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Design and Simulation of Sugar Juice Evaporator
(Case study: Metehara Sugar Factory)

A Thesis Submitted to the School of Graduate Studies of Addis Ababa
University in Partial Fulfillment of the Requirements for Degree of
Masters of Science in Mechanical Engineering

(Specialization: Thermal Engineering)

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NOMENCLATURE

E- Weight of water to be evaporated % cane
J - Weight of juice obtained % cane
S- Weight of syrup % cane
B - Brix of solution
V - Vapor flow rate
h - Enthalpy of juice
F - Feed flow rate
H - Enthalpy of vapor
L - Product flow rate
v- Velocity of steam
U- Overall heating coefficient
S- Heating surface area
q-Specific heating
T- Temperature
c-Specific evaporation rate
P -Pressure
d- Diameter of tube
A- Surface area of tube
N - Number of tube
 ρ - Density of fluid
RI- Relative cost

Subscripts

i -Vessel number
j- Juice
s – Syrups

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CHAPTER ONE

1. INTRODUCTION

1.1. Background and Justification

Sugar is consumed by households as well as different industries such as confectioneries, food processing and beverage industries, institution like colleges and universities, military, hotels, restaurants and bars. Due to its wide application in different sectors the demand for sugar is very huge in the domestic as well as international markets.

Ethiopia has been meeting most of its sugar requirement through local production. However, due to the shortages created in the past few years nearly 20% of sugar requirement is met through import. The historical domestic production and consumption/sales data of sugar is shown in the table below [1].

Table 1.1:- Domestic production and sales of sugar (ton)[1]

Year	Production	Consumption/Sales	Per Cent Sold
1996/92	172,217	145,357	84.4
1997/98	172,571	184,528	106.9
1998/99	234,987	198,164	84.3
1999/00	250,869	246,364	98.2
2000/01	251,349	245,498	97.7
2001/02	248,152	203,246	81.9
2002/03	268,008	283,300	105.7
2003/04	198,762	276,400	139.1
2004/05	274,836	273,777	99.6
Total	2,071,751	2,056,634	99.4

Table 1.2:- Need of sugar cane in tons [1]

Year	Quantity	Value(Birr)
1997	1,403	2,797,773
1998	1,925	5,255,238
1999	1,995	5,098,249
2000	2,770	7,062,891
2001	4,724	13,060,176
2002	825	2,570,990
2003	5,971	17,755,870
2004	53,771	133,657,497
2005	37,758	112,262,173
2006	52,407	212,711,375

The above data show us the need for construction of more sugar factory as well as improving the efficiency of the available sugar factory. Ethiopian Sugar Development Agency has been established under proclamation No. 504/2006 by the House of Peoples' Representatives of the Federal Democratic Republic of Ethiopia on the 6th of July 2006, In order to make public sugar enterprises efficient, modern & competitive [2].

Sugar refining has a number of process as starting from the harvesting up to grading and packing. One of the most energy intensive processes is evaporation in which the dilute sugar juice solution will concentrate to sugar juice (syrup). A number of researches and experiment have take place to improve the system, the development of sugar refinery is more related with the evolution of evaporator.

1.2. Thesis Objectives

The objective of this thesis is to design sugar juice evaporator with consideration of minimum energy consumption and simulate with the available data from one of the major sugar factories in Ethiopia (Methara Sugar Factory), considering it will introduce

- Available evaporator technology in sugar refinery.
- Alternative way for producing evaporator in our country.
- For existing sugar factories way of improving their evaporator efficiency.
- For new built sugar factories way for choosing their evaporator system.
- Relation of basic components in evaporator with efficiency of the system.

The specific objectives of the thesis are;

- Selection of appropriate evaporator for the system.
- Determination of the main factor affecting the efficiency of evaporator.
- Selection of the appropriate design method by considering minimum energy consumption and lowest cost.
- Determination of the efficiency of evaporator.

1.3. Sugar Refining Process

The major processes involved in sugar refinery processes are harvesting , preparation , milling ,clarification , evaporation and heating ,crystallization, centrifuging , drying , grading and bagging as described in figure 1.1[3]:

1.3.1. *Harvesting*

Mature sugar canes are gathered manually and mechanically. Hand cutting is the most common method, but some locations use mechanical harvesters. Canes are cut at ground level, the leaves are removed and the top is trimmed by cutting off the last mature joint. Cane is then tied in bundles and transported to a sugar factory. After cutting, cane deteriorates rapidly, so the sugar cane cannot be stored for later processing without excessive deterioration of the sucrose content.

1.3.2. *Preparation (Knives and fibrizor)*

The cane stalks are unloaded from tractors/trucks to the cane table and thoroughly washed (depending on local condition) and let to pass to sets of rotating knives and fibrizers/shredder. The sets of rotating knives cut the cane into pieces, and fibrizers or shredders rapture the cell of the sugar cane and then transferred to the mills by conveyers for juice extraction process.

1.3.3. *Milling (Juice extraction)*

The shredded sugarcane travels on a conveyer belt through a series of heavy-duty rollers, which extract juice from the prepared cane. During juice extraction, hot water is sprayed onto the sugarcane to dissolve any remaining hard sugar. The prepared cane residue (bagasse) that remains at the last mill with a moisture content of 49-51% passes to the steam generating plant as a main

fuel and the raw (mixed juice) is pumped to the boiling house for further weighing clarification, heating, evaporation and crystallization process.

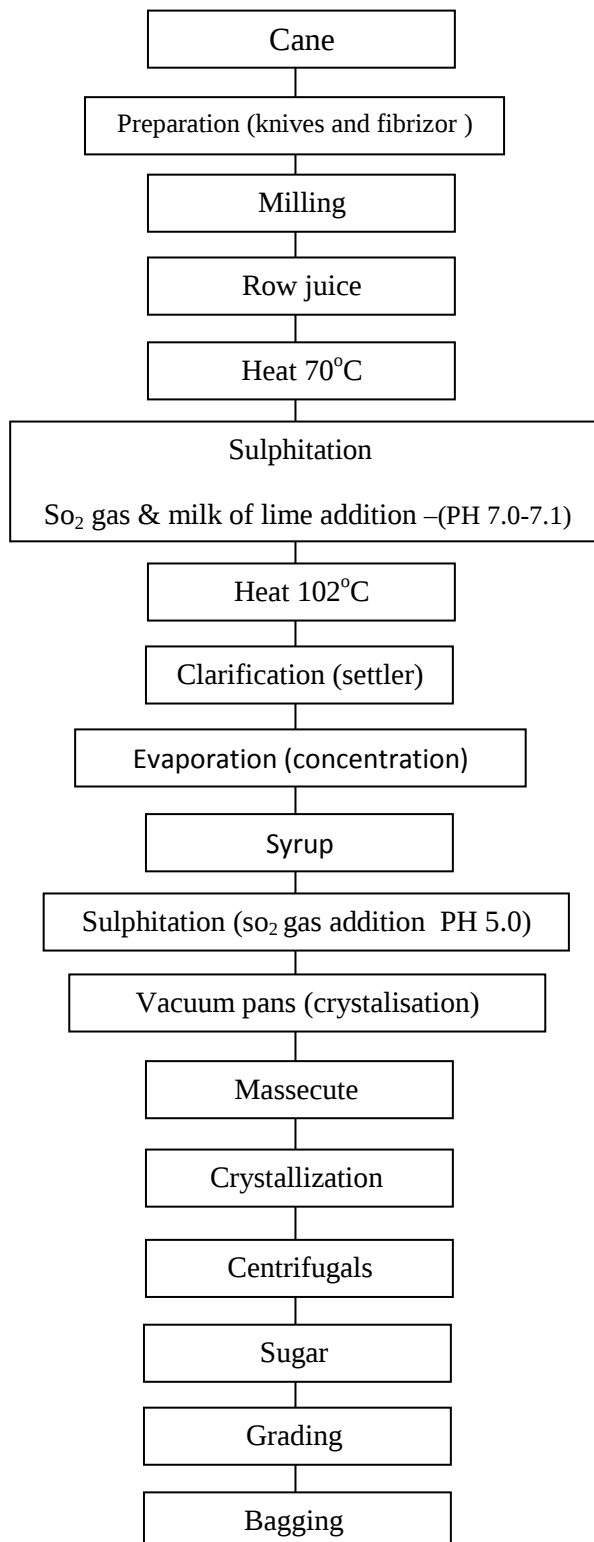


Fig 1.1:- Sugar refining process

1.3.4. Clarification:

Carbon dioxide and lime juice are added to the liquid sugar and heated to around 95⁰C. As the carbon dioxide travels through the liquid, it forms calcium carbonate, which precipitates non-sugar debris (fats, gums and wax) from the juice. This precipitate, called "mud," is then separated from the juice by vacuum rotary filters. The juice is then sulphited to remove any remaining impurities.

1.3.5. Evaporation and heating:

The factory can clean up the juice quite easily with slaked lime, which settles out a lot of the dirt so that it can be sent back to the fields. Once this is done, the juice is thickened up into syrup by boiling off the water using steam in a process called evaporation. Sometimes the syrup is cleaned up again but more often it just goes on to the crystal-making step without any more cleaning. The evaporation is undertaken to improve the energy efficiency of the factory. The syrup is then heated and sulphited to get the required temperature and pH before passing to vacuum pans for further evaporation and crystallization.

1.3.6. Crystallization:

The syrup is placed into a very large pan for boiling, the last stage. In the pan even more water is boiled off until conditions are right for sugar crystals to grow. The workers usually have to throw in some sugar dust to initiate crystal formation. Once the crystals have grown mixture of crystal and mother liquor (massacuiet) is formed.

1.3.7. Centrifuging:

The resulting mixture of crystals and mother liquor is spun in centrifuges to separate the two, rather like washing is spin-dried.

1.3.8. Drying:

The crystals then dry with hot air before being stored ready for dispatch.

1.3.9. Grading and Bagging:

The dried sugar then passes through a set of graders (sieves) to get the required crystal sizes before bagging of the final product.

1.4. Metehara Sugar Factory (MSF)

1.4.1. History and location

Metehara Sugar Factory is located some 200km South East of the capital city Addis Ababa, on the Addis-Dire Dawa- Djibouti road within the upper Awash Valley. It is situated at 8 53'N and 39 52'E. In the immediate vicinity of the enterprise one can find tourist attractions such as Awash National Park, Fentale Mountain and Lake Beseka are found.

The establishment date of Metehara Sugar Factory goes as far back as 1965, the time when the Dutch company, named as Hanger Vondr Amsterdam (H.V.A) had surveyed the area for future sisal development. The increasing demand or sugar in Ethiopia and the suitability of the land and climate for sugar cane cultivation urged H.V.A to extend the sugar industry to Metehara plains.

As a result, in July 1965 an agreement was signed between the Ethiopian Government and the Dutch company (H.V.A) under which the company acquired a concession of 11,000 hectares of land, Subsequent to the signing of the agreement, sugar cane cultivation was started in 1966.

The Factor started producing plantation of white sugar on the 9 of November 1969 with an initial crushing capacity of 1700 tons of cane per day (TCD). Since then, the factory had undergone successive phases of expansions. The first expansion was made in 1973 to raise the crushing capacity of the factory to 2450 TCD. The Enterprise was nationalized in 1975 and organized under the Ethiopian Sugar Corporation. Then the second and the third expansion took place in 1976 and in 1981, which raised crushing capacity to 3000 and 5000 TCD respectively. The Enterprise currently has a total concession area of 14733 hectares out of which about 10,300 hectares is covered with cane plantation[4].



Fig 1.2:- Metehara sugar factory

The mission of the organization is to produce sugar of standard quality at a least possible cost and satisfy its customers; and utilizes all resources at disposal and to provide best service to the society at large and remain competitive & profitable, to be environmentally friendly in its process as well as to provide affordable living standard to its employees.

And the main purposes of the Enterprise are to:

- Grow sugar cane and other sugar yielding plants
- Process and produce sugar & sugar by products.
- Distribute and sell sugar and sugar related products within the country and abroad.
- Study, plan and implement various sugar development programs.
- Carry on scientific, industrial and agricultural research and surveys to enhance its programs.
- Possess and develop agricultural lands in the country whenever it is deemed appropriate to fulfill its purposes.
- Engage in other activities that enables the attainment of its purposes

1.4.2. Organizational structure

The Enterprise operates as an independent economic entity with relative management autonomy. The enterprise has an automated Management Information System (MIS) that enables generation of reliable and simplified information for decision making.

The Enterprise has also built Quality Management System (ISO 9001:2000) into its processes that will ensure the capability of the enterprise to deliver quality products & services to its customers.

