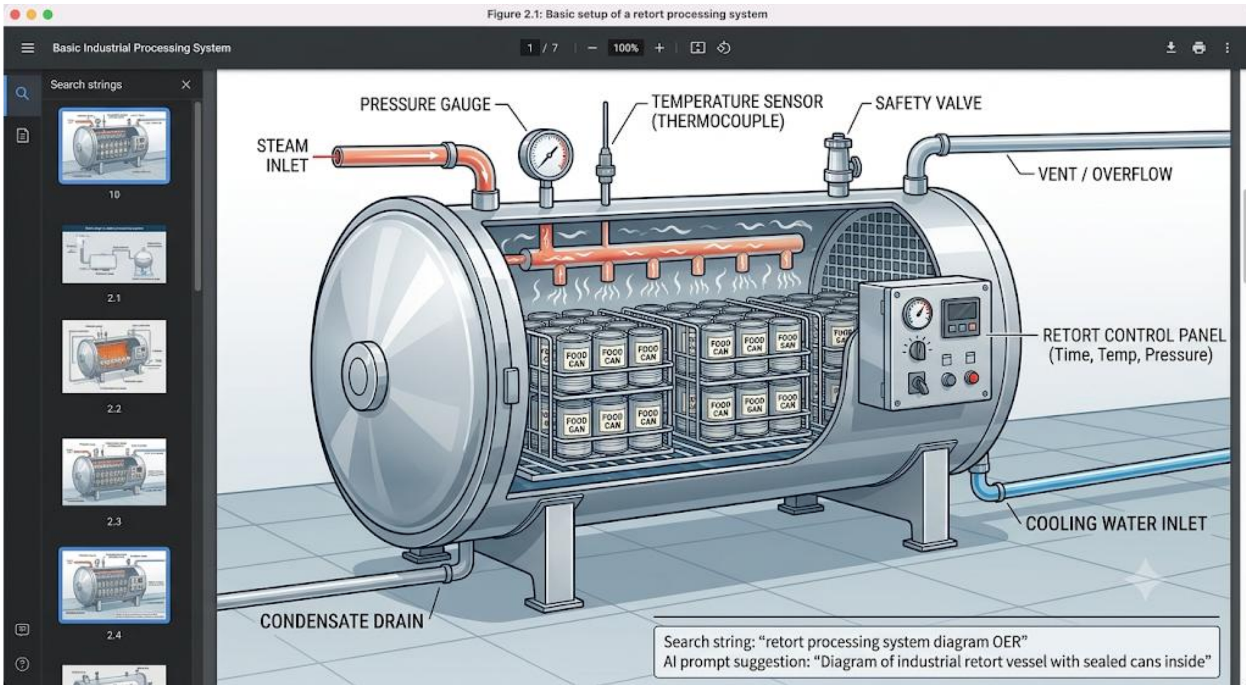


Diagram showing a retort vessel with sealed cans inside *Figure 2.1: Basic setup of a retort processing system*

2.1.2 Control parameters and monitoring

Effective retort processing requires careful control of parameters such as **temperature**, **pressure**, and **time**. Temperature must be high enough to achieve microbial destruction, pressure ensures containers remain sealed, and time determines the extent of sterilisation. Monitoring devices such as thermocouples and pressure gauges are used to maintain these parameters within safe limits. Engineers must also validate processes to ensure uniform heating across all containers.

Fill in the blank: The three main parameters controlled during retort processing are temperature, _________, and time.

PLATE 2.1: MODERN RETORT EQUIPMENT WITH MONITORING INSTRUMENTS

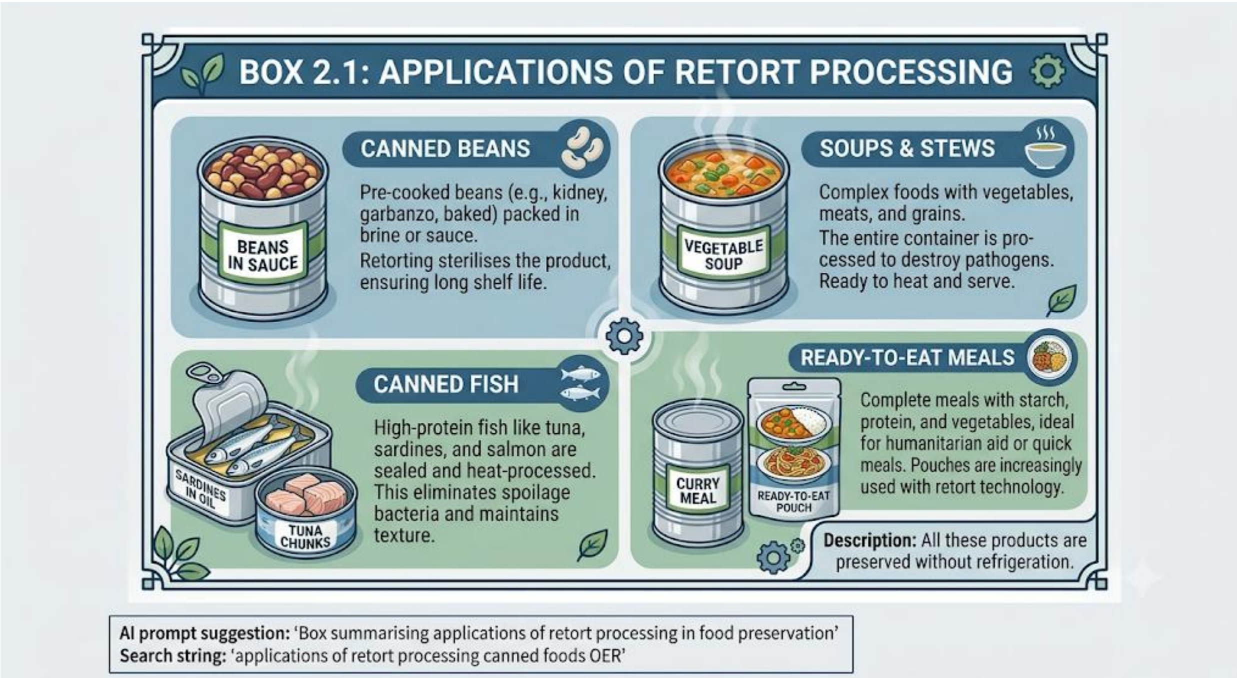
AI prompt suggestion:	Photograph of modern retort system with monitoring controls’
Search string:	“modern food retort monitoring equipment OER”

Image of a modern retort system with monitoring controls *Plate 2.1: Modern retort equipment with monitoring instruments*

2.1.3 Applications in food preservation

Retort processing is applied to a wide range of foods, including vegetables, meats, fish, and ready-to-eat meals. It ensures long shelf life without refrigeration, making it vital for global food distribution. For example, canned beans processed in retorts can remain safe for consumption for years. The method balances microbial safety with product quality, although excessive heating may reduce nutritional value.

Fill in the blank: Retort processing allows foods to be stored safely for long periods without __________.



Box 2.1: Applications of retort processing Description: Examples include canned beans, soups, fish, and ready-to-eat meals, all preserved without refrigeration.

Pilot questions 2.1

1. What is the main purpose of retort processing?
2. At what minimum temperature are foods typically processed in retorts?
3. Name the three main parameters controlled during retort processing.
4. Why is pressure important in retort processing?
5. Give two examples of foods commonly preserved using retort processing.

2.2 Thermal Death Time Equivalent

2.2.1 Concept of microbial inactivation

Thermal death time (TDT) refers to the minimum time required to kill a specific number of microorganisms at a given temperature. It is a critical concept in food safety because it ensures that harmful bacteria such as *Clostridium botulinum* are destroyed during processing. The principle is based on the fact that microorganisms are sensitive to heat, and their destruction follows predictable patterns.

Fill in the blank: Thermal death time is the minimum __________ required to kill microorganisms at a given temperature.

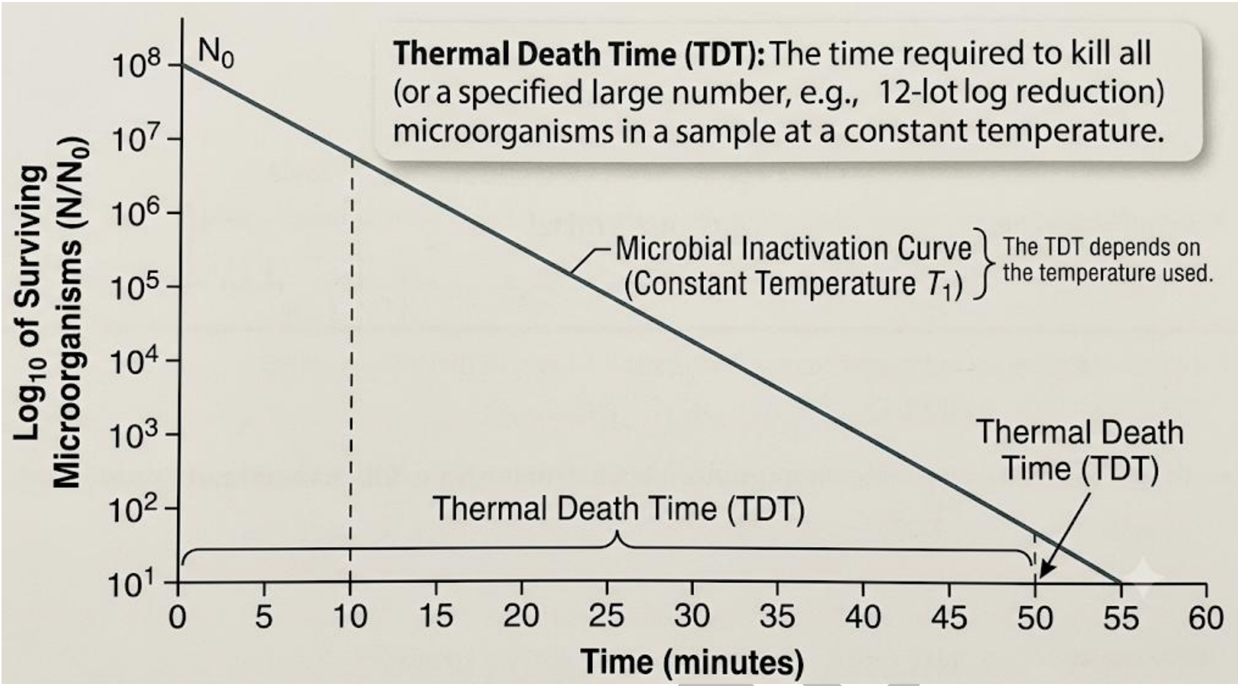


Diagram showing microbial inactivation curve at constant temperature *Figure 2.2: Microbial inactivation curve illustrating thermal death time*

2.2.2 Calculation of thermal death time

The calculation of TDT involves plotting microbial survival data against time at a constant temperature. The point at which the curve reaches zero survivors indicates the thermal death time. Engineers use this data to design safe processing schedules. For example, if a microorganism requires 10 minutes at 121°C to be destroyed, then the retort process must maintain that condition for at least 10 minutes.

Fill in the blank: If a microorganism requires 10 minutes at 121°C to be destroyed, the thermal death time is __________ minutes.

Table showing survival times of microorganisms at different temperatures *Table 2.1: Survival times of selected microorganisms under thermal treatment*

Microorganism	Type/State	Temperature (°C)	Typical Survival Time (min)*
Salmonella spp.	Vegetative	55	60–80
		60	5–10
		65	<1

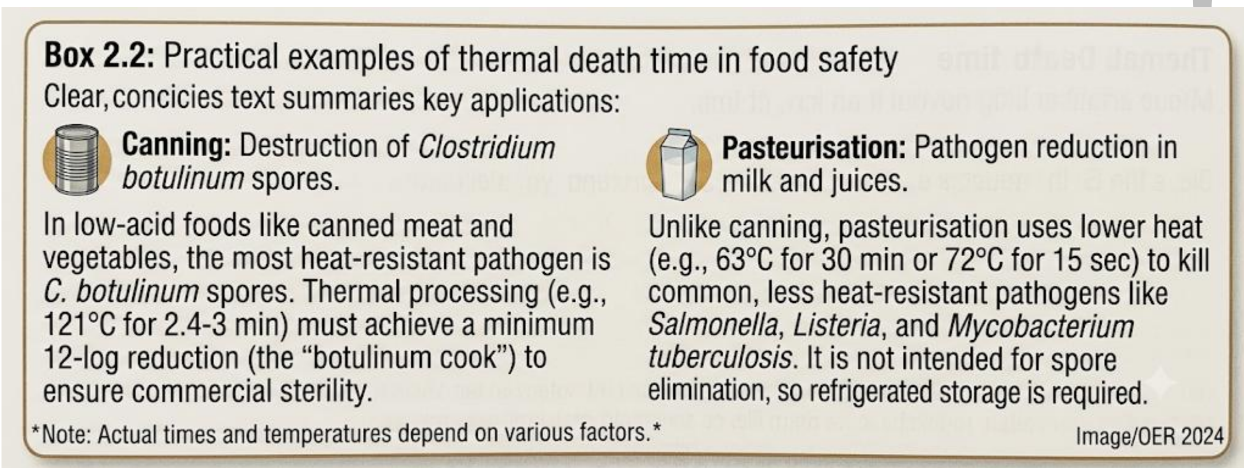
Microorganism	Type/State	Temperature (°C)	Typical Survival Time (min)*
Escherichia coli	Vegetative	55	60–90
		60	5–10
		65	<1
Staphylococcus aureus	Vegetative	60	15–30
		65	5–10
Listeria monocytogenes	Vegetative	60	15–30
		65	1–5
Bacillus cereus	Spores	90	30–60
		100	5–10
		121	<1
Clostridium botulinum	Spores (proteolytic)	100	100–300
		121	2.4–3

2.2.3 Practical examples in food safety

In practice, thermal death time is applied to ensure foods are safe for consumption. For instance, canned meat must be processed long enough to eliminate spores of *Clostridium botulinum*. Similarly, pasteurisation schedules for milk are based on the destruction of pathogens such as

Salmonella. These examples highlight how TDT is not just theoretical but directly linked to consumer safety.

Fill in the blank: Pasteurisation schedules for milk are designed to destroy pathogens such as _________.


Box 2.2: Practical examples of thermal death time in food safety
Clear, concicies text summaries key applications:

Canning: Destruction of *Clostridium botulinum* spores.

In low-acid foods like canned meat and vegetables, the most heat-resistant pathogen is *C. botulinum* spores. Thermal processing (e.g., 121°C for 2.4-3 min) must achieve a minimum 12-log reduction (the "botulinum cook") to ensure commercial sterility.

Pasteurisation: Pathogen reduction in milk and juices.

Unlike canning, pasteurisation uses lower heat (e.g., 63°C for 30 min or 72°C for 15 sec) to kill common, less heat-resistant pathogens like *Salmonella*, *Listeria*, and *Mycobacterium tuberculosis*. It is not intended for spore elimination, so refrigerated storage is required.

Note: Actual times and temperatures depend on various factors.

Image/OER 2024

Box 2.2: Practical examples of thermal death time in food safety Description: Canned meat requires elimination of *Clostridium botulinum* spores, while milk pasteurisation targets pathogens like *Salmonella*.

Pilot questions 2.2

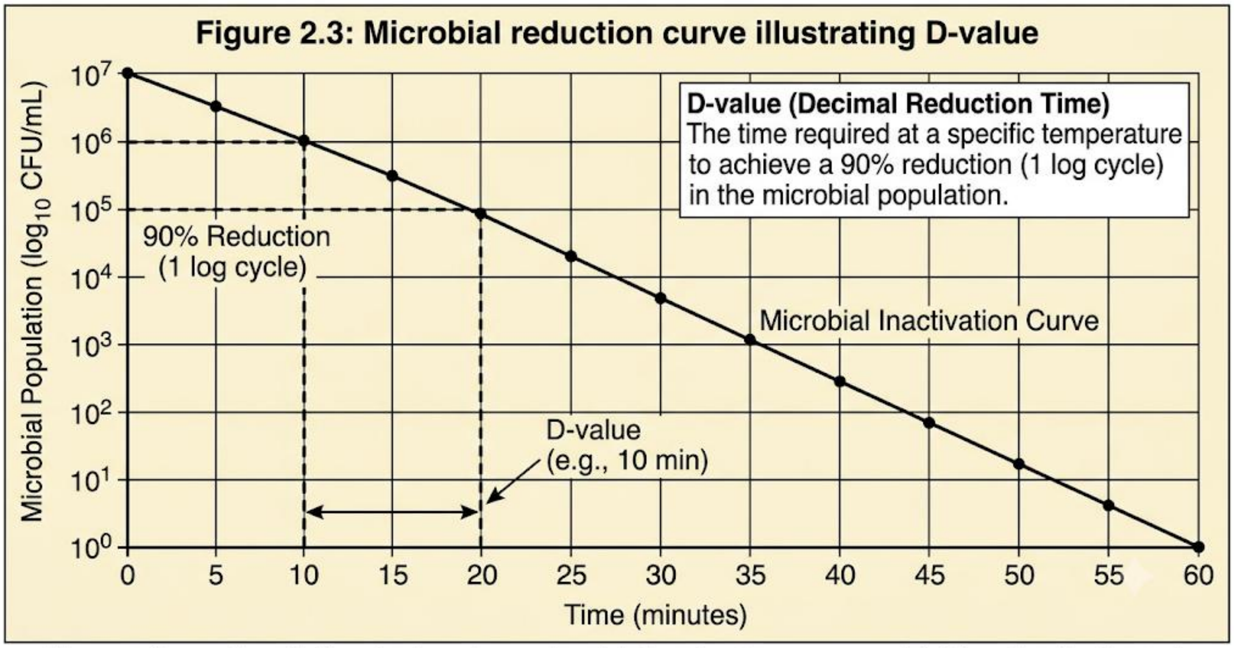
1. What does thermal death time measure?
2. How is thermal death time calculated from microbial survival data?
3. If a microorganism requires 10 minutes at 121°C to be destroyed, what is its TDT?
4. Which microorganism is a major concern in canned meat processing?
5. Name one pathogen targeted during milk pasteurisation.

2.3 Calculation Of D, Z, And Q10 Values

2.3.1 Definition of D-value

The **D-value** (decimal reduction time) is the time required at a specific temperature to reduce the microbial population by 90 percent, or one log cycle. It is a measure of microbial resistance to heat and is used to design safe processing schedules. For example, if the D-value of a microorganism at 121°C is 2 minutes, then every 2 minutes of heating reduces the population by one log cycle.

Fill in the blank: The D-value represents the time required to reduce the microbial population by _________ percent at a specific temperature.



[Insert figure here] Graph showing microbial reduction curve with D-value indicated

Graph showing microbial reduction curve with D-value indicated *Figure 2.3: Microbial reduction curve illustrating D-value*

2.3.2 Definition of Z-value

The **Z-value** is the temperature change required to alter the D-value by a factor of ten. It indicates how sensitive a microorganism is to changes in temperature. A smaller Z-value means the microorganism is more sensitive to temperature changes, while a larger Z-value indicates greater resistance. Engineers use Z-values to adjust processing temperatures for efficiency and safety.

Fill in the blank: The Z-value is the temperature change required to alter the D-value by a factor of __________.

