

Evaporation Technology: Equipment and Process Optimization-A Minireview

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ABSTRACT

Evaporation is a crucial unit operation in various industries, including chemical, pharmaceutical, food and energy sectors. This paper reviews recent advances in evaporation technology, focusing on equipment design, process optimization and control strategies. The authors also discussed the principles of evaporation, types of evaporators, and factors influencing evaporation rates. The role of heat transfer, mass transfer and fluid dynamics in evaporation processes was examined, along with strategies for enhancing efficiency and reducing energy consumption. Process optimization in evaporation involves improving the efficiency, productivity and cost effectiveness of evaporation processes. The key strategies for process optimization include: heat recovery and energy integration, multiple effect evaporation, mechanical vapour recompression, thermal vapour recompression, process control automation, fouling mitigation and scale up and equipment design. Benefits of process optimization include reduced energy consumption, increased productivity, improved product quality and extended equipment life.

Keywords: Evaporation, Process Optimization, Unit Operation, Equipment Design.

INTRODUCTION

Evaporation is a surface phenomenon where large quantities of volatile liquid are evaporated in order to get a concentrated product [1]. This phenomenon involves the supply of heat to the evaporator which subsequently, transmits it to the evaporating liquid in order to produce the latent heat of evaporation [2]. An increase in temperature or pressure causes the liquid state of a substance to change to a gaseous state [3]. Although evaporation can be applied on both solutions and suspensions,

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one condition that should be considered is the volatility of the liquid [4]. Discussing evaporation technology and equipment process optimization is crucial for several reasons which include the following:

- 1) Energy Efficiency: Optimizing evaporation processes reduces energy consumption, lowering operating costs and environmental impact.
- 2) Product Quality: Improved process control enhances product consistency and quality.
- 3) Cost Savings: Efficient equipment and processes reduce maintenance and operational costs.
- 4) Sustainability: Minimizing energy use and waste supports sustainable practices.
- 5) Competitiveness: Industries that adopt optimized evaporation technologies stay competitive.
- 6) Innovation: Discussing advancements drives innovation in equipment design and processes.
- 7) Problem Solving: Identifying challenges and solutions improves reliability and performance.
- 8) Evaporation plays a crucial role in pharmaceutical manufacturing, particularly in [8]:
- 9) Solvent Removal: Evaporation is used to remove solvents from active pharmaceutical ingredients (APIs) and intermediates.
- 10) Concentration: Concentrating solutions to achieve desired potency or to prepare for crystallization.
- 11) Drying: Preparing powders or granules for formulation into tablets, capsules, or other dosage forms.
- 12) Lyophilization (Freeze-Drying): Used for heat-sensitive products like biologics and vaccines.

Importance of evaporation in pharmaceutical industry

Evaporation has a key role to play in the pharmaceutical sector; which include the following:

- 1) Product Stability: Controlled evaporation ensures stability and efficacy of pharmaceutical products.
- 2) Regulatory Compliance: Meeting stringent regulatory standards for product quality and safety.
- 3) Efficiency: Optimizing evaporation processes improves yield and reduces costs.

FACTORS AFFECTING EVAPORATION

Mathematical equation that is used to express the relationship between the rate of evaporation and other several factors is represented as:

$$M = \frac{KS}{P(b-b')}$$

M: Mass of vapour formed per unit time (rate)

S: Surface area of the liquid exposed, (m²)

P: Atmospheric pressure, (KPa)

b: Maximum vapour pressure of the atmosphere of air, (KPa)

b': pressure due to the vapour of the liquid, (KPa)

k: constant (m/s)

a. Temperature

Increase in temperature, increases the rate of evaporation. When temperature of the liquid is raised, more molecules acquire sufficient kinetic energy and escape from the surface to vapour state. Formation of vapour occurs on the body of a liquid and surface at a given boiling point [5].

b. Vapour pressure

Increase in vapour pressure leads to a decrease in the rate of evaporation and vice-versa, which subsequently affects the boiling point of the liquid [6]. If the vapour of the liquid is removed as soon as it is formed, the space above the liquid does not become saturated with the vapour which makes the evaporation to proceed faster.

c. Surface area

An increase in the surface area of a liquid, leads to an increase in the rate of evaporation.

d. Types of products required

There are different types of products used, and they are dependent on the rate of evaporation and the appropriate apparatus. To produce liquid or dry concentrate, open pan evaporator is used. Film evaporator yields liquid concentrate, while vacuum evaporator produces porous products [7].

e. Time of evaporation

An increase in the time of exposure of a substance, increases the rate of evaporation and vice versa.

