

Performance Investigation of Multiple Effect Evaporator For Sugar Industry.

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Abstract

A number of process industries, including pulp and paper, sugar, desalination, pharmaceuticals, dairy and food processing, etc., have evaporators as one of their most energy-intensive components. If the heat from the vapour is not used, a single effect evaporator might be energy inefficient. Using multiple-effect evaporators solves this problem. Because Vapour bleeding is implemented, falling film tubular & Robert type evaporators are typically regarded as the preferred evaporator design in the cane sugar industry. The Quintuple-effect evaporator system model that will be created for this project has five effects. The model includes vapour bleeding as a way to cut back on the amount of steam used in the evaporator. Using waste heat while lowering steam consumption and heating power are the goals of multiple effect arrangements. This is accomplished by employing the vapour produced in the first stage as the second stage's heat source and the third stage's heat source. Condensate, feed and product flashing, vapour compression, and other energy-saving techniques are also available. Vapour bleeding improves the process's steam economy, but at the increased expense of the necessary heat exchangers. Along with designing this evaporator, we will analyse data to identify various stresses and develop a support system to minimise the evaporator's weight.

Pinch technology is a complete methodology derived from simple scientific principles by which it is possible to design new plants with reduced energy and capital costs as well as where the existing processes require modification to improve performance. Pinch Analysis also analyze the process data using its methodology to predict energy and other design targets such that it's possible to assess the consequences of a new design or potential modification before embarking on actual implementation . Energy saving in the Nigerian industrial sector has several possibilities, due to the fact that almost all the industrial equipment stocks in Nigeria were imported during the era of cheap energy. Consequently, they are inherently energy inefficient; the improvement of energy efficiency can provide substantial benefit in general to all sector of the economy of the process plants.'

Keywords- Evaporator, Multi-effect, Robert type, Sugar industry, vapour bleeding.

1. Introduction

Across the world, raw sugar is produced from sugarcane, which contains mostly water with a small amount of sucrose and fibrous debris. A mixture of fibrous debris and water called bagasse is left behind after a series of crushing mills separate the juice from the cane. This bagasse serves as fuel for boilers that produce the steam necessary to power steam turbines and heat industrial processes. A succession of juice heaters heat the extracted juice before feeding it through a clarifier, where most of the insoluble contaminants are eliminated. After that, a multi-effect evaporator (MEE) set is used to evaporate more than 90% of the juice's water content. [1]

A MEE set consists of many vessels through which juice flows serially as steam cascades from one vessel's vapour space into the calandria (steam chamber) of the next. Low pressure (LP) steam is utilised to heat the first vessel, and a condenser is used to create a vacuum after the pan stage evaporation operation, which works similarly to an individual evaporator vessel. However, because the pan stage vessels are not cascaded, they perform less effectively in terms of steam utilisation. Masecuite, a product comprised of sugar crystals encased in molasses, is created during the pan stage. After drying, this is fed into centrifuges where the crystals are separated to become the raw sugar product. [2]

A. Objective of Evaporation

The procedure of clarifying produced a clear juice. This juice is made up of sugar that has been dissolved in water along with some contaminants. It's still necessary to drain the water after we've done our best to remove the pollutants. This is the thing that evaporates. The sugar will, however, concentrate in direct proportion to the amount of water we remove from the juice. Then, it will get close to the point of saturation, which is when crystals start to form in the liquid. The concentration is increased to the point that the mother liquor is only left in the residual empty space between the crystals. "Masecuite" is the term used to describe the resulting mixture of crystalline crystals and sticky mother liquid.

It goes without saying that such a mass cannot be handled like juice or syrup. Hence, the concentration procedure is divided into two stages: (A) so-called evaporation, which progresses from clear juice to syrup and in which we are just working with a liquid substance. (b) The sugar is boiled, which starts just as the syrup starts to crystallize and continues until the concentration is at its highest. Of course, the contaminants and some of the sucrose are still present in the mother liquor. The next step is to separate the sugar crystals from the mother liquor and work to extract as much of the sugar that is still present from it as you can. We'll look at these processes under the evaporation and centrifugation of sugar. [3]

B. Single and multi-effect evaporator

Until the development of a multi effect evaporator, the sugar industry used a single effect evaporator for evaporation. The steam is injected into a single effect evaporator where it condenses on the tube surface and transfers heat to the solution. The evaporator releases saturated vapour, which can either be vented outside or condensed. The evaporator's concentrated solution is removed. We may now decide if we want to concentrate even more by sending the solution into a different, analogous evaporator that will have fresh steam to generate the required heat. [3][4]

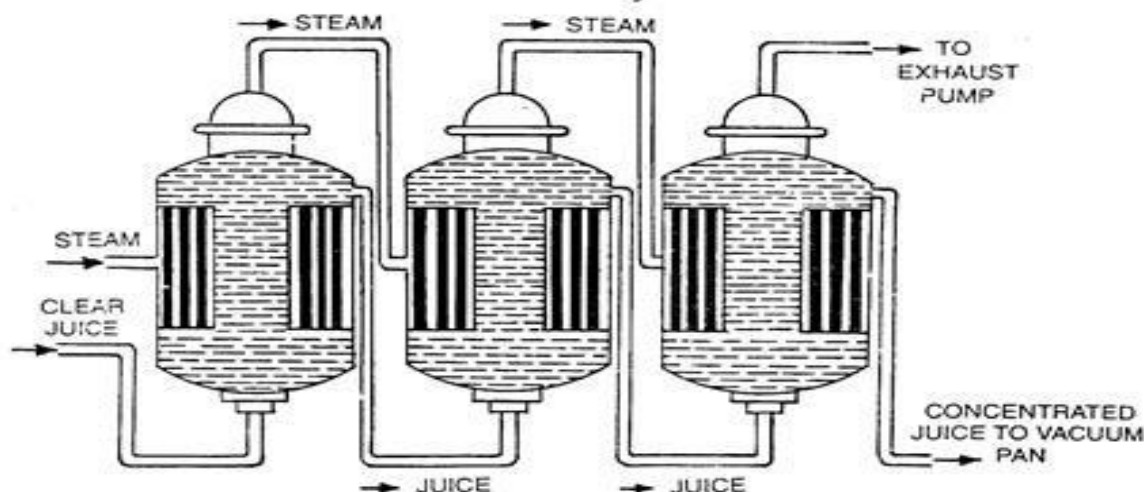


Fig.1.1 Multi-Effect Evaporator

Note: Adapted from Example Book by J. Smith 2016, p. 115. Copyright 2016 by Scibber.