Table showing D-values of microorganisms at different temperatures and corresponding Z-values
Table 2.2: D-values and Z-values of selected microorganisms

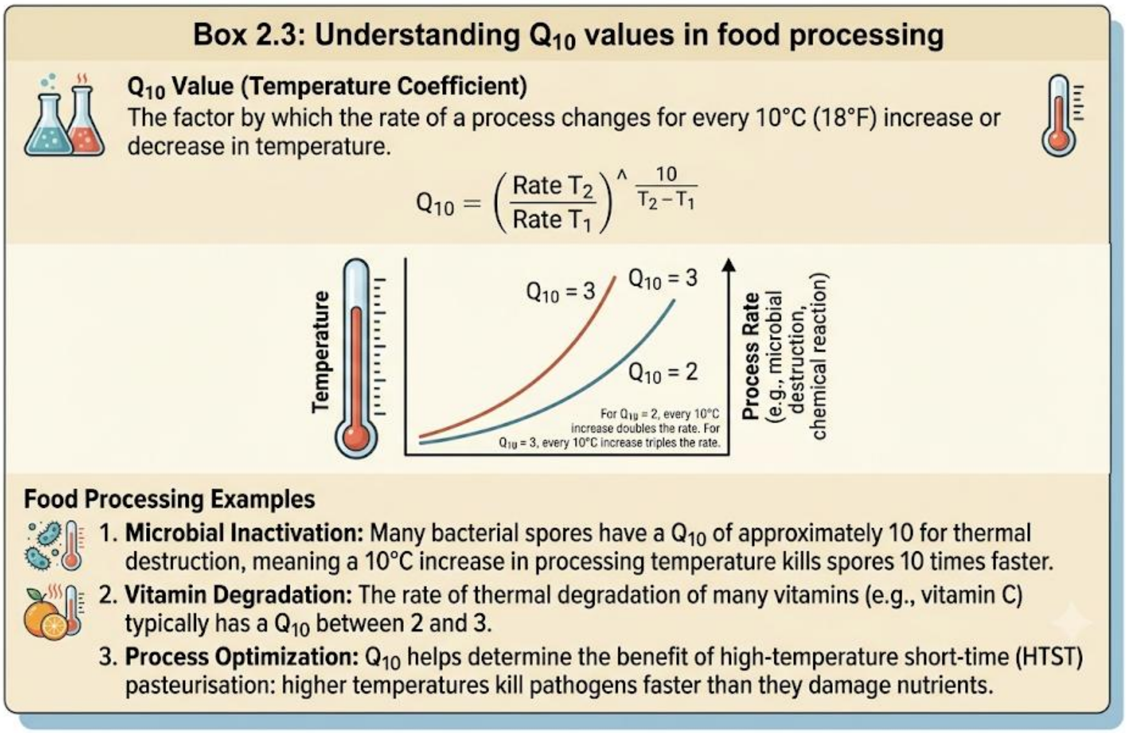
Microorganism	Temperature (°C)	D-value (minutes)	Reference Temp. Tr (°C)	Z-value (°C)*
Clostridium botulinum (spores)	110	~30	121	~10
	115	~10		
	121	~2.4		

Microorganism	Temperature (°C)	D-value (minutes)	Reference Temp. Tr (°C)	Z-value (°C)*
Bacillus stearothermophilus (spores)	115	~35	121	~12
	121	~4		
	127	~0.5		
Salmonella spp. (vegetative)	55	~60	60	~5-7
	60	~5		
	65	~0.5		
Escherichia coli (vegetative)	55	~80	60	~5-7
	60	~6		
	65	~0.8		

2.3.3 Definition of Q10 value

The **Q10 value** is a measure of the rate of change in a biological or chemical process with a 10°C rise in temperature. In food processing, it is used to estimate how reaction rates, such as microbial destruction or enzyme activity, change with temperature. A Q10 value of 2 means the rate doubles with every 10°C increase.

Fill in the blank: A Q10 value of 2 means the rate of reaction __________ with every 10°C increase.

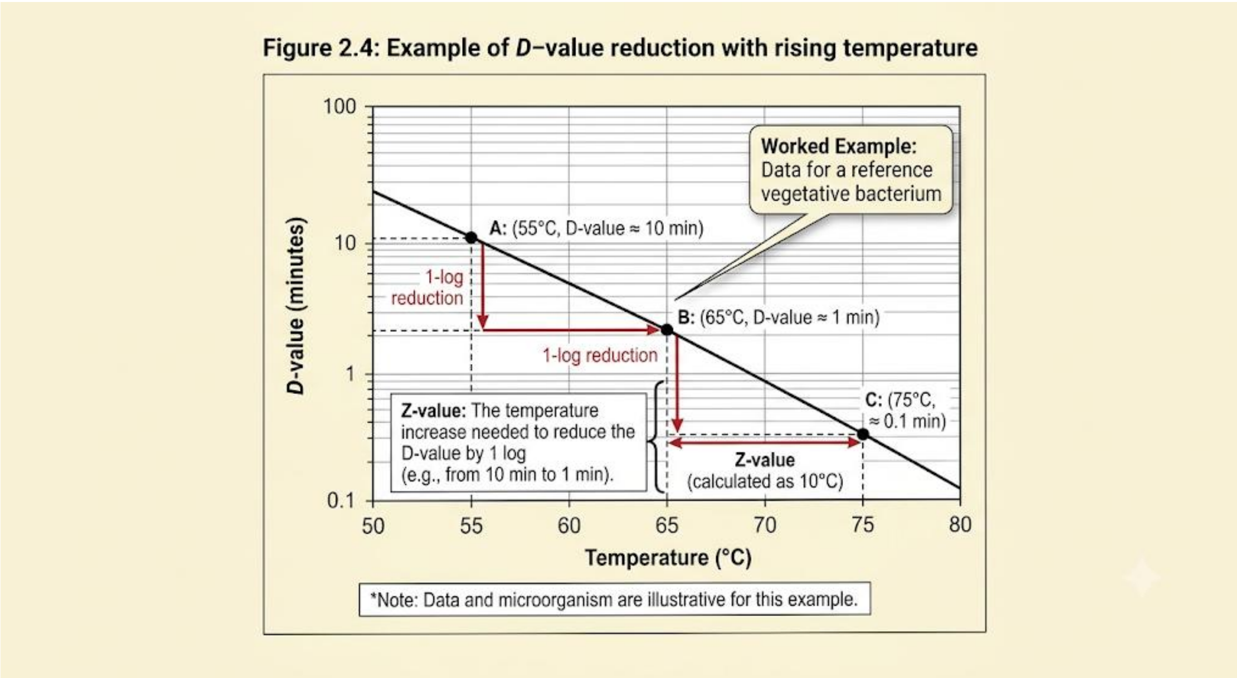


Box 2.3: Understanding Q10 values in food processing Description: Q10 values help predict how microbial destruction rates change with temperature, aiding in process optimisation.

2.3.4 Worked examples and applications

To apply these values, consider a microorganism with a D-value of 2 minutes at 121°C and a Z-value of 10°C. If the temperature is increased to 131°C, the D-value decreases to 0.2 minutes. Similarly, if the Q10 value of a reaction is 2, raising the temperature from 30°C to 40°C doubles the rate of microbial destruction. These calculations allow engineers to design efficient and safe thermal processes.

Fill in the blank: If the D-value at 121°C is 2 minutes and the Z-value is 10°C, the D-value at 131°C will be _________ minutes.



Worked example graph showing D-value reduction with temperature increase *Figure 2.4: Example of D-value reduction with rising temperature*

Pilot questions 2.3

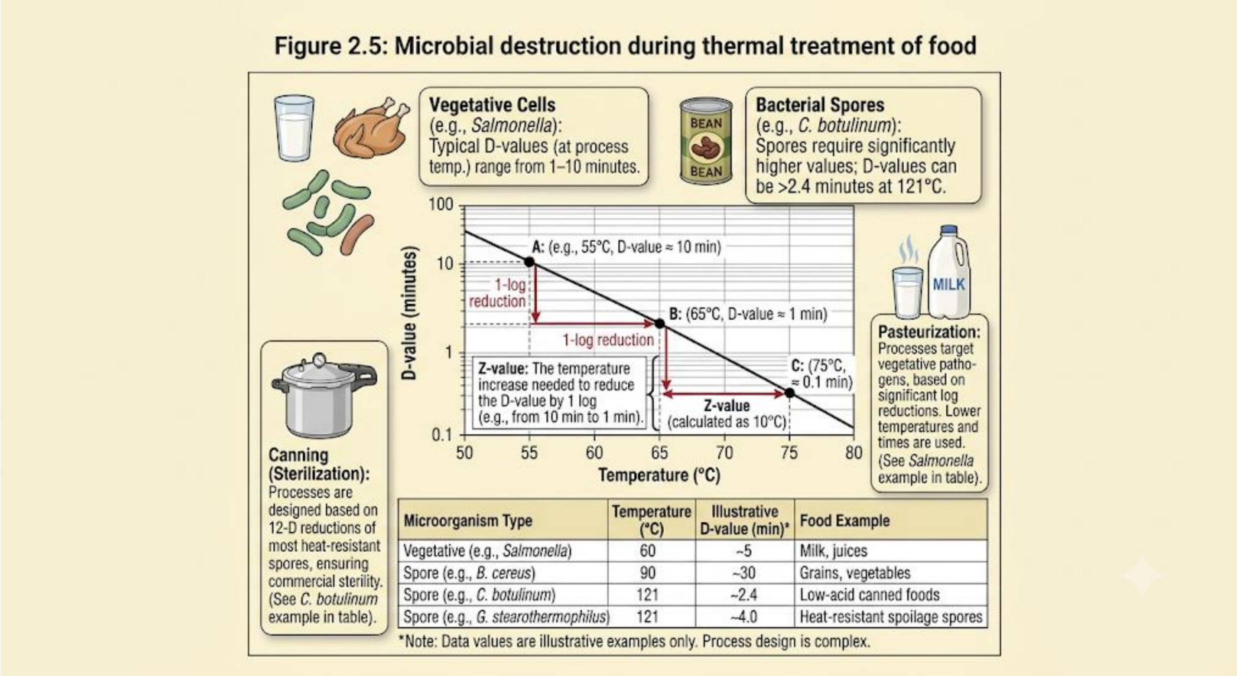
1. What does the D-value measure in microbial inactivation?
2. How much microbial reduction does one D-value represent?
3. What does the Z-value indicate about microorganisms?
4. If the Q10 value of a reaction is 2, what happens to the rate when temperature increases by 10°C?
5. A microorganism has a D-value of 2 minutes at 121°C and a Z-value of 10°C. What is its D-value at 131°C?

2.4 Relevance Of Thermal Treatments

2.4.1 Importance in food safety

Thermal treatments are essential for ensuring food safety because they destroy harmful microorganisms and spores that could cause illness. For example, sterilisation of canned foods eliminates *Clostridium botulinum*, while pasteurisation of milk reduces pathogens such as *Salmonella*. These processes are carefully designed to meet safety standards and protect consumers.

Fill in the blank: Sterilisation of canned foods is designed to eliminate spores of _________.



Microorganism Type	Temperature (°C)	Illustrative D-value (min)*	Food Example
Vegetative (e.g., *Salmonella*)	60	~5	Milk, juices
Spore (e.g., *B. cereus*)	90	~30	Grains, vegetables
Spore (e.g., *C. botulinum*)	121	~2.4	Low-acid canned foods
Spore (e.g., *G. stearothermophilus*)	121	~4.0	Heat-resistant spoilage spores

Diagram showing microbial destruction during thermal treatment *Figure 2.5: Microbial destruction curve during thermal treatment*

2.4.2 Impact on nutritional quality

While thermal treatments improve safety, they can also affect nutritional quality. Heat-sensitive vitamins such as vitamin C may degrade during processing, and proteins may undergo denaturation. Engineers must therefore balance microbial safety with nutritional preservation by optimising time and temperature conditions.

Fill in the blank: Heat-sensitive vitamins such as __________ may degrade during thermal processing.

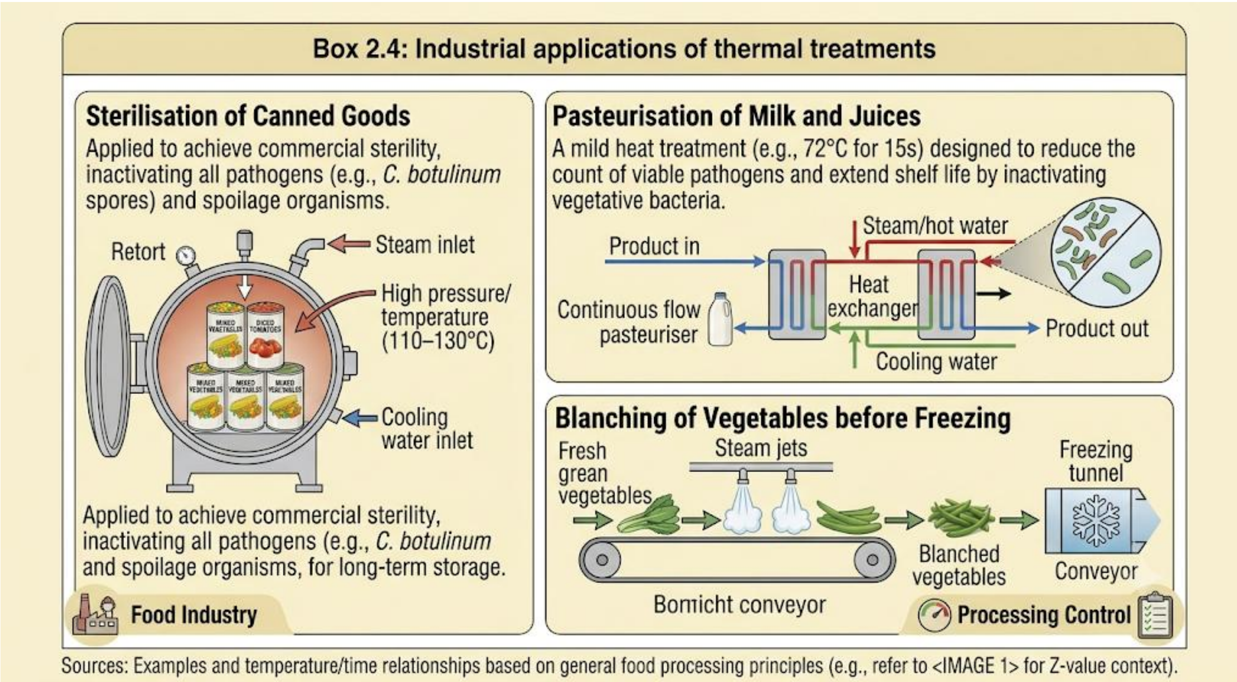
Plate 2.2: Canned vegetables after thermal processing. Each can has been processed according to a specified thermal death time schedule based on the the Z-value and D-value data of target microorganisms (referencing data such as Figure 2.5).

Image of canned vegetables processed by thermal treatment *Plate 2.2: Canned vegetables after thermal processing*

2.4.3 Industrial applications

Thermal treatments are widely applied in the food industry. Examples include sterilisation of canned goods, pasteurisation of dairy products, and blanching of vegetables before freezing. These applications ensure long shelf life, safe distribution, and consumer confidence. Engineers must select appropriate thermal processes depending on the product type and desired quality outcomes.

Fill in the blank: Blanching of vegetables before freezing is an example of _________ treatment.



Box 2.4: Industrial applications of thermal treatments Description: Examples include sterilisation of canned goods, pasteurisation of milk, and blanching of vegetables before freezing.

Pilot questions 2.4

1. Why are thermal treatments important for food safety?
2. Which microorganism is targeted during sterilisation of canned foods?
3. Name one nutrient that may degrade during thermal processing.
4. What is the purpose of blanching vegetables before freezing?
5. Give two examples of industrial applications of thermal treatments.

Series Summary

This Series has explored the principles of thermal processing, a cornerstone of food preservation and safety. We began with retort processing, examining how sealed containers are heated under pressure and controlled through parameters such as temperature, pressure, and time. We then moved on to the concept of thermal death time, learning how microbial inactivation is calculated and applied in practice. Following that, we studied the calculation of D, Z, and Q10 values, supported by worked examples to show their application in food engineering. Finally, we considered the broader relevance of thermal treatments, including their importance for food safety, their impact on nutritional quality, and their industrial applications.

By completing this Series, you should now be able to explain retort processing principles, define and calculate thermal death time, calculate D, Z, and Q10 values, and evaluate the relevance of thermal treatments in food safety and industry. These outcomes directly align with the Series Learning Outcomes and prepare you for more advanced topics in food process engineering.

Glossary of Terms

- **D-value**: The time required at a specific temperature to reduce the microbial population by 90 percent.
- **Q10 value**: A measure of the rate of change in a process with a 10°C rise in temperature.
- **Retort processing**: A thermal preservation method where sealed food containers are heated under pressure to destroy microorganisms.
- **Thermal death time (TDT)**: The minimum time required to kill a specific number of microorganisms at a given temperature.
- **Z-value**: The temperature change required to alter the D-value by a factor of ten.

Concept Check Questions [Series 2]

Objective questions

1. What is the minimum temperature typically used in retort processing? (Linked to SLO 2.1)
2. The D-value represents a __________ percent reduction in microbial population. (Linked to SLO 2.3)
3. Which microorganism is a major concern in canned food sterilisation? (Linked to SLO 2.2)

Short-answer questions

4. Explain why pressure is important in retort processing. (Linked to SLO 2.1)
5. Define the Z-value and describe its significance in food processing. (Linked to SLO 2.3)

Long-answer questions

6. Analyse how thermal death time is applied in food safety, giving at least two examples. (Linked to SLO 2.2)
   - *Basic response*: Discuss canned meat sterilisation and milk pasteurisation.
   - *Value-added response*: Extend discussion to include other pathogens and industrial validation procedures.
7. Evaluate the impact of thermal treatments on both food safety and nutritional quality, using examples from vegetables, dairy, and canned foods. (Linked to SLO 2.4)
   - *Basic response*: Explain microbial destruction and vitamin degradation.
   - *Value-added response*: Include industrial optimisation strategies and balancing consumer demands for safety and nutrition.

Answers to Pilot Questions [Series 2]

Part 2.1

1. To destroy harmful microorganisms and extend shelf life
2. 100°C
3. Temperature, pressure, and time
4. It ensures containers remain sealed during heating
5. Canned beans and ready-to-eat meals

Part 2.2

1. Minimum time required to kill microorganisms at a given temperature
2. By plotting survival data against time at constant temperature
3. 10 minutes
4. *Clostridium botulinum*
5. *Salmonella*

Part 2.3

1. Microbial resistance to heat
2. 90 percent
3. Sensitivity of microorganisms to temperature changes
4. The rate doubles
5. 0.2 minutes

Part 2.4

1. They destroy harmful microorganisms and spores
2. *Clostridium botulinum*
3. Vitamin C
4. To inactivate enzymes and preserve quality before freezing
5. Sterilisation of canned goods and pasteurisation of milk

References and Attributions [Series 2]

- *Figure 2.1*: Basic setup of a retort processing system. Suggested AI prompt: "Diagram of industrial retort vessel with sealed cans inside."

- *Plate 2.1*: Modern retort equipment with monitoring instruments. Suggested AI prompt: "Photograph of modern retort system with monitoring controls."
- *Box 2.1*: Applications of retort processing. Suggested AI prompt: "Box summarising applications of retort processing in food preservation."
- *Figure 2.2*: Microbial inactivation curve illustrating thermal death time. Suggested AI prompt: "Diagram of microbial inactivation curve showing thermal death time at constant temperature."
- *Table 2.1*: Survival times of selected microorganisms under thermal treatment. Suggested AI prompt: "Table showing survival times of microorganisms at different temperatures for thermal death time calculation."
- *Box 2.2*: Practical examples of thermal death time in food safety. Suggested AI prompt: "Box summarising practical examples of thermal death time in food safety."
- *Figure 2.3*: Microbial reduction curve illustrating D-value. Suggested AI prompt: "Graph showing microbial reduction curve with D-value marked at one log cycle reduction."
- *Table 2.2*: D-values and Z-values of selected microorganisms. Suggested AI prompt: "Table showing D-values at different temperatures and calculated Z-values for microorganisms."
- *Box 2.3*: Understanding Q10 values in food processing. Suggested AI prompt: "Box explaining Q10 values with examples in food processing."
- *Figure 2.4*: Example of D-value reduction with rising temperature. Suggested AI prompt: "Graph showing worked example of D-value reduction with temperature increase."
- *Figure 2.5*: Microbial destruction curve during thermal treatment. Suggested AI prompt: "Diagram showing microbial destruction curve during thermal treatment of food."
- *Plate 2.2*: Canned vegetables after thermal processing. Suggested AI prompt: "Photograph of canned vegetables processed by thermal treatment."
- *Box 2.4*: Industrial applications of thermal treatments. Suggested AI prompt: "Box summarising industrial applications of thermal treatments in food processing."