APPLICATIONS OF EVAPORATION

- 1) Evaporation is used in the demineralization of water: This is achieved by boiling water for more than 20 minutes. This causes the evaporation of mineral ions leaving behind demineralized water. Also, the passage of water via anion and cation exchange resins helps to obtain very pure water.
- 2) Evaporation can be used to concentrate and recover dissolved solutes from aqueous solution in order to produce salt. This is achieved by evaporating the solvent, allowing the solute to remain behind. Also, when components of a mixture are separated with a dissolved solid in a liquid, dissolved solutes can be recovered.
- 3) Evaporation process can be deployed in the manufacture of bulk drugs. This is achieved by concentration of solutions which allows the removal of excess solvent, thereby increasing the concentration of the desired solute. Also, the evaporation of the solvent, enables the separation of impurities from the desired product, which subsequently produces a better final result.
- 4) Evaporation is useful in the concentration of pharmaceutical herbal extracts used in herbal industry. This is achieved by removing excess solvent which subsequently increases the concentration of the desired solute. When this is achieved, a concentrated drug formulation is produced.
- 5) Evaporation is useful in the manufacture of biological products. Some of the biological products include: insulin, enzymes, hormones and other biological products.
- 6) Evaporation is useful in the stabilization of enzymes in laboratories. This is achieved by eliminating excess moisture, making handling easier and preserving long-term activity.

Process optimization in evaporation involves improving the efficiency, productivity, and cost-effectiveness of evaporation processes. Here are some key aspects:

APPLICATIONS OF EVAPORATION

Some of the key strategies associated with process optimization include [16]:

- 1) Heat Recovery and Energy Integration: Implementing heat recovery systems to minimize energy consumption.
- 2) Multiple Effect Evaporation: Using multiple evaporators in series to improve energy efficiency.

- 3) Mechanical Vapor Recompression (MVR): Compressing vapor to increase its temperature and reuse its energy.
- 4) Thermal Vapor Recompression (TVR): Using steam ejectors to compress vapor and recover energy.
- 5) Process Control and Automation: Implementing advanced control systems to optimize process conditions.
- 6) Fouling Mitigation: Designing evaporators to minimize fouling and implementing cleaning strategies.
- 7) Scale-Up and Equipment Design: Optimizing equipment design for efficient scaling up of evaporation processes.

Key Strategies for Process Optimization

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Benefits of Process Optimization

Process optimization has numerous benefits which include the following:

- 1) Reduced Energy Consumption: Lower operating costs and environmental impact.
- 2) Increased Productivity: Improved evaporation rates and capacity.
- 3) Improved Product Quality: Better control over product properties and consistency.
- 4) Extended Equipment Life: Reduced maintenance and longer equipment lifespan.

Classification of evaporators

Evaporators are classified based on the following properties [16-18]:

Table 1. Types and examples of evaporators use in pharmaceutical industry

Types	Examples
Evaporators with heating medium in jacket	Steam jacketed kettle
Vapour heated evaporators with tubular heating surfaces	Horizontal tube evaporator
Evaporators with short tubes	Short tube vertical evaporator
Evaporators with long tubes	Climbing film evaporator

CLASSIFICATION OF EVAPORATION EQUIPMENT

1. Steam jacketed kettle or evaporating pan: The substance to be evaporated is placed on the pan and steam is applied. The heat that is generated works on the principle of conduction and convection [19]. When the pan is heated, an increase in temperature occurs which causes the solvent to get evaporated. This equipment is designed in such a way that the pan is present in the inner side, also known as kettle, while the outer surface is covered with a jacket. One of the metals used in the construction of the evaporating pan is copper, because of its good electrical and conducting property. The working principle is based on the fact that an aqueous extract to be evaporated is placed on top of the kettle. Steam is applied which causes the evaporation of the solvent and condensate. This type of equipment is suitable for both aqueous and thermostable liquors [19].

Advantages

- 1) The evaporating pan can be used for both small and large-scale operations.
- 2) Construction is simple
- 3) Low cost of maintenance and installation
- 4) Suitable for a wide variety of metals
- 5) Easy removal of products from the equipment

Disadvantages

- 1) Less heat economy occurs in the evaporating pan
- 2) Heat sensitive materials cannot be used
- 3) More concentration of the product decreases the heating area.
- 4) Reduction of the boiling point of water cannot be achieved.

