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A Computational Frame Work for Multi-Effect Evaporator Optimization

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***Abstract*- With the goal of enhancing heat transfer efficiency and lowering operating expenses, this paper offers an optimization strategy for multiple effect evaporators (MEEs) in sodium hydroxide (NaOH) solutions. Important factors that were examined to maximize tube counts and diameters during design included heat flow, heat transfer coefficients, and temperature variations. Rates of flow, speeds, and material costs were considered using cost estimation models. A case study revealed notable increases in efficiency and cost reductions when the vessel height was determined using heat transfer requirements. For low-cost and energy-efficient MEE design in NaOH concentration operations, the framework provides invaluable guidance.**

***Keywords*- Heat Transfer Efficiency; Operational Cost Reduction; Multiple Effect Evaporators (MEEs); Optimization Methodology; Sodium Hydroxide (NaOH) Concentration**

I. INTRODUCTION

Evaporators utilize heat transfer mechanisms driven by either forced or natural convection to concentrate solutions. These systems are typically heated by a steam source, allowing a solution containing the target product to enter the evaporator. As heat is applied, the water in the solution evaporates, leaving behind a more concentrated mixture, which can either be removed or transferred to a secondary evaporator for further concentration.

A single effect evaporator focuses on concentrating on a single solution, while a multiple effect evaporator employs several stages to enhance efficiency. In this setup, the vapor generated in one evaporator is redirected into the steam chest of the subsequent evaporator, effectively recycling heat from the first stage to heat the next. This method maximizes energy use by utilizing the heat from previous stages to minimize overall energy consumption in the process.

A. Application of evaporators

According to Bhargava et al. (2010), evaporators are essential to many process sectors, including sugar, pharmaceuticals, desalination, dairy and food processing, pulp and paper, chemicals, and sugar. Within the food and beverage business, evaporators find one of their most significant uses. In order to preserve food, such as coffee, for extended periods of time, evaporators are utilized in these sectors to change the food's consistency. When it's necessary to preserve long-term activity, evaporation is frequently utilized in laboratories as a drying method. Expensive solvents like hexane are not wasted thanks to its application in recovery processes. Reduction of waste management costs is another significant application of evaporation.

Weak black liquor is concentrated using the multiple effect evaporator system that is the subject of this study. There are seven impacts in all. The system receives live steam in the first two effects, and the feed flow sequence under consideration is backward. To increase the system's total steam economy, feed and condensate flashing is integrated into the system to produce auxiliary vapor for use in vapor bodies.

B. Problems associated with multiple effect evaporators

Numerous energy-intensive problems exist with the multiple effect evaporator system. Therefore, reducing the amount of steam used will help to increase plant profitability through reduced energy usage. A number of researchers have tried to solve this problem by proposing novel operating strategies that increase the system's steam economy by lowering the amount of live steam consumed in multiple effect evaporator systems. Utilizing the optimal feed flow sequence is one of these operating strategies, along with feed-and-steam splitting and feed-, product-, and condensate flashing. One of the earliest studies to optimize a multiple effect evaporator was Harper and Tsao's from 1972, which changed the feed flow sequence. They developed a model to optimize a multiple effect evaporator system by taking into account both forward and backward feed flow sequences. Building on previous work, Nishitani and Kunugita (1979) optimized a multiple effect evaporator system to produce a non-inferior feed flow sequence by considering all possible feed flows. These mathematical models are usually based on a set of linear or nonlinear equations, and a new set of model equations was required to support the amended operating strategy when the operating strategy was changed. Stewart and Beveridge (1977) and Ayangbile, Okeke, and Beveridge (1984) also addressed this issue. The researchers developed a repeatable generalized cascade algorithm for the different operating strategies of a multiple effect evaporator system. The current work builds upon the modeling technique initially published by Ayangbile et al. (1984) by integrating feed and condensate flashing and accounting for changes in the boiling point elevation and overall heat transfer coefficient.

C. Objectives

- To research the black liquor concentration using the seven-effect evaporator method.
- To create a generalized algorithm that is applicable to various operating methods.
- To improve the system's steam economy by considering the impact of feed and condensate flashing.
- To contrast the outcomes with the models that have been published.