All suggested search strings point to Open Educational Resources (OER) for sourcing illustrations.

Series 3: Fluid Flow In Food Systems

Series outline

- **3.1 Fundamentals Of Fluid Flow**
  - 3.1.1 Definition and classification of fluids
  - 3.1.2 Newtonian and non-Newtonian behaviour
  - 3.1.3 Flow regimes: laminar and turbulent
- **3.2 Governing Equations Of Fluid Flow**
  - 3.2.1 Continuity equation
  - 3.2.2 Bernoulli's principle
  - 3.2.3 Energy balance in food systems
- **3.3 Measurement And Characterisation**
  - 3.3.1 Instruments for measuring flow (flow meters, viscometers)
  - 3.3.2 Rheological characterisation of food fluids
  - 3.3.3 Case examples in dairy and beverage industries
- **3.4 Applications In Food Engineering**
  - 3.4.1 Pumping and mixing operations
  - 3.4.2 Heat exchangers and fluid transport
  - 3.4.3 Industrial relevance and optimisation

Introduction

Fluid flow is a central aspect of food process engineering because many food products are handled in liquid form during processing. From pumping milk in dairies to mixing sauces in industrial kitchens, understanding how fluids behave under different conditions ensures efficiency, safety, and quality. This Series will help you grasp the scientific principles of fluid mechanics as they apply specifically to food systems.

The aim of this Series is to introduce you to the fundamentals of fluid flow, equip you with the ability to apply governing equations, demonstrate how to measure and characterise fluid behaviour, and evaluate practical applications in food engineering operations.

We shall commence this Series by exploring the fundamentals of fluid flow, including fluid classification, Newtonian and non-Newtonian behaviour, and flow regimes. Next, we will study the governing equations of fluid flow, focusing on continuity, Bernoulli's principle, and energy balance. Following that, we will examine measurement and characterisation techniques, including instruments and rheological analysis with case examples. Finally, we will conclude by considering applications in food engineering, such as pumping, mixing, and heat exchanger operations.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 3.1** define the fundamentals of fluid flow and distinguish between Newtonian and non-Newtonian behaviours,
- **SLO 3.2** apply governing equations such as continuity and Bernoulli's principle to food fluid systems,
- **SLO 3.3** demonstrate how to measure and characterise fluid flow using appropriate instruments and rheological methods, and
- **SLO 3.4** evaluate the applications of fluid flow in food engineering operations such as pumping, mixing, and heat exchange.

3.1 Fundamentals Of Fluid Flow

3.1.1 Definition and classification of fluids

A **fluid** is any substance that can flow, typically liquids and gases. In food systems, fluids include water, milk, juices, oils, and even semi-liquid products like sauces. Fluids are classified as **Newtonian** or **non-Newtonian** depending on how they respond to applied force. Newtonian fluids, such as water, have a constant viscosity regardless of shear rate, while non-Newtonian fluids, such as ketchup, change viscosity depending on how they are stirred or pumped.

Fill in the blank: Fluids that maintain constant viscosity regardless of shear rate are called __________ fluids.

Figure 3.1: Comparison of Newtonian and non-Newtonian fluids

[Insert figure here] Diagram showing Newtonian vs non-Newtonian fluid behaviour

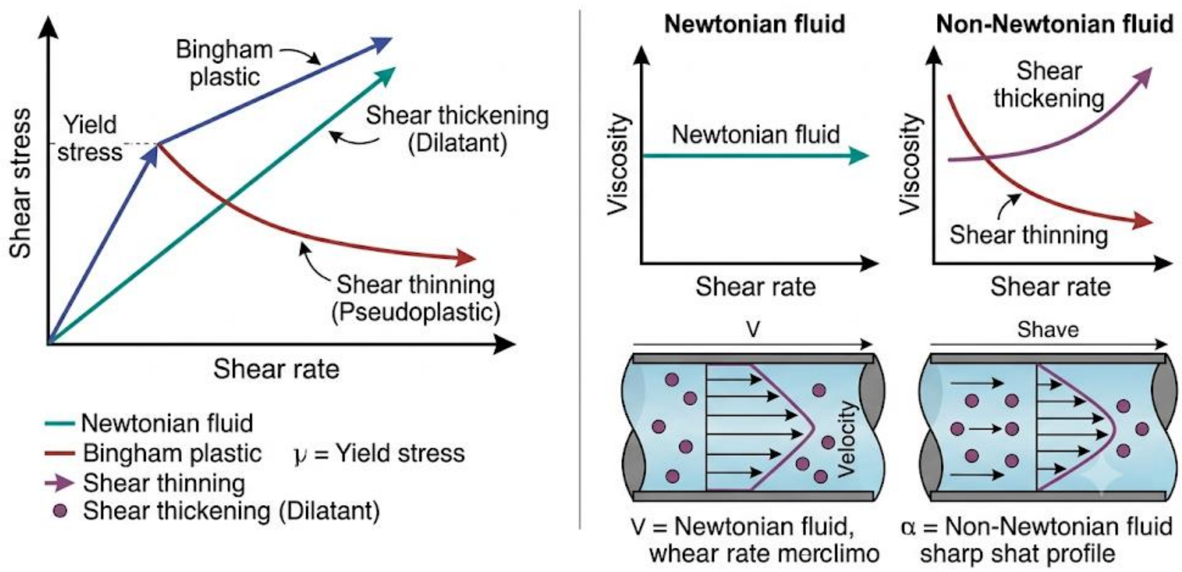


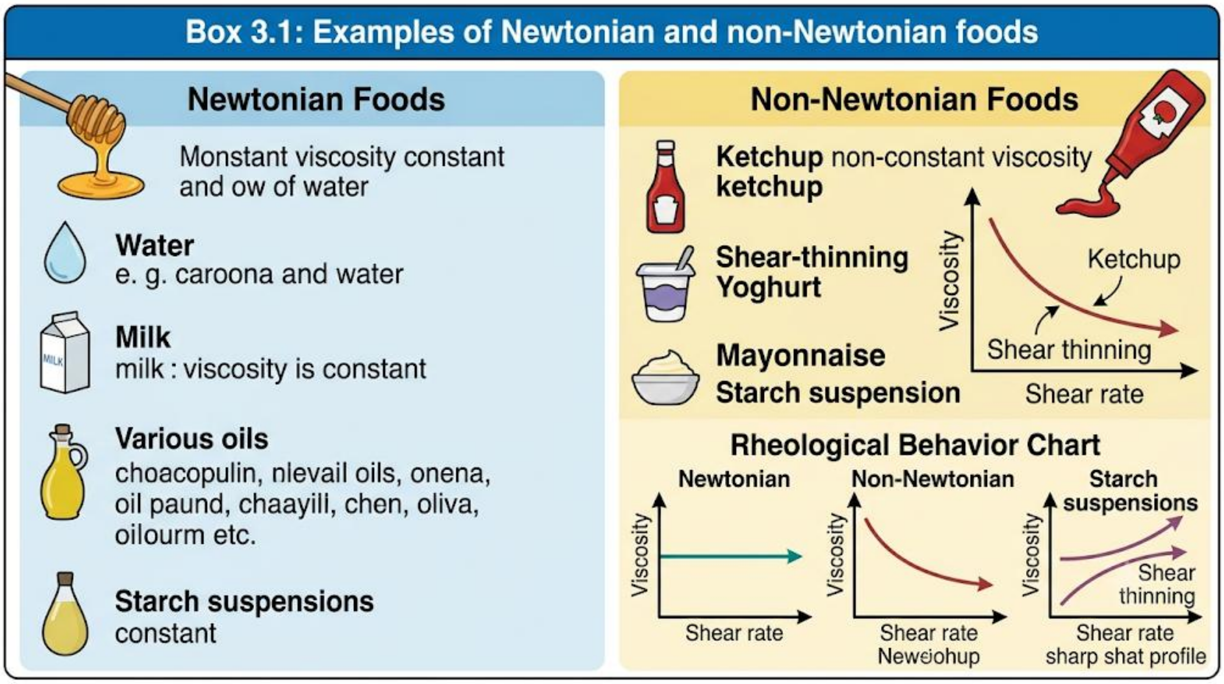
Diagram showing Newtonian vs non-Newtonian fluid behaviour *Figure 3.1: Comparison of Newtonian and non-Newtonian fluids*

3.1.2 Newtonian and non-Newtonian behaviour

Newtonian behaviour means viscosity remains constant under different flow conditions. Examples include water, milk, and vegetable oils. **Non-Newtonian behaviour** means viscosity changes with shear rate. Non-Newtonian fluids can be classified further:

- **Shear-thinning fluids** (e.g., ketchup, yoghurt) become less viscous when stirred.
- **Shear-thickening fluids** (e.g., starch suspensions) become more viscous when stirred.
- **Bingham plastics** (e.g., mayonnaise) behave like solids until a certain stress is applied.

Fill in the blank: Ketchup is an example of a _________ fluid because its viscosity decreases when stirred.



Box 3.1: Examples of Newtonian and non-Newtonian foods Description: Newtonian – water, milk, oils. Non-Newtonian – ketchup, yoghurt, mayonnaise, starch suspensions.

3.1.3 Flow regimes: laminar and turbulent

Fluid flow can occur in two main regimes: **laminar flow** and **turbulent flow**. Laminar flow is smooth and orderly, with fluid particles moving in parallel layers. It occurs at low velocities and is common in viscous fluids like honey. Turbulent flow is chaotic, with eddies and mixing, and occurs at higher velocities, such as water flowing rapidly in pipes. Engineers use the **Reynolds number** to predict whether flow will be laminar or turbulent.

Fill in the blank: Smooth, orderly fluid movement in parallel layers is called _________ flow.

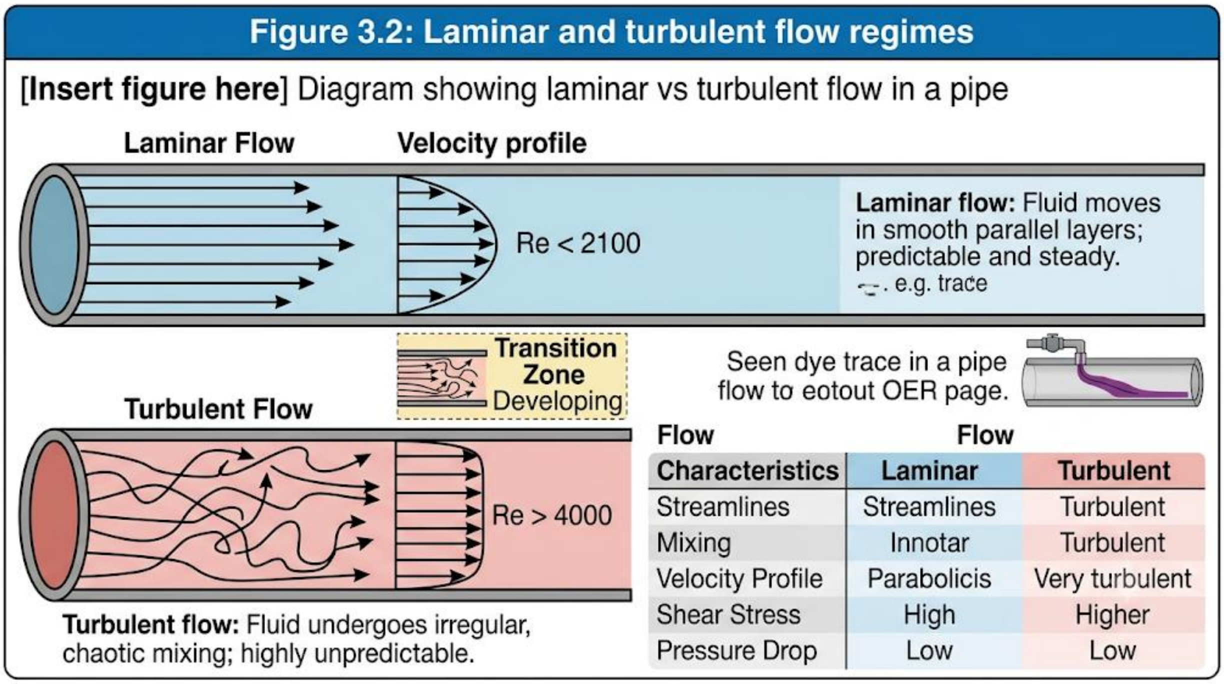


Diagram showing laminar vs turbulent flow in a pipe *Figure 3.2: Laminar and turbulent flow regimes*

Pilot questions 3.1

1. What is the difference between Newtonian and non-Newtonian fluids?
2. Give two examples of Newtonian fluids in food systems.
3. What type of non-Newtonian fluid is ketchup?
4. What is the Reynolds number used for in fluid flow analysis?
5. Which flow regime is common in viscous fluids like honey?

3.2 Governing Equations Of Fluid Flow

3.2.1 Continuity equation

The **continuity equation** expresses the principle of conservation of mass in fluid flow. It states that the mass flow rate of a fluid must remain constant from one cross-section of a pipe to another, provided there is no accumulation or loss. In simpler terms, if fluid velocity increases, the cross-sectional area must decrease, and vice versa. This principle is vital in food systems where fluids are transported through pipes, ensuring consistent flow rates.

Fill in the blank: The continuity equation is based on the principle of conservation of __________.

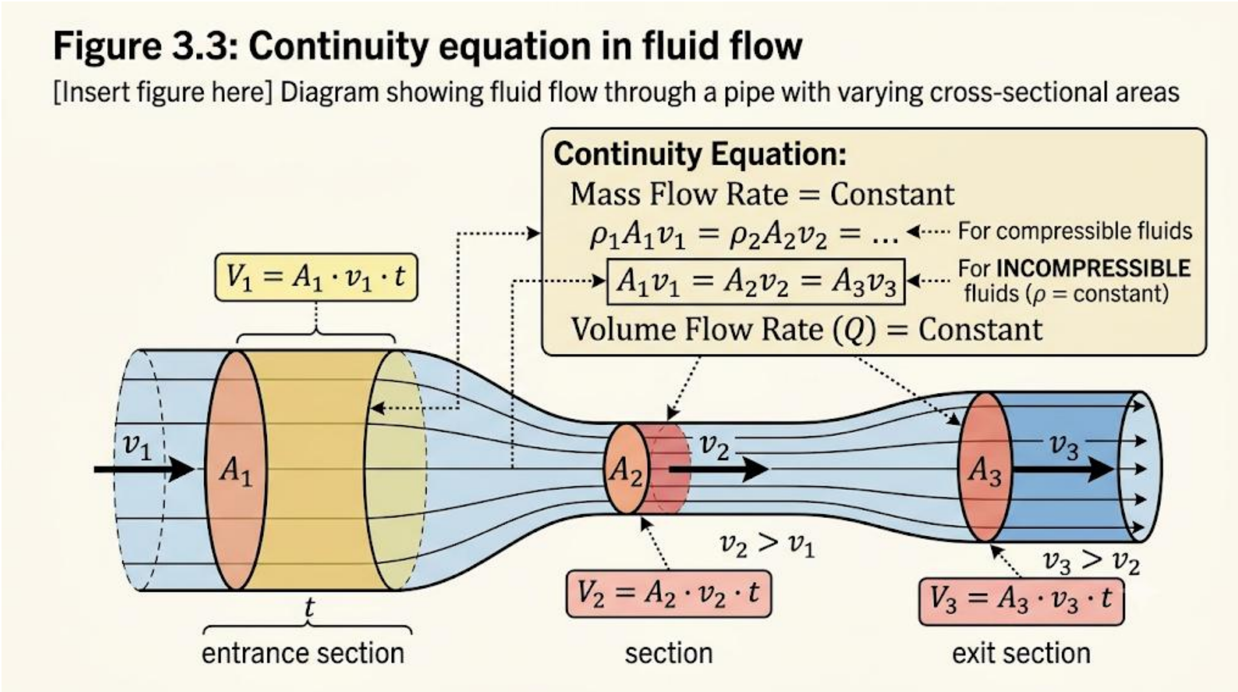


Diagram showing fluid flow through a pipe with varying cross-sectional areas *Figure 3.3: Continuity equation in fluid flow*

3.2.2 Bernoulli's principle

Bernoulli's principle states that in a streamline flow, the sum of pressure energy, kinetic energy, and potential energy per unit volume remains constant. In food systems, this principle explains how pressure changes when fluid velocity changes. For example, in milk pipelines, an increase in velocity leads to a decrease in pressure. Engineers use Bernoulli's principle to design pumps and fluid transport systems.

Fill in the blank: Bernoulli's principle states that the sum of pressure energy, kinetic energy, and __________ energy remains constant in streamline flow.

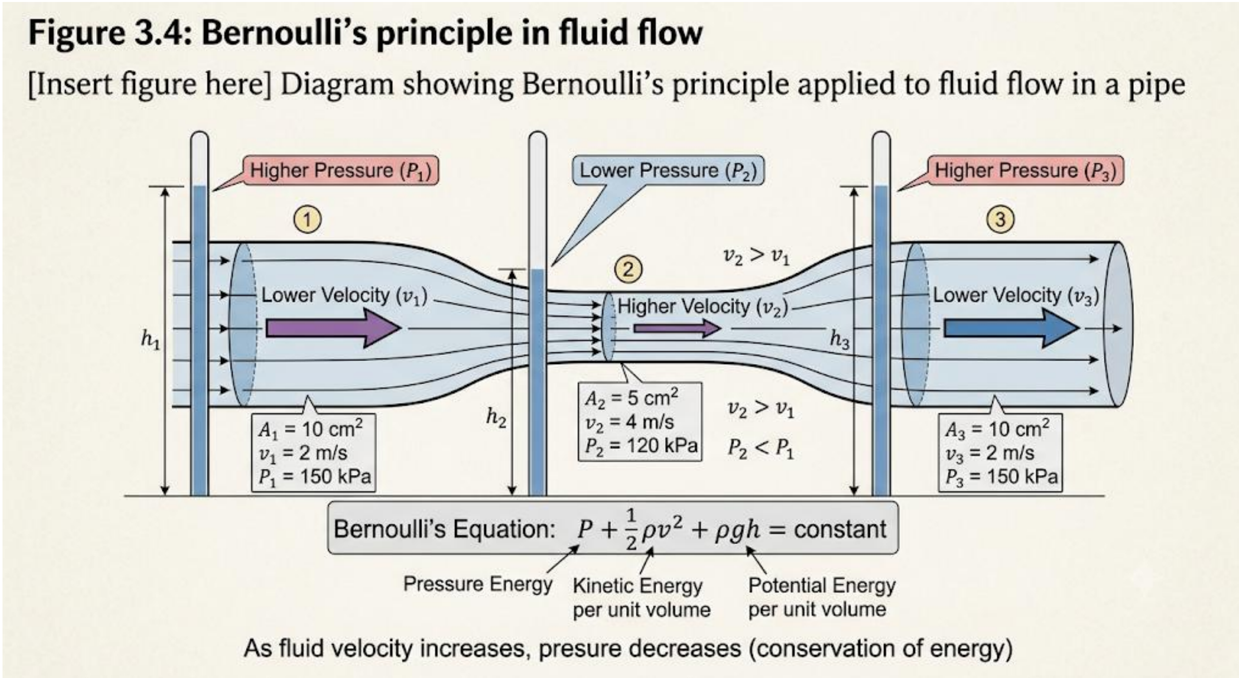
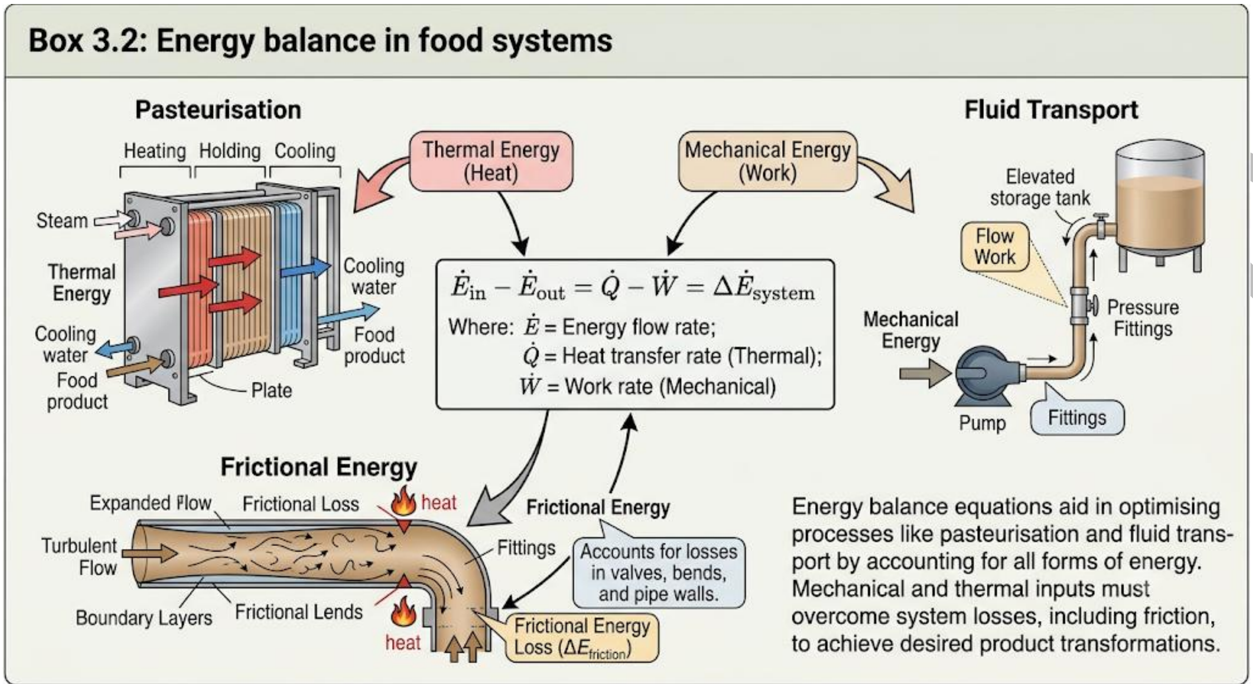


Diagram showing Bernoulli's principle applied to fluid flow in a pipe *Figure 3.4: Bernoulli's principle in fluid flow*

3.2.3 Energy balance in food systems

An **energy balance** in fluid flow considers all forms of energy entering and leaving a system. In food engineering, this includes mechanical energy from pumps, thermal energy from heat exchangers, and losses due to friction. By applying energy balance equations, engineers can optimise processes such as pasteurisation, ensuring efficient use of energy while maintaining product quality.