It should be noted that new steam is needed for the second evaporator in this operation, but the vapour is not used at the same time. As a result, it may be concluded that the single effect evaporator does not utilise the steam effectively. Hence, the single effect evaporator's economy is below one. The fact that the feed temperature frequently lingers below the solution's boiling point is another factor contributing to the low economy. As a result, some of the heat is used to increase the supply temperature to boiling. Multi-effect evaporators are used in place of single effect evaporators to combat their drawbacks. [5]

Chemical engineers refer to a multiple-effect evaporator as a device for effectively employing steam heat to evaporate water. Water is boiled in a series of vessels in a multiple-effect evaporator, each held at a lower pressure than the one before it. Just the first vessel (at the maximum pressure) requires an external source of heat because the boiling temperature of water lowers as pressure increases. This allows the vapour that has been boiled off in one vessel to be utilised to heat the next.[6]

Norbert Rillieux is an African-American inventor and engineer who created the multiple-effect evaporator. He might have created a prototype of the device in 1834 after designing it in the 1820s, but it wasn't until 1845 that he created the first industrially useful evaporator. It was initially created to concentrate sugar in sugar cane juice, but it is now widely employed in all industrial applications that require evaporating significant amounts of water, like salt manufacturing and water desalination. [7][8]

C. Principle of Multi-Effect Evaporator

There is no doubt that Norbert Rillieux, an American of French ancestry, discovered multiple effect evaporation in Louisiana around 1830. This discovery of multiple effect evaporation is the most significant and remarkable advancement that has shaped the history of sugar manufacture. Juice evaporation by heating with steam had already started when evaporation in open pots over an open fire was discontinued. [8]

Rillieux had the following idea: if steam is used to heat juice and evaporate the water it contains, why not use the juice's own vapour in a similar manner to heat further portions of juice or complete the evaporation that ordinary steam had already started? The first challenge is immediately apparent: juice at atmospheric pressure can be heated and evaporated with steam at 110°C (230°F) (pressure 6 psi). Under atmospheric pressure, the vapour of juice reaches a temperature of 212°F or 100°C. Juice cannot be boiled at the same temperature as vapour at that temperature; a temperature differential between the heating fluid and the fluid that has to be heated is required.[9]

Rillieux overcame this obstacle by vacuum-sealing the vessels that came after the first. It became possible to create the necessary temperature difference and use the vapour arising from the juice in the first vessel to heat the juice in the second vessel, the vapour produced by the second to heat the third, etc. by boiling water or juice at 90°C under 23 cm of vacuum, at 80° under 40 cm of vacuum, at 70° under 52 cm, etc. The drawback of this approach is that it necessitates installation in order to produce the required vacuum. However there are two significant benefits to boiling under

vacuum: (A) It can raise the total temperature differential between steam and juice by an amount equal to the decrease in the juice's boiling point between the pressures of the first and last vessel. (b) When the juice gets more concentrated and viscous, it allows evaporation to take place at temperatures that are correspondingly less harmful from the perspective of inversion and coloration of the juice. [10]

2. Material and Methods

SUB-ASSEMBLIES OF MEE

A. Evaporator vessel

The tubular calandria across which the heat exchange occurs is supported by a vertical cylinder, which is the basic design of a multiple effect evaporator. The "save-all" at the top of this cylindrical body serves the purpose of separating the juice from any liquid droplets that might be entrained with the vapour. The evaporator bodies were formerly always made of cast iron. Steel plate fabrication has increased in popularity more lately. This enables the use of less expensive, lighter, and fragile evaporator bodies. [11]

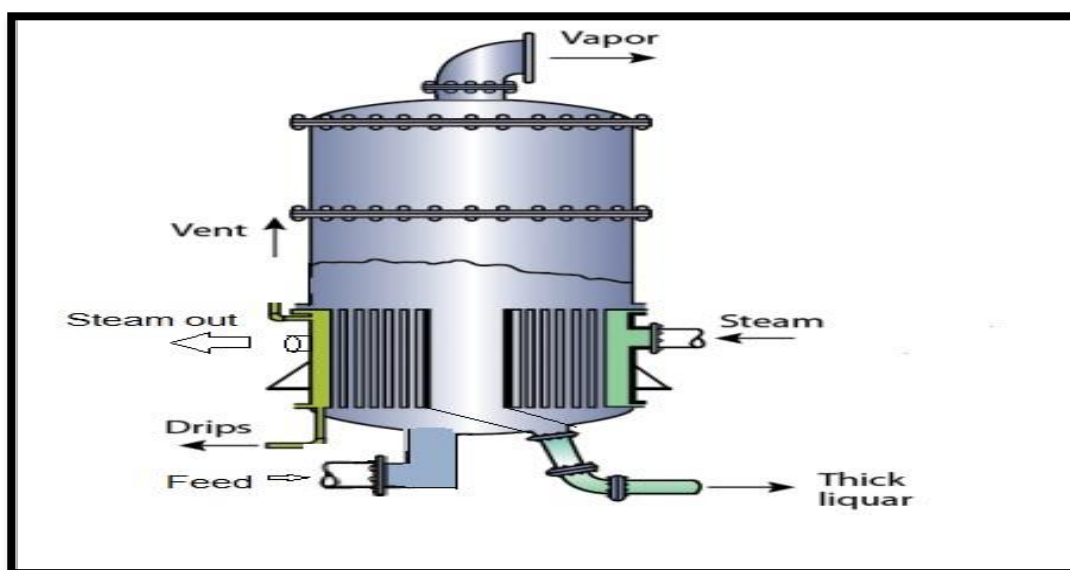


Fig.2.1 Evaporator Vessel.

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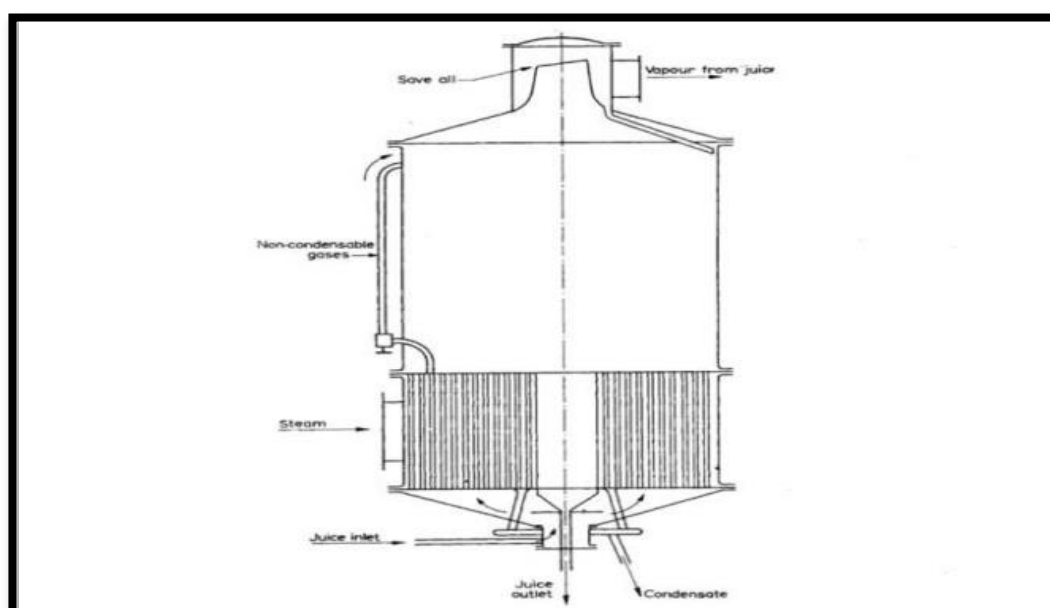


Fig.2.2 Evaporator Vessel.