II. LITERATURE REVIEW

Evaporators are heat-transfer devices that use a heat source, such as steam, to turn water into a solution into vapor by forced or natural convection. For additional concentration, the concentrated solution is either taken out of the evaporator or supplied into another one. Multiple-effect evaporators increase efficiency and lower energy usage by reusing vapor from one evaporator in succeeding ones, as opposed to single-effect evaporators, which only employ one unit. Paper & paper, sugar, pharmaceuticals, desalination, dairy, and food processing are just a few of the businesses that depend on these systems [1]. They lower waste handling expenses, recover solvents, and concentrate on goods. Evaporators are used in the food and beverage sector to give items like coffee the right consistency and increase shelf life.

A multiple-effect evaporator system used for concentrating black liquor in the Kraft process involves complex operational strategies to minimize energy consumption, such as feed and condensate flashing. These strategies have been optimized through mathematical models and generalized algorithms to improve steam economy and adaptability to various operating conditions. Black liquor, a byproduct of the Kraft process, is an aqueous solution containing lignin residues, hemicelluloses, and inorganic chemicals, and it is distinctly alkaline with a high solids content [1]. The spent liquor is often used as a biomass-derived liquid fuel. Evaporators are categorized into different types based on their heating mechanisms, including tubular heating surfaces, confined heating mediums like coils and jackets, direct contact with the evaporating fluid, and solar radiation. They can be operated as once-through units or recirculating systems, with each type offering advantages for specific applications, such as handling heat-sensitive materials or achieving higher concentration ratios.

Single- or multiple-effect evaporators can be used to evaporate a solvent as vapor from a solution in order to concentrate it. In a multiple-effect evaporator, the steam economy of the system increases with each additional effect. These systems are essential to many different industries, including food processing, dairy, desalination, sugar, caustic soda, medicines, and pulp and paper. This article focuses on the caustic soda industry, which uses a quadruple-effect system in a forward-feed arrangement with falling film evaporators. This work gives a steady-state model for multiple-effect evaporators that may be used for simulation. It includes energy balance equations, mass balance equations for the overall and component masses, and heat transfer rate equations for calculating area across all effects. The model was created with SCILAB and verified against real-world data [3]. The variables in each effect are linked via feed, product, and vapor flow energy and material balance equations.

Previous research developed a framework for Multiple-Effect Evaporation Systems (MEESs) using Non-Linear Programming (NLP), integrated with a Heat Exchanger Network (HEN) model to optimize heat production. The study focused on a forward-feed evaporation system with hot and cold streams, showing that adding multi-stage flash tanks enhanced energy efficiency [1,2]. We explored different heat-integrated MEES configurations and the trade-offs between energy and investment costs to determine the optimal number of effects. The initial MEES NLP model served as a basis for solving the combined MEES-HEN network as a Mixed-Integer Non-Linear Programming (MINLP) model using the General Algebraic Modelling System (GAMS). A case study on milk concentration demonstrated that a forward-feed pattern with three evaporation effects, fully integrated with hot and cold streams, minimized the Total Annualized Cost (TAC) [2].

Heat transfer, vapor-liquid separation, and economical energy use are the three main components of evaporator design. Calandrias, which are heating units, help transfer heat, and bodies, or flash chambers, which are vapor-liquid separators, control the separation process. Because of their low residence time and appropriateness for viscous fluids, falling film evaporators are especially useful for concentrating heat-sensitive goods. However, ensuring even liquid distribution across all tubes remains a challenge, often necessitating liquid recirculation via pumping. The selected system, a quadruple-effect evaporator for caustic soda concentration, operates with a feed flow rate of 10,000 kg/hr, increasing caustic soda concentration from 0.05 to 0.3. Design steps include calculating the product amount, evaporation rate, steam requirement, and solving mass and energy balance equations iteratively until the desired concentration is achieved. Area and the number of tubes are then calculated, followed by determining the pump flow rate. Operating parameters for this system are detailed in Table 1, highlighting the system's efficiency and effectiveness in achieving the desired concentration.