The Enterprise has adapted a team management style and the structure comprises four broad sectors, namely, Agricultural Operations Factory and Logistics Finance and Human Resource. Support giving and advisory services also available[4].

1.4.3. Agricultural operations

Agricultural operations comprises of various activities like topographic survey, land preparation, sugar cane cultivation and harvesting which are essential to the sustainable supply of sugar cane required by the factory.

Currently eleven commercial and semi commercial cane varieties have been used by the Enterprise. These varieties have been selected on the basis of compatibility to the soil characteristics of the area and their ability to resist prevalent diseases.

Most of the plains in Metehara are gentle and suitable for gravity irrigation where 81.7% irrigated by gravity. There are 1200km irrigation canals on the cane fields. Water drawn from Awash River is stored in 23 reservoirs whose water holding capacity ranges from 6500m to 93,000 m. The average land productivity is about 165 tons of cane per hectare, which makes the Enterprise one of the highest cane producing farm in the world. About 1.091,100 tons of cane is supplied to the factory annually.

Along with the cane plantation, the Enterprise owns 140 hectares of land covered with various types of fruits such as orange, mango, lemon, grape-fruit, etc. About 3000 tons of fruits are produced annually.

1.4.4. Factory operations

The factory operates for about 8 & 1/2 months annually and produces 120,000 tons of sugar and other useful by products. By-products that have economic value are molasses, bagasse and filter cake.

The average annual production of molasses is about 35,580 tons and it is a basic material from which ethanol, baker's yeast, fodder yeast, organic fertilizer, lysine, ethylene, etc... can be produced. Apart from these, molasses can be mixed with materials like wheat barn, wheat meddling and oil cake to make a concentrated cattle feed.

Bagasse is a fibrous residue that remains after cane is crushed and the juice is extracted. It is used as a boiler fuel where steam needed to run the factory is produced. Part of the steam so produced is used to run steam turbines that generate about 5.2 MW of electricity. On the average, 312,115 tons of bagasse is extracted as by-products of the sugar production process.

When cane juice is treated chemically for clarification, most of the solid impurities that settle down are removed in the form of filter cake. Filter cake is rich in organic materials and in its dried form is used for soil amendment in cane fields. On average, 35,590 tons of filter cake is removed as by-products of the sugar production process.

1.4.5. Sugar manufacturing processes in MSF

The sugar manufacturing from sugar cane is started from harvesting sugar cane plant by the sugar factory itself. The bulk of sugar cane is cut by hand with a cane cutting knife. The cut sugar cane is then loaded to vehicles and transported to the mill. At the first end of the factory the cane is usually weighted, washed and chopped in to smaller pieces before the cane is fed to mills (Tandems) for juice extraction.



Fig1.3:- Sugar cane farm Metehara Sugar Factory

Juice extraction is mostly done by passing the chopped cane through a series of three roller horizontal mills. The rollers are laid in a triangle which is supported by a mill housing made of cast iron or cast steel, and they revolve in water cooled bearings made up of brass or bronze. The prime objective in sugar cane milling is to extract the greatest possible amount of sucrose from sugar cane, and to make the final bagasse as dry as possible so that it will burn readily in the boilers. The tandems are a train of six mills preceded by various combinations of cane preparation devices. The power required by the mills is obtained from steam turbines followed by gear boxes for speed reduction.

During the last few years diffusers have been installed in various sugar factories instead of mills. This new method of extracting sugar from sugar cane has proved advantages from the technical point of view. Diffusion has been accepted as an efficient way of achieving high extraction. The capital investment and maintenance costs of diffusers are lower than those of mills. Metehara Sugar Factory has one diffuser in tandem B between the mills.



Fig 1.4:- Series of mills in Metehara Sugar Factory

Next to this important process of juice extraction, the raw cane juice is weighted and carried to liming process. The fibrous part called bagasse is transported to furnaces for burning. The liming station of the cane juice is one of the most important stations in a raw-cane sugar factory. Raw sugar cane juice is composed of a great number of organic and inorganic compounds, acids, salts, etc in varying amounts. When it comes from the mill tandem, the juice is an opaque liquid varying in color from greenish-gray to dark green, and it carries suspended matter such as fine bagasse (bagacillo), gums, albumin, wax, coloring matter, particles of soil sand clay and muck. The normal cane juice has PH 5.2-5.4. The gums, wax and albumin make the raw sugar juice rather viscous. Therefore, it must be readily filtered when cold. Liming and heating causes many impurities in the juice to become coagulated and precipitated out. At the same time the acids are neutralized and any phosphates present are flocculated, adsorbing a large amount of coloring matter, solids and other impurities. Usually the lime is added to the raw sugar cane juice in the form of milk of lime, for better dispersion and quicker reaction.

The next process after liming of sugar cane juice is clarification. Without good clarification of sugar cane juice, the production of good quality raw sugar is impossible. The purpose of clarification is the precipitation and removal of all possible non sugars, (organic & inorganic) and the preservation of the maximum sucrose and reducing sugars possible in the clarified juice. The greatest part of sugar cane consists of soluble inorganic compounds or ashes. A certain amount of fiber, mainly cellulose, also remains in sugar cane juice after crushing, which passes through the crush-screen in the form of bagacillo. The raw cane juice is generally limed to PH 8 to obtain clarified juice of

about PH 6.8-7.2 Clarified juice is concentrated to a syrupy consistency before it is sent to the vacuum pans to be crystallized in to raw sugar. The concentrate is made in several evaporators connected in series called a multiple effect. The juice travels from one vessel to another because of the gradual increase of vacuum. The vapors obtained in each body of the multiple effects serve to heat the calandria tubes and to evaporate additional water in the following vessel. And after being evaporated in a multiple effect evaporator to be a syrupy consistency, clarified juice must be evaporated further for the sugar to crystallize. This is accomplished in vacuum to form a heavy mixture of crystals and mother liquor, called massecute. The raw sugar massecute is then crystallized by cooling. In this process residual syrup incapable of crystallizing called black strap molasses is separated. And finally batch & continuous centrifugals are used to separate the liquid and hard phases of raw sugar

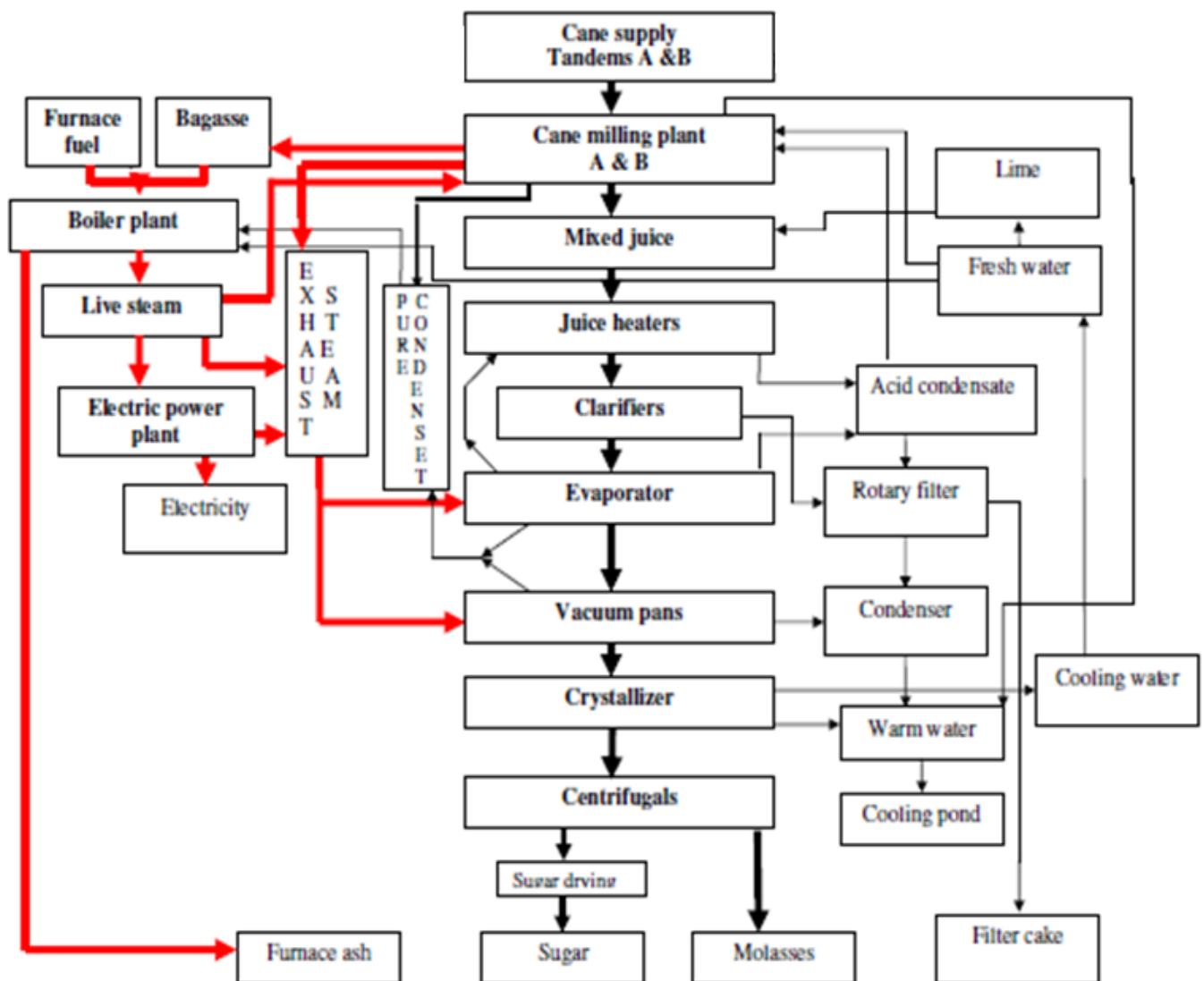


Fig 1.5:- flow chart of overall sugar production process flow chart of MSF[4]

CHAPTER TWO

2. EVAPORATION

Evaporation is one of the major steps in sugar production process. And also it is the most energy intensive. The purpose of the evaporation process is the formation of a more concentrated solution from a dilute feed. To obtain the concentrated product, the feed is boiled to vaporize most of the water from a solution.

Based on the number of evaporator involved in the system for concentrating solution an evaporator system can be categorized as single and multiple effect evaporator system.

If a single evaporator is used for the concentration of any solution, it is called a single effect evaporator system and if more than one evaporator is used in series for the concentration of any solution, it is called a multiple effect evaporator system. There are different types of evaporator applied for concentrating the sugar juice in sugar industries. However in order to use the energy efficiently almost all the factories utilize multiple effect evaporator system. In old system they use up to six effects. But now days due to improvement take place in heat exchanging component and other parts which increase the efficiency of evaporation the number of effect applied in the system is reduced..

2.1. Evolution of Evaporator

Evaporators being highly energy intensive systems offer a great scope for reduction of costs by reducing the live steam requirements. Therefore many researches have been conducted to improve the efficiency of heat transferring mechanism in the evaporator system and literature show us that the research is ongoing in the field. The major evolution on evaporator in sugar industries are [5]:-

- 1813 The British chemist Edward Charles Howard invented a method of refining sugar that involved boiling the cane juice not in an open kettle, but in a closed vessel heated by steam and held under partial vacuum. At reduced pressure, water boils at a lower temperature, and this development both saved fuel and reduced the amount of sugar lost through caramelization.
- 1840 The Robert evaporator (natural circulation evaporator) was introduced; the Kestner evaporator (rising film evaporator) followed later.

- 1845 Multiple-effect evaporator, designed by the American engineer Norbert Rillieux. This system consisted of a series of vacuum pans, each held at a lower pressure than the previous one. The vapors from each pan served to heat the next, with minimal heat wasted. Modern industries use multiple-effect evaporators for evaporating water.
- 1967 By using the first falling-film tube bundle evaporator in Germany it was possible to improve the thermal performance at Südzucker AG.
- 1987 The first rising film plate evaporators were tested at Britisch Sugar plc in the U.K. and at Südzucker AG in Germany.
- 1992 The first falling-film plate evaporator of the EVAPplus type from Balcke-Dürr was put into successfully operation at Südzucker AG in Germany.