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B. The Calandria

The body or shell of the evaporator continues into the calandria. The various solutions are chosen in this situation since leaks can only communicate with the vessel's exterior. Juice or vapour leaking from the calandria of the vessel will be apparent if it is under pressure. If the area is vacuumed, the leak may be found by the suction that is created on a flame that is placed close to the joint. The tube plates' supplied holes for the tubes should have a bore that is about 1/32 in larger than the tubes' outer diameter. In the calandria, vertical baffles are frequently positioned with the intention of forcing the steam along a specific channel. [12]

Sadly, these metal baffles, which are prone to corrosion, cannot be removed or replaced. The position of the incondensable gas withdrawal pipes typically becomes inappropriate for the new steam channel when they are destroyed or damaged because the steam does not follow the path that was originally planned for it. [12][13]



Fig.2.3 The Calandria

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Centre well

The purpose of the calandria's wide tube or centre well is to return the juice that has been projected over the top tube plate to the bottom. The concentrated juice is frequently collected in this centre well and transferred from one vessel to the next. A number of small-diameter downtakes dispersed across the calandria or a lateral well may be used by some manufacturers to replace the centre well. [14]

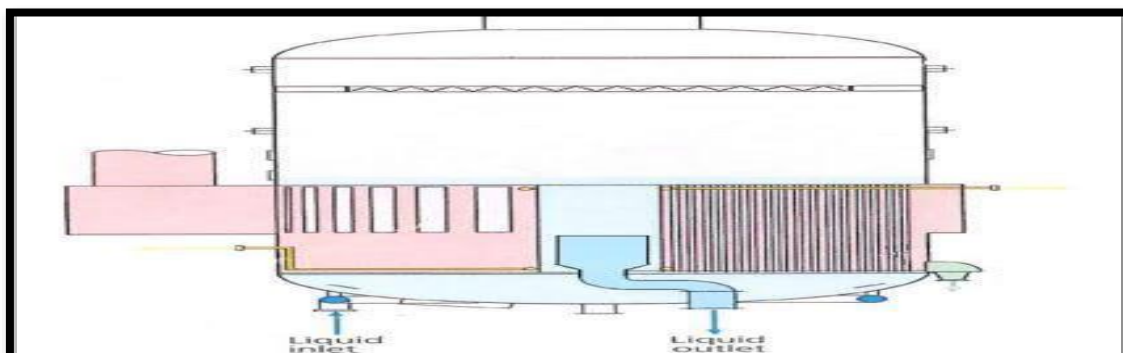


Fig. 2.4 Center well

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C. Tubes

Brass or steel are used to make the calandria's tubes. Brass tubes last far longer. The following is the composition of the best brass for the tubes of a multiple effect: Ideally, Cu = 70% Zn = 30% or Cu = 70% Zn = 29% Sn = 1%. If the copper content falls below 60%, the metal is vulnerable to attack from the incondensable gases. [15]

D. Catch hall

It is known as a "save all" or "entrainment separator" and is often located at the top of the vessel. It is essential to equip the evaporator vessels with a system for separating the juice drops in order to prevent losses due to entrainment. [16]

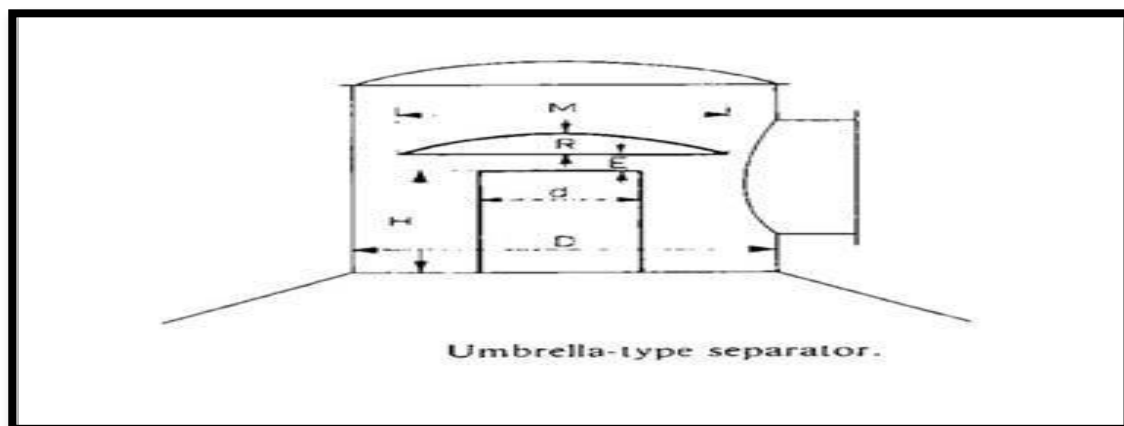


Fig.2.4 Catch hall

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E. Governing Equation of Multiple Effect Evaporator [17]

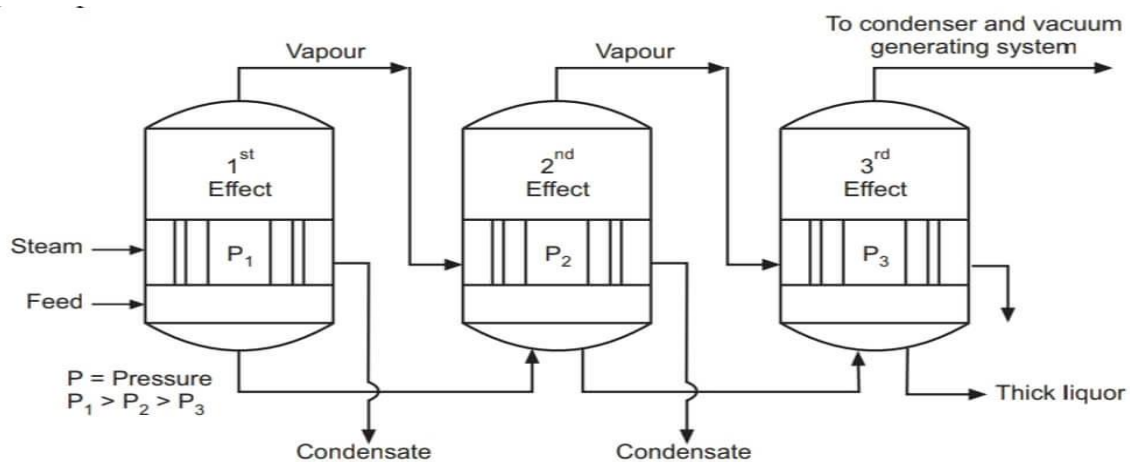


Fig.2.5: Forward feed arrangement for feeding multiple effect evaporator system.