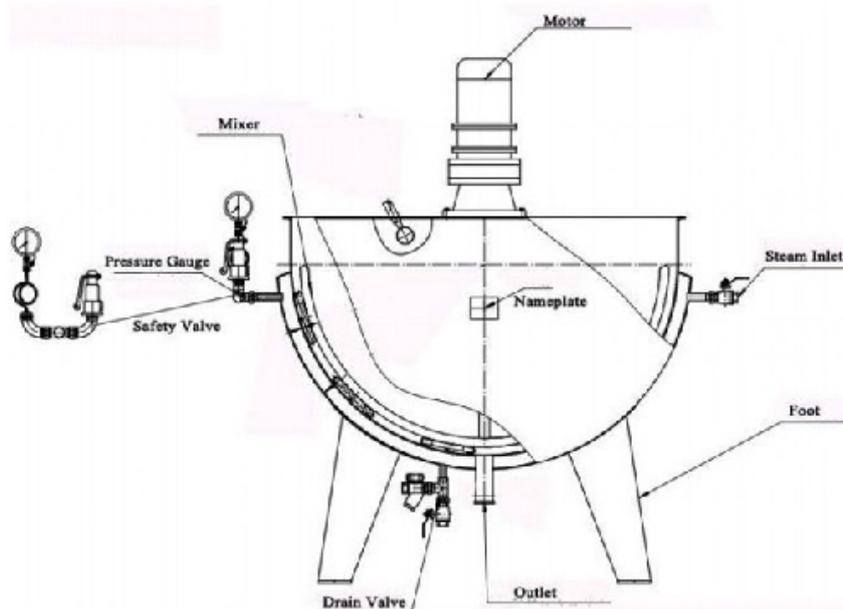


Figure 1. Steam jacketed kettle [20].

2. Horizontal tube evaporator

This allows the passage of steam via the horizontal tubes. The substance inside the horizontal tubes gets heated when heat is applied. This causes the elimination of either the solvent or the substance from the upper part of the apparatus. Some of the metals used in the construction of this apparatus are cast iron and plate steel [21]. There are two vents present, which are the inlet vent for the stem, and the outlet vent for the non-condensed gases. It is suitable for non-viscous solutions.

Advantages

- 1) High Heat Transfer Coefficients: Horizontal tube evaporators often achieve high heat transfer rates due to efficient condensate drainage and thin film formation.
- 2) Compact Design: They can be more compact than some other evaporator types for similar capacities.

3) Suitable for Scaling Liquids: Good for liquids that scale or foul, as tubes are often easier to clean.

4) Flexibility: Can handle a range of fluids and operating conditions.

Disadvantages

1) Limited Vapor-Liquid Separation: May require additional separation equipment.

2) Potential for Uneven Distribution: Liquid distribution can be uneven, affecting performance.

3) Fouling in Tubes: Scaling or fouling inside tubes can reduce efficiency.

4) Higher Cost for Special Materials: May need special materials for corrosion resistance, increasing cost.