2.2. Evaporator Type

The typical evaporator is made up of three functional sections[6]: the heat exchanger, the evaporating section, where the liquid boils and evaporates, and the separator in which the vapor leaves the liquid and passes off to the condenser or to other equipment. In many evaporators, all three sections are contained in a single vertical cylinder. In the centre of the cylinder there is a steam heating section, with pipes passing through it in which the evaporating liquors rise. At the top of the cylinder, there are baffles, which allow the vapors to escape but check liquid droplets that may accompany the vapors from the liquid surface. A diagram of this type of evaporator, which may be called the conventional evaporator, is given in Fig.2.1

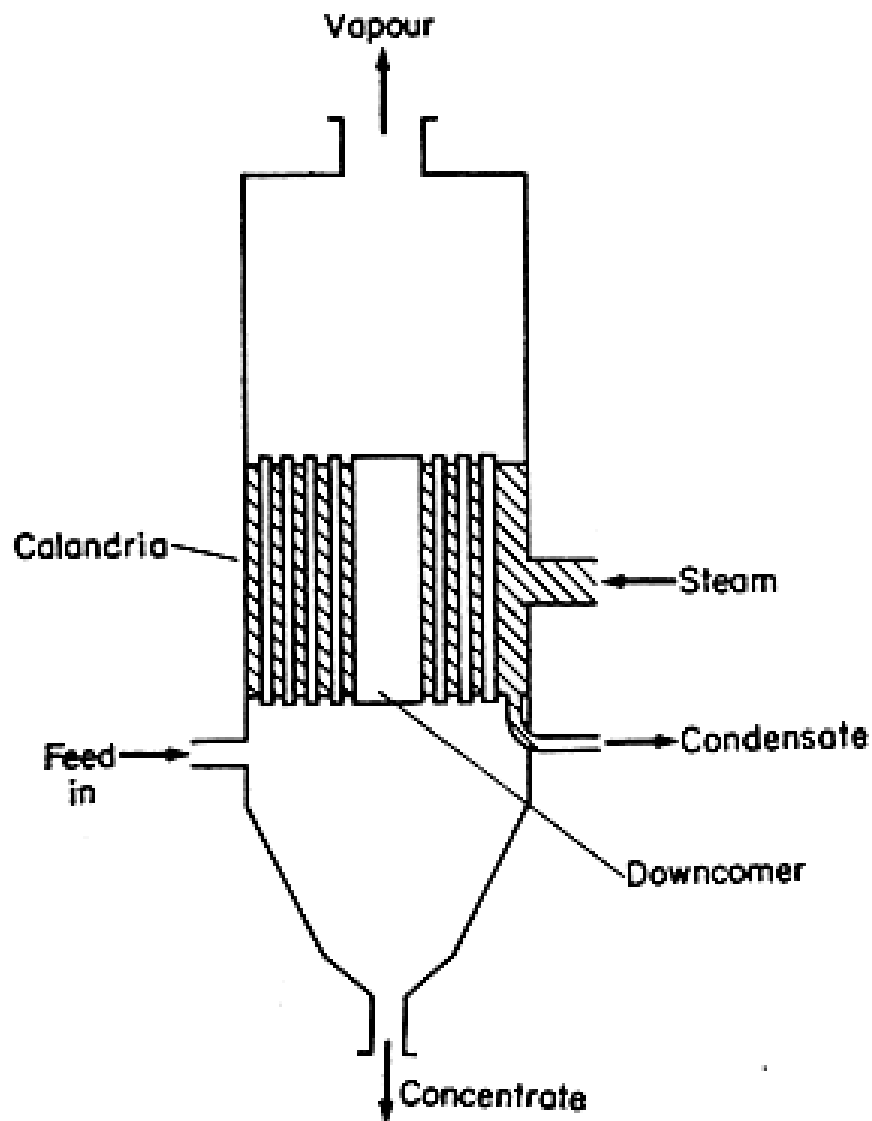


Fig 2.1:- Major component of evaporator

In the heat exchanger section, called a calandria where steam condenses in the outer jacket and the liquid being evaporated boils on the inside of the tubes and in the space above the upper tube plate. The resistance to heat flow is imposed by the steam, liquid film coefficients and by the material of the tube walls. The circulation of the liquid greatly affects evaporation rates, but circulation rates and patterns are very difficult to predict in any detail. Values of overall heat transfer coefficients that have been reported for evaporators are of the order of $1800\text{--}5000 \text{ W/m}^2 \text{ } ^\circ\text{C}$ for the evaporation of distilled water in a vertical-tube evaporator with heat supplied by condensing steam. However, with dissolved solids as evaporation proceeds, the remaining liquors become more concentrated and because of this the boiling temperatures rise. The rise in the temperature of boiling reduces the available temperature drop, assuming no change in the heat source. And so the total rate of heat

transfer will drop accordingly. Also, with increasing solute concentration, the viscosity of the liquid will increase, often quite substantially, and this affects circulation and the heat transfer coefficients leading again to lower rates of boiling. Yet another complication is that measured, overall, heat transfer coefficients have been found to vary with the actual temperature drop, so that the design of an evaporator on theoretical grounds is inevitably subject to wide margins of uncertainty.

Some of evaporators available in industry are [6][7]:-

- i. Short tube vertical
- ii. Long tube vertical
- iii. Plate evaporator
- iv. Agitated thin film
- v. Forced circulation
- vi. Horizontal tube

2.2.1. Short tube vertical evaporators

Although the vertical tube evaporator was not the first to be built, it was the first type to receive wide popularity. The first was built by Robert and often called the Robert type evaporator. It became so common that this evaporator is sometimes known as the standard evaporator. It is also called a calandria. A Robert evaporator consist of a calandria located in the bottom of the evaporator and the heating tubes are relatively shorter (2 to 3 m) compared with those in thin film evaporator (5 to 10m).

2.2.2. Long tube vertical evaporators

More evaporator systems employ this type than any other because it is versatile and often the cheapest per unit capacity. These evaporators are less sensitive to changes in operating conditions at high temperature differences than at lower temperature differences. The effects of hydrostatic head upon the boiling point are quite pronounced for long tube units.

- i. ***Rising or Climbing Film Evaporators:*** - in rising film evaporator the steam flows downward while the solution flow upward. The theory of the climbing film is that vapor traveling faster than the liquid flows in the core of the tube causing the liquid to rise up the tube in a film. This type of flow can occur only in a portion of the tube. When it occurs, the liquid film is highly

turbulent and high heat transfer rates are realized. Residence time is also low permitting application for heat sensitive materials.

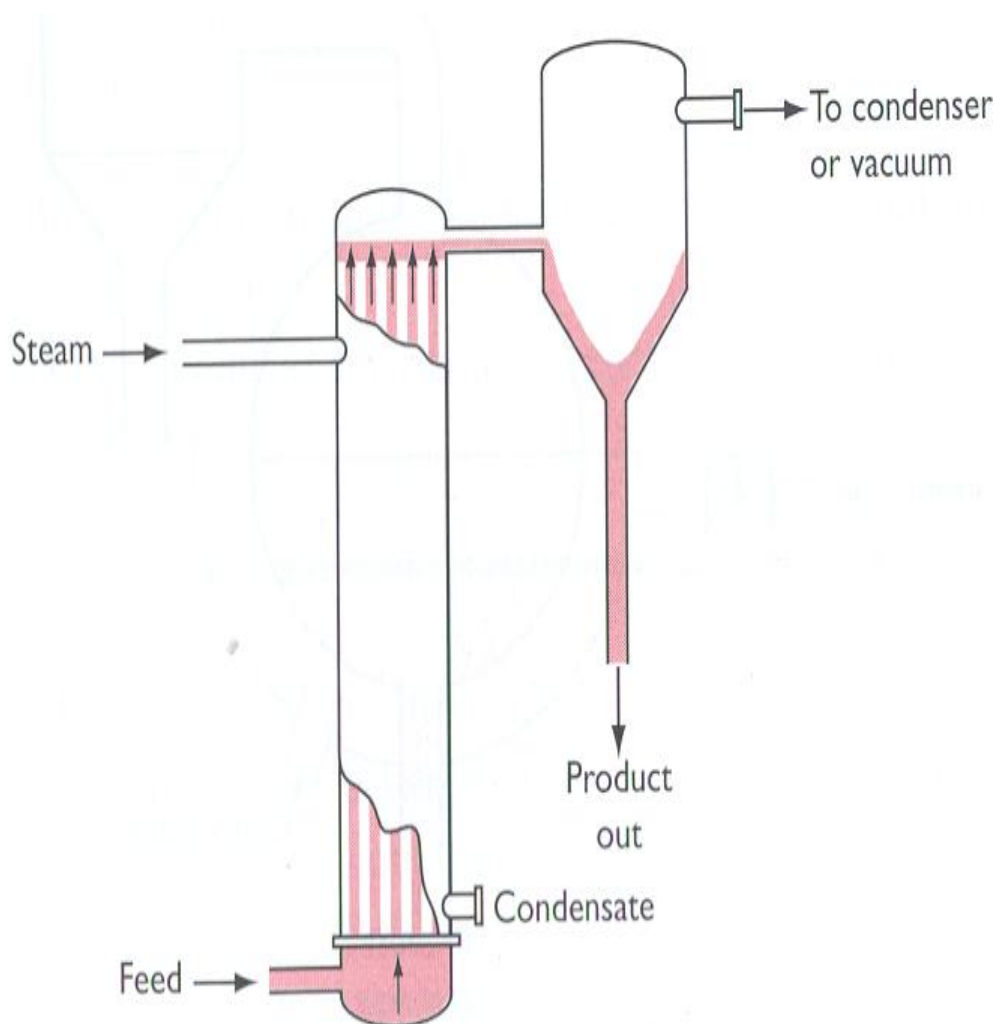


Fig 2.2 Rising film evaporator

- ii. **Falling Film Evaporators:-** The falling film version of the long tube evaporator eliminates the problems associated with hydrostatic head. Liquid is fed at the top of long tubes and allowed to fall down the walls as a film. Evaporation occurs on the surface of the highly turbulent film and not on the tube surface. This requires that temperature differences be relatively low. Vapor and liquid are usually separated at the bottom of the tubes. Sometimes vapor is allowed to flow up the tube counter to the liquid. Pressure drop is low and boiling point rises are minimal. Heat transfer rates are high even at low temperature differences. The falling film evaporator is widely used for concentrating heat sensitive products because the residence time is low.

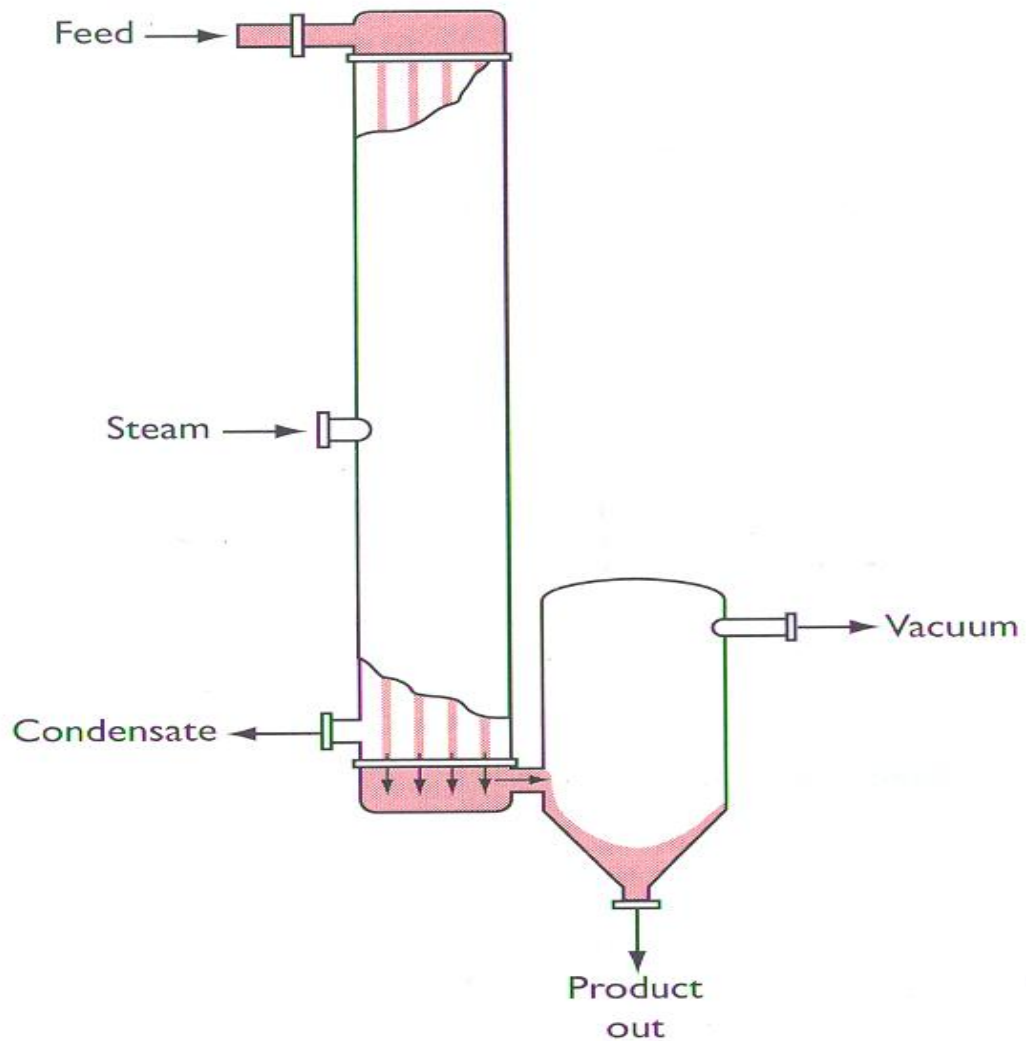


Fig 2.3 Falling film evaporator

- iii. **Rising-Falling Film Evaporators:**-A rising and a falling film evaporator are sometimes combined into a single unit. When a high ratio of evaporation to feed is required and the concentrated liquid is viscous, a tube bundle can be divided into two sections with the first section functioning as a rising film evaporator and the second section serving as a falling film evaporator. The most concentrated liquid is formed on the downward passage.