Note: Adapted from Example Book by J. Smith 2016, p. 115. Copyright 2016 by Scibber

Governing Equation of Multiple effect Evaporator is derived: -

Mass energy balance [18]

Basic Equation Energy Balance

$$Q = m \cdot c_p \cdot \Delta T = m \cdot \lambda \cdot \{ \text{Latent Heat} = \lambda = H_s - h_s \}$$

For steady state'

Rate of mass in = rate of mass out

For total balance

$$F = L + V$$

For balance of solute

$$F \cdot X_F = L \cdot X_L \quad V = 0 \quad \dots \dots \text{Vapours Solute free}$$

For Heat Balance[19]

Heat in feed + Heat in Steam = Heat in Conc. Liquid + Heat in Vapour + Heat in Condensate Steam.

$$F \cdot h_f + S \cdot H_s = L \cdot h_L + V \cdot H_v + S \cdot h_s$$

By Substitution,

$$F.hf + S.(H_s - h_s) = L.hL + V.H_v.$$

The Heat transferred in the evaporator is then.

$$q = S.(H_s - h_s) = S.\lambda = U.A.\Delta T = U.A.(T_s - T_1)$$

Assume $P_1 > P_2 > P_3$ (fixed), T_3 (Fixed Known).

When V_1 & T_1 both exists at same temperature.

Governing Equation of Multiple effect Evaporator

Effect 1:- $\lambda_0 = H_0 - h_0$ = Change in Enthalpy.

Enthalpy Balance[20]

$$F.hf + Q_1 - V_1 H_1 - L_1 h_1 = 0$$

$$F.hf + V_0 \lambda_0 - (F - L_1) H_1 - L_1 h_1 = 0$$

$$F.C_p (T_f - T_1) + V_0 \lambda_0 - (F - L_1) \lambda_1 = 0$$

Rate Equation

$$U_1.A.(T_0 - T_1) = V_0 \lambda_0 = Q_1$$

Effect 2: $V_1 = F - L_1$

Enthalpy Balance

$$L_1(h_1 - h_2) + V_1 \lambda_1 - (L_1 - L_2) \lambda_2 = 0$$

$$L_1.C_p.(T_1 - T_2) + (F - L_1) \lambda_1 - (L_1 - L_2) \lambda_2 = 0$$

Rate Equation

$$U_2.A.(T_1 - T_2) = (F - L_1) \lambda_1 = Q_2$$

Effect 2: $V_2 = L_1 - L_2$

Enthalpy Balance

$$L_2(h_2 - h_3) + (L_1 - L_2) \lambda_2 - (L_2 - L_3) \lambda_3 = 0$$

$$L_2.C_p.(T_2 - T_3) + (L_1 - L_2) \lambda_2 - (L_2 - L_3) \lambda_3 = 0$$

Rate Equation

$$U_3.A.(T_2 - T_3) = (F - L_1) \lambda_1 = (L_1 - L_2) \lambda_2$$

Badger Mc-Cabe Method [21]

To find the different parameters for design considerations of MEE, with help of Badger Mc-Cabe Method

In this method to find the design Parameter with consideration some assumption of known parameters where X_F , T_F , P_F , T_0 , P_0 , X_3 , T_3 , & L_3 & Finding unknown Parameter, V_0 , L_1 , L_2 . etc. from the trial of this method 4 to 5 times we get closer value at 4 & 5 Rows of table. And with the help of that value known & finding parameter we also find the average area of evaporators.

Trial No.	1	2	3	4	5	6	7
Parameters	L_1	L_2	V_0	A	ΔT_1	ΔT_2	ΔT_3
Units	T/Hr	T/Hr	T/Hr	m^2	$^{\circ}C$	$^{\circ}C$	$^{\circ}C$
1	195.5	119.4	189.5	2661.5	7	16	42
2	194.94	119.5	189.75	2662	6.5	15.5	42.5
3	194.9	119.32	189.9	2661.8	6.5	15.5	42.3
4	194.92	119.4	189.55	2661.7	7	16	42.5
5	194.9	11.45	189.55	2661.5	7	16	42.5

F. DESIGN CONSIDERATION[22]**a) Length of tubes**

The tubes in typical multiple effects range in length from 4 to 5 feet. Yet recently, 15 feet has been added to the tubes' length by European producers. The evaporation rate does not increase as a result, but for a given evaporation duty, this method yields containers that are more space-efficient and cost-effective. The lengths that are currently most frequently used range from 6 to 8 feet. The outer space between the tube plates should be approximately in. longer than the length of the tubes. They will then extend slightly beyond the tube plates, about in.

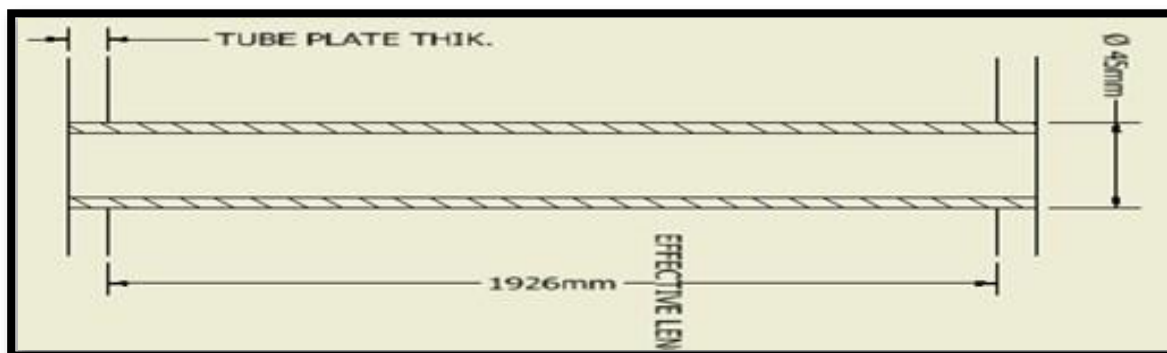


Fig.2.6 Tube effective Length and Diameter

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b. Diameter of tubes[23]

The interior diameter of the tubes used for various effects ranges from 1 in. to 2 in. For steel tubes, their thickness ranges from 0.06 to 0.10 in, whereas for brass tubes, it ranges from 0.06 to 0.08 in. The following are the most typical dimensions:

c. Arrangement of the tubes

The tubes in the tube plates are often arranged in a staggered pattern. At a specific spacing between the tubes, this configuration enables the most tubes to be accommodated per unit area of the plates. Hence, the tubes are arranged in three distinct orientations at a 120° angle to one another in straight lines. What relationship should be seen between the outer diameter d_o of the tubes and distance p between the tubes, centre to centre, given that this design allows for the highest density of tubes?