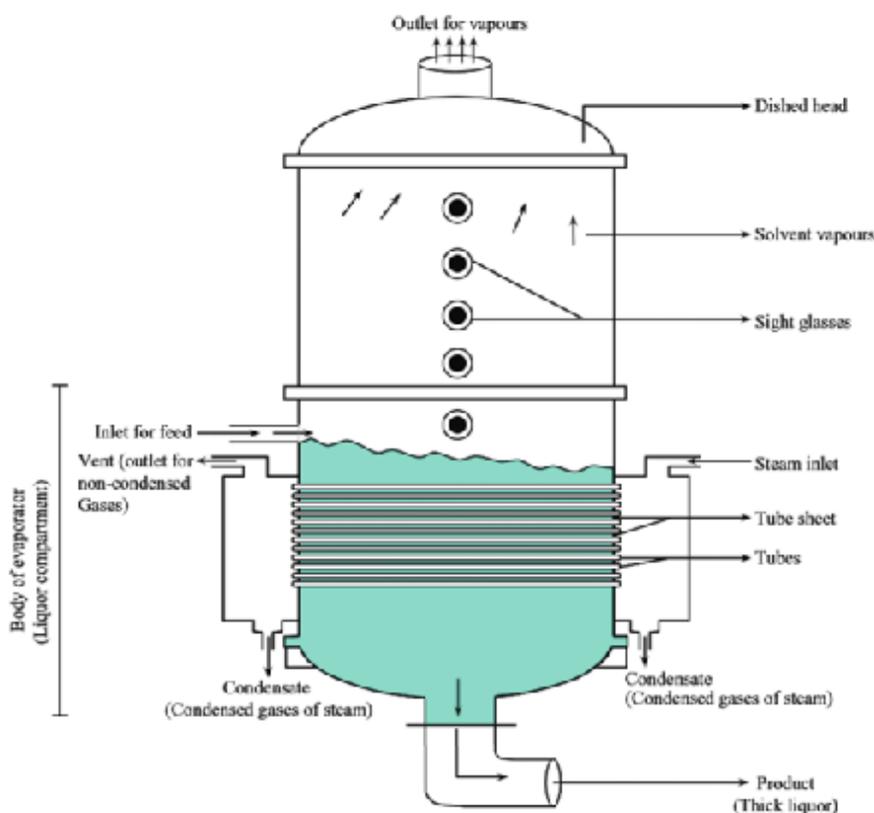


Figure 2. Horizontal tube evaporator [20].

3. Vertical tube evaporator

The main principle involves the passage of liquid through the vertical tubes. When heat transfer takes place, it causes the liquid inside the tube to get heated up. This causes both the solvents to evaporate and the escape of vapour. When this

is achieved, the outlet is used to collect the final product. Its construction is made up of a large cylindrical body with a cast iron round it. It is used in the manufacture of salt and caustic soda [21].

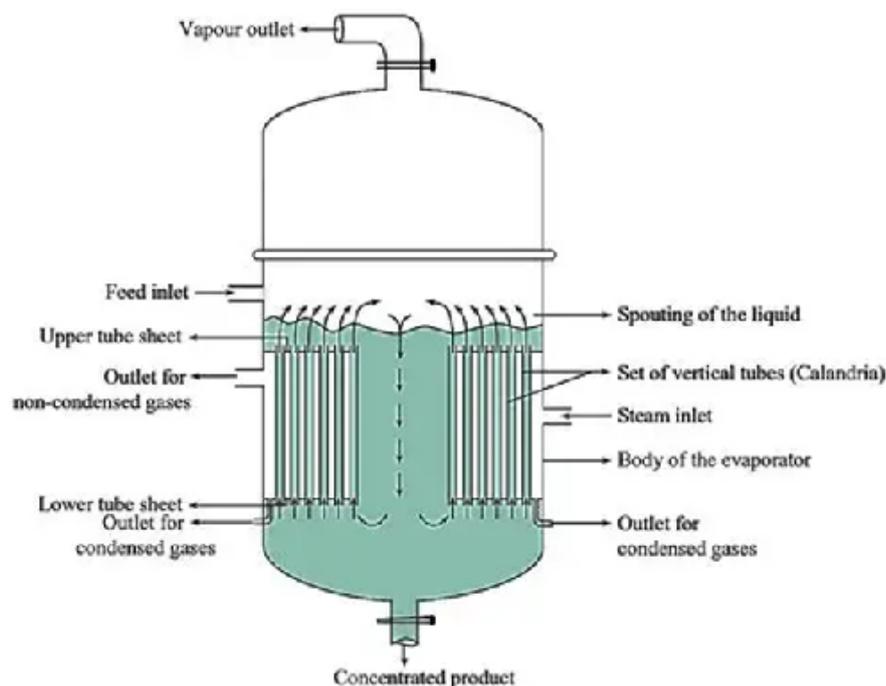


Figure 3. Vertical tube evaporator [20].

There are two vents present at the top and bottom, for removing the vapors and collection of the final product respectively.

Advantages

- 1) Heating surface increases faster than in stem jacketed kettle.
- 2) Increased rate of evaporation due to multiple connections
- 3) Flexibility in joining multiple units together.

Disadvantages

- 1) Longer time is required for the liquid to get heated.
- 2) Higher installation cost

3) Difficulty in maintenance and cleaning

4) Increase in the evaporators pressure.

4. Climbing film evaporator

This involves the external heating of the tubes by steam. This causes the preheated feed to enter the bottom and flow up via the heated tubes. The liquid near the wall becomes vapour and forms small bubbles. These tend to fuse to larger bubbles that travel up in the tubes along with entrapped slug. Its construction is made up of steam jacketed tubes. The working principle is based on the fact that the preheated liquid feed is directly introduced from the bottom of the unit. Heat is transferred to the liquid via the walls of the tubes. This leads to the formation of both vapour and smaller bubbles.