Fill in the blank: Energy balance in food systems accounts for mechanical energy, thermal energy, and losses due to __________.



Box 3.2: Energy balance in food systems Description: Energy balance equations help optimise processes like pasteurisation and fluid transport by accounting for mechanical, thermal, and frictional energy.

Pilot questions 3.2

1. What principle does the continuity equation express?
2. How does fluid velocity affect pressure according to Bernoulli's principle?
3. Name the three forms of energy considered in Bernoulli's principle.
4. Why is energy balance important in food fluid systems?
5. Give one example of a food process where energy balance is applied.

3.3 Measurement And Characterisation Of Fluid Flow

3.3.1 Instruments for measuring flow

Fluid flow in food systems is measured using specialised instruments. **Flow meters** are used to determine the rate of fluid movement through pipes, while **viscometers** measure viscosity. In dairy plants, flow meters ensure consistent milk delivery, and in beverage industries, they help maintain uniform filling rates. Accurate measurement is essential for quality control and process optimisation.

Fill in the blank: The instrument used to measure viscosity in fluid foods is called a __________.

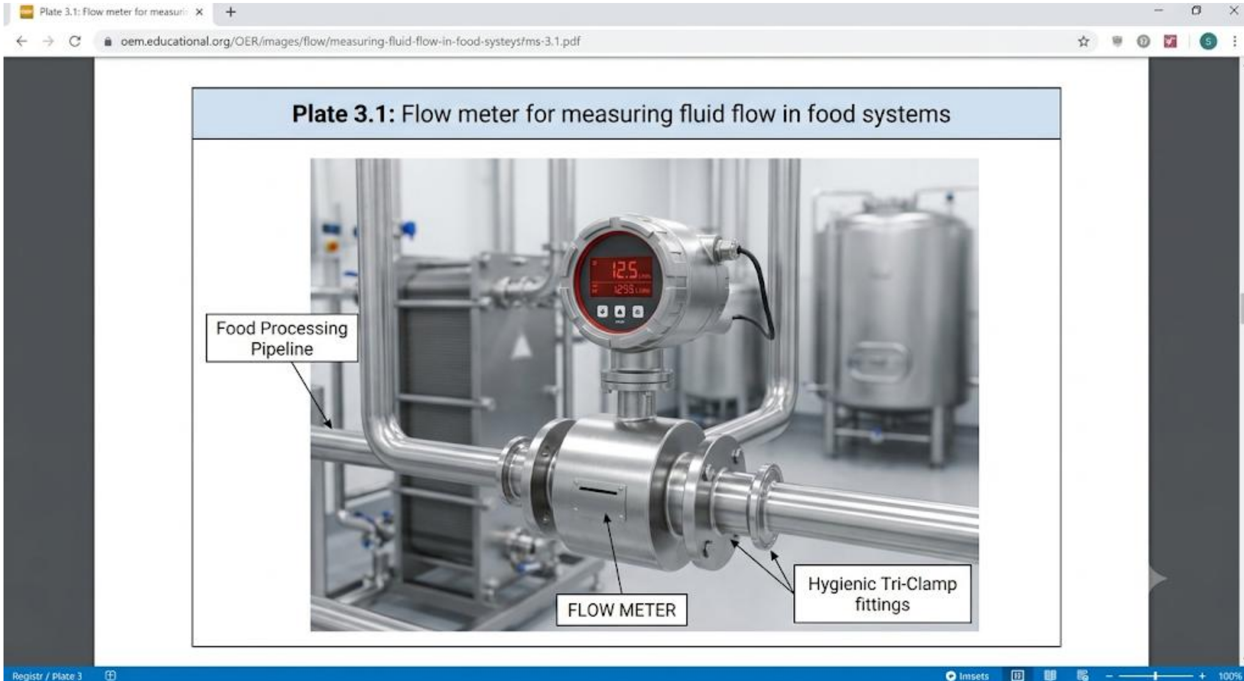


Image of a flow meter used in food processing pipelines *Plate 3.1: Flow meter for measuring fluid flow in food systems*

3.3.2 Rheological characterisation of food fluids

Rheology is the study of how materials flow and deform. In food systems, rheological characterisation involves measuring viscosity, elasticity, and yield stress. Non-Newtonian fluids such as ketchup or yoghurt require rheological analysis to understand their behaviour under different shear conditions. This helps engineers design pumps, mixers, and packaging systems that handle these fluids efficiently.

Fill in the blank: The study of how materials flow and deform is called __________.

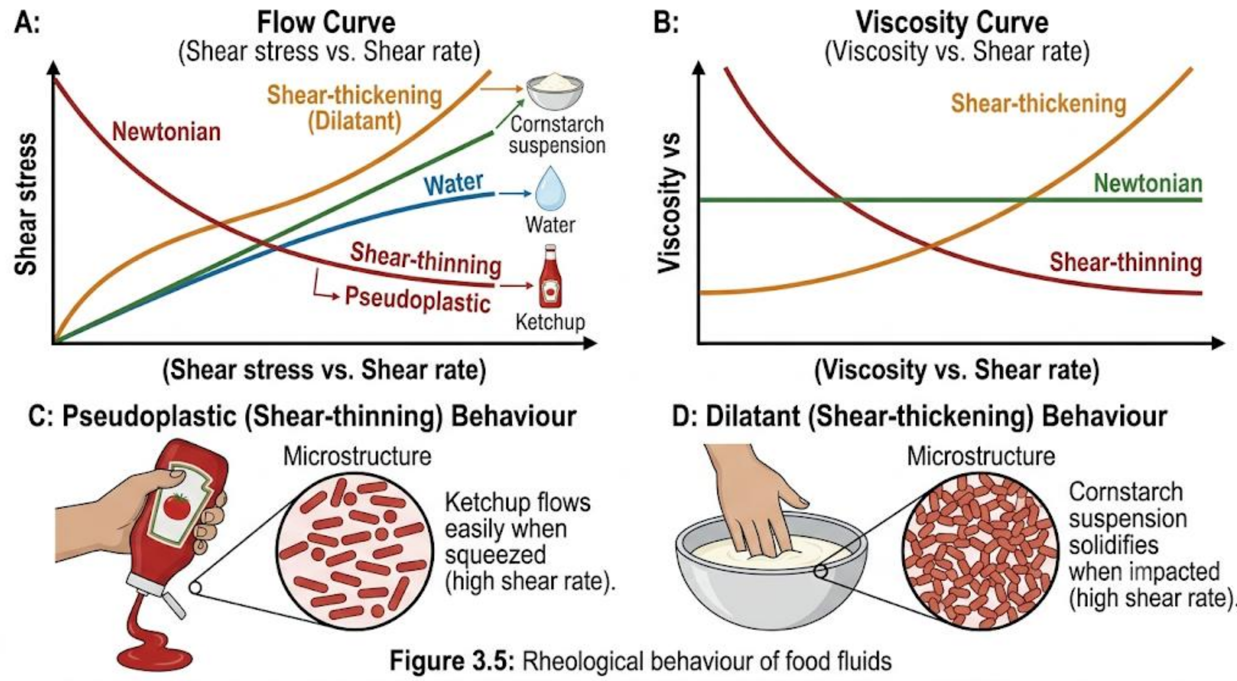
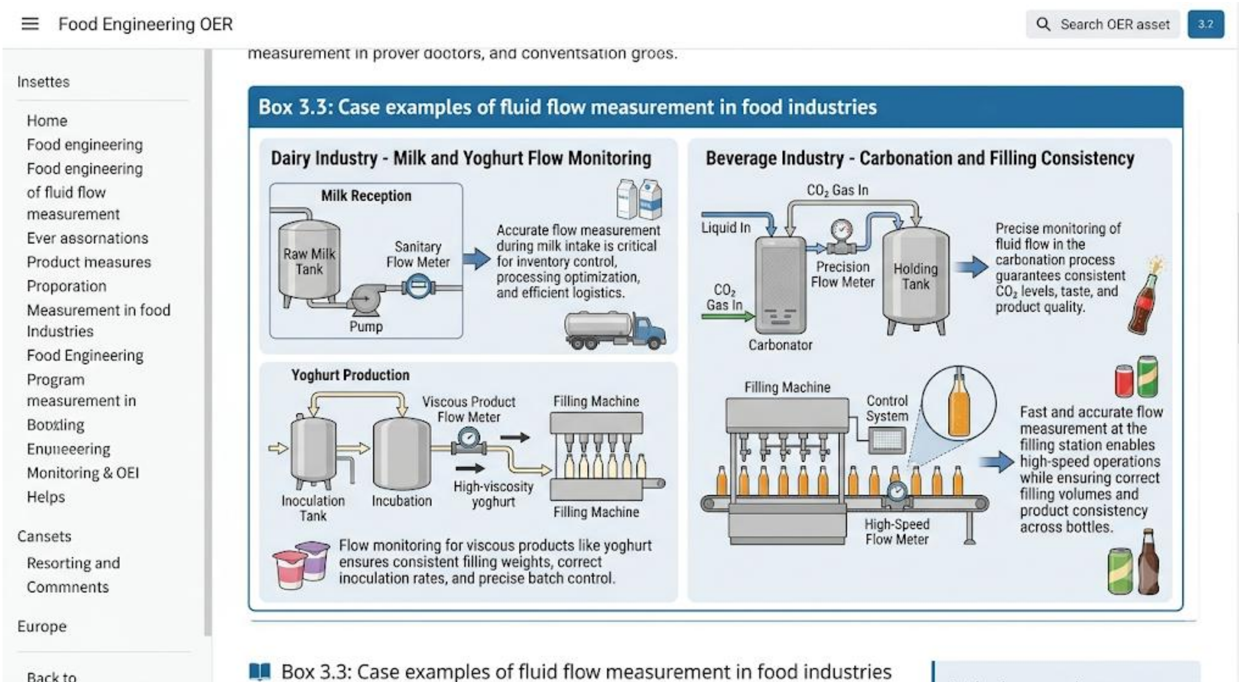


Diagram showing rheological curves for shear-thinning and shear-thickening fluids *Figure 3.5: Rheological behaviour of food fluids*

3.3.3 Case examples in dairy and beverage industries

In dairy industries, rheological measurements ensure milk and yoghurt flow smoothly through pipelines without clogging. In beverage industries, flow meters and rheological data help maintain consistent carbonation and filling rates. These case examples highlight how measurement and characterisation are directly applied to maintain product quality and efficiency.

Fill in the blank: Rheological measurements in dairy industries help ensure smooth flow of __________ through pipelines.



Box 3.3: Case examples of fluid flow measurement in food industries Description: Dairy – milk and yoghurt flow monitoring. Beverage – carbonation and filling consistency.

Pilot questions 3.3

1. What instrument is used to measure fluid flow rates in pipelines?
2. Define rheology in the context of food systems.
3. Why is rheological characterisation important for non-Newtonian fluids?
4. Give one example of how flow measurement is applied in the dairy industry.
5. How do beverage industries use flow meters to maintain product quality?

3.4 Applications In Food Engineering

3.4.1 Pumping and mixing operations

In food engineering, **pumping** ensures that fluids such as milk, juices, and sauces are transported efficiently through pipelines. The design of pumps must consider viscosity and flow behaviour, especially for non-Newtonian fluids. **Mixing operations** are equally important, as they ensure uniform distribution of ingredients in products like soups or yoghurt. Engineers select pumps and mixers based on fluid properties to avoid clogging or uneven mixing.

Fill in the blank: Pump design in food systems must consider the __________ of the fluid being transported.

Image of industrial pumps and mixers used in food processing *Plate 3.2: Pumps and mixers in food engineering*

3.4.2 Heat exchangers and fluid transport

Heat exchangers are widely used in food processing to heat or cool fluids efficiently. For example, milk pasteurisation relies on plate heat exchangers to achieve uniform heating. Fluid transport systems must be designed to minimise energy losses and maintain product quality. Engineers use fluid flow equations to optimise these systems, ensuring safe and cost-effective operations.

Fill in the blank: Plate heat exchangers are commonly used in _________ pasteurisation.

Figure 3.6: Plate heat exchanger in milk pasteurisation

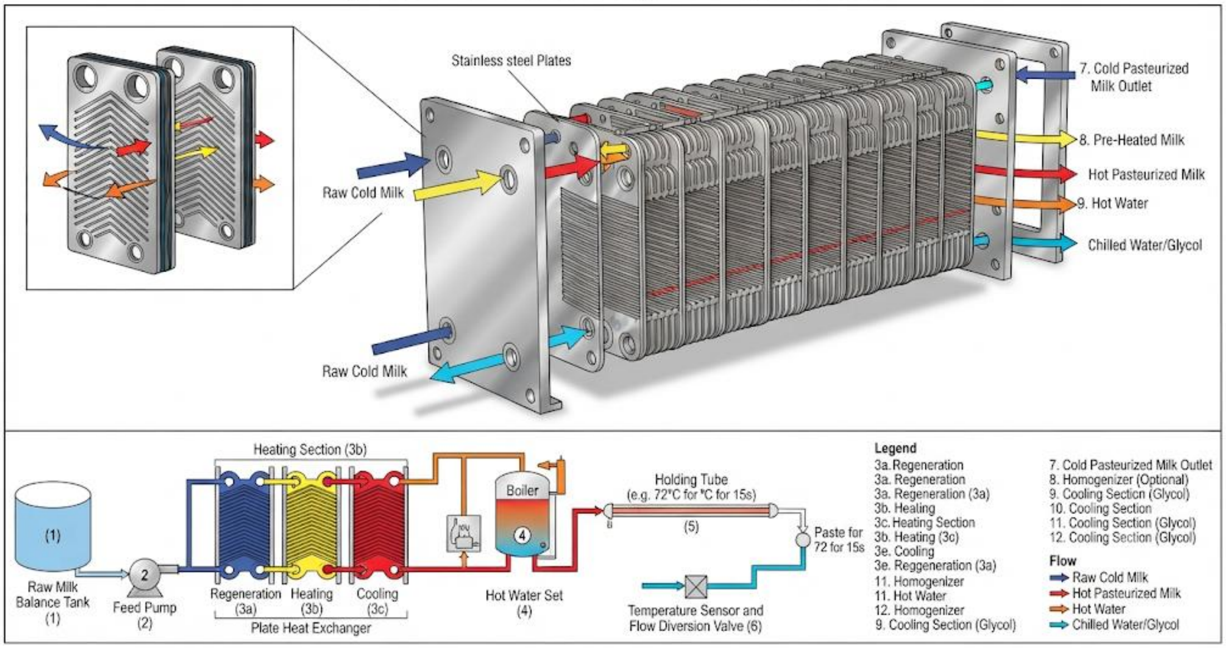
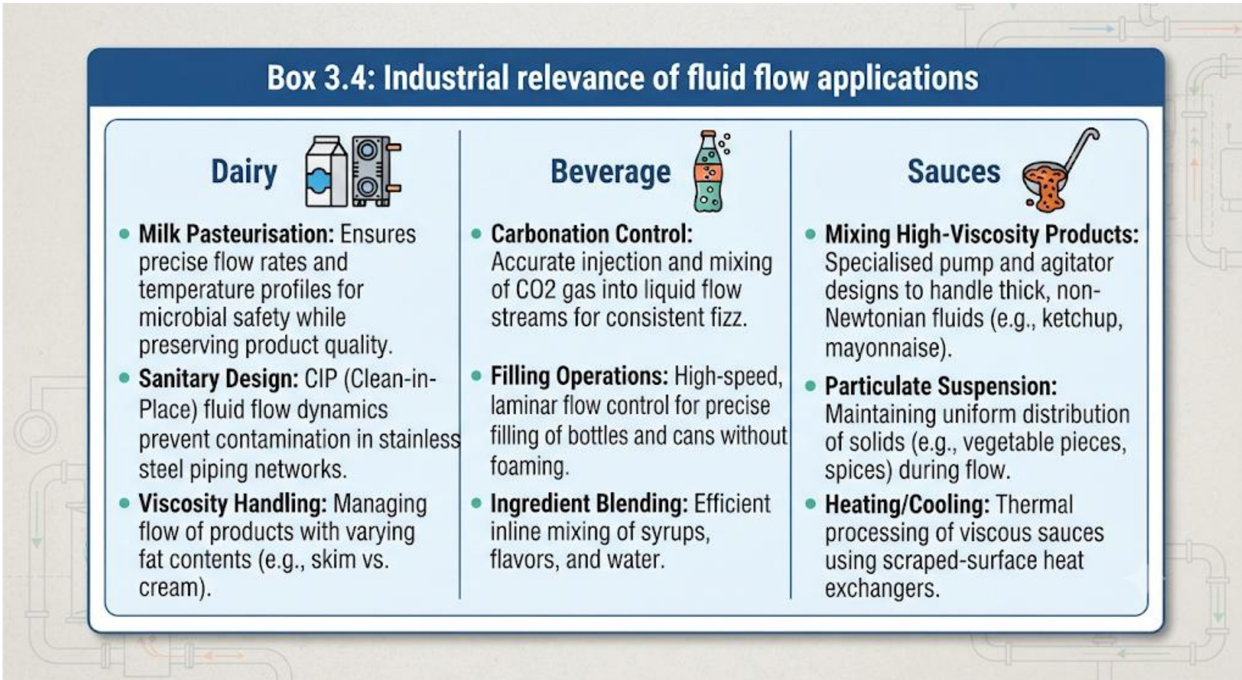


Diagram of a plate heat exchanger used in milk pasteurisation *Figure 3.6: Plate heat exchanger in milk pasteurisation*

3.4.3 Industrial relevance and optimisation

Fluid flow applications are critical in industries such as dairy, beverages, and sauces. Engineers optimise pumping, mixing, and heat exchange operations to reduce energy consumption and improve efficiency. For example, beverage industries rely on precise fluid flow control to maintain carbonation levels, while sauce manufacturers use rheological data to design mixers that handle high-viscosity products.