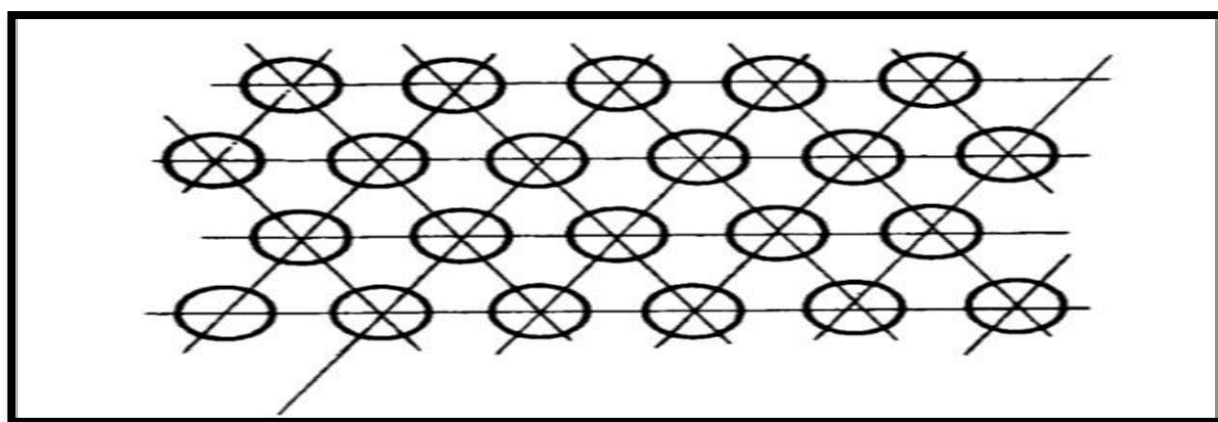


Fig.2.7 Arrangement of tubes

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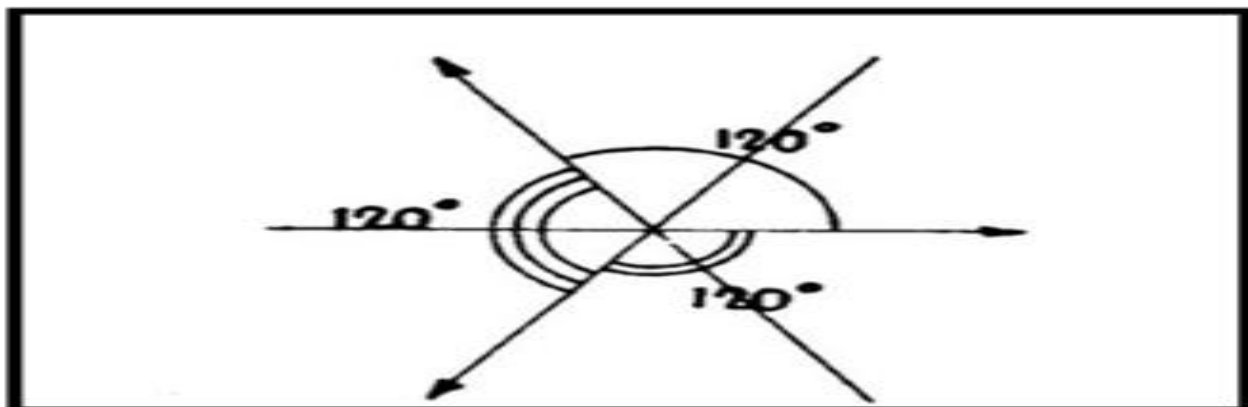


Fig.2.8 Layout of staggered arrangement

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d. Vapour Lanes and Tube sheet Hole arrangement[24]

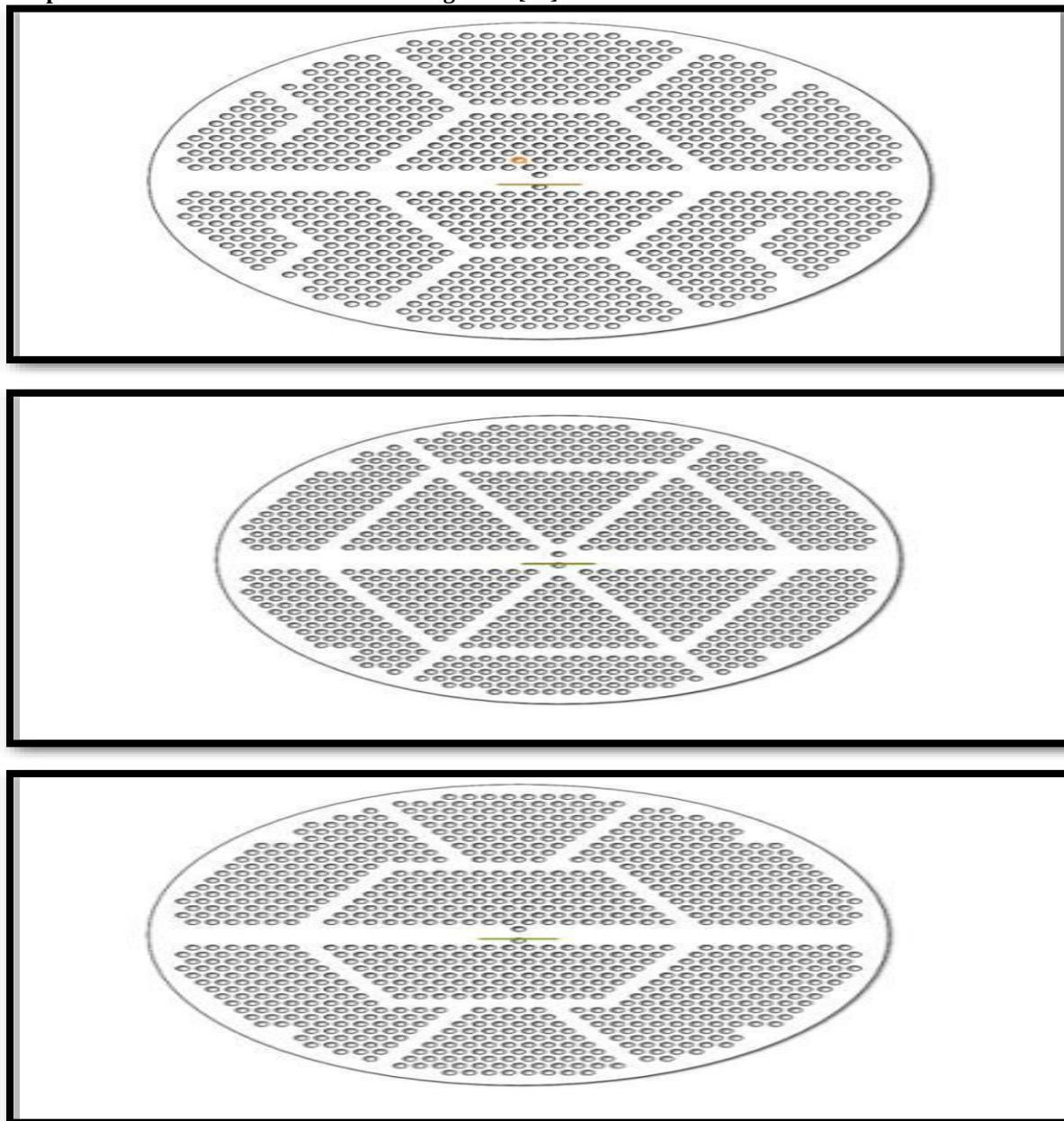


Fig. 2.9 Vapour Lane Arrangements

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G. EXPERIMENTAL VALIDATION[25]