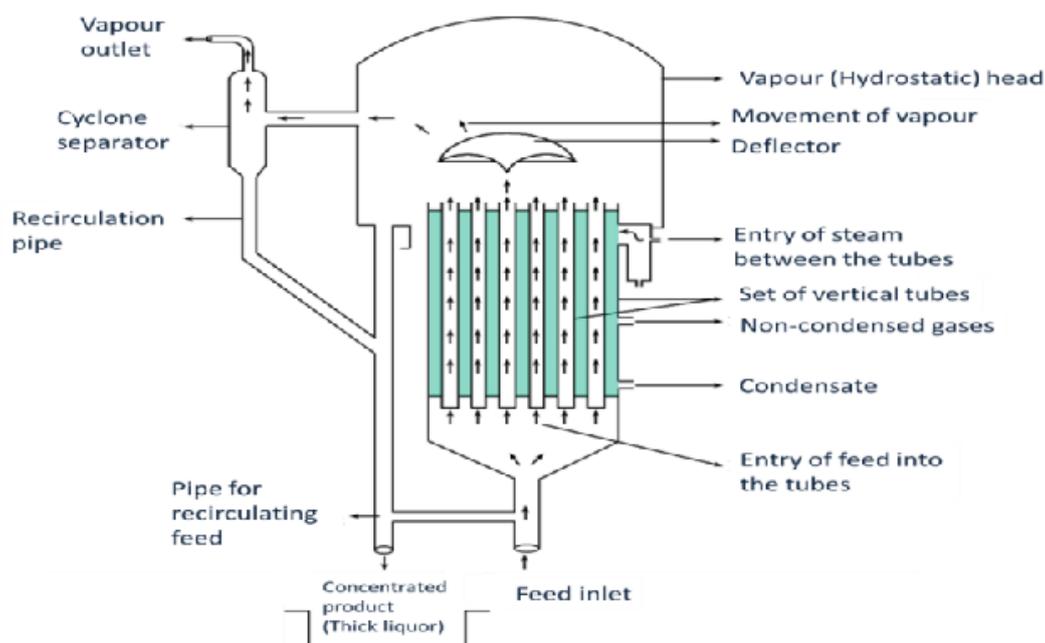


Figure 4. Climbing film evaporator [20].

Climbing film evaporator is useful in the concentration of thermolabile substances like insulin. It is also suitable for large quantities of corrosive solutions. Reducing the steam rate can also help to quickly remove the deposit of scales [22].

Advantages

- 1) It provides large area for heat transfer.
- 2) Reduction in the resistance of heat transfer at the boundary layers.
- 3) Short contact time between the liquor and the heating surface
- 4) The tubes are not submerged
- 5) It is suitable for foam-forming liquids

Disadvantages

- 1) It is expensive
- 2) Difficulty in cleaning and maintenance.
- 3) Large head space is required
- 4) Not suitable for salting liquids

- 5) Insufficient concentration of liquor at high feed rate

5. Falling film evaporator

The principle is based on the fact that the feed enters from the top and subsequently flows down the walls of the tubes. The heat transfer from steam makes the liquid to get heated rapidly [23]. The vaporized liquid then forms small bubbles. Steam is supplied into the steam compartment which causes the liquid to get heated up rapidly. It is used in the separation of both volatile and non-volatile materials.

Advantages

- 1) It is suitable for high viscous liquids.
- 2) Small hold-up time
- 3) The liquid is not overheated.
- 4) Concentration of highly acidic and corrosive feeds.