III. METHODOLOGY

A. Types of evaporators

The process of concentrating a solution by eliminating water or other liquids is called evaporation. One way to reduce the amount of time needed to concentrate a solution is to heat it to a higher temperature or expose it to a larger surface area, which would require a longer residence time. However, many solutions experience thermal deterioration because of exposure to higher temperatures and longer residence times; therefore, minimizing both the temperature and the residence duration is necessary to reduce this. Numerous evaporator kinds have been developed as a result of this need.

In general, evaporators fall into one of four categories:

- Evaporators with tubular heating surfaces separating the heating medium from the liquid being evaporated.
- Evaporators that use jackets, coils, double walls, or other similar barriers to contain the heated medium.
- Evaporators that place the heating medium and evaporating fluid in direct contact.
- Evaporators that heat water using sun light.

Tubular heating surface evaporators are the most widely used type of evaporator among these designs. These evaporators use forced circulation (mechanical techniques) or natural circulation (boiling) to produce liquid circulation past the heating surfaces. Evaporators can function as once-through machines or repeatedly cycle the solution that needs to be condensed through the heating element. In a once-through evaporator, the feed only goes through the heating element once. This causes the feed to heat up and produce vapor, which exits the evaporator as thick liquor. As a result, the evaporation to feed ratio is constrained. These evaporators are particularly helpful for materials that are heat sensitive.

a. Horizontal tube evaporators -

These were the original kind of evaporators to be created and used. Of all the evaporators, their design is the most straightforward. It has a horizontal tube and a shell with the solution that needs to evaporate in the shell and the heating fluid in the tube. It is appropriate for fluids with low viscosity and no scaling, and it requires a relatively small initial expenditure. These days, very little of this type of evaporator is used other than for boiler feedwater preparation.

i. Horizontal spray film evaporators -

This evaporator is an adaptation of the horizontal tube evaporator. This type of horizontal falling film evaporator distributes the liquid using a spray method. Gravity causes this sprayed liquid to descend from one tube to another. Such evaporators make fluid distribution simple and eliminate the need for exact fluid levelling.

b. Short tube vertical evaporators -

These evaporators were among the first to gain popularity and were created after horizontal tube evaporators. The tubes inside their cylindrical shell measure between two and three inches in width and four to ten feet in length. A vertical pipe known as a downcomer is located in the shell's centre. After boiling and swirling inside the evaporator, the liquid exits through the downcomer and descends back into the tubes.

i. Basket type evaporators –

These evaporators are constructed similarly to vertical short tube evaporators. The annular downcomer seen on basket type evaporators is the sole distinction between the two. Because of this, the arrangement is more cost-effective. A simple-to-install deflector on these evaporators aids in lowering entrainment.

c. Long tube vertical evaporators -

Long tube vertical evaporators are commonly used due to their versatility and cost-effectiveness. These systems typically feature tubes that range from 12 to 30 feet in length, with diameters between 1 and 2 inches. When employed as once-through evaporators, the liquid residence time is only a few seconds, as there is no liquid level maintained in the vapor space. In contrast, when these evaporators function as recirculation types, it is crucial to maintain a specific liquid level within the vapor chamber, which includes a deflector plate to assist in flow management. Additionally, predicting the fluid temperature within the tubes can be difficult and may vary significantly.

i. Rising or climbing film evaporators -

The idea behind climbing or rising film evaporators is that the liquid rises up the tube as a film because the vapor is moving through the tube's core quicker than the liquid is. The liquid film becomes extremely turbulent when it flows in this way. Such evaporators can also be employed for heat-sensitive materials because of their low residence time.