A. Technical Specification[26]

- 1) Evaporator type:- Falling Film Tubular type or Robert type.
- 2) Calandria height:- 2.91m
- 3) Body height:-5.5m
- 4) Bottom cone thickness:-25 mm
- 5) Calandria thickness:-15mm
- 6) Body thickness:-15 mm
- 7) Overall height:-12.025 m
- 8) Tube plate thickness:-Top & bottom=33 mm
- 9) Water filled equipment load:-200 tonnes
- 10) Total no. of nozzles:- 18

Material Conditions

- 11) Tube plate: - IS 2062-2011
- 12) Tubes: - Stainless steel 304
- 13) Calandria: - IS 2062-2011 # All Nozzles: - IS 1239- Grade1
- 14) Body: - IS 2062-1192 or equivalent # Nozzles: - IS 1239-Grade1
- 15) Catch hall material details:-
 - i. vent:- SS409
 - ii. Centrifugal Other:- IS 2062-1992
 - iii. Connection:- IS 1239-Grade C

B. Inputs [27]

- 1) Heating surface= 2000m².
- 2) Tube O.D.= 45 mm
- 3) Tube thickness=1.25 mm
- 4) Tube length= 2000 mm
- 5) Tube plate thickness=35 mm
- 6) Tube expansion allowance= 6 mm
- 7) Legment=12 mm
- 8) Tube clearance=0.5 mm
- 9) Tube plate hole clearance=0.1 mm
- 10) Proportional factor(β)=0.85
- 11) % of downtake diameter on tube plate area=21%
- 12) Inlet vapour temperature=1050C
- 13) Outlet vapour temperature=950C
- 14) Velocity of inlet vapour= 32m/s
- 15) Velocity of outlet vapour= 36m/s
- 16) Velocity of condensation=0.7m/s
- 17) Evaporation rate of body=24kgs/m²/hr
- 18) Inlet vapour specific volume= 1.515 m³/kg
- 19) Outlet vapour specification volume=2.13 m³/kg
- 20) Specific volume of vapour= 21.03 m³ /kg

C. Calculated Dimensions [28]

- 1) Number of tubes:
 - a. Main diameter of tube= 44 mm
 - b. Effective length of tube= 1.95 m
 - c. Number of tubes= 7500
- 2) Downtake diameter and tube plate diameter
 - a. Tube pitch= 55 mm
 - b. Tube plate area required for tubes only= 26.7m²
 - c. Tube plate diameter required for tubes only= 5.84m
 - d. Diameter of single downtake= 1175mm
 - e. Area of downtake= 1.0750m²
 - f. Total area of tube plate= 27.84m²
 - g. Final diameter of tube plate= 5955mm
 - h. Total area of peripheral downtake= 251328mm²
 - i. Available area of central downtake= 824000mm²
 - j. Diameter of central downtake= 1025mm
- 3) Diameter required for vapour inlet and diameter of calandria in vapour entry:
 - a. Number of vapour entries= 2
 - b. Evaporation rate of body= 24.5 kgs/m²/hr
 - c. Vapour required for calandria= 50000 kgs/hr
 - d. Total area of vapour entry=0.71 m²
 - e. Diameter of steam entry= 700 mm

- f. Area of each steam entry=385000 mm²
- g. Width of steam entry = 200mm
- 4) Vapour outlet pipe diameter:
 - a. Vapour volume =30 m³/s
 - b. Vapour outlet pipe diameter=1050mm
- 5) Diameter of condenser:
 - a. Volume of condensate=13.85 m³/s
 - b. Condensate pipe diameter each=160mm
- 6) Toxic Gases:
 - a. Cross section area of non-condensable gases= 200cm²
 - b. Number of non-condensable gases= 6
 - c. Diameter of each non condensable gas line= 65.150 mm
- 7) Vapour space height:
 - a. Vapour space height =5000mm
- 8) Velocity in vapour space of the body:
 - a. Vapour volume = 30 m³/s
 - b. C/S area of body = 28m²
 - c. Velocity in vapour space of body=1.06 m/s
- 9) Calandria shell thickness:
 - a. Maximum allowable pressure = 3.1 kg/cm²
 - b. Allowable stress =1410kg/cm²
 - c. Joint efficiency =0.71
 - d. Corrosion allowance =1.55 mm
 - e. Calandria shell thickness= 12.5 mm
 - f. Calandria ID=5900mm
- 10) Vapour shell thickness:
 - a. Maximum allowable pressure = 2.1 kg/cm²
 - b. Allowable stress =1410kg/cm²
 - c. Joint efficiency =0.71
 - d. Corrosion allowance =1.55mm
 - e. Vapour shell thickness=8.1mm
- 11) Tube plate thickness:
 - a. Maximum allowable pressure = 2.8 kg/cm²
 - b. Allowable stress =1410kg/cm²
 - c. Modulus factor for MS sheet= 210000
 - d. Corrosion allowance = 1.55mm
 - e. Tube plate thickness= 8.1mm