Fill in the blank: Beverage industries rely on precise fluid flow control to maintain _________ levels.



Box 3.4: Industrial relevance of fluid flow applications Description: Dairy – milk pasteurisation with heat exchangers. Beverage – carbonation control. Sauces – mixing of high-viscosity products.

Pilot questions 3.4

1. Why must pump design consider fluid viscosity?
2. What type of heat exchanger is commonly used in milk pasteurisation?
3. How do beverage industries use fluid flow control?
4. Give one example of a mixing operation in food engineering.
5. Why is optimisation of fluid flow systems important in industry?

Series Summary

This Series has introduced you to the principles of fluid flow in food systems, which are vital for transporting, mixing, and processing liquid foods. We began by defining fluids and distinguishing between Newtonian and non-Newtonian behaviours, then explored laminar and turbulent flow regimes. We moved on to governing equations, including the continuity equation, Bernoulli's principle, and energy balance, which provide the scientific foundation for analysing fluid behaviour. Following that, we examined measurement and characterisation techniques, focusing on instruments and rheological analysis with case examples in dairy and beverage industries. Finally, we considered practical applications in food engineering, such as pumping, mixing, heat exchangers, and industrial optimisation.

By completing this Series, you should now be able to define fluid flow fundamentals, apply governing equations, measure and characterise fluid behaviour, and evaluate applications in food engineering. These outcomes align directly with the Series Learning Outcomes and prepare you to apply fluid mechanics principles in real-world food processing contexts.

Glossary of Terms

- **Bernoulli's principle**: States that the sum of pressure, kinetic, and potential energy remains constant in streamline flow.
- **Continuity equation**: Expresses conservation of mass in fluid flow, ensuring mass flow rate remains constant.
- **Flow meter**: An instrument used to measure the rate of fluid movement through pipelines.
- **Laminar flow**: Smooth, orderly fluid movement in parallel layers.
- **Newtonian fluid**: A fluid with constant viscosity regardless of shear rate.
- **Non-Newtonian fluid**: A fluid whose viscosity changes with shear rate, such as ketchup or yoghurt.
- **Rheology**: The study of how materials flow and deform under applied forces.
- **Reynolds number**: A dimensionless number used to predict whether fluid flow is laminar or turbulent.
- **Turbulent flow**: Chaotic fluid movement with eddies and mixing, common at high velocities.
- **Viscometer**: An instrument used to measure the viscosity of fluid foods.

Concept Check Questions [Series 3]

Objective questions

1. Which type of fluid maintains constant viscosity regardless of shear rate? (Linked to SLO 3.1)
2. The continuity equation is based on conservation of __________. (Linked to SLO 3.2)
3. What instrument is used to measure viscosity in fluid foods? (Linked to SLO 3.3)

Short-answer questions

4. Define rheology and explain its importance in food systems. (Linked to SLO 3.3)
5. What is the Reynolds number used for in fluid flow analysis? (Linked to SLO 3.1)

Long-answer questions

6. Analyse how Bernoulli's principle applies to food fluid systems, giving at least two examples. (Linked to SLO 3.2)

- *Basic response*: Discuss milk pipelines and beverage filling systems.
- *Value-added response*: Extend discussion to include pump design and energy efficiency in fluid transport.

7. Evaluate the industrial applications of fluid flow in food engineering, focusing on pumping, mixing, and heat exchangers. (Linked to SLO 3.4)
    - *Basic response*: Explain how pumps transport milk, mixers blend sauces, and heat exchangers pasteurise dairy.
    - *Value-added response*: Include optimisation strategies for energy savings and maintaining product quality.

Answers to Pilot Questions [Series 3]

Part 3.1

1. Newtonian fluids have constant viscosity; non-Newtonian fluids change viscosity with shear rate.
2. Water and milk.
3. Shear-thinning fluid.
4. To predict laminar or turbulent flow.
5. Laminar flow.

Part 3.2

1. Conservation of mass.
2. Increased velocity leads to decreased pressure.
3. Pressure, kinetic, and potential energy.
4. It ensures efficient energy use and product quality.
5. Pasteurisation.

Part 3.3

1. Flow meter.
2. The study of how materials flow and deform.
3. To design equipment for fluids with variable viscosity.
4. Monitoring milk and yoghurt flow.
5. To maintain carbonation and filling consistency.

Part 3.4

1. Because viscosity affects pumping efficiency.
2. Plate heat exchanger.
3. To maintain carbonation levels.
4. Mixing yoghurt or soups.
5. To reduce energy use and improve efficiency.

References and Attributions [Series 3]

- *Figure 3.1*: Comparison of Newtonian and non-Newtonian fluids. Suggested AI prompt: “Diagram comparing Newtonian and non-Newtonian fluid flow behaviour.”
- *Box 3.1*: Examples of Newtonian and non-Newtonian foods. Suggested AI prompt: “Box listing examples of Newtonian and non-Newtonian food fluids.”
- *Figure 3.2*: Laminar and turbulent flow regimes. Suggested AI prompt: “Diagram comparing laminar and turbulent flow in a pipe.”
- *Figure 3.3*: Continuity equation in fluid flow. Suggested AI prompt: “Diagram of fluid flow through a pipe showing continuity equation with varying cross-sectional areas.”
- *Figure 3.4*: Bernoulli’s principle in fluid flow. Suggested AI prompt: “Diagram showing Bernoulli’s principle applied to fluid flow in a pipe with velocity and pressure changes.”
- *Box 3.2*: Energy balance in food systems. Suggested AI prompt: “Box summarising energy balance in food systems with mechanical, thermal, and frictional energy.”
- *Plate 3.1*: Flow meter for measuring fluid flow in food systems. Suggested AI prompt: “Photograph of flow meter used in food processing pipelines.”
- *Figure 3.5*: Rheological behaviour of food fluids. Suggested AI prompt: “Diagram showing rheological curves for shear-thinning and shear-thickening food fluids.”
- *Box 3.3*: Case examples of fluid flow measurement in food industries. Suggested AI prompt: “Box summarising case examples of fluid flow measurement in dairy and beverage industries.”
- *Plate 3.2*: Pumps and mixers in food engineering. Suggested AI prompt: “Photograph of industrial pumps and mixers used in food processing.”
- *Figure 3.6*: Plate heat exchanger in milk pasteurisation. Suggested AI prompt: “Diagram of plate heat exchanger used in milk pasteurisation.”

- *Box 3.4*: Industrial relevance of fluid flow applications. Suggested AI prompt: "Box summarising industrial relevance of fluid flow applications in dairy, beverage, and sauce industries."

Series 4: Pumping Power And Classification

Series outline

- **4.1 Fundamentals Of Pumping Power**
    - 4.1.1 Definition and importance of pumping in food systems
    - 4.1.2 Energy requirements and efficiency considerations
    - 4.1.3 Factors affecting pumping power (viscosity, density, flow rate)
- **4.2 Classification Of Pumps**
    - 4.2.1 Positive displacement pumps
    - 4.2.2 Centrifugal pumps
    - 4.2.3 Specialised pumps for food applications
- **4.3 Pump Performance And Selection**
    - 4.3.1 Pump curves and performance characteristics
    - 4.3.2 Criteria for selecting pumps in food industries
    - 4.3.3 Case examples in dairy, beverage, and sauce processing
- **4.4 Industrial Applications And Optimisation**
    - 4.4.1 Pumping operations in food transport and processing
    - 4.4.2 Energy optimisation and sustainability
    - 4.4.3 Maintenance and reliability in industrial settings

Introduction

Pumping operations are fundamental in food process engineering because fluids such as milk, juices, oils, and sauces must be transported efficiently through pipelines and equipment. The power required to pump these fluids depends on their properties and the design of the pumping system. Understanding pumping power and pump classification ensures that engineers can select the right equipment, optimise energy use, and maintain product quality.

The aim of this Series is to introduce you to the principles of pumping power, explain the classification of pumps, demonstrate how to evaluate pump performance and selection, and highlight industrial applications with a focus on optimisation and sustainability.

We shall commence this Series by examining the fundamentals of pumping power, including energy requirements and factors affecting efficiency. Next, we will study the classification of pumps, distinguishing between positive displacement, centrifugal, and specialised pumps. Following that, we will explore pump performance and selection, supported by case examples in dairy, beverage, and sauce processing. Finally, we will conclude by considering industrial applications and optimisation strategies, including energy savings and maintenance practices.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 4.1** explain the fundamentals of pumping power and identify factors affecting energy requirements,
- **SLO 4.2** classify pumps into positive displacement, centrifugal, and specialised types,
- **SLO 4.3** interpret pump performance curves and apply criteria for selecting pumps in food industries, and
- **SLO 4.4** evaluate industrial applications of pumps, including optimisation, sustainability, and maintenance practices.

4.1 Fundamentals Of Pumping Power

4.1.1 Definition and importance of pumping in food systems

Pumping power refers to the energy required to move fluids through pipelines and equipment. In food systems, pumping is essential for transporting milk, juices, oils, sauces, and other liquid products. Efficient pumping ensures smooth operations, reduces energy costs, and maintains product quality by preventing damage to sensitive fluids.

Fill in the blank: Pumping power is the energy required to move _________ through pipelines and equipment.

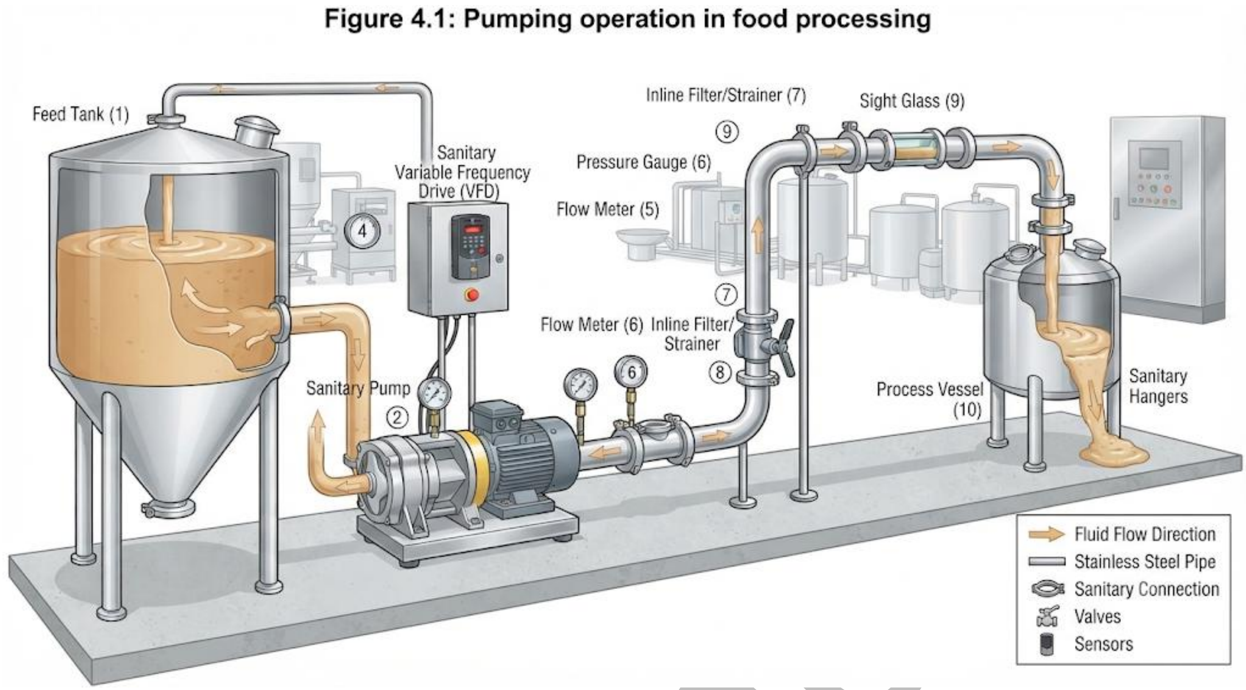
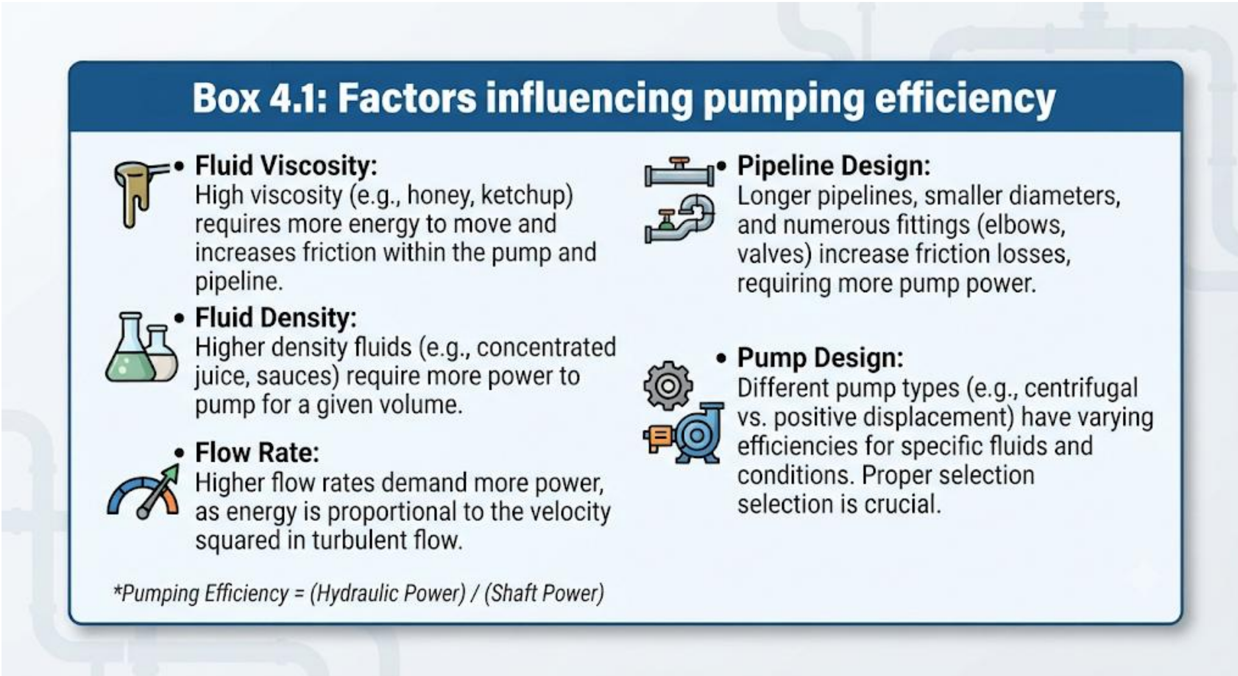


Diagram showing fluid being pumped through a pipeline in a food plant *Figure 4.1: Pumping operation in food processing*

4.1.2 Energy requirements and efficiency considerations

The energy required for pumping depends on factors such as fluid viscosity, density, flow rate, and pipeline length. Engineers aim to maximise efficiency by selecting pumps that match the fluid properties and system design. Inefficient pumping leads to higher energy consumption and increased operational costs.

Fill in the blank: The energy required for pumping depends on fluid viscosity, density, flow rate, and _________ length.



Box 4.1: Factors influencing pumping efficiency Description: Fluid viscosity, density, flow rate, pipeline length, and pump design all affect energy requirements.

4.1.3 Factors affecting pumping power

Several factors influence pumping power in food systems:

- **Viscosity**: Thicker fluids like sauces require more energy to pump.
- **Density**: Heavier fluids exert more resistance.
- **Flow rate**: Higher flow rates demand greater power.
- **Pipeline design**: Longer or narrower pipelines increase resistance.
- **Pump type**: Positive displacement vs centrifugal pumps affect efficiency differently.

Fill in the blank: Thicker fluids such as sauces require more pumping power because of their higher __________.

Image of sauce being pumped in a food processing plant *Plate 4.1: Pumping viscous fluids in food systems*

Pilot questions 4.1

1. What is pumping power in food systems?
2. Name two examples of fluids commonly pumped in food industries.
3. List three factors that influence energy requirements for pumping.
4. Why does pipeline length affect pumping power?
5. Which property of sauces makes them require more pumping power?

4.2 Classification Of Pumps

4.2.1 Positive displacement pumps

Positive displacement pumps move fluid by trapping a fixed volume and forcing it through the system. They are ideal for viscous, non-Newtonian fluids such as sauces, yoghurt, and syrups. Common types include piston pumps, gear pumps, and diaphragm pumps. These pumps deliver a constant flow regardless of pressure, making them suitable for precise dosing in food industries.

Fill in the blank: Positive displacement pumps deliver a _________ flow regardless of pressure.

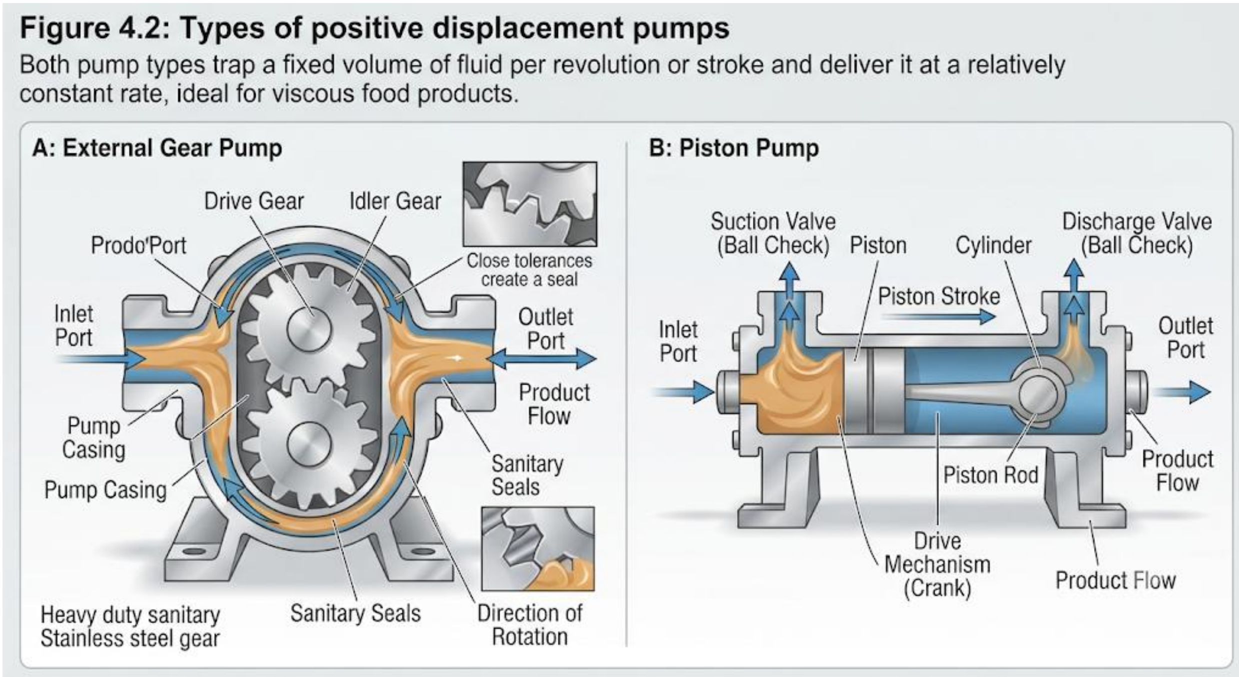


Diagram showing gear and piston positive displacement pumps *Figure 4.2: Types of positive displacement pumps*

4.2.2 Centrifugal pumps

Centrifugal pumps use a rotating impeller to impart velocity to the fluid, converting it into pressure energy. They are widely used in food industries for low-viscosity fluids such as milk, water, and juices. Centrifugal pumps are efficient, easy to maintain, and suitable for high flow rates, but they are less effective for very viscous fluids.