ii. Falling film evaporators –

This type of evaporator feeds the liquid into long tubes at the top, where it is allowed to fall as films due to gravity. The tubes contain the heating medium. In these types of evaporators, evaporation takes place on the highly turbulent film surfaces. Vapor and liquid are often separated at the tubes' bottoms in such an arrangement. There are instances where the vapor is permitted to ascend the tubes in the opposite direction from the liquor flow. Due to their shorter residence times, falling film evaporators are mostly used for heat-sensitive materials. Additionally, since the evaporation occurs at the film's surface and any salt that accumulates as a result of vaporization can be readily removed, it is helpful for fouling fluids. Since these evaporators can easily flow when subjected to gravity, they are ideal for handling viscous fluids. The primary issue with falling film evaporators is that all of the tubes need to be uniformly wetted, meaning that the concentrated fluid needs to be spread evenly throughout each tube.

d. Forced circulation evaporators -

This type of evaporator is utilized in situations where it is necessary to prevent product boiling on the heating surface due to the liquid's fouling properties. High-capacity pumps are needed to do this since the liquid in the tubes needs to move at a high velocity.

e. Mechanically aided evaporators -

The main applications for these evaporators are twofold. The first justification is to remove the fouling materials from the heat transfer surface mechanically. Creating turbulence serves as a means of enhancing heat transfer, which is the second reason.

They come in a variety of forms, like as
1. Agitated watercraft
2. Evaporators with scoured exteriors
3. Thin film evaporators with mechanical agitation

B. The MEE System

Modeling and simulation of the MEE system are the focus of this work. This chapter covers the typical operating parameters of MEE systems used for caustic soda concentration. Several effect evaporator (MEE) systems are commonly used for the economical and efficient concentration of caustic soda (sodium hydroxide). For caustic soda, the MEE system usually consists of a sequence of forward-feeding evaporator units.

Feed Preheating: In order to use the least amount of energy possible, the caustic soda solution is heated before joining the first effect. This preheating might be accomplished externally using heating techniques or with waste heat from other processes.

Forward-Feed Configuration: In a forward-feed MEE system, the vapor produced in one effect acts as a heating medium for the effect that comes after, and the concentrated solution from each effect is fed into the following effect. The cascade configuration facilitates the effective use of thermal energy.

Evaporation in Each Effect: A more concentrated solution and vapor are produced as the caustic soda solution partially evaporates as it passes through each effect. Every effect produces vapor at a pressure and temperature that is usually lower than the one before it, which guarantees a steady rise in concentration.

Heat Recovery: To achieve the highest level of energy efficiency, heat recovery devices are frequently used in MEE systems. These devices recycle the extra heat they extract from the vapor streams to warm feed or heat the plant in various ways.

Recuperated Product and Condensation: A condenser is used to return the vapor from the final effect to liquid state. As a byproduct, the resultant distillate may be released or recycled for use in other processes. The concentrated caustic soda solution is removed from the final product and transferred to be processed or stored further.

Control and Monitoring: Accurate control and vigilant observation of several parameters, including temperatures, pressures, concentrations, and flow rates, are essential for MEE systems that concentrate caustic soda. To maximize efficiency and guarantee product quality and safety, sophisticated control systems may be used.

C. Design of Evaporator

a. Evaporator Vessel:

The structure of the evaporator vessel is the main component of vacuum evaporator design. Usually, a vertical cylinder with an incorporated tubular calandria for heat exchange serves as this vessel. Evaporator bodies were traditionally made of cast iron, although more recently, steel plate construction has become more popular. Benefits of steel plate construction include less brittleness, less weight, and economic effectiveness. A "save-all" component at the top of the cylindrical body is in charge of removing liquid droplets that are entrained with the vapor from the solution that has been treated.

b. The Calandria:

The calandria is an extension of the evaporator's shell or body and plays a critical role in the design. There are various arrangements, but it's important that leaks communicate with the exterior only in case the calandria operates under pressure. Leaks can be visually detected in such cases. However, when operating under a vacuum, leaks might not be visible. To detect vacuum leaks, one can use the suction effect near the joint, which is demonstrated by a flame. The bore of the holes in the tube plates for tube insertion should be slightly larger than the exterior tube diameter. Vertical baffles are often incorporated in the calandria to direct the steam's path. However, these baffles can corrode over time and are challenging to replace. When damaged or corroded, steam may not follow the intended path, affecting the placement of incondensable gas withdrawal pipes.