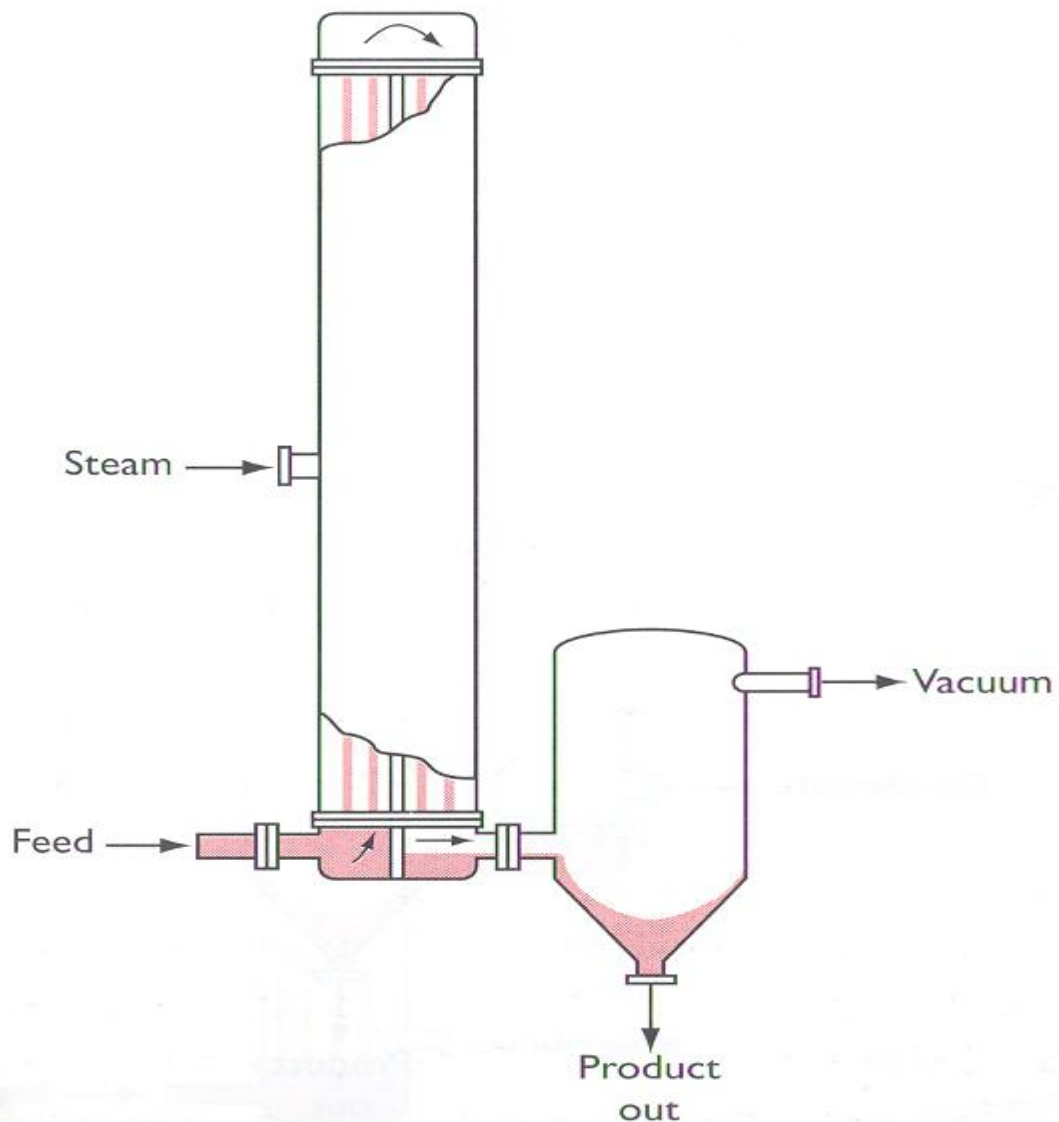


Fig 2.4 Rising - falling film evaporator

2.2.3. Plate evaporators

Plate evaporators may be constructed of flat plates or corrugated plates, the latter providing an extended heat transfer surface and improved structural rigidity. Two basic types of heat exchangers are used for evaporation systems: plate-and-frame and spiral-plate evaporators.

Plate units are sometimes used because of the theory that scale will flake off such surfaces, which can flex more readily than curved tubular surfaces. In some plate evaporators, flat surfaces are used, each side of which can serve alternately as the liquor side and the steam side. Scale deposited while in contact with the liquor can then be dissolved while in contact with the steam condensate. There

are still potential scaling problems, however. Scale may form in the valves needed for cycling the fluids and the steam condensate simply does not easily dissolve the scale produced.

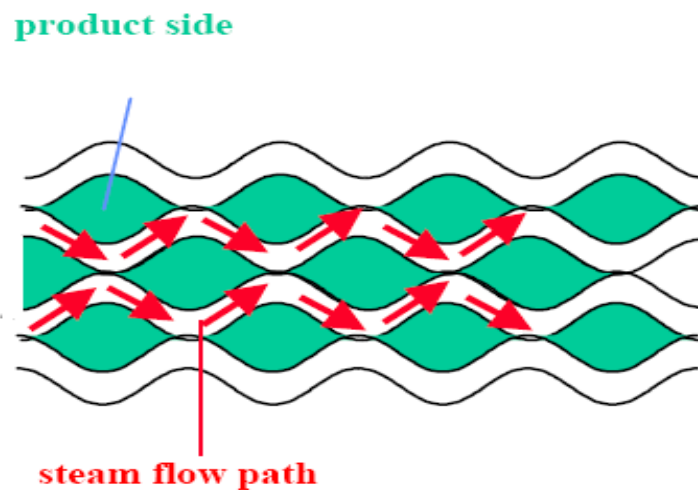


Fig 2.5 Corrugated plate evaporator

2.2.4. *Agitated thin film evaporator*

One of the more useful types of evaporators for difficult to-handle materials is the agitated thin-film evaporator. Agitated thin-film evaporators have a wide processing flexibility, and a single system can often be designed to process different products under varied operating conditions. Normally, a thin-film evaporator is operated under reduced pressures in the range of 2—250 mmHg abs.

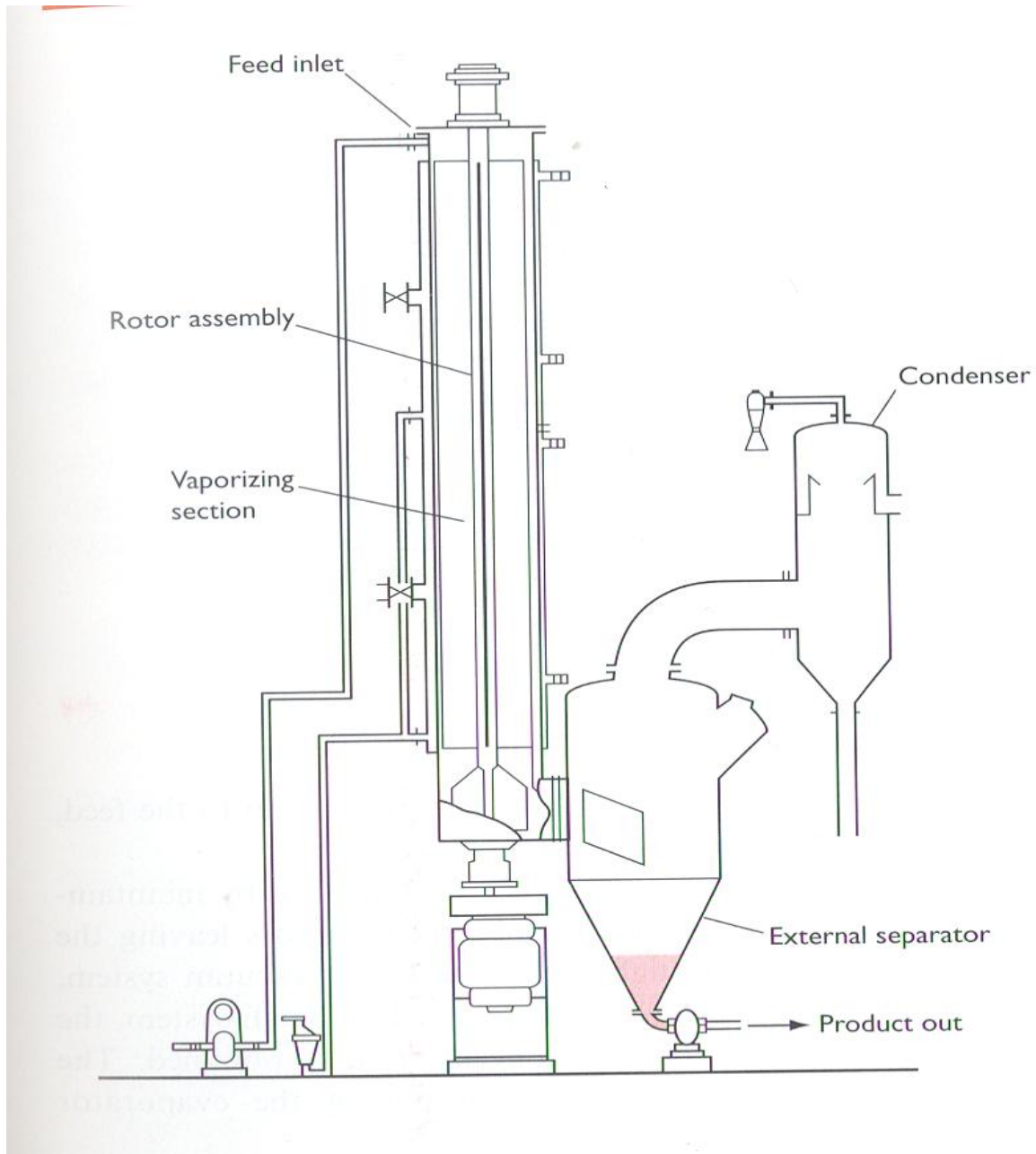


Fig 2.6:- Agitated thin film evaporator

2.2.5. *Forced circulation evaporator*

In most cases where the feed contains solids or crystallisation is present, forced circulation should be used. Typical applications where forced circulation should be used are sodium sulfate, urea, sodium chloride, ammonium sulfate, magnesium chloride, citric acid and caustic potash.