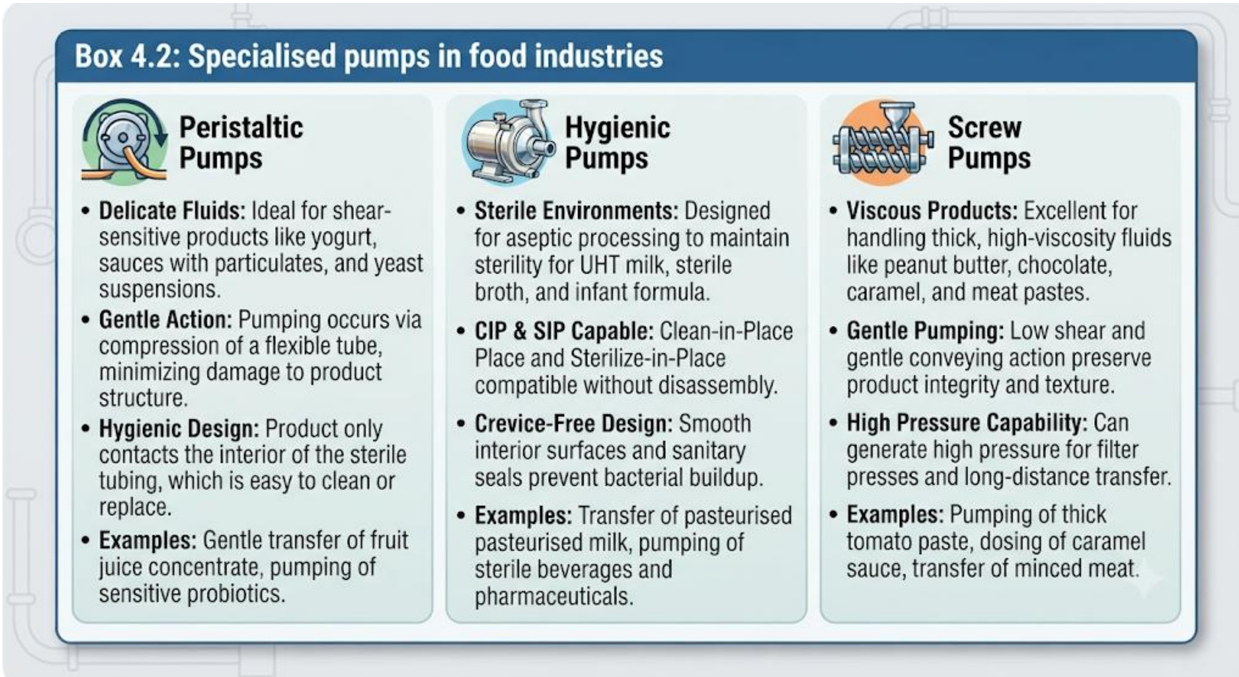
Fill in the blank: Centrifugal pumps use a rotating __________ to impart velocity to fluids.

Image of a centrifugal pump used in dairy processing *Plate 4.2: Centrifugal pump in dairy industry*

4.2.3 Specialised pumps for food applications

Specialised pumps are designed to handle unique food processing needs. Examples include peristaltic pumps for delicate fluids, hygienic pumps for sterile environments, and screw pumps for high-viscosity products. These pumps ensure product integrity, prevent contamination, and meet strict food safety standards.

Fill in the blank: Peristaltic pumps are often used for handling _________ fluids in food systems.



Box 4.2: Specialised pumps in food industries Description: Peristaltic pumps – delicate fluids; Hygienic pumps – sterile environments; Screw pumps – viscous products.

Pilot questions 4.2

1. What is the main advantage of positive displacement pumps?
2. Which type of pump is most suitable for low-viscosity fluids like milk?
3. What component does a centrifugal pump use to impart velocity?
4. Name one specialised pump used for delicate fluids.
5. Why are hygienic pumps important in food industries?

4.3 Pump Performance And Selection

4.3.1 Pump curves and performance characteristics

Pump performance curves show the relationship between flow rate, head (pressure), and efficiency. Engineers use these curves to determine how a pump will perform under different operating conditions. For example, centrifugal pumps have characteristic curves that indicate optimal efficiency zones. Understanding these curves helps avoid energy waste and ensures reliable operation.

Fill in the blank: Pump performance curves show the relationship between flow rate, head, and __________.

Figure 4.3: Pump performance curve for centrifugal pumps

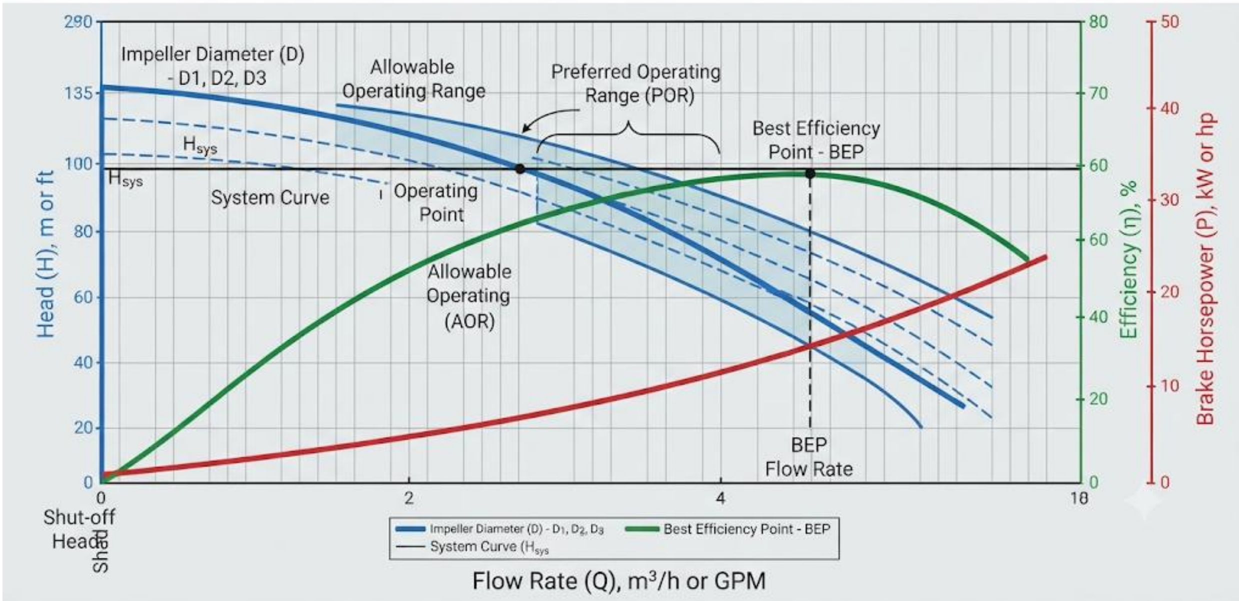


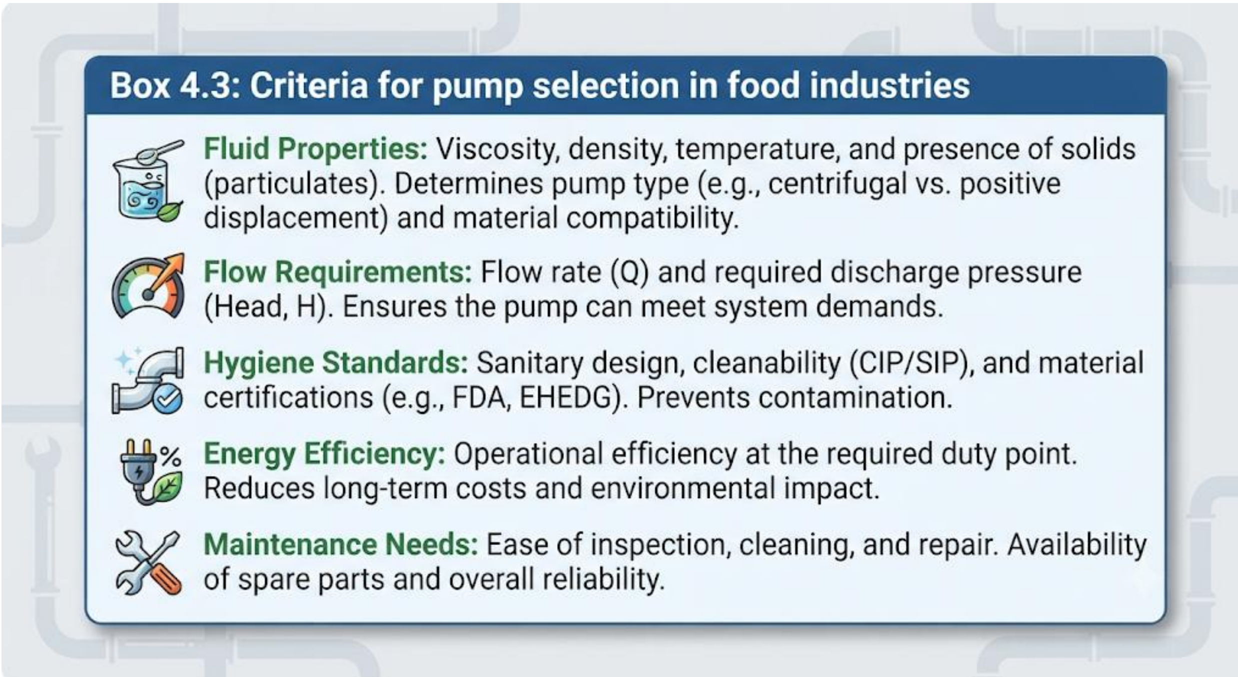
Diagram of a typical centrifugal pump performance curve *Figure 4.3: Pump performance curve for centrifugal pumps*

4.3.2 Criteria for selecting pumps in food industries

Selecting the right pump depends on several criteria:

- **Fluid properties**: viscosity, density, and whether the fluid is Newtonian or non-Newtonian.
- **Flow requirements**: desired flow rate and pressure.
- **Hygiene standards**: pumps must meet sanitary requirements for food safety.
- **Energy efficiency**: choosing pumps that minimise energy consumption.
- **Maintenance needs**: ease of cleaning and servicing.

Fill in the blank: Pump selection in food industries must consider both fluid properties and _________ standards.



Box 4.3: Criteria for pump selection in food industries Description: Fluid properties, flow requirements, hygiene standards, energy efficiency, and maintenance needs.

4.3.3 Case examples in dairy, beverage, and sauce processing

- **Dairy industry**: Centrifugal pumps are used to transport milk due to its low viscosity.
- **Beverage industry**: Positive displacement pumps are used for syrups to ensure accurate dosing.
- **Sauce processing**: Screw pumps handle viscous products like tomato paste without damaging texture.

These examples show how pump selection depends on product type and processing requirements.

Fill in the blank: Screw pumps are commonly used in sauce processing to handle __________ products like tomato paste.

Image of industrial screw pump used in sauce processing *Plate 4.3: Screw pump in tomato paste processing*

Pilot questions 4.3

1. What do pump performance curves illustrate?
2. Name two criteria for selecting pumps in food industries.
3. Which type of pump is commonly used in the dairy industry for milk?
4. Why are positive displacement pumps used in beverage industries for syrups?
5. What type of pump is suitable for viscous products like tomato paste?

4.4 Industrial Applications And Optimisation

4.4.1 Pumping operations in food transport and processing

Pumping operations are critical in transporting fluids across food plants. In dairy industries, pumps move milk from storage tanks to pasteurisation units. In beverage industries, pumps ensure consistent flow during bottling. For viscous products like sauces, specialised pumps prevent clogging and maintain texture. Efficient pumping guarantees smooth production and product integrity.

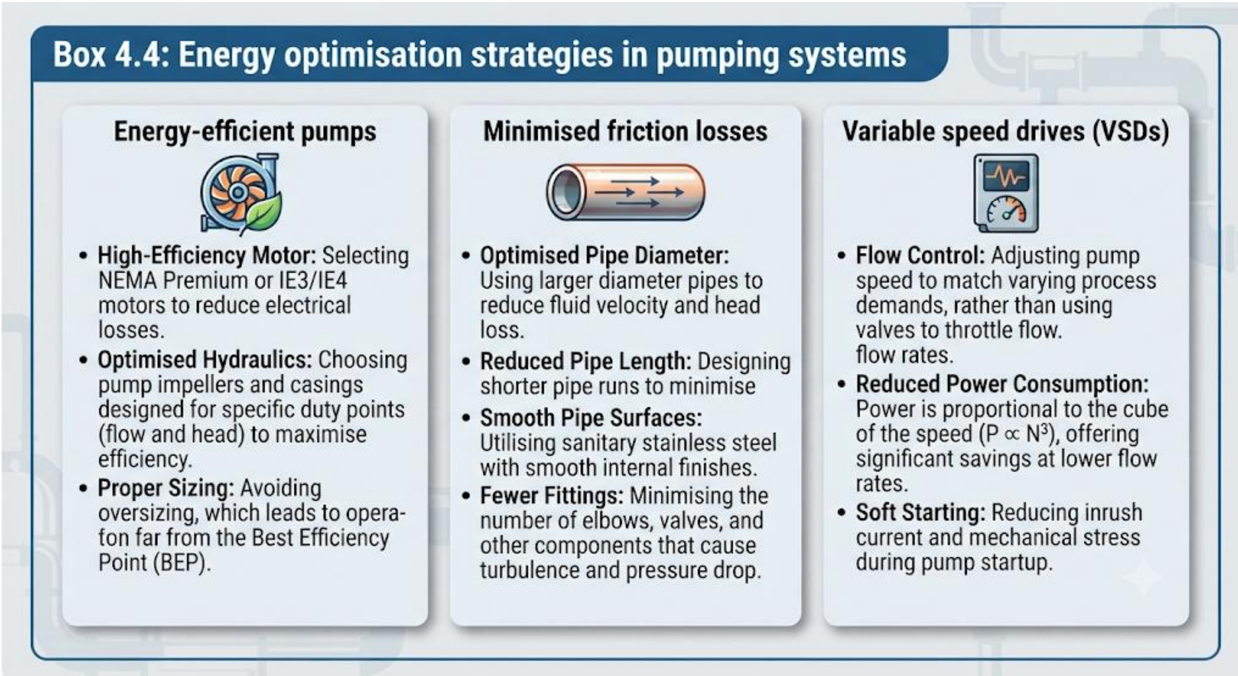
Fill in the blank: In dairy industries, pumps move milk from storage tanks to __________ units.

] Image of milk being pumped into a pasteurisation unit *Plate 4.4: Pumping operations in dairy processing*

4.4.2 Energy optimisation and sustainability

Energy optimisation in pumping systems reduces operational costs and supports sustainability. Engineers achieve this by selecting energy-efficient pumps, minimising friction losses in pipelines, and using variable speed drives to adjust flow rates. Sustainable pumping practices help food industries lower carbon footprints while maintaining high productivity.

Fill in the blank: Variable speed drives are used in pumping systems to adjust _________ rates efficiently.



Box 4.4: Energy optimisation strategies in pumping systems Description: Energy-efficient pumps, minimised friction losses, and variable speed drives for sustainable operations.

4.4.3 Maintenance and reliability in industrial settings

Regular maintenance ensures pumps remain reliable and efficient. Food industries implement preventive maintenance schedules, including cleaning, lubrication, and inspection of seals. Hygienic design is crucial to prevent contamination, especially in dairy and beverage plants. Reliable pumps reduce downtime, improve safety, and extend equipment lifespan.

Fill in the blank: Preventive maintenance schedules in food industries include cleaning, lubrication, and inspection of _________.

Figure 4.4: Preventive maintenance in food pumping systems

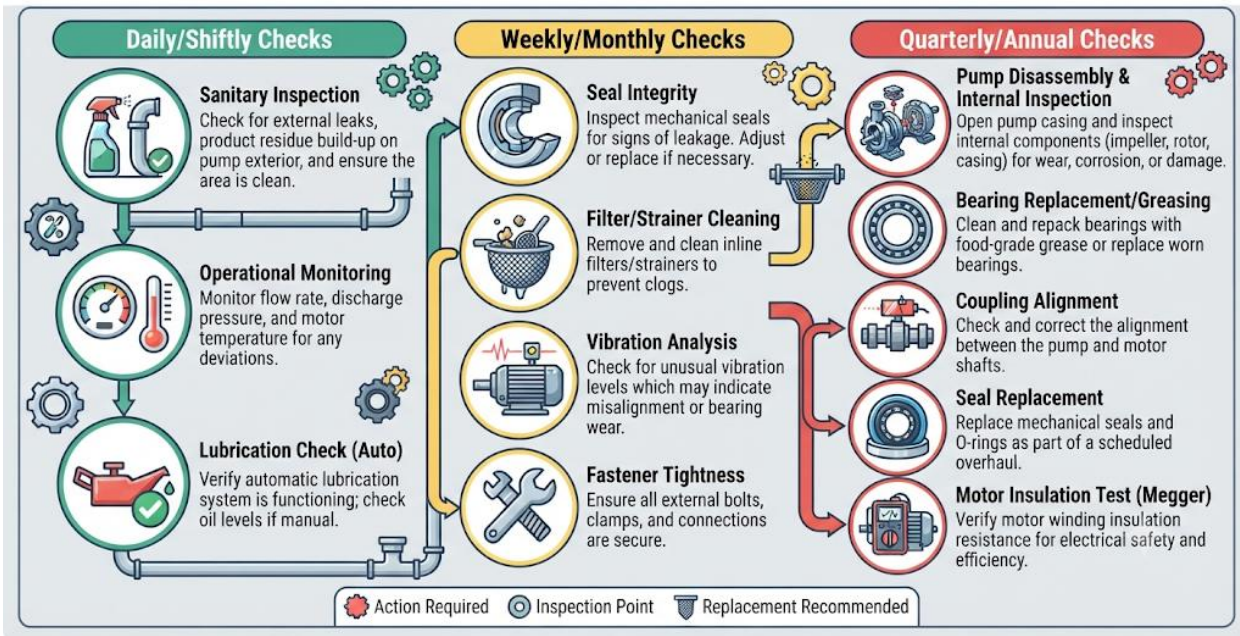


Diagram showing preventive maintenance steps for food pumps *Figure 4.4: Preventive maintenance in food pumping systems*

Pilot questions 4.4

1. What role do pumps play in dairy processing?
2. How do variable speed drives improve energy efficiency in pumping systems?
3. Name two strategies for energy optimisation in food pumping operations.
4. Why is hygienic design important in pump maintenance?
5. What are the benefits of preventive maintenance in food industries?

Series Summary

This Series has explored the principles of pumping power and classification, which are essential for fluid transport in food process engineering. We began with the fundamentals of pumping power, examining energy requirements and factors affecting efficiency. Next, we studied the classification of pumps, distinguishing between positive displacement, centrifugal, and specialised pumps. We then analysed pump performance and selection, focusing on performance curves, criteria for choosing pumps, and case examples in dairy, beverage, and sauce industries. Finally, we considered industrial applications and optimisation, including energy efficiency, sustainability, and maintenance practices.

By completing this Series, you should now be able to explain pumping power fundamentals, classify pumps, interpret performance curves, select appropriate pumps for food systems, and evaluate industrial applications with optimisation strategies.

Glossary of Terms

- **Centrifugal pump**: A pump that uses a rotating impeller to impart velocity and convert it into pressure energy.
- **Efficiency**: The ratio of useful pumping work to energy input.
- **Positive displacement pump**: A pump that moves fluid by trapping a fixed volume and forcing it through the system.
- **Pump curve**: A graph showing the relationship between flow rate, head, and efficiency.
- **Peristaltic pump**: A specialised pump used for delicate fluids, operating by compressing flexible tubing.
- **Screw pump**: A pump designed for high-viscosity fluids, such as tomato paste.
- **Variable speed drive**: A device that adjusts pump speed to optimise energy use.
- **Viscosity**: A measure of a fluid's resistance to flow.