c. Centre Well:

A broad tube or center well is usually included in the design inside the calandria. Its dual functions are to gather juice that has overflowed the top tube plate and return it to the bottom and to make it easier to gather concentrated juice for moving to the following vessel. A lateral well or a number of down-takes with smaller diameters spaced throughout the calandria are two options that some manufacturers provide in place of the center well.

d. Tubes:

Tubes in the calandria can be made of steel or brass. Brass tubes tend to have a longer lifespan, with the best brass composition for multiple-effect evaporators containing 70% copper (Cu) and 30% zinc (Zn), or preferably 70% copper, 29% zinc, and 1% tin (Sn). When the copper content falls below 60%, the brass becomes susceptible to attack by incondensable gases.

e. Catchall:

A catchall component is typically positioned at the top of the vessel and is referred to as a "save-all" or "entrainment separator." Its primary function is to prevent losses by separating drops of juice from the vapor.

This comprehensive design structure ensures the efficient and reliable operation of a vacuum evaporator, with specific attention to vessel construction, heat exchange, structural components, and materials used.

f. Design:

Figure 1 shows a triple effect evaporator, operated in forward feed arrangement for concentrating caustic soda solution.

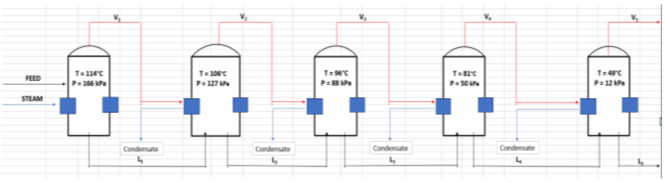


Fig.1. 5 Stage Evaporator

- First Effect

$F[h(TF, xF) - h(\tau 1, x1)] + V0^{*} \lambda 0 - (F - L1) * [H(\tau 1) - h(\tau 1, x1)] = 0.0$---(1)

$U1^{*}A1(T0 - \tau 1) - V0^{*} \lambda 0 = 0.0$------------------------------(2)

$m(x1) * T1 + b(x1) - \tau 1 = 0.0$ --------------------------------(3)

$FxF - L1x1 = 0.0$-- (4)

- Second Effect

$L1[h(\tau1, x1) - h(\tau2, x2)] + (F - L1)[H(\tau1) - h(T1)] -(L1-L2)[H(\tau2) - h(\tau2, x2)] = 0.0$---------------------------------------(5)

$U2*A2(T1 - \tau2) - (F - L1)[H(\tau1) - h(T1)] = 0.0$----------- (6)

$m(x2) * T2 + b(x2) - \tau2= 0.0$--------------------------------- (7)

$FxF – L2x2 = 0.0$-- (8)

- Third Effect

$L2[h(\tau2, x2) - h(\tau3, x3)] + (L1-L2)[H(\tau2) - h(T2)] -(L2-L3)[H(\tau3) - h(\tau3, x3)] = 0.0$---------------------------------------(9)

$U3*A3(T2 – \tau3) - (L1-L2)[H(\tau2) - h(T2)] = 0.0$--------- (10)

$m(x3) * T3 + b(x3) – \tau3= 0.0$------------------------------ (11)

$FxF – L3x3 = 0.0$-- (12)

- Fourth Effect

$L3[h(\tau3, x3) - h(\tau4, x4)] + (L2-L3)[H(\tau3) - h(T3)] -(L3-L4)[H(\tau4) - h(\tau4, x4)] = 0.0$--------------------------------------(13)

$U4*A4(T3 – \tau4) - (L2-L3)[H(\tau3) - h(T3)] = 0.0$--------- (14)

$m(x4) * T4 + b(x4) – \tau4= 0.0$------------------------------ (15)

$FxF – L4x4 = 0.0$-- (16)

- Fifth Effect

$L4[h(\tau4, x4) - h(\tau5, x5)] + (L3-L4)[H(\tau4) - h(T4)] -(L4-L5)[H(\tau5) - h(\tau5, x5)] = 0.0$--(17)