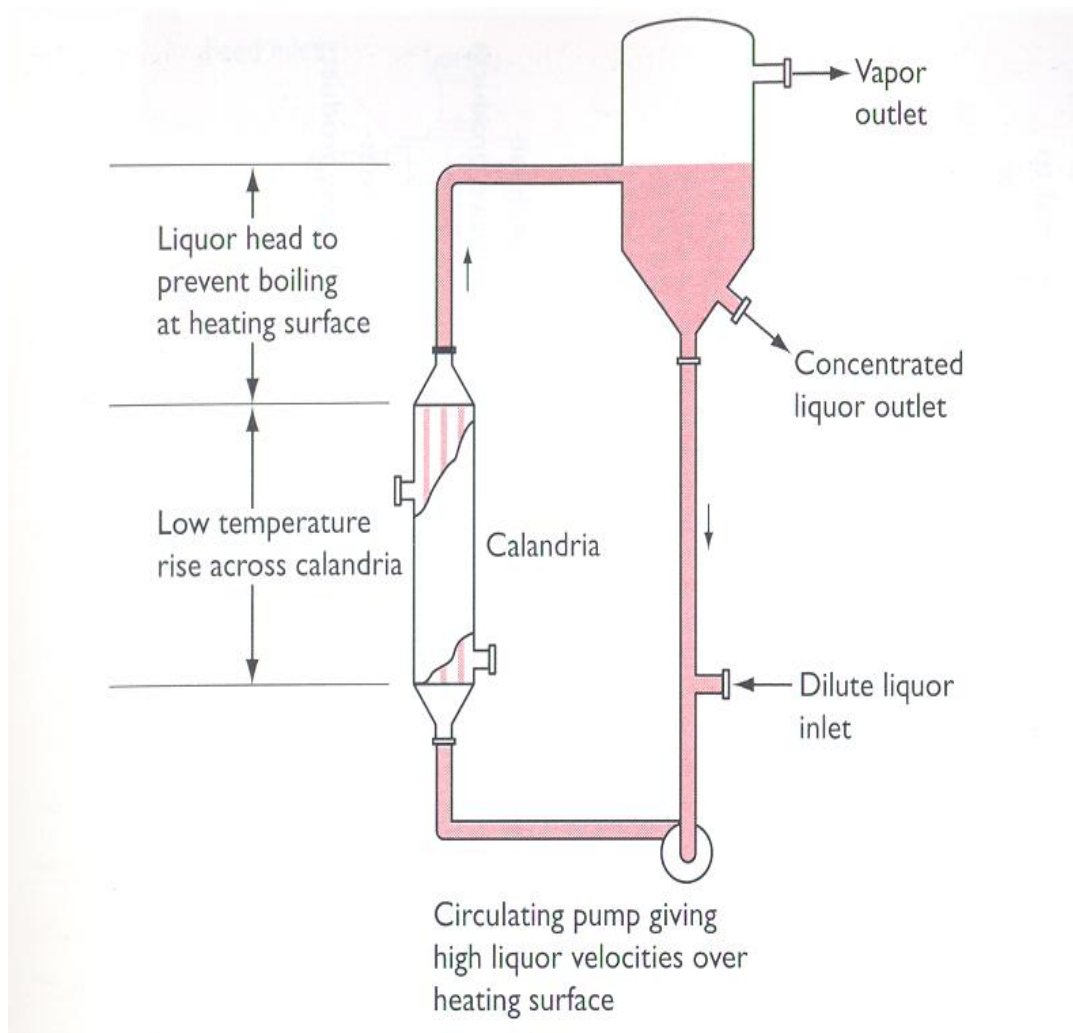


Fig 2.7:- Forced circulation evaporator

2.2.6. Horizontal tube evaporators

The first evaporator to receive general recognition was a design utilizing horizontal tubes. This type is seldom used except for a few special applications. Horizontal tube evaporators are best applied for small capacity evaporation.

CHAPTER THREE

3. DESIGN AND SIMULATION MULTIPLE EFFECT EVAPORATOR

Designing multiple effects evaporator requires determining the property of fluid with different condition in the process, (like relating temperature, pressure & brix formation of solution etc) and determining the size and number of effect involved in the system. However, it is difficult to get true relation between the properties of the fluid for given temperature and pressure of the system. There are a number of correlations developed by different researchers in order to describe the property of juice for different conditions in the system and proportion the size of vessel involved in the system, some of the relations are used in this paper .

3.1. Basic Equation For Multiple Effect evaporator

Mass balance

$$E = J - S \dots\dots\dots \text{eqn 3.1}$$

Solution mass balance:-Since the weight of dissolved material is the same before and after evaporation

(Wight of the juice %cane) * (brix of juice) = (weight of syrup% cane) * (brix of syrup)

$$J * B_j = S * B_s$$

$$S = J * \frac{B_j}{B_s}$$

Substituting eq 2 in to eq 1 the evaporation rate can be determine

$$E = J * \left(1 - \frac{B_j}{B_s}\right) \dots\dots\dots \text{eqn 3.2}$$

With the same step the concentration in each effect can be calculated

$$B_n = B_j * \left(\frac{J}{J - \sum_{i=1}^n Q_i}\right) \dots\dots\dots \text{eqn 3.3}$$

Energy balance¹¹

$$\lambda_{i-1} * V_{i-1} + h_{Fi} * F_i = h_i * L_i + H_i * V_i \dots\dots\dots \text{eqn 3.4}$$

Heat transfer

$$\frac{\lambda_{i-1} * V_{i-1}}{U_i * A} = T_{i-1} - BPR_i - T_i \dots\dots\dots \text{eqn 3.5}[8][9]$$

Using the specific evaporation rate (c)

$$Q = c * S * \Delta T \dots\dots\dots \text{eqn 3.6}$$

Where from Dessin formula

$$c = 0.001 * (100 - B) * (T - 54) \dots\dots\dots \text{eqn 3.7}$$

3.2. Design Approach

3.2.1. *Equal pressure drop*

In the design approach the total pressure drop of a multiple effect between the vessels is distributed in such a way that individual pressure drops under which the deferent vessels are working are approximately equal. This approach gives uniform height of siphon between vessels; avoid withdrawals of juice, water or incondensable gases too great in certain vessels and too small in others, and above all to avoid risks entrainment which would be caused by giving the earlier vessel too high pressure drop [8].

Table 3.1 pressure drop distribution between vessels

Number of Effects	Distribution of pressure drop
Triple effect	11/30+ 10/30+ 9/30
Quadruple effect	11/40+ 10.3/40+ 9.7/40+ 9/40
Quintuple effect	11/50+ 10.5/50+ 10/50+9.5/50+ 9/50

3.2.2. *Minimum heating surface area*

Designing multiple effects based on distributing pressure drop equally has a number of advantages; however it doesn't give economical use of material and space available in the plant. So in order to have an economical design compromise the advantage from equal pressure drop with the minimum heating surface available very important.

Minimum heating surface area can be determined by iterating the initial surface area found by using equal pressure drop in order to proportion the vessels involved in multiple effect evaporation system.

Proportion the vessels in order to get minimum heating surface areas by optimizing the temperature drop and relate with the heating surface area. The relation can be modeled using the following steps [8].

The quantity of water evaporated by each effect can be expressed as follows

$$Q_1 = c_1 S_1 \Delta T_1 \quad Q_2 = c_2 S_2 \Delta T_2 \quad \dots \dots \dots \quad Q_n = c_n S_n \Delta T_n \quad \dots \dots \dots \text{eqn 3.9}$$

The total water evaporated from the solution will be the total sum of evaporated in each effect

$$Q_1 + Q_2 + Q_3 + \dots \dots + Q_n = Q \quad \dots \dots \dots \text{eqn 3.10}$$

Where the total apparent temperature drop ($\Delta' T$) and net temperature drop of exhaust steam and condenser (ΔT) are the total sum of temperature drop in each effect.

$$\Delta T_1 + \Delta T_2 + \Delta T_3 + \dots \dots + \Delta T_n = \Delta T \quad \dots \dots \dots \text{eqn 3.11}$$

$$\Delta' T_1 + \Delta' T_2 + \Delta' T_3 + \dots \dots + \Delta' T_n = \Delta' T \quad \dots \dots \dots \text{eqn 3.12}$$

By proportioning the first effect in relation to the remainder

$$\Delta T_1 = m \Delta T \quad \Delta T_2 = k_2 (1 - m) \Delta T \quad \Delta T_3 = k_3 (1 - m) \Delta T \quad \dots \quad \Delta T_n = k_n (1 - m) \Delta T$$

$$\Delta' T_1 = m \Delta' T \quad \Delta' T_2 = k_2 (1 - m) \Delta' T \quad \Delta' T_3 = k_3 (1 - m) \Delta' T \quad \dots \quad \Delta' T_n = k_n (1 - m) \Delta' T$$

$k_2, k_3, k_4, k_5, \dots \dots \dots k_n$ coefficient of proportionality for the temperature drop for the rest effects

using Dessin formula

$$c_1 = 0.001(100 - b_1)(T_0 - 54) = a_1 \Delta' T$$

$$a_1 = 0.001(100 - b_1)$$

$$S_1 = \frac{Q_1}{a_1 m \Delta T \Delta' T}$$

$$c_2 = 0.001(100 - b_2)(\Delta' T - \Delta' T_1) = a_2 \Delta' T (1 - m)$$

$$S_2 = \frac{Q_2}{c_2 \Delta T_2} = \frac{Q_2}{a_2 k_2 (1-m)^2 \Delta T \Delta' T}$$

$$c_3 = 0.001(100 - b_3)(\Delta' T - \Delta' T_1 - \Delta' T_2) = a_3 \Delta' T (1 - k_2)(1 - m)$$

$$S_3 = \frac{Q_3}{c_3 \Delta T_3} = \frac{Q_3}{a_3 k_3 (1 - k_2)(1 - m)^2 \Delta T \Delta' T}$$

$$S_n = \frac{Q_n}{c_n \Delta T_n} = \frac{Q_n}{a_n k_n (1 - k_2 - k_3 - \dots - k_n)(1 - m)^2 \Delta T \Delta' T} \dots \dots \dots \text{eqn 3.12}$$

Total heating surface will be the sum of heating surface area in each effect

$$S = S_1 + S_2 + S_3 + \dots + S_n \dots \dots \dots \text{eqn 3.13}$$

In order to get the minimum heating surface the derivation must be zero

$$\begin{aligned} \frac{dS}{dm} &= \frac{dS_1}{dm_1} + \frac{dS_2}{dm_2} + \frac{dS_3}{dm_3} + \dots \dots \dots + \frac{dS_n}{dm_n} = 0 \\ -\frac{q_1}{a_1 \Delta T \Delta' T m^2} &+ \frac{2q_2}{a_2 k_2 \Delta T \Delta' T (1-m)^3} + \frac{2q_3}{a_3 k_3 (1-k_2) \Delta T \Delta' T (1-m)^3} + \\ \dots \dots &+ \frac{2q_n}{a_n k_n \Delta T \Delta' T (1-k_2-k_3-\dots-k_n)(1-m)^3} = 0 \dots \dots \dots \text{eqn 3.14} \end{aligned}$$

By substituting equation 3.12 in to equation 3.14

$$\begin{aligned} \frac{S_1}{m} &= \frac{2S_2}{1-m} + \frac{2S_3}{1-m} + \dots \dots \dots + \frac{2S_n}{1-m} \\ \frac{2m}{1-m} &= \frac{S_1}{S_2 + S_3 + \dots + S_n} \dots \dots \dots \text{eqn 3.15} \end{aligned}$$

Based on temperature drops

$$\begin{aligned} \frac{S_1}{S_2 + S_3 + \dots + S_n} &= \frac{2\Delta T_1}{\Delta T_2 + \Delta T_3 + \dots + \Delta T_n} \\ \frac{S_2}{S_3 + S_4 + \dots + S_n} &= \frac{2\Delta T_2}{\Delta T_3 + \Delta T_4 + \dots + \Delta T_n} \\ \frac{S_3}{S_4 + S_5 + \dots + S_n} &= \frac{2\Delta T_3}{\Delta T_4 + \Delta T_5 + \dots + \Delta T_n} \\ \frac{S_{i-1}}{\sum_i^n S_i} &= \frac{2\Delta T_{i-1}}{\sum_i^n \Delta T_i} \dots \dots \dots \text{eqn 3.16} \end{aligned}$$

Where

$$\frac{Q_1}{c_1} = t_1 \quad \frac{Q_2}{c_2} = t_2 \quad \dots \dots \dots \frac{Q_n}{c_n} = t_n \dots \dots \dots \text{eqn 3.17}$$

The heating surface area will be

$$S_1 = \frac{t_1}{\Delta T_1} \quad S_2 = \frac{t_2}{\Delta T_2} \quad \dots \dots \dots S_n = \frac{t_n}{\Delta T_n} \dots \dots \dots \text{eqn 3.18}$$

Using the temperature drop ratio (r)

$$r_1 = \frac{\Delta T}{\Delta T_1} \quad r_2 = \frac{\Delta T_1}{\Delta T_2} \quad \dots \dots \dots r_n = \frac{T_{n-1}}{\Delta T_n} \dots \dots \dots \text{eqn 3.19}$$