Concept Check Questions [Series 4]

Objective questions

1. Positive displacement pumps deliver a __________ flow regardless of pressure. (Linked to SLO 4.2)
2. Centrifugal pumps use a rotating __________ to impart velocity to fluids. (Linked to SLO 4.2)
3. Pump performance curves show the relationship between flow rate, head, and __________. (Linked to SLO 4.3)

Short-answer questions

4. List three factors that influence pumping power in food systems. (Linked to SLO 4.1)
5. Why are hygienic pumps important in food industries? (Linked to SLO 4.2)

Long-answer questions

6. Analyse the criteria for selecting pumps in food industries, giving examples from dairy, beverage, and sauce processing. (Linked to SLO 4.3)
    - *Basic response*: Discuss fluid properties, flow requirements, and hygiene standards.
    - *Value-added response*: Extend discussion to include energy efficiency and maintenance considerations.
7. Evaluate industrial applications of pumps in food systems, focusing on energy optimisation and maintenance. (Linked to SLO 4.4)

- *Basic response*: Explain pumping in dairy, beverage, and sauce industries.
- *Value-added response*: Include sustainability strategies and preventive maintenance practices.

Answers to Pilot Questions [Series 4]

Part 4.1

1. Energy required to move fluids through pipelines.
2. Milk and juices.
3. Viscosity, density, flow rate.
4. Longer pipelines increase resistance.
5. Viscosity.

Part 4.2

1. Constant flow.
2. Impeller.
3. Impeller.
4. Peristaltic pump.
5. To prevent contamination and meet food safety standards.

Part 4.3

1. Relationship between flow rate, head, and efficiency.
2. Fluid properties and hygiene standards.
3. Centrifugal pump.
4. For accurate dosing of syrups.
5. Screw pump.

Part 4.4

1. Moving milk from storage tanks to pasteurisation units.
2. By adjusting flow rates efficiently.
3. Energy-efficient pumps and minimising friction losses.
4. To prevent contamination.
5. Reduced downtime and extended lifespan.

References and Attributions [Series 4]

- *Figure 4.1*: Pumping operation in food processing. Suggested AI prompt: "Diagram of fluid being pumped through a pipeline in a food processing plant."
- *Box 4.1*: Factors influencing pumping efficiency. Suggested AI prompt: "Box listing factors influencing pumping efficiency in food systems."
- *Plate 4.1*: Pumping viscous fluids in food systems. Suggested AI prompt: "Photograph of sauce being pumped in a food processing plant."
- *Figure 4.2*: Types of positive displacement pumps. Suggested AI prompt: "Diagram showing gear pump and piston pump used in food processing."
- *Plate 4.2*: Centrifugal pump in dairy industry. Suggested AI prompt: "Photograph of centrifugal pump used in dairy processing."
- *Box 4.2*: Specialised pumps in food industries. Suggested AI prompt: "Box summarising specialised pumps used in food industries."
- *Figure 4.3*: Pump performance curve for centrifugal pumps. Suggested AI prompt: "Diagram of centrifugal pump performance curve showing flow rate, head, and efficiency."
- *Box 4.3*: Criteria for pump selection in food industries. Suggested AI prompt: "Box listing criteria for pump selection in food industries."
- *Plate 4.3*: Screw pump in tomato paste processing. Suggested AI prompt: "Photograph of industrial screw pump used in tomato paste processing."
- *Plate 4.4*: Pumping operations in dairy processing. Suggested AI prompt: "Photograph of milk being pumped into a pasteurisation unit in a dairy plant."
- *Box 4.4*: Energy optimisation strategies in pumping systems. Suggested AI prompt: "Box summarising energy optimisation strategies in food pumping systems."
- *Figure 4.4*: Preventive maintenance in food pumping systems. Suggested AI prompt: "Diagram showing preventive maintenance steps for pumps in food industries."

Series 5: Food Dehydration Theory

Series outline

- **5.1 Fundamentals Of Food Dehydration**

- 5.1.1 Definition and importance of dehydration in food preservation
- 5.1.2 Principles of moisture removal
- 5.1.3 Factors affecting dehydration (temperature, humidity, air velocity)

- **5.2 Mechanisms And Models Of Drying**
  - 5.2.1 Heat and mass transfer in drying
  - 5.2.2 Drying rate curves and critical moisture content
  - 5.2.3 Mathematical models of drying behaviour
- **5.3 Methods And Equipment For Dehydration**
  - 5.3.1 Sun and solar drying
  - 5.3.2 Hot air and tray dryers
  - 5.3.3 Freeze drying and spray drying
- **5.4 Industrial Applications And Quality Considerations**
  - 5.4.1 Applications in fruits, vegetables, dairy, and meat products
  - 5.4.2 Effects of dehydration on nutritional quality and texture
  - 5.4.3 Optimisation and sustainability in industrial dehydration

Introduction

Food dehydration is one of the oldest and most widely used methods of food preservation. By removing moisture, microbial growth is inhibited, enzymatic activity is slowed, and shelf life is extended. In modern food engineering, dehydration is not only about preservation but also about creating products with desirable textures, concentrated flavours, and reduced weight for easier storage and transport.

The aim of this Series is to introduce you to the theory behind food dehydration, explain the mechanisms and models of drying, present the methods and equipment used, and highlight industrial applications with a focus on quality and sustainability.

We shall commence this Series by exploring the fundamentals of food dehydration, including its definition, importance, and the principles of moisture removal. Next, we will study the mechanisms and models of drying, focusing on heat and mass transfer, drying rate curves, and mathematical models. Following that, we will examine methods and equipment for dehydration, such as sun drying, tray dryers, freeze drying, and spray drying. Finally, we will conclude by considering industrial applications, quality effects, and optimisation strategies in food dehydration.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 5.1** explain the fundamentals of food dehydration and identify factors affecting moisture removal,
- **SLO 5.2** describe the mechanisms and models of drying, including drying rate curves and critical moisture content,
- **SLO 5.3** compare different methods and equipment for food dehydration, such as sun drying, tray dryers, freeze drying, and spray drying,
- **SLO 5.4** evaluate industrial applications of food dehydration, considering effects on quality, optimisation, and sustainability.

5.1 Fundamentals Of Food Dehydration

5.1.1 Definition and importance of dehydration in food preservation

Food dehydration is the process of removing moisture from food to extend shelf life, reduce weight, and inhibit microbial growth. It is one of the oldest preservation methods, still widely used today in fruits, vegetables, dairy, and meat products. Dehydration also enhances flavour concentration and makes foods easier to store and transport.

Fill in the blank: Food dehydration extends shelf life by removing _________ from food.

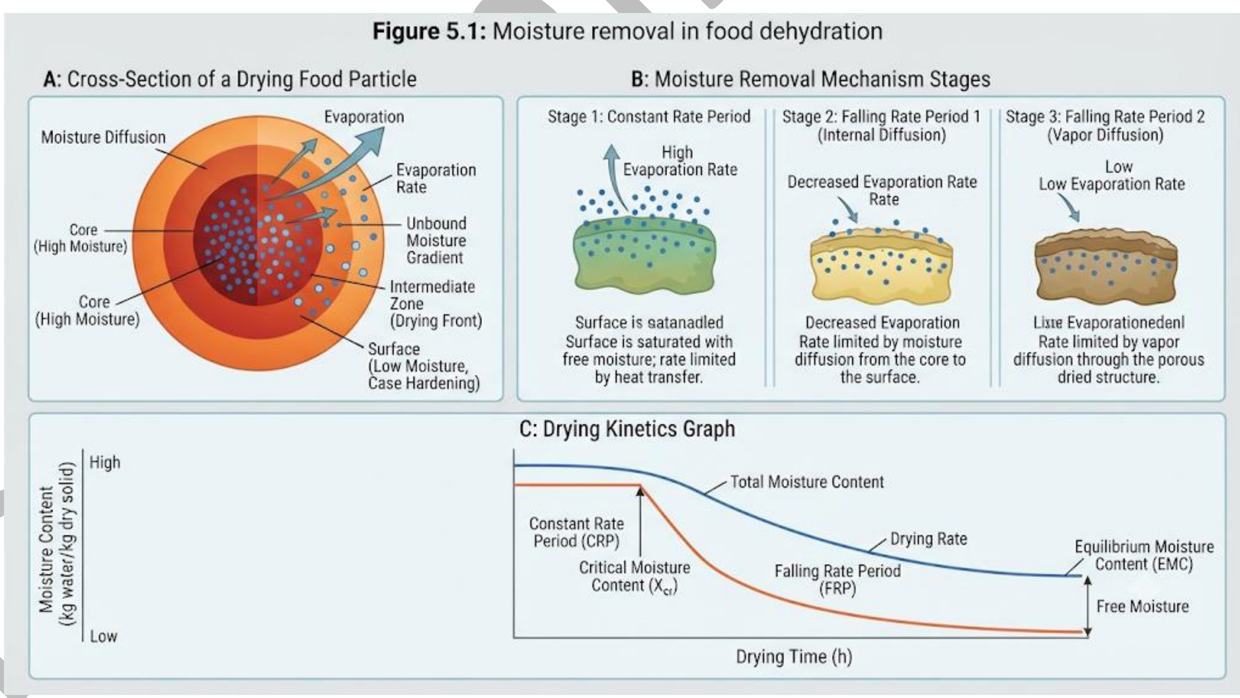


Figure 5.1: Moisture removal in food dehydration

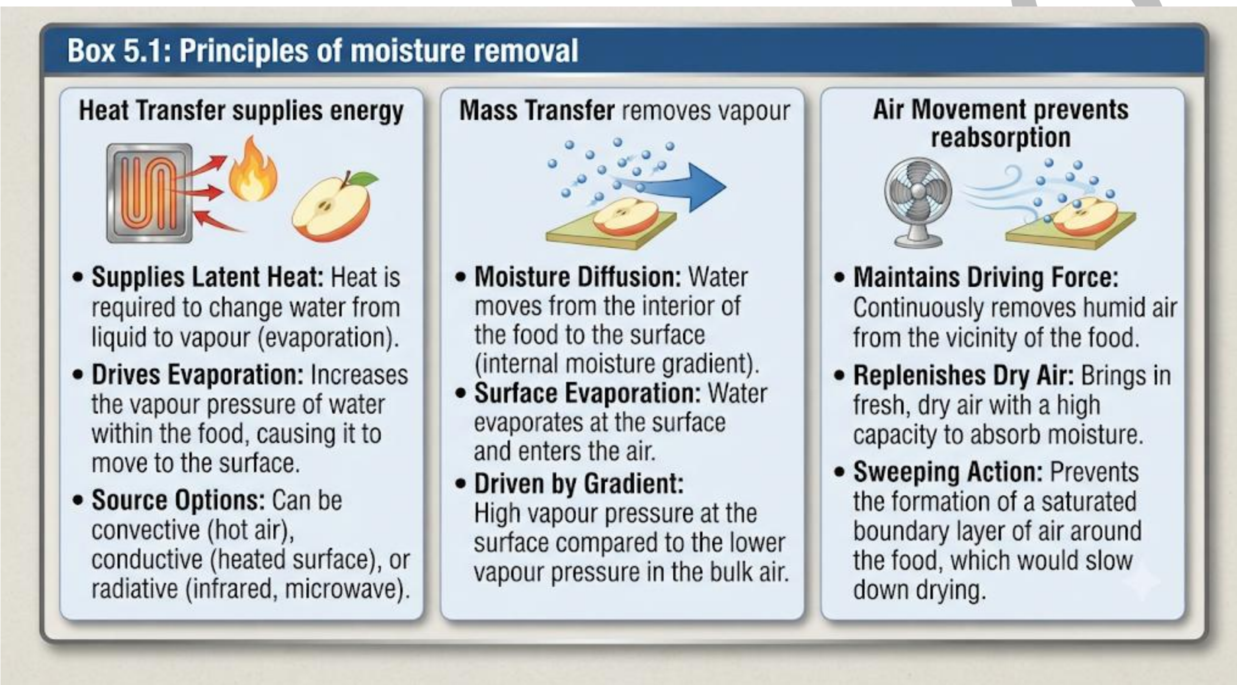
Diagram showing moisture removal during food dehydration *Figure 5.1: Moisture removal in food dehydration*

5.1.2 Principles of moisture removal

Moisture removal in dehydration relies on **heat transfer** to supply energy and **mass transfer** to remove water vapour. The process involves:

- Heating the food to evaporate water.
- Moving air to carry away the vapour.
- Maintaining conditions to prevent reabsorption of moisture.

Fill in the blank: Moisture removal in dehydration involves both heat transfer and _________ transfer.



Box 5.1: Principles of moisture removal Description: Heat transfer supplies energy; mass transfer removes vapour; air movement prevents reabsorption.

5.1.3 Factors affecting dehydration

Several factors influence the rate and efficiency of dehydration:

- **Temperature**: Higher temperatures speed up drying but may damage nutrients.
- **Humidity**: Low humidity promotes faster drying.
- **Air velocity**: Faster air movement removes moisture more effectively.
- **Food properties**: Thickness, porosity, and composition affect drying behaviour.

Fill in the blank: Higher air velocity during dehydration helps remove _________ more effectively.

Image of sliced fruits being dehydrated in a tray dryer *Plate 5.1: Fruit dehydration in tray dryer*

Pilot questions 5.1

1. What is food dehydration and why is it important?
2. Which two processes are involved in moisture removal during dehydration?
3. Name three factors that influence the rate of dehydration.
4. Why does low humidity promote faster drying?
5. Give one example of a food product commonly dehydrated.

5.2 Mechanisms And Models Of Drying

5.2.1 Heat and mass transfer in drying

Drying involves simultaneous **heat transfer** (to supply energy for evaporation) and **mass transfer** (to remove water vapour from the food surface). Heat is usually supplied by hot air, radiation, or conduction, while mass transfer occurs as vapour diffuses into the surrounding air. The efficiency of drying depends on balancing these two processes.

Fill in the blank: Drying involves both heat transfer and _________ transfer.

Figure 5.2: Heat and mass transfer in food drying

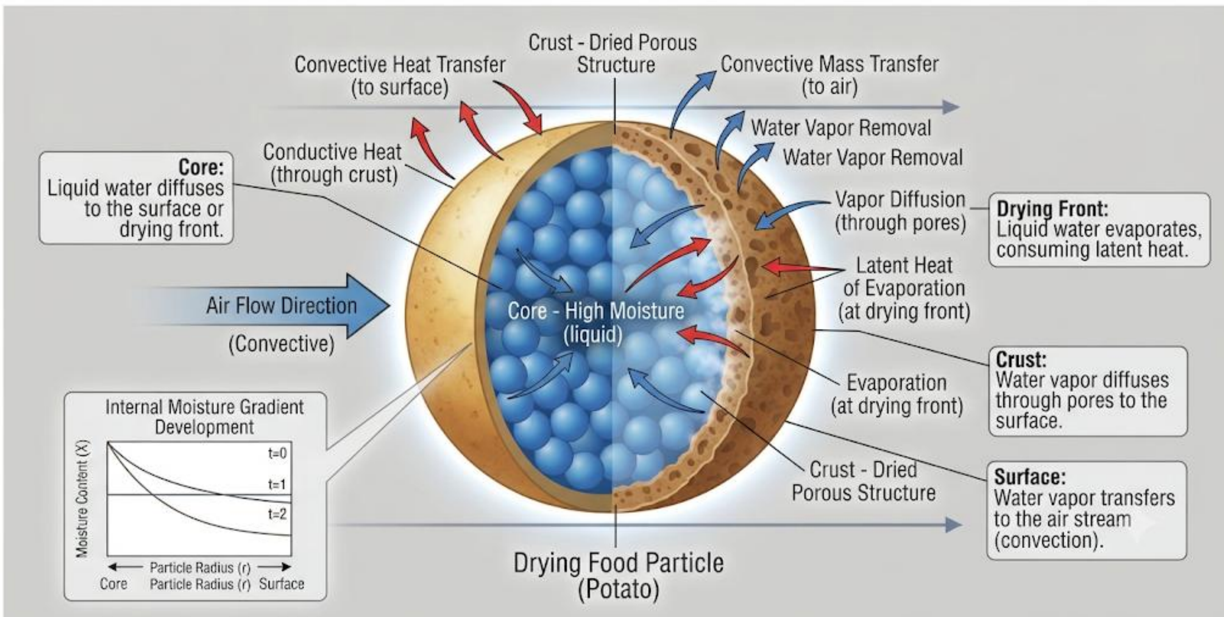
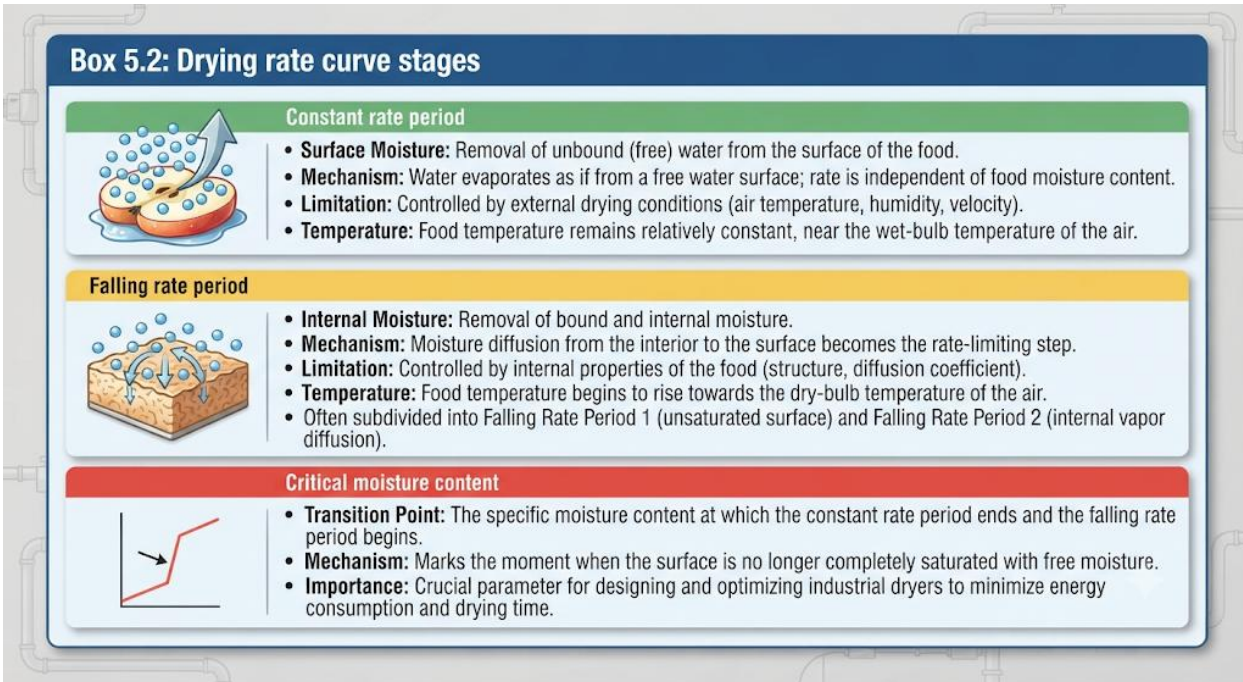


Diagram showing heat and mass transfer during drying *Figure 5.2: Heat and mass transfer in food drying*

5.2.2 Drying rate curves and critical moisture content

The **drying rate curve** illustrates how moisture content changes over time. Initially, drying occurs at a constant rate as surface water evaporates. Later, the rate decreases as water moves from inside the food to the surface. The point at which drying slows is called the **critical moisture content**. Understanding these curves helps engineers design efficient drying processes.

Fill in the blank: The point at which drying slows down is called the __________ moisture content.



Box 5.2: Drying rate curve stages Description: Constant rate period – surface water removal; Falling rate period – internal moisture removal; Critical moisture content – transition point.

5.2.3 Mathematical models of drying behaviour

Mathematical models describe drying behaviour to predict moisture removal. Common models include:

- **Newton's law of cooling model** – assumes exponential moisture loss.
- **Page model** – improves accuracy by modifying Newton's law.
- **Henderson-Pabis model** – widely used for agricultural products.

These models help engineers simulate drying processes, optimise equipment design, and reduce trial-and-error in industrial settings.

Fill in the blank: The _________ model modifies Newton's law to improve accuracy in predicting drying behaviour.

Image of laboratory drying experiment with moisture measurement equipment *Plate 5.2: Laboratory drying experiment for modelling moisture removal*

Pilot questions 5.2

1. What two processes occur simultaneously during drying?
2. What does the drying rate curve illustrate?
3. Define critical moisture content.
4. Name one mathematical model used to describe drying behaviour.
5. Why are drying models important in food engineering?