Disadvantage

- 1) It is not suitable for salting liquids

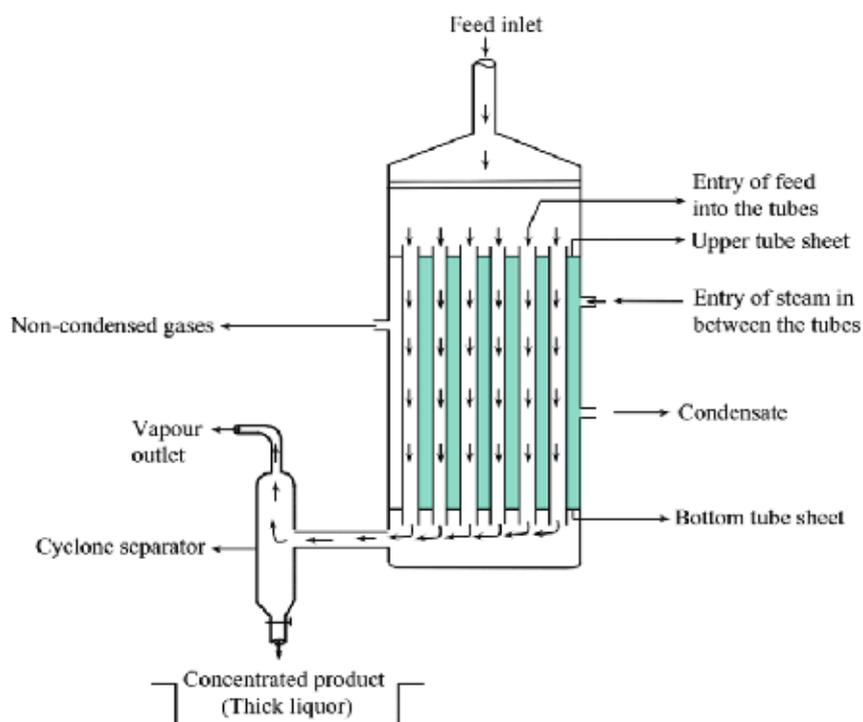


Figure 5. Falling film evaporator [20].

6. Forced circulation evaporator

A pump is used to circulate the liquids via the tubes at high pressures [24]. This causes the boiling point to be elevated. The construction is based on the fact that the steam jacketed tubes are held between two tube sheets. It is suitable for thermolabile substances.

Advantages

- 1) High heat transfer coefficient
- 2) Suitable for thermolabile substances
- 3) Suitable for high viscous preparations

Disadvantages

- 1) High hold-up of liquid
- 2) Expensive equipment

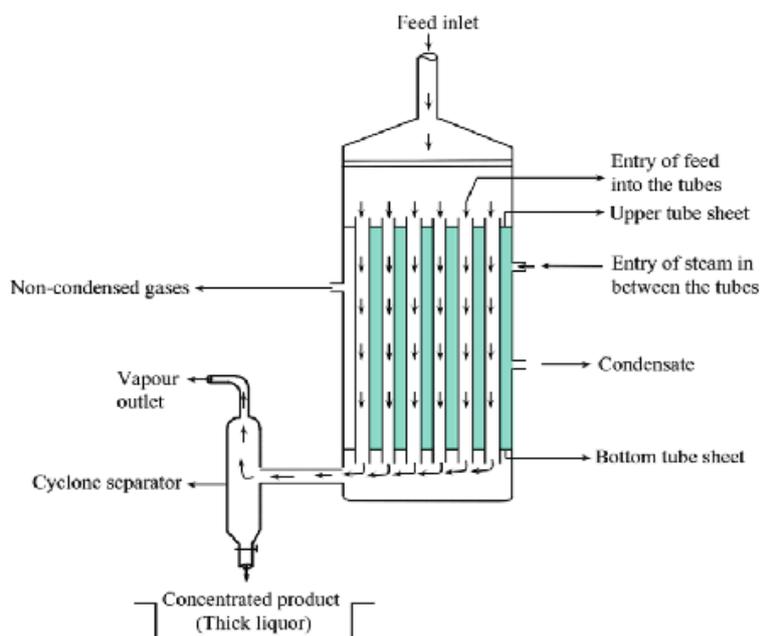


Figure 6. Forced circulation evaporator [20].

CONCLUSION

Evaporation technology is a vital process in various industries, and optimizing equipment and processes can significantly improve efficiency, productivity, and sustainability. By implementing advanced equipment designs, heat recovery systems, and process control strategies, industries can reduce energy consumption, lower operating costs, and minimize environmental impact. As industries continue to evolve, embracing innovations in evaporation technology will be crucial for maintaining competitiveness and achieving sustainable growth.

CONFLICT OF INTEREST

Authors declare no competing interest.

AUTHORS CONTRIBUTION

Chekwube A. Ezegebe: Writing, John I. Osaro: Conceptualization, Writing.

Chisom G. Ezegebe: Conceptualization, Writing, Ezinne C. Okorafor: Conceptualization, Writing, Emeka E. Ogbonna: Conceptualization, Writing.

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