For triple effect

$$r_1 = \frac{\Delta T}{\Delta T_1} = 1 + \frac{1}{r_2} + \frac{1}{r_2 r_3}$$

$$r_2 = \frac{\Delta T_1}{\Delta T_2} = \sqrt{\frac{\left(1 + \frac{1}{r_3}\right) t_1}{2 (t_2 + t_3 r_3)}}$$

$$r_3 = \frac{\Delta T_2}{\Delta T_3} = \sqrt{\frac{t_2}{2 t_3}}$$

For quadruple effect

$$r_1 = \frac{\Delta T}{\Delta T_1} = 1 + \frac{1}{r_2} + \frac{1}{r_2 r_3} + \frac{1}{r_2 r_3 r_4}$$

$$r_2 = \frac{\Delta T_1}{\Delta T_2} = \sqrt{\frac{\left(1 + \frac{1}{r_3} + \frac{1}{r_3 r_4}\right) * t_1}{2 * (t_2 + t_3 r_3 + t_4 r_4 r_3)}}$$

$$r_3 = \frac{\Delta T_2}{\Delta T_3} = \sqrt{\frac{\left(1 + \frac{1}{r_4}\right) * t_2}{2 * (t_3 + t_4 r_4)}}$$

$$r_4 = \frac{\Delta T_3}{\Delta T_4} = \sqrt{\frac{t_3}{2 * t_4}}$$

For quintuple effect

$$r_1 = \frac{\Delta T}{\Delta T_1} = 1 + \frac{1}{r_2} + \frac{1}{r_2 r_3} + \frac{1}{r_2 r_3 r_4} + \frac{1}{r_2 r_3 r_4 r_5}$$

$$r_2 = \frac{\Delta T_1}{\Delta T_2} = \sqrt{\frac{\left(1 + \frac{1}{r_3} + \frac{1}{r_3 r_4} + \frac{1}{r_3 r_4 r_5}\right) * t_1}{2 * (t_2 + t_3 r_3 + t_4 r_4 r_3 + t_5 r_5 r_4 r_3)}}$$

$$r_3 = \frac{\Delta T_2}{\Delta T_3} = \sqrt{\frac{\left(1 + \frac{1}{r_4} + \frac{1}{r_4 r_5}\right) * t_2}{2 * (t_3 + t_4 r_4 + t_5 r_5 r_4)}}$$

$$r_4 = \frac{\Delta T_3}{\Delta T_4} = \sqrt{\frac{\left(1 + \frac{1}{r_5}\right) * t_3}{2 * (t_4 + t_5 r_5)}}$$

$$r_5 = \frac{\Delta T_4}{\Delta T_5} = \sqrt{\frac{t_4}{2 * t_5}}$$

3.3. Energy conservation

The efficiency of the evaporator can be evaluated with the amount of steam consumed to concentrate the solution. However the steam consumption of the evaporator depends on different component used in the evaporation, the type of evaporator system, material used for components and type of evaporation process followed.

3.3.1. Heat transfer

Heat transfer is the most important single factor in evaporator design, since the heating surface represents the largest part of evaporator cost. With other things being equal, the type of evaporator selected is the one having the highest heat-transfer cost coefficient under desired operating conditions in terms of W.K per installation cost. When power is required to induce circulation past the heating surface, the coefficient must be even higher to offset the cost of power for circulation [9].

Heat transfer in evaporators is governed by the equations for heat transfer to boiling liquids and by the convection and conduction equations. The heat must be provided from a source at a suitable temperature, for most cases heat source will be condensing steam. The steam comes either directly from a boiler or from a previous stage of evaporation. Major objections to other forms of heating, such as direct firing or electric resistance heaters, arise because of the need to avoid local high temperatures and because of the high costs in the case of electricity.

3.3.2. Materials selection

The metal used for constructing components of the evaporator will vary according to their application. The recommended metals used for evaporator are brass and stainless steel for tubes construction, cast iron and stainless steel for shell and other parts. Due to its brittleness, high weight and less weldable currently cast iron is not used in the production process due to high cost brass tube is not used in most of sugar factories. Therefore stainless steel is most appropriate and economical for construction of different parts of evaporator.

However most sugar factories use evaporators with carbon steel intensively because it is a low priced material, which possesses inferior corrosion resistance. The materials more indicated for the substitution of carbon steel are stainless steels, however, they are considered expensive. The environmental and financial performances of evaporator pipes constructed with carbon steel and with types AISI 304, 444 and 439 stainless steel were evaluated by some researches for the environmental evaluation, Life Cycle Assessment (LCA) methodology was used and it, revealed

that stainless steel is more environmentally efficient than carbon steel. The life cycle costing (LCC) technique was the tool chosen for the financial evaluation and it showed that stainless steel is a better investment option compared to carbon steel[9].

Stainless steel has [9][10]:-

- High temperature corrosion resistance: - it is widely used for elevated temperature service. In more aggressive environment with temperature 871°C the surface film may break down with sudden increase in scale. Depending on alloy content and environment, the film may be self healing for a period of time followed by another breakdown. Under extreme conditions of high temperature and corrosion the surface film may not be protected at all.
- Heat transfer properties: - it is used extremely for heat exchanger because their ability to remain clean enhances heat transfer efficiently.

There is a wide variety of stainless steel available and in use today. But only three types serve the vast majority of applications, characterized as “general purpose” stainless steels. They are the aforementioned type 304, 430 and 410. Virtually all other stainless steels are variations of these grades.

Type 304 serves a wide range of applications. It withstands ordinary rusting in architecture, it is immune to food processing environment (except possibly for high temperature condition involving high acid and chloride content). It resists organic chemicals, dye stuffs and a wide variety of inorganic chemicals. Most of the time it is applied in tube production.

Type 430 has lowest alloy content than type 304 and is used for highly polished trim applications in mild atmospheres. It is also used in nitric acid and food processing on contracting the vessel.

Type 410 has the lowest alloy content of the three general purpose stainless steels and is selected for highly stressed parts needing the combination of strength and corrosion resistance, such as pump shaft, valve stems or fasteners. It can resist corrosion in mild atmosphere, steam and many mild chemical environments.

3.3.3. Vacuum Evaporation

For the evaporation of liquids that are adversely affected by high temperatures, it may be necessary to reduce the temperature of boiling by operating under reduced pressure. When the vapor pressure of the liquid reaches the pressure of its surroundings, the liquid boils. The reduced pressures required to boil the liquor at lower temperatures are obtained by mechanical or steam jet ejector vacuum pumps, combined generally with condensers for the vapors from the evaporator. Mechanical vacuum pumps are generally cheaper in running costs but more expensive in terms of

capital than are steam jet ejectors. The condensed liquid can either be pumped from the system or discharged through a tall barometric column in which a static column of liquid balances the atmospheric pressure. Vacuum pumps are then left to deal with the non-condensable, which of course is much less in volume but still had to be discharged to the atmosphere.

3.3.4. Vapor-liquid Separation

This design problem may be important for a number of reasons. The most important is usually prevention of entrainment because of value of product lost, pollution, contamination of the condensed vapor, or fouling or corrosion of the surfaces on which the vapor is condensed. Vapor-liquid separation in the vapor head may also be important when spray forms deposits on the walls, when vortices increase head requirements of circulating pumps, and when short circuiting allows vapor or un flashed liquid to be carried back to the circulating pump and heating element[.

3.3.5. Steam economy (Vapor Recycling)

Evaporator performance is rated on the basis of steam economy kilograms of solvent evaporated per kilogram of steam used. Heat is required (1) to raise the feed from its initial temperature to the boiling temperature, (2) to provide the minimum thermodynamic energy to separate liquid solvent from the feed, and (3) to vaporize the solvent. The first can be changed appreciably by reducing the boiling temperature or by heat interchange between the feed and the residual product and/or condensate. The greatest increase in steam economy is achieved by reusing the vaporized solvent. This is done in a multiple-effect evaporator by using the vapor from one effect as the heating medium for another effect in which boiling takes place at a lower temperature and pressure. Another method of increasing the utilization of energy is to employ a thermo compression evaporator, in which the vapor is compressed so that it will condense at a temperature high enough to permit its use as the heating medium in the same evaporator.

Multiple-effect evaporator: - Multiple-effect evaporators are widely used and the principles well known. A multiple-effect system may be considered as a number of resistances, in series, to the flow of heat. The driving force causing heat to flow is the difference in temperatures of the steam condensing in the first effect and the temperature of the heat sink, often cooling water. Some of the available driving force is lost when the liquid exhibits a boiling-point elevation, the total loss equal to the sum of the boiling-point elevations in all the effect.

Other resistances result from pressure loss in vapor and liquid lines, from the cooling water temperature rise, and from the approach between cooling water and condensing temperature in the condenser. The largest resistances are those to heat transfer across the calandria in each evaporator effect and across the condenser if a surface condenser is used. The resistances of the heating surface are equivalent to the reciprocal of the product of the area and the overall heat transfer coefficient ($1/UA$)[11].

Neglecting all resistances except those due to heat transfer and assuming they are equal, it is apparent that if the number of resistances (effects) is doubled, the flow of heat (steam consumption) will be reduced by half. With half as much heat, each effect will evaporate about half as much water but, since there are now twice as many effects, total evaporation will be the same. Using these simplifying assumptions, the same evaporation would be obtained regardless of the number of effects (of equal resistance), and the steam usage would be inversely proportional to the number of effects or the total heat transfer surface provided. The resistance analogy can be used to explain design and operation of evaporator systems. The designer provides as many resistances (effects) in series as he can justify in order reducing the flow of heat (steam consumption). If the overall heat transfer coefficient in one effect is lower than the others, the designer does not increase only the area in that effect to maintain equal resistance. He can more economically (less area) achieve the desired evaporation by adding only part of the increased area to the high resistance effect and the rest to each of the other effects. This reduces individual resistances but the total resistance is the same[11].

Usually, heat transfer rates decrease as temperature decreases so that the last effects have the lowest rates of heat transfer. By leaving the resistances of these effects higher, the designer can increase the temperature difference across them, increasing temperatures and heat transfer rates in all the earlier effects. It has been shown that the lowest total area is required when the ratio of temperature difference to area is the same for all effects. When the materials of construction or evaporator type vary among effects, lowest total cost is achieved when the ratio of temperature difference to cost is the same for each effect. However, in most cases where evaporator type and materials of construction are the same for all effects, equal heat transfer surfaces are supplied for all effects. In addition to the reduction in steam usage, there is also a reduction in cooling water required to operate the last effect condenser. Approximately 30 pounds of cooling water must be provided for each pound of steam supplied to the first effect. The increased energy economy of a multiple-effect evaporator is gained only as a result of increased capital investment. The investment increases

almost at the same rate as the required area increases. A five-effect evaporator will usually require more than five times the area of a single effect. The only accurate method to predict changes in energy economy and heat transfer surface requirements as a function of the number of effects is to use detailed heat and material balances together with an analysis of the effect of changes in operating conditions on rates of heat transfer. The distribution in each effect of the available temperature differences between condensing steam and process liquid can be allocated by the designer. Once the evaporator is put into operation, the system establishes its own equilibrium. This operating point depends upon the amount of fouling and the actual rates of heat transfer. Usually it is best not to interfere with this operation by attempting to control temperatures of different effects of an evaporator. Such attempts result in a loss of capacity since control usually can be accomplished only by throttling a vapor imposing an additional resistance. The pressure loss results in a loss of driving force and reduction in capacity. The designer has a number of options to achieve the greatest energy economy with a given number of effects. These are usually associated with the location of the feed in respect to the introduction of the steam.

Vapor compression: - In addition to the possibility of taking the steam from one effect and using it in the steam chest of another, a further possibility for economy of steam is to take the vapor and, after compressing it, return it to the steam chest of the evaporator from which it was evaporated called recompression.

It is evaporation process in which a part, or all, of the evaporated vapor is compressed by means of a suitable compressor to a higher pressure level and then condensed; the compressed vapor making up a large percentage of the heat required for evaporation. The compression can be effected either by using some fresh steam, at a suitably high pressure, in a jet ejector pump(Steam jet thermo compression), or by mechanical compressors[11].

- i. **Steam jet thermo compression:-** A steam jet thermo compressor can be used with a single-effect evaporator or a multiple-effect evaporator. For a multiple-effect installation the most typical arrangement would be compressing vapor across the first effect although it is possible to compress over two or more effects. Dodge outlines the basic theory of steam jet compression, and Freneau gives an excellent description on the effect of varying steam pressure, suction pressure, and/ or discharge pressure on the performance characteristics of a thermo compressor.

As a rough rule-of-thumb, the addition of a thermo compressor will give an improved steam economy equivalent to the addition of one additional effect, and at considerably lower cost. In addition to giving an improved economy at low capital cost, the thermo compressor also has the advantages of being available in a wide range of standard and corrosion resistant materials, and being suitable for a wide range of design operating conditions from high vacuum to high-pressure operation.

Thermo compressors should be considered when only high-pressure steam is available and the evaporator can be operated with low-pressure steam. Space limitations would favor a thermo compressor installation.

- ii. **Mechanical recompression:** - A mechanical recompression evaporator is generally limited to a single effect, compressing vapor by means of a positive displacement or centrifugal compressor, which can be driven by electric motor, steam turbine, or gas or Diesel engine. The entire vapor is compressed and returned to the heat exchanger, with no vapor going to a condenser. This eliminates the cooling water requirement normally associated with conventional or steam jet thermo compression evaporators and would be an important advantage where cooling water is costly. It is ideally suited for locations where power is cheap and fuel is expensive.