H. CAD MODEL[29]

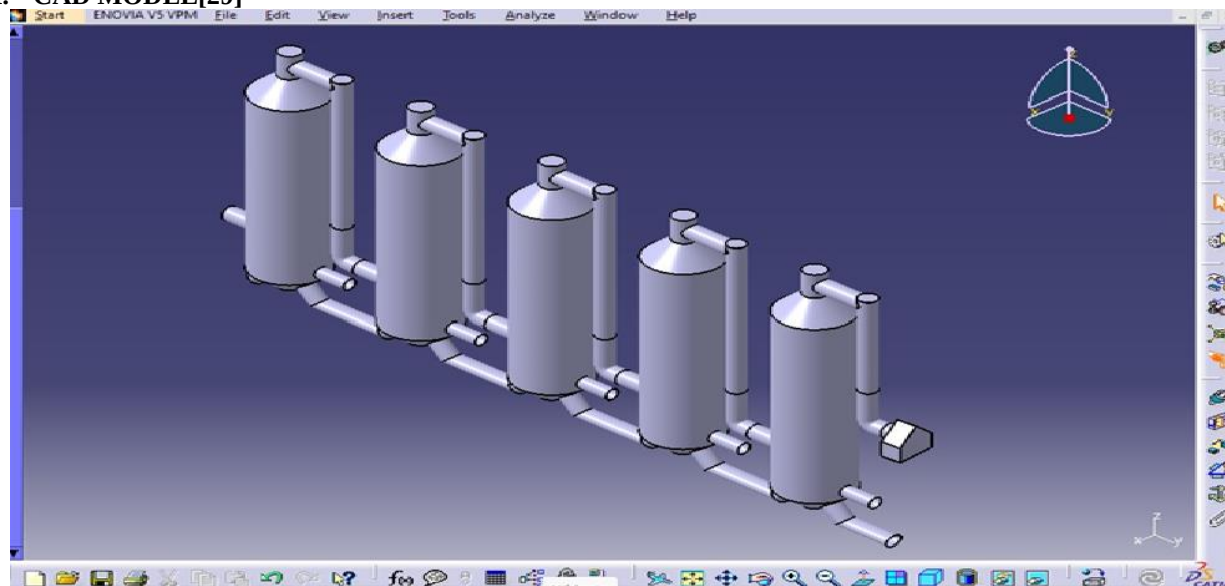


Fig. 2.10 CATIA Drawing of Multiple effect Evaporator

A. Material1: Plain Carbon Steel

- 1) Young's Modulus (E) = 200 GPa
- 2) Tensile Strength= 410MPa
- 3) Poisson's Ratio= 0.275
- 4) Density = 7810kg/m³
- 5) Thickness = 10.5mm
- 6) Overall deformation = 11.5mm

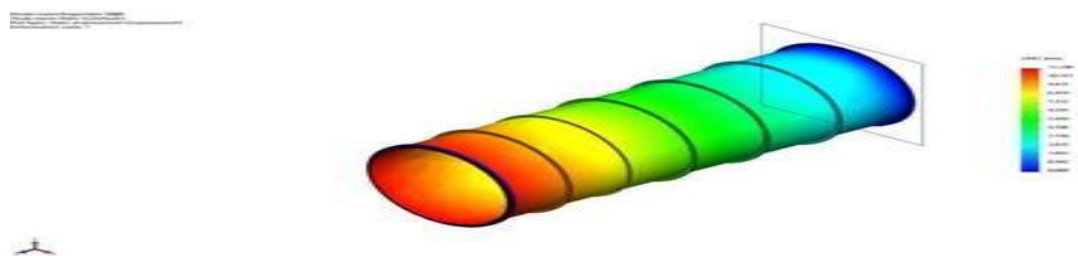


Fig. 2.11 Vapour Lane Arrangements

B. Note: Adapted from www.jetir.org by Deshmukh et.al. 2019, p. 101. Copyright 2019 by JETIR.

C. Material2: Stainless Steel 304

- 1) Young's Modulus (E) = 195 GPa
- 2) Tensile Strength = 520 MPa
- 3) Poisson's Ratio = 0.29
- 4) Density = 8050kg/m³
- 5) Thickness = 12.5mm
- 6) Overall deformation = 2.25 mm