$U5*A5(T4 – \tau5) - (L3-L4)[H(\tau4) - h(T4)] = 0.0$--------- (18)

$m(x5) * T5 + b(x5) – \tau5= 0.0$------------------------------ (19)

$FxF – L5x5 = 0.0$-- (20)

IV. RESULT AND DISCUSSION

A. Algorithm of Models

The final set of solutions is obtained by a thorough iterative process that begins with the meticulous derivation of the set for each model of the system. The set of equations and all of the constants are entered into the "system of non-linear equations" tool. For the first iteration, an estimate of the entire heat transfer coefficient, U, is made. The following is a thorough algorithm that explains the processes taken to arrive at the final solution:

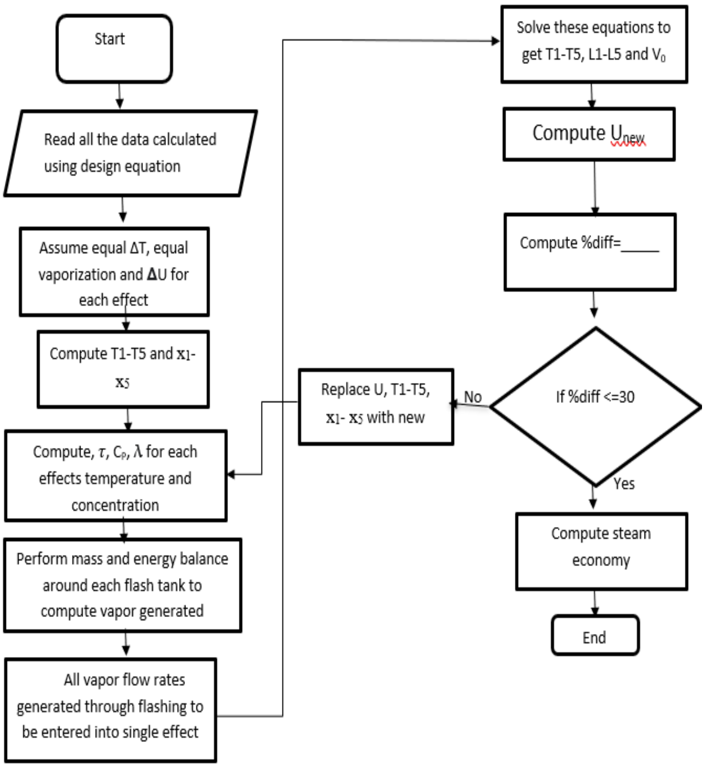


Fig.2. Flow Chart for Solution

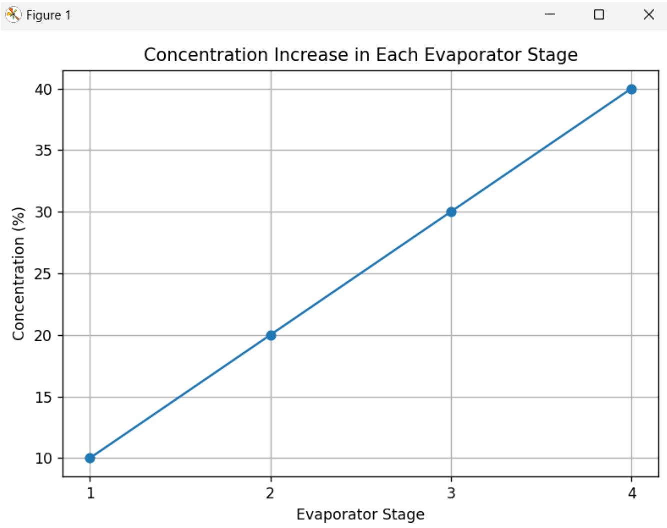
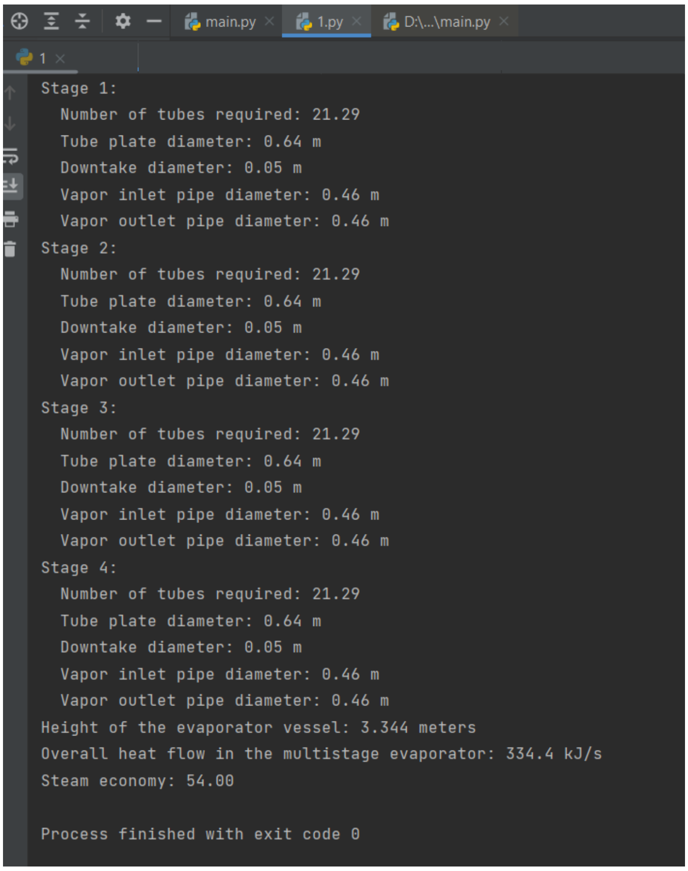


Fig.3. Concentration vs Stages output graph



```
Stage 1:
  Number of tubes required: 21.29
  Tube plate diameter: 0.64 m
  Downtake diameter: 0.05 m
  Vapor inlet pipe diameter: 0.46 m
  Vapor outlet pipe diameter: 0.46 m
Stage 2:
  Number of tubes required: 21.29
  Tube plate diameter: 0.64 m
  Downtake diameter: 0.05 m
  Vapor inlet pipe diameter: 0.46 m
  Vapor outlet pipe diameter: 0.46 m
Stage 3:
  Number of tubes required: 21.29
  Tube plate diameter: 0.64 m
  Downtake diameter: 0.05 m
  Vapor inlet pipe diameter: 0.46 m
  Vapor outlet pipe diameter: 0.46 m
Stage 4:
  Number of tubes required: 21.29
  Tube plate diameter: 0.64 m
  Downtake diameter: 0.05 m
  Vapor inlet pipe diameter: 0.46 m
  Vapor outlet pipe diameter: 0.46 m
Height of the evaporator vessel: 3.344 meters
Overall heat flow in the multistage evaporator: 334.4 kJ/s
Steam economy: 54.00

Process finished with exit code 0
```

Fig.4. output result

CONCLUSION

Optimizing a multistage evaporator system necessitates a combination of theoretical analysis and practical computational methods. By conducting detailed manual calculations, critical parameters such as heat flow, the number of tubes, tube plate diameters, down take diameters, and vapor pipe diameters can be accurately determined. These parameters are crucial for creating an efficient evaporator system that meets specific industrial requirements. The manual calculations offer a deep understanding of the heat transfer processes and the cost considerations associated with each part of the system. In addition to the manual calculations, the use of a Python-based computational tool significantly enhances the optimization process. This code enables precise and automated computations of the overall heat flow, the required number of tubes for each stage, tube plate diameters, downtake diameters, vapor pipe diameters, and the steam economy of the multistage evaporator. It takes into account various factors such as inlet and outlet temperatures, flow rates, specific heat capacity, and material properties to deliver a thorough analysis of the system's performance. The combination of manual calculations and Python programming ensures a comprehensive and optimized design for the multistage evaporator, leading to improved efficiency and reduced operational costs. This integrated approach not only confirms the theoretical principles but also offers practical insights and adaptability for engineers to modify the design for various industrial applications.

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