In addition to high economy and water savings, there are several other factors, which would tend to favor mechanical recompression. If only high-pressure steam were available, and if there is a demand for exhaust steam, a turbine driven compressor would be indicated. Relatively cheap diesel fuel would favor a diesel driven compressor. Space limitations might justify a recompression evaporator.

3.4. Data Collection and Analysis

3.4.1. Data collected

For undergoing the research work in Metehara Sugar Factory data has been collected from many sources; documentation archival records, interviews, direct observation, readings.

Generally, two types of data have been collected: primary data and secondary data. Primary data is obtained by the researcher, and is the result of own studies of the problem. It includes the collection of information through direct observation, personal interviews, and conducting conversation. The secondary data, on the other hand, is the result of other people's research in the same problem area, or from other related problem areas. It includes the study of document, web-sites and other historical and documentary records relevant for the research.

Table 3.2 :- Design data for multiple effect evaporators

		Value	Unit
1	Crashing rate	210	Ton/hr
2	Clear juice to evaporator % of cane	92.0	-
3	Evaporation in pre –evaporator	51.5	Ton/hr
4	Brix of juice	16.56	-
5	Brix required for syrup	65	-
6	Juice temperature before heating	29.8	°C

Table 3.3:- Design temperature for vapor

	Actual Pressure (kg/cm²)	Actual Temperature (°C)
Exhaust	2	119.6
Vapor 1	1.53	111.0
Vapor 2	1.07	101.5
Vapor 3	0.61	85.5
Vapor 4	0.14	51.6

Table 3.4:- Vapor to heaters from first and second effect

Purpose	Type	Amount (tone/hr)
Heating mixed juice	Vapor 2	16.7
Heating sulphited juice	Vapor 1	6.4
Heating scalding juice	Vapor 1	4.9

3.4.2. Data analysis

The analysis is performed using the above data from the Metehara Sugar Factory as input and applying for designing triple, quadruple and quintuple effects. Full design steps are described for quadruple effect and at the end of each step the result for triple and quintuple effect will given for the same procedure.

1) Evaporation in multiple effects

The total water evaporated from the solution can be distribute can be distributed within each effect in different multiple effect system (i.e. triple effect, four effect, five effect) can be calculated as follow

$$E = J * \left(1 - \frac{B_j}{B_s} \right)$$

Where the value of cleared juice through the evaporator will be

$$J = (\text{crushing rate}) * (\text{Clear juice to evaporator \% of cane})$$

$$J = (210 * 0.92) \text{ ton/hr}$$

$$J = (210 * 0.92) \text{ ton/hr}$$

$$J = 193 \text{ ton/hr}$$

$$E = 193 * \left(1 - \frac{16.65}{65} \right) \text{ ton/hr}$$

$$E = 193 * \left(1 - \frac{16.65}{65} \right) \text{ ton/hr}$$

$$E = 143.56 \text{ ton/hr}$$

Therefore the total quantity of water to be evaporated will be 143.56 ton per hour. From the total evaporation about 51.5 ton will be evaporated in the pre evaporator and the rest will evaporate by the successive four effects which are calculated the individual evaporation of vessels as follows:-

$$\text{total evaporation in multiple effect}(E_{me}) = 143.56 \text{ ton/hr} - 51.5 \text{ ton/hr}$$

$$E_{me} = 92.06 \text{ ton/hr}$$

From table 3.4, we can see heater consume 11.3 tone/hr from the first effect and 16.7 tone/hr from second effect. Therefore the mass balance will be

$$E_1 + E_2 + E_3 + E_4 + 11.3 \text{ ton/hr} + 16.7 \text{ ton/hr} = 92.06 \text{ ton/hr}$$

$$E_1 + E_2 + E_3 + E_4 = 64.06 \text{ ton/hr}$$

Where if the total steam evaporated from the first effect represented by Q then the steam distribution in each effect will be

$$E_1 = Q - 11.3$$

$$E_2 = E_1 + X_1 - 16.7$$

$$= Q + X_1 - 28.0$$

$$E_3 = E_2 + X_2$$

$$= Q + X_1 + X_2 - 28.0$$

$$E_4 = E_3 + X_3$$

$$= Q + X_1 + X_2 + X_3 - 28.0$$

Where lose of steam in each effect can be approximated by

$$X_1 = 0.0179 * Q + 0.92$$

$$X_2 = 0.03 * Q - 0.363$$

$$X_3 = 0.065 * Q - 1.7$$

$$E_2 = Q + (0.0179 * Q + 0.92) - 28.0$$

$$= 1.0179Q - 27.08$$

$$E_3 = Q + (0.0179 * Q + 0.92) + (0.03 * Q - 0.363) - 28.0$$

$$= 1.0479 Q - 27.443$$

$$E_4 = Q + (0.0179 * Q + 0.92) + (0.03 * Q - 0.363) + (0.065 * Q - 1.7) - 28.0$$

$$= 1.1129 Q - 29.143$$

$$64.06 \text{ ton/hr} = (Q - 11.3) + (1.0179 * Q - 27.08) + (1.0479 * Q - 27.443) + (1.1129 * Q - 29.143)$$

$$64.06 \text{ ton/hr} = 4.1787 * Q - 94.966$$

$$Q = 38.0563 \text{ ton/hr} \simeq 38.1 \text{ ton/hr}$$

By the same step for quintuple and triple effect as shown in the table 3.5

Table 3.5:- Water evaporated in multiple effects

Effect	Evaporation (ton/hr)		
	Triple effect	Quadruple effect	Quintuple effect
First Effect	42.4	38.1	35.4
Second Effect	32.7	28.4	25.7
Third Effect	17	12.5	9.7
Fourth Effect		13.3	10.2
			10.9

2) Concentration of juice

The concentration of the juice will increase when it passes each effect due to the evaporation of water from it. We can determine the concentration of the juice by using equation 3.3 as follow

$$B_n = B_j * \left(\frac{J}{J - \sum_{i=1}^n Q_i} \right)$$

$$B_{pre\ evaporator} = 16.56 * \left(\frac{193.56}{193.56 - (51.5)} \right) = 22.56$$

$$B_1 = 16.56 * \left(\frac{193.56}{193.56 - (51.5 + 42.4)} \right) = 30.83$$

By same method we can determine for other effect, however for determine different property of the juice we use an average brix concentration value which can be calculated based on the inlet brix value and the out let brix value of the solution.

Table 3.6 :- Concentration of juice for quadruple effect

Effects	Concentration of brix(%)	Average concentration of brix(%)
Pre evaporator	22.56	19.56
Effect 1	30.83	26.69
Effect 2	42.42	36.62
Effect 3	50.83	46.62
Effect 4	64.41	57.62

3) Temperature distribution

The temperature distribution will be determined by using the steam pressure in each effect. The available steam pressure for heating the evaporator will be 2 kg/cm² and 0.14 kg/cm² at the last effect.

Therefore the overall pressure distribution will be as follow

$$\Delta Dp = 2 \text{ kg/cm}^2 - 0.14 \text{ kg/cm}^2$$

$$= 1.86 \text{ kg/cm}^2$$

For quadruple effect the pressure distribution will be

$$\begin{aligned}
 \text{pressure of 1st effect}(p_1) &= p_s - \left(\Delta Dp * \left(\frac{11}{40} \right) \right) \\
 &= 2 \text{ kg/cm}^2 - (1.86 * (11/40)) \\
 &= 1.4885 (\approx 1.5 \text{ kg/cm}^2)
 \end{aligned}$$

$$\begin{aligned}
 \text{pressure of 2nd effect}(p_2) &= p_1 - \left(\Delta Dp * \left(\frac{10.3}{40} \right) \right) \\
 &= 1.00955 (\approx 1.0 \text{ kg/cm}^2)
 \end{aligned}$$

$$\begin{aligned}
 \text{pressure of 3rd effect}(p_3) &= p_2 - \left(\Delta Dp * \left(\frac{9.7}{40} \right) \right) \\
 &= 0.5585 (\approx 0.56 \text{ kg/cm}^2)
 \end{aligned}$$

$$\begin{aligned}
 \text{pressure of 4th effect}(p_4) &= p_3 - \left(\Delta Dp * \left(\frac{9}{40} \right) \right) \\
 &= 0.14 \text{ kg/cm}^2
 \end{aligned}$$

Using the above pressure distribution the corresponding temperature of the steam can be determined from the steam table.

Table 3.7(a):- Vapor pressure and temperature for triple effect

	Calculated Pressure (kg/cm²)	Temperature (°C)
Exhaust	2	119.6
Vapor 1	1.32	107
Vapor 2	0.7	89.4
Vapor 3	0.56	52.17

Table 3.7(b):- Vapor pressure and temperature for quadruple effect

	Calculated Pressure (kg/cm²)	Temperature (°C)
Exhaust	2	119.6
Vapor 1	1.5	110.79
Vapor 2	1	99.1
Vapor 3	0.56	83.70
Vapor 4	0.14	52.17

Table 3.7(c):- Vapor pressure and temperature for quintuple effect

	Calculated Pressure (kg/cm²)	Temperature (°C)
Exhaust	2	119.6
Vapor 1	1.6	112.55
Vapor 2	1.2	104.25
Vapor 3	0.83	93.92
Vapor 4	0.47	79.58
Vapor 5	0.14	52.17

4) Specific evaporation rate

Specific evaporation rate is the weight of vapor supplied by the evaporator per hour per unit heating surface and degree drop of temperature between steam and juice. It can be calculated by using Dessin formula which is correlated with the consideration of the temperature and brix of the juice. It also takes into account the effect of scale and so there is no need to use another coefficient to take such effect into account.[7]

$$c = 0.001 * (100 - B) * (T - 54)$$

Table 3.8:- Specific evaporation for quadruple effect

Specific evaporation rate (C)	Value
First effect(c_1)	5.28
Second effect(c_2)	4.16
Third effect(c_3)	2.85
Fourth effect(c_4)	1.58

5) *Temperature drop*

It is the temperature difference between the heating steam temperature and the maximum temperature of the juice with considering the boiling point elevation due to concentration and hydrostatic pressures. Where the boiling point elevation can be calculated using the correlation developed by Peacock (1995).

Table 3.9(a):- Temperature drop in triple effect

	Vapor temperature	Drop (BPE)	Juice temperature	True temperature drop
Exhaust	119.6			
Vapor 1	107	0.01	107.01	12.59
Vapor 2	89.4	0.01	89.41	17.59
Vapor 3	83.70	0.02	52.19	37.21
Total drop				67.39

Table 3.9(b):- Temperature drop in quadruple effect

	Vapor temperature	Drop (BPE)	Juice temperature	True temperature drop
Exhaust	119.6			
Vapor 1	110.79	0.01	110.8	8.8
Vapor 2	99.1	0.012	99.112	11.68
Vapor 3	83.70	0.017	83.72	15.4
Vapor 4	52.17	0.02	52.19	31.51
Total drop				67.39

Table 3.9(c):- Temperature drop in quintuple effect

	Vapor temperature	Drop (BPE)	Juice temperature	True temperature drop
Exhaust	119.6			
Vapor 1	112.5	0.01	112.51	7.09
Vapor 2	104.2	0.01	104.21	8.29
Vapor 3	94	0.014	94.014	10.19
Vapor 4	79.3	0.017	79.317	14.68
Vapor 5	52.17	0.021	52.191	27.11
Total drop				67.36

6) Heating surface area

The heating surface area can be calculated using equation 7

$$S_i = Q_i / (C_i * \Delta T_i)$$

For vessel 1

$$\begin{aligned}
 S_1 &= (38100) / (5.28 * 7.72) \\
 &= 934 \text{ m}^2
 \end{aligned}$$

For vessel 2

$$S_2 = (28400)/(4.16 * 10.68) \\ = 639 \text{ m}^2$$

For vessel 3

$$S_3 = (12500)/(2.85 * 14.49) \\ = 302.7 \text{ m}^2$$

For vessel 4

$$S_1 = (13300)/(1.58 * 30.77) \\ = 273.6 \text{ m}^2$$

Table 3.10:- Heating surface area

Vessels	Heating surface area(m ²)		
	Triple effect	Quadruple effect	Quintuple effect
1	638	934	946
2	483	639	719
3	216	303	291
4		274	300
5			195

7) Minimum heating surface

In order to determine the minimum total heating surface we use iteration successive approximation starting from the normal scale of pressure by using the above results as initial condition and iteration for proportionality.