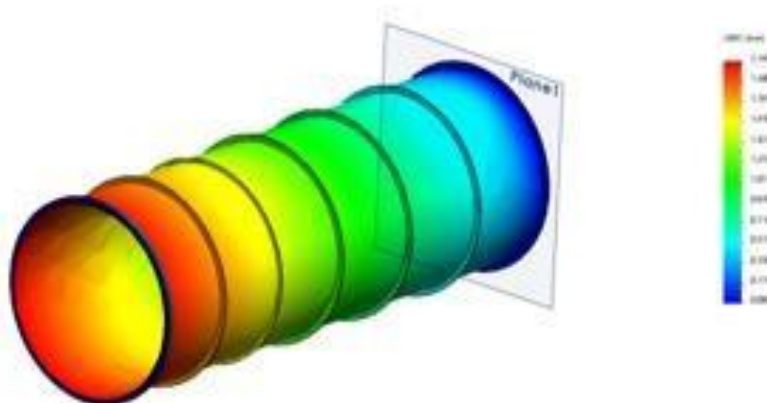


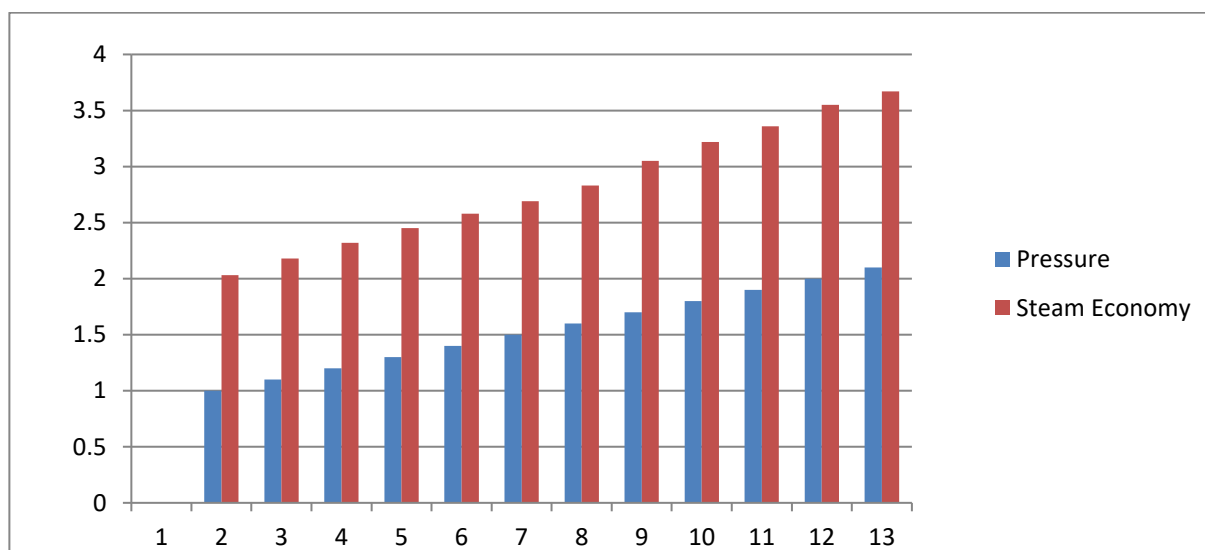
Fig. 2.11 Vapour Lane Arrangements

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3. Result and Discussion

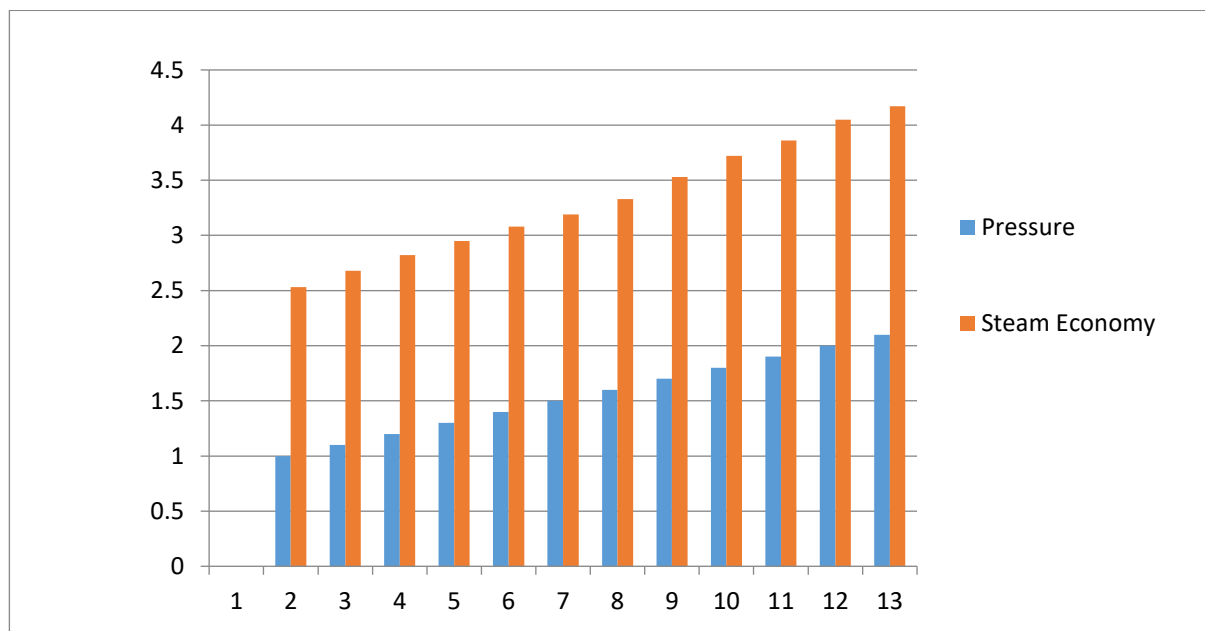
Case Studies to Calculate the Steam Economy for Multiple Effect Evaporators in Sugar Industry [30]

1) Triple Effect Evaporator used for sugar Industry



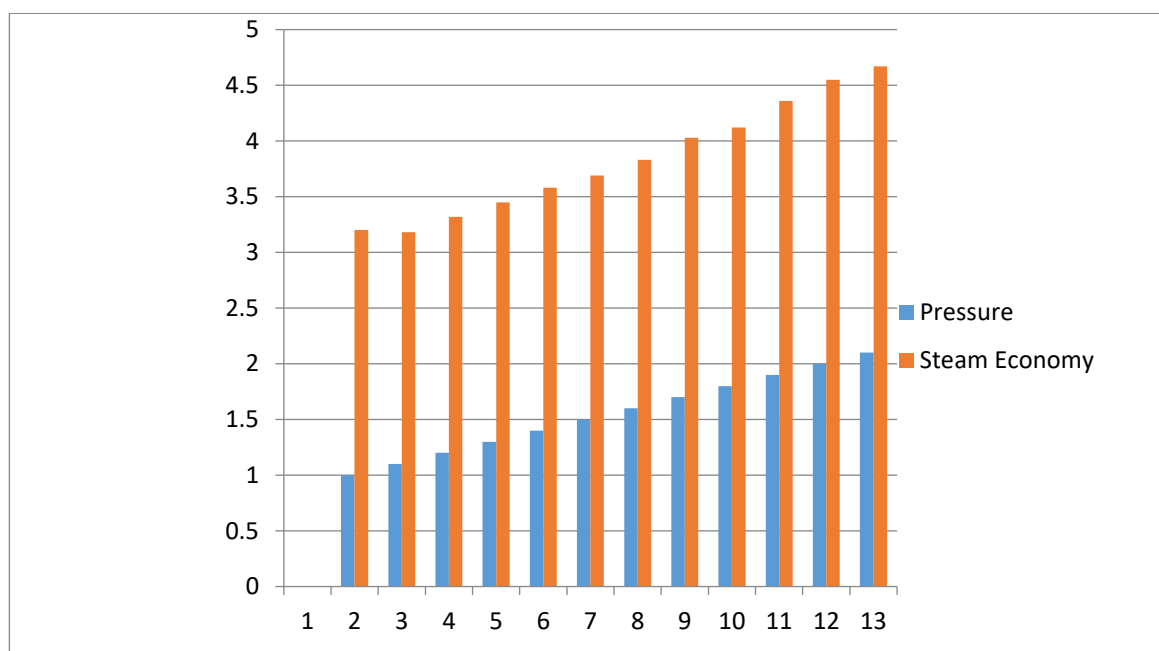
Graph No. 3.1 Pressure Vs Steam Economy of Triple Effect Evaporator

2) Quadruple Effect Evaporator used for sugar Industry



Graph No. 3.2 Pressure Vs Steam Economy of Quadruple Effect Evaporator

3) Quintuple Effect Evaporator used for sugar Industry



Graph No. 3.3:- Pressure Vs Steam Economy of Quintuple Effect Evaporator

4. CONCLUSION

According to the findings of numerous theses and research papers, the impacts needed for the sugar business are solely dependent on the size of the industry. For large-scale enterprises, a multi-effect evaporator with seven to eight effects is highly successful in utilising steam efficiently while also producing the appropriate quality and amount of condensate from each effect. More than three effect evaporators are useless for small-scale industry. It is evident that the sugar juice should be injected into tubes from bottom to top. Juice will move faster due to gravity if it is supplied from top to bottom, which will reduce the amount of time needed to heat the juice. While juice is flowing from bottom to top, it moves slowly until it reaches the tube's top before flowing from the centre of the downtake. As a result, there will be more time for heating. The various dimensions of an evaporator are determined using standard methods and a design data book as a guide.

During the designing phase, it was discovered that a multi-effect evaporator's performance is primarily influenced by four key factors. These four factors are the tube's length, diameter, body material, and configuration of the vapour lanes. According to the needed capacity and temperature, the tube's length and diameter are calculated.

The placement of the vapour lanes is intended to evenly heat all of the tubes. The overall structure's material is dependent on a number of elements. In order to successfully heat juice, the material should have a sufficient thermal conductivity. Moreover, as little heat as possible should be transferred to the environment. By contrasting the many needed parameters, the material is chosen in accordance with industry-standard material selection tables. Thermal analysis is used to test the material further. Thermal investigation revealed that the overall deformation for plain carbon steel at 103°C was found to be 11mm. Instead, there was a 2mm total distortion for the stainless steel 304 material. The material chosen for the evaporator body is stainless steel 304.

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5. CONCLUSION

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