5.3 Methods And Equipment For Dehydration

5.3.1 Sun and solar drying

Sun drying is the oldest method of food dehydration, relying on natural sunlight to remove moisture. It is inexpensive but slow and dependent on weather conditions. **Solar drying** improves efficiency by using enclosed structures with transparent covers to trap heat, protecting food from contamination while speeding up drying.

Fill in the blank: Solar drying improves efficiency by using enclosed structures with _________ covers to trap heat.

Image of fruits being dried under the sun and in a solar dryer *Plate 5.3: Sun and solar drying methods*

5.3.2 Hot air and tray dryers

Hot air drying uses heated air to evaporate moisture, while **tray dryers** arrange food on trays with air circulation. These methods are widely used in industrial settings for fruits, vegetables, and grains. Tray dryers allow better control of temperature and airflow, resulting in more uniform drying compared to sun drying.

Fill in the blank: Tray dryers improve drying uniformity by controlling temperature and __________ circulation.

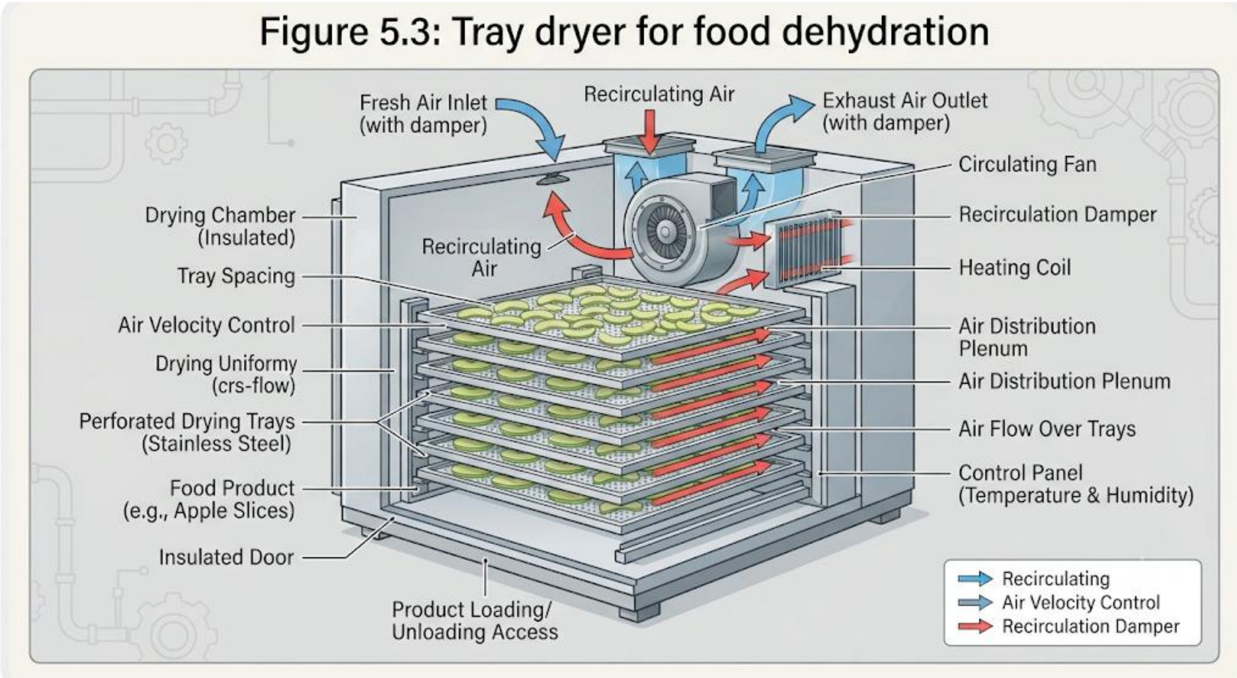
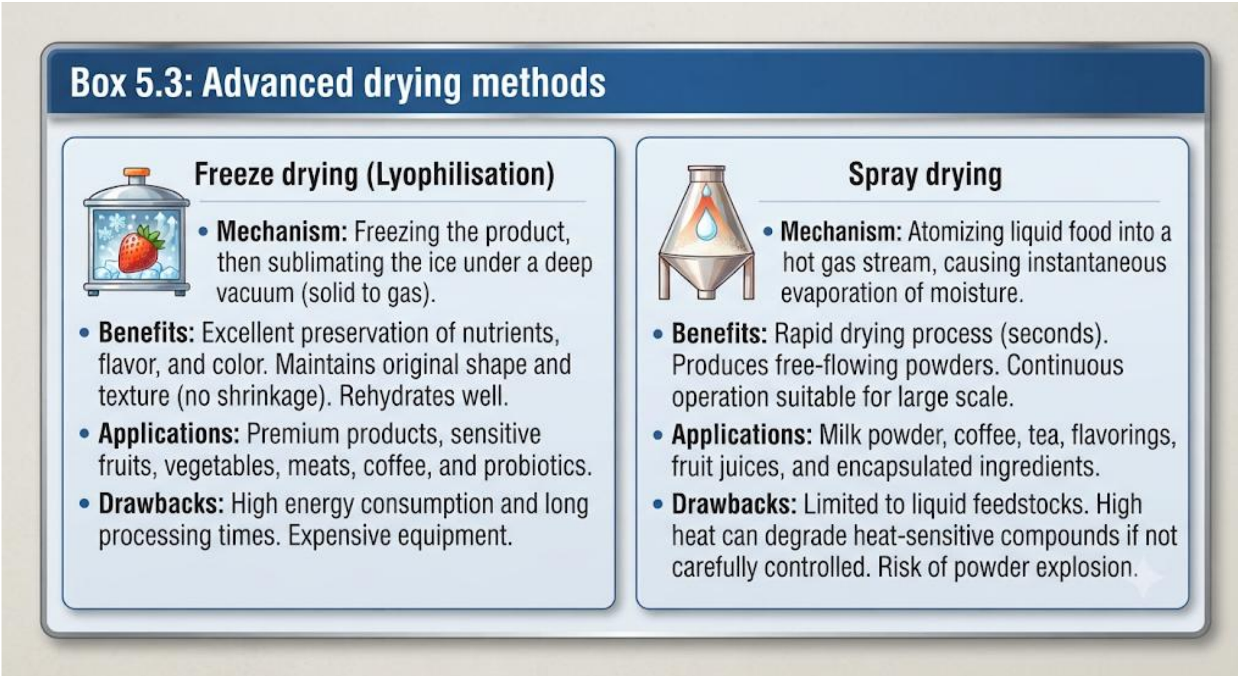


Diagram of a tray dryer showing airflow and trays *Figure 5.3: Tray dryer for food dehydration*

5.3.3 Freeze drying and spray drying

Freeze drying removes moisture by freezing food and then sublimating ice under vacuum. It preserves nutrients, flavour, and texture, making it ideal for high-value products like coffee, dairy, and instant meals. **Spray drying** atomises liquid foods into fine droplets, which dry quickly in hot air. It is commonly used for milk powder, flavourings, and fruit juices.

Fill in the blank: Freeze drying preserves nutrients and flavour by sublimating __________ under vacuum.



Box 5.3: Advanced drying methods Description: Freeze drying – preserves nutrients and texture; Spray drying – rapid drying of liquid foods into powders.

Pilot questions 5.3

1. What is the main limitation of sun drying?
2. How does solar drying improve upon traditional sun drying?
3. Why are tray dryers more efficient than sun drying?
4. What process does freeze drying use to remove moisture?
5. Name one food product commonly produced using spray drying.

5.4 Industrial Applications And Quality Considerations

5.4.1 Applications in fruits, vegetables, dairy, and meat products

Food dehydration is widely applied across industries:

- **Fruits**: Apples, bananas, and mangoes are dehydrated for snacks and long-term storage.
- **Vegetables**: Onions, tomatoes, and peppers are dried for seasoning and soups.
- **Dairy**: Milk is spray-dried into milk powder for easy transport and storage.
- **Meat**: Beef jerky and dried fish are preserved through dehydration.

Fill in the blank: Spray drying is commonly used to produce _________ powder in the dairy industry.

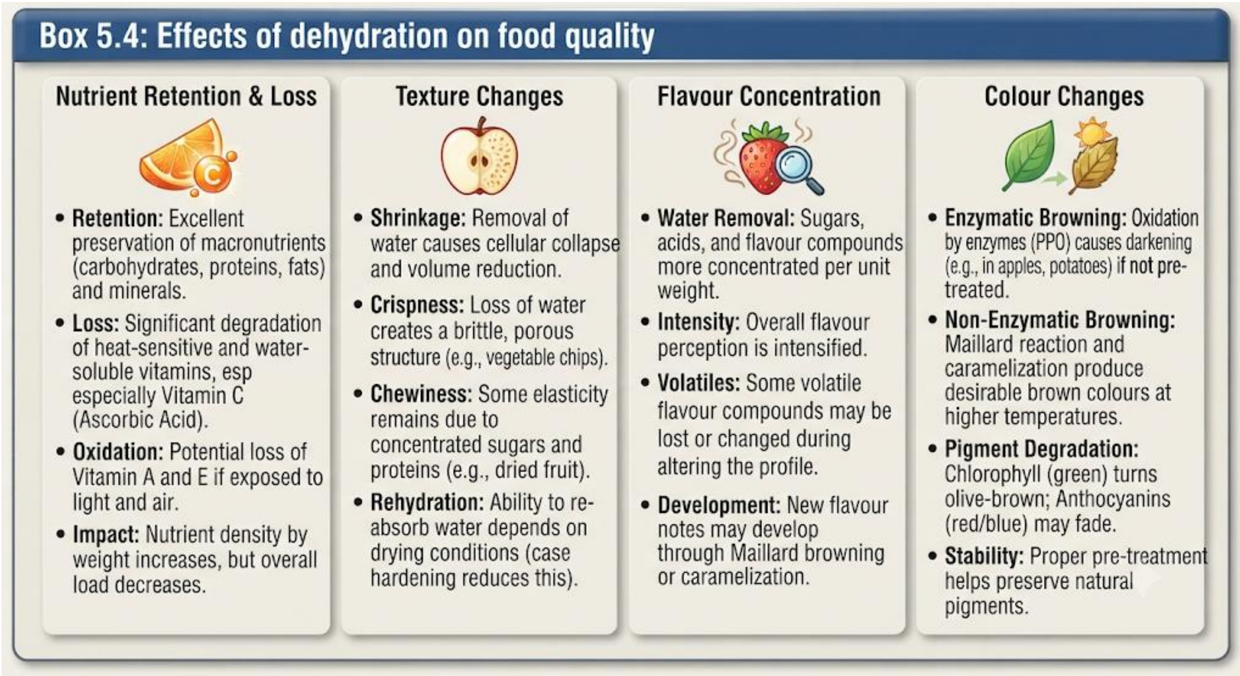
Image of dried fruits, milk powder, and beef jerky *Plate 5.4: Applications of food dehydration in different industries*

5.4.2 Effects of dehydration on nutritional quality and texture

Dehydration affects food quality in several ways:

- **Nutritional quality**: Some vitamins (like vitamin C) are sensitive to heat and may degrade.
- **Texture**: Foods become crisp or chewy depending on the method used.
- **Flavour**: Concentration of flavours often enhances taste.
- **Colour**: Improper drying may cause browning or fading.

Fill in the blank: Vitamin __________ is particularly sensitive to heat during dehydration.



Box 5.4: Effects of dehydration on food quality Description: Nutrient loss (vitamin C), texture changes (crisp/chewy), flavour concentration, colour changes.

5.4.3 Optimisation and sustainability in industrial dehydration

Modern food industries optimise dehydration to balance efficiency and quality. Strategies include:

- Using **energy-efficient dryers** to reduce costs.
- Applying **controlled temperature and humidity** to preserve nutrients.
- Incorporating **renewable energy sources** (solar dryers) for sustainability.
- Designing processes to minimise waste and environmental impact.

Fill in the blank: Renewable energy sources such as _________ dryers support sustainable food dehydration.

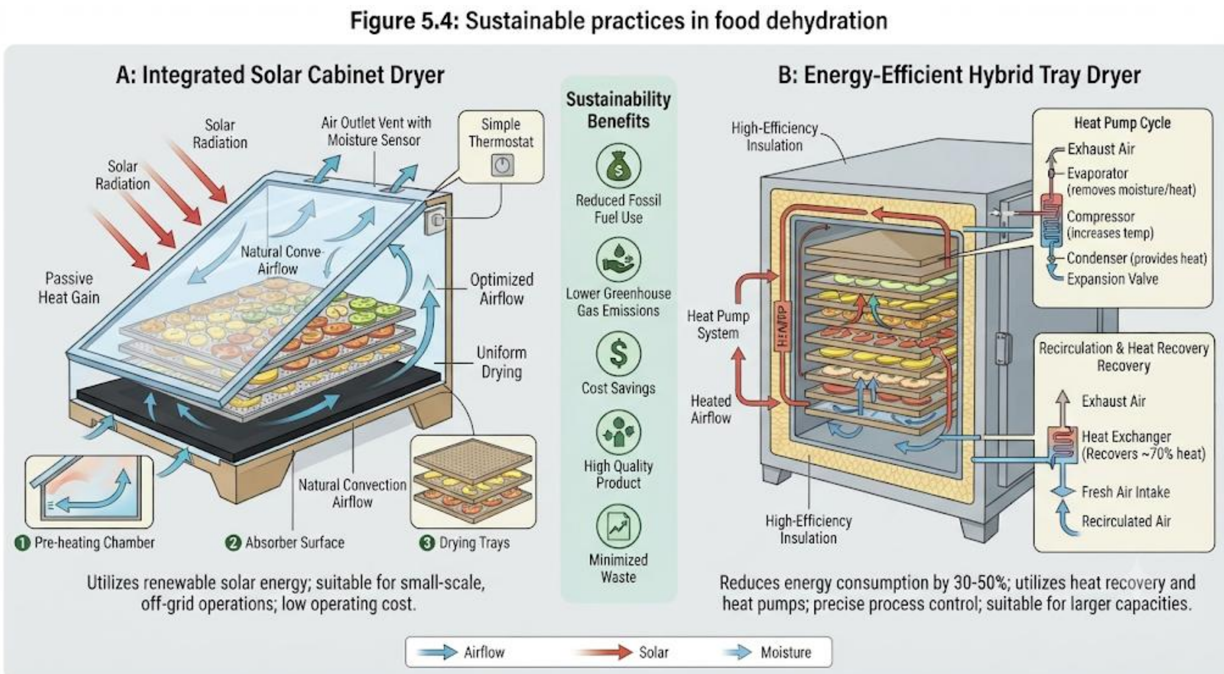


Diagram showing sustainable dehydration practices (solar dryer, energy-efficient tray dryer) *Figure 5.4: Sustainable practices in food dehydration*

Pilot questions 5.4

1. Name one fruit and one vegetable commonly dehydrated.
2. What dairy product is produced using spray drying?
3. Which vitamin is most sensitive to heat during dehydration?
4. How does dehydration affect food flavour?
5. Mention one sustainability strategy used in industrial dehydration.

Series Summary

This Series has introduced the **theory of food dehydration**, a key preservation method in food process engineering. We began with the fundamentals, explaining the importance of moisture removal and the factors influencing dehydration. Next, we studied the mechanisms and models of drying, focusing on heat and mass transfer, drying rate curves, and mathematical models. We then explored methods and equipment, including traditional sun drying, tray dryers, and advanced techniques like freeze drying and spray drying. Finally, we examined industrial applications, effects on nutritional quality and texture, and optimisation strategies for sustainability.

By completing this Series, you should now be able to explain dehydration fundamentals, describe drying mechanisms and models, compare methods and equipment, and evaluate industrial applications with quality and sustainability considerations.

Glossary of Terms

- **Critical moisture content**: The point at which drying rate begins to decrease as internal moisture removal dominates.
- **Freeze drying**: A dehydration method that removes moisture by sublimating ice under vacuum.
- **Mass transfer**: The movement of water vapour from food into surrounding air during drying.
- **Moisture content**: The amount of water present in food, expressed as a percentage.
- **Spray drying**: A rapid drying method where liquid foods are atomised into droplets and dried in hot air.
- **Sun drying**: Traditional method using natural sunlight to remove moisture.
- **Tray dryer**: Equipment that uses heated air circulation around trays of food for uniform drying.
- **Vitamin C**: A heat-sensitive nutrient often degraded during dehydration.

Concept Check Questions [Series 5]

Objective questions

1. Food dehydration extends shelf life by removing _________. (Linked to SLO 5.1)
2. The point at which drying slows down is called the _________ moisture content. (Linked to SLO 5.2)
3. Freeze drying removes moisture by sublimating _________ under vacuum. (Linked to SLO 5.3)

Short-answer questions

4. List three factors that influence the rate of food dehydration. (Linked to SLO 5.1)
5. Why are drying rate curves important in food engineering? (Linked to SLO 5.2)

Long-answer questions

6. Compare sun drying, tray drying, and freeze drying in terms of efficiency, quality, and applications. (Linked to SLO 5.3)
    - *Basic response*: Discuss differences in speed, cost, and product quality.
    - *Value-added response*: Include industrial examples and sustainability considerations.
7. Evaluate the effects of dehydration on food quality, focusing on nutrients, texture, flavour, and colour. (Linked to SLO 5.4)

- *Basic response*: Explain nutrient loss and texture changes.
- *Value-added response*: Extend discussion to include optimisation strategies for sustainability.

Answers to Pilot Questions [Series 5]

Part 5.1

1. Removing moisture to preserve food.
2. Heat transfer and mass transfer.
3. Temperature, humidity, air velocity.
4. Because dry air absorbs moisture faster.
5. Fruits like mangoes.

Part 5.2

1. Heat transfer and mass transfer.
2. Moisture content change over time.
3. Critical moisture content.
4. Page model.
5. To predict drying behaviour and optimise processes.

Part 5.3

1. Slow and weather-dependent.
2. By trapping heat in enclosed structures.
3. Controlled temperature and airflow.
4. Sublimation of ice.
5. Milk powder.

Part 5.4

1. Mango (fruit) and onion (vegetable).
2. Milk powder.
3. Vitamin C.
4. It concentrates flavours.
5. Using solar dryers.

References and Attributions [Series 5]

- *Figure 5.1*: Moisture removal in food dehydration. Suggested AI prompt: “Diagram showing moisture removal process in food dehydration.”
- *Box 5.1*: Principles of moisture removal. Suggested AI prompt: “Box summarising principles of moisture removal in food dehydration.”
- *Plate 5.1*: Fruit dehydration in tray dryer. Suggested AI prompt: “Photograph of sliced fruits being dehydrated in a tray dryer.”
- *Figure 5.2*: Heat and mass transfer in food drying. Suggested AI prompt: “Diagram showing heat and mass transfer in food drying.”
- *Box 5.2*: Drying rate curve stages. Suggested AI prompt: “Box summarising drying rate curve stages in food dehydration.”
- *Plate 5.2*: Laboratory drying experiment. Suggested AI prompt: “Photograph of laboratory drying experiment with moisture measurement equipment.”
- *Plate 5.3*: Sun and solar drying methods. Suggested AI prompt: “Photograph of fruits being dried under the sun and in a solar dryer.”
- *Figure 5.3*: Tray dryer for food dehydration. Suggested AI prompt: “Diagram of tray dryer showing airflow and trays for food dehydration.”
- *Box 5.3*: Advanced drying methods. Suggested AI prompt: “Box summarising freeze drying and spray drying methods in food dehydration.”
- *Plate 5.4*: Applications of food dehydration. Suggested AI prompt: “Photograph of dried fruits, milk powder, and beef jerky.”
- *Box 5.4*: Effects of dehydration on food quality. Suggested AI prompt: “Box summarising effects of dehydration on food quality.”
- *Figure 5.4*: Sustainable practices in food dehydration. Suggested AI prompt: “Diagram showing sustainable food dehydration practices with solar and energy-efficient dryers.”