Algorithm for iteration

The algorithm of the MATLAB code is as follow

- i. Read the following data
 - Quantity of water to evaporate in each effect.
 - Initial value specific evaporation rate
 - Initial pressure and temperature distribution
 - Temperature drop in each effect
 - Total and individual true temperature drop

ii. Calculation of the evaporation capacity (t):- it can be calculated by dividing the quantity of water to be evaporated in each effect with value of specific evaporation rate of the previous step. $t_i = \frac{Q_i}{c_i}$

iii. Calculation of the recurrence quotients(r)

$$r_1 = \frac{\Delta T}{\Delta T_1}$$

$$r_2 = \frac{\Delta T_1}{\Delta T_2}$$

$$r_n = \frac{\Delta T_{n-1}}{\Delta T_n}$$

iv. Calculation of the new theoretical temperature drops (ΔT)

$$\Delta T_1 = \frac{\Delta T}{r_1}$$

$$\Delta T_2 = \frac{\Delta T_1}{r_2}$$

$$\Delta T_n = \frac{\Delta T_{n-1}}{r_n}$$

In order to get proportion temperature drop the correction to be applied consists adding the following amount, as a very close approximation to the net temperature drop obtained in previous step

Table 3.11:- addition for temperature drop

effects	Multiple effect		
	For triple	For quadruple	For a quintuple
1 st effect	+0.7%	+0.8%	+0.9%
2 nd effect	+0.5%	+0.6%	+0.7%
3 rd effect	-1.7%	+0.3%	+0.4%
4 th effect		-1.7%	-0.3%
5 th effect			-1.7%

Therefore by subtracting the newly found temperature drop from previous steam temperatures we can determine the new temperature distribution in each effect as well as the corresponding pressure from steam table. By using the new temperature distribution we can also determine new specific evaporation coefficient.

Now we can calculate the heating surface using the quantity of water to be evaporated in each effect and newly determined specific heat transfer coefficient and temperature drop. The loop will continue until newly calculated temperature close to the previous temperature with some limited variation error.

$$error = |T_i - T_{i-1}|$$

Based on the iteration the minimum heating surface area will be

Table 3.12:- Minimum heating surface area

Vessels	Heating surface area(m ²)		
	Triple effect	Quadruple effect	Quintuple effect
1	638	415	447
2	483	363	386
3	216	251	249
4	-----	248	282
5	-----	-----	312

3.5. Tube Design

3.5.1. Tube layout

Tubes are installed in the heat exchanger in a specific pattern, the most common being triangular although a square pattern is sometimes used. In addition, the tubes are spaced at equal intervals – the distance from tube centre to tube centre is called the tube pitch. TEMA requires that the ratio of tube pitch to the outside diameter be 1.25 or greater. In practice, the minimum pitch is usually used to keep the shell diameter as small as possible. However, larger pitches are sometimes used to reduce shell side pressure drop or to facilitate cleaning of the outer tube surfaces.

Triangular layouts are either 30o or 60o as shown below. Square layouts are either 90o or 45o. Triangular layouts give a higher heat transfer coefficient and pressure drop than square layouts, particularly for sensible heating and cooling of single-phase fluids and for condensing. The difference is not great for vaporization and as a result square layouts are often used for shell side vaporizers – particularly when the process is such that the shell side of the exchanger requires frequent cleaning.

Since staggered arrangement permits greater number of tubes to accommodate per unit area of the plate it is generally followed in most evaporator design and the pitch commonly calculated by

$$P_T = 1.35 d_e \dots\dots\dots \text{eqn 3.20}[8][9]$$

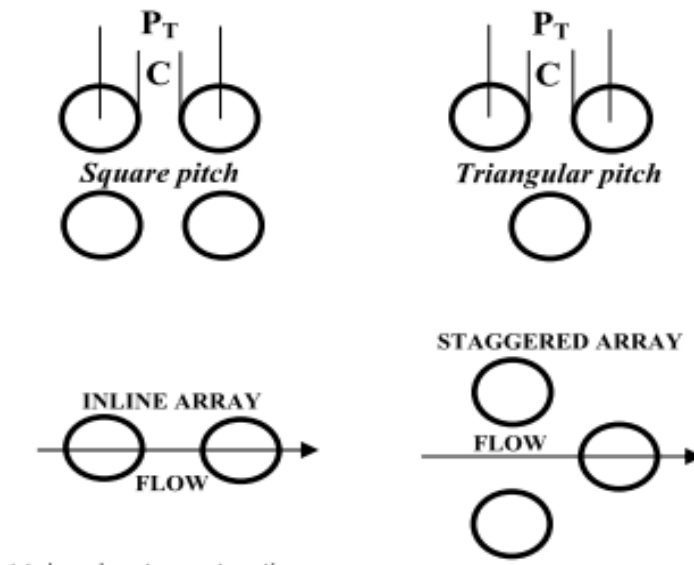


Fig 4.6 tube arrangement

3.5.2. Tube sheets

Tube sheets are the plates that support the ends of the tubes. The tube to tube sheet joint must be mechanically strong enough to resist the forces that would tend to separate the tube from the tube sheet during operation and it must be leak tight. Typically tubes are “rolled” or mechanically expanded into grooves that have been cut inside the tube holes. Often, tubes are also “seal welded” at the face of the tube sheet to prevent leakage. Sometimes, a deeper penetration “strength weld” is specified to provide additional mechanical integrity.

The tube sheet is normally a single round plate drilled in the appropriate pattern to accept the tubes, tie-rods, spacers and gaskets.

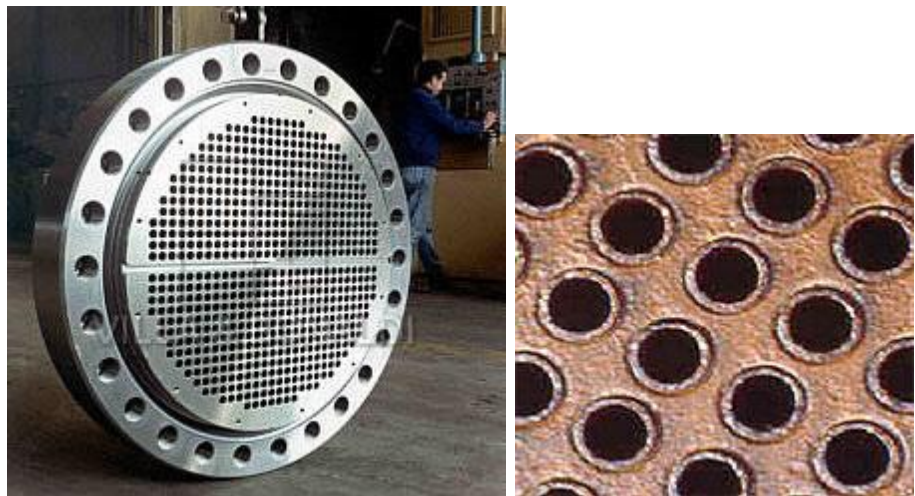


Fig 4.7:- Tube sheets

3.5.3. Number of tube

The number of tube can be determine using the heating surface required for concentrating solution in each effect and the heating surface area of single tube based tube length and diameter.

Heating surface area of single tube will be calculated by

$$A_i = \pi D_i L_i \dots\dots\dots \text{eqn 3.21}^{12}$$

The number of tube will be

$$N_t = \frac{S_i}{A_i} \dots\dots\dots \text{eqn 3.22}$$

The total area covered by the tube in staggered arrangement can be approximated by the product of number of tube with the corresponding triangular area within the pitch (Pt) as follow

$$\text{area occupied by tube } (t_{area}) = N_t * \frac{1}{2} * P_t * P_t (\sin \alpha) \dots \text{eqn 3.23}^{12}$$

But actually the area is higher than the calculated result using above equation in order to get approximated actual result we have divide the result by the number between 0.8 to 1.

3.6. Vessel Design

Standard multiple effect evaporator have a vertical cylinder, built onto the tube tubular calandria across which the heat exchange take place. The cylinder body terminates at the top in a "save all", the objective of which is to separate the liquid droplets which may be entrained with the vapor from the juice.

Clandria is part of an evaporator where the heat exchange takes place. It has vertical baffles for compelling the steam to follow a certain path. Also the calandria designed with a wide tube or center wall for returning the concentrated juice.

The bore of the hole provide in tube plates to take the tube should be about 0.75 mm greater than the exterior diameter of the tube and the diameter of the central wall varies from 1/4 to 1/8 of the interior diameter of the vessel.

3.6.1. Diameter of evaporator vessel

Since the central down take will cover from 1/4 to 1/8 of the interior diameter of the vessel, by considering it can be occupy 1/4 of the interior diameter of the vessel we can calculate area using equation.

$$A_{vessel} = A_{center\ wall} + t_{area}$$

$$A_{center\ wall} = \frac{1}{4} (A_{vessel})$$

$$A_{vessel} = \frac{4}{5} (t_{area}) \dots \dots \dots \text{eqn 3.24}$$

$$D_{vessel} = \sqrt{\frac{(4 A_{vessel})}{\pi}} \dots \dots \dots \text{eqn 3.25}$$

3.6.2. Steam inlet and outlet pipes diameter

Vapor outlet and inlet diameter can be calculated using the mass flow rate and velocity of the steam.

$$Q_1 = V_1 * \rho_1 * A_1 \dots\dots\dots \text{eqn 3.26}$$

Table 3.13:- Velocity of vapor[8]

	Vapor velocity (m/s)		
	Triple effect	Quadruple effect	Quintuple effect
Exhaust steam to 1 st effect	25-30	25-30	25-30
Vapor from 1 st effect	30-35	30-35	30-35
Vapor from 2 nd effect	40-45	35-40	30-35
Vapor from 3 rd effect	50-60	40-45	35-40
Vapor from 4 th effect	-----	50-60	40-45
Vapor from 5 th effect	-----	-----	50-60

3.7. Condensate Removal

In the condensate removal process the tube must be mounted further from the inlet and hugot recommends one drain for a condensate removal for each 3m² cross section of the vessel and the internal cross section of the vessels and the internal cross section of the drain should be to give a velocity of 0.5 -0.6 m/sec.

Chapter Four

4. OPTIMIZATION OF MULTIPLE EFFECT

The efficiency and cost of evaporators will be affected by (Heat-transfer area, Tube diameter, Tube length, Pressure, Materials of construction for tubes and shell, Degree and type of baffling, Supports, auxiliaries, and installation). From those factor Heat-transfer area, Tube diameter, Tube length have highest degree for manipulate the other factors.

The tube diameter used in multiple effects varies from 27 mm to 50 mm and the length of tube from 2 m to 4 m for short tube vertical evaporator; it can be very long incase of film (from 5 - 10m)[8][13] .

Table 4.1 Effect of changing tube diameter on efficiency of energy requirement and transfer

Diameter of tube	Length of tube	Diameter of the vessel	Climbing efficiency of steam	Heat loss
Increase	Reduce	Increase	Increase	Increase
Decrease	Increase	Decrease	Decrease	Decrease

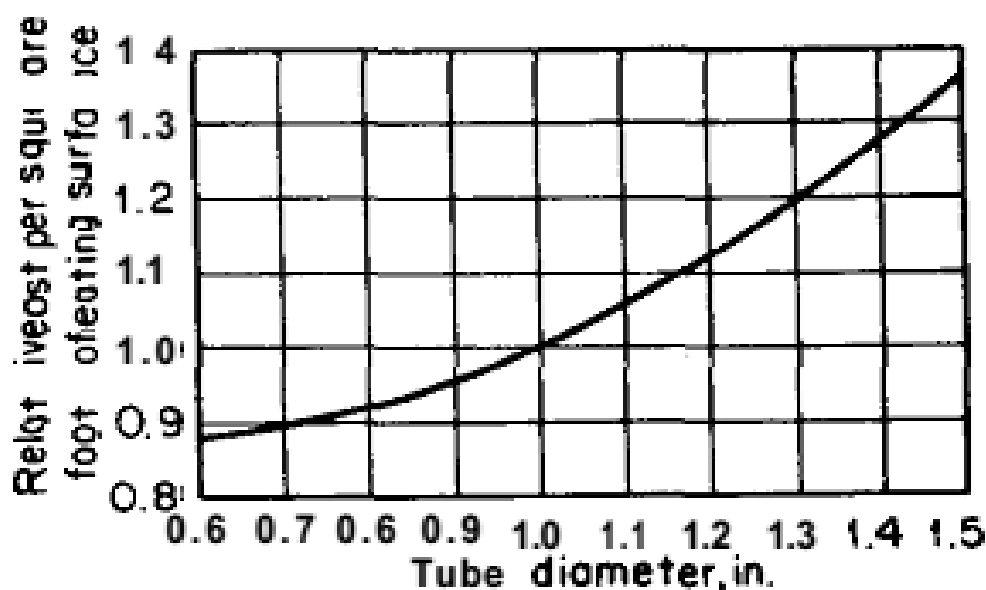


Fig 4.1 Effect of tube diametere on relative cost of evaporator¹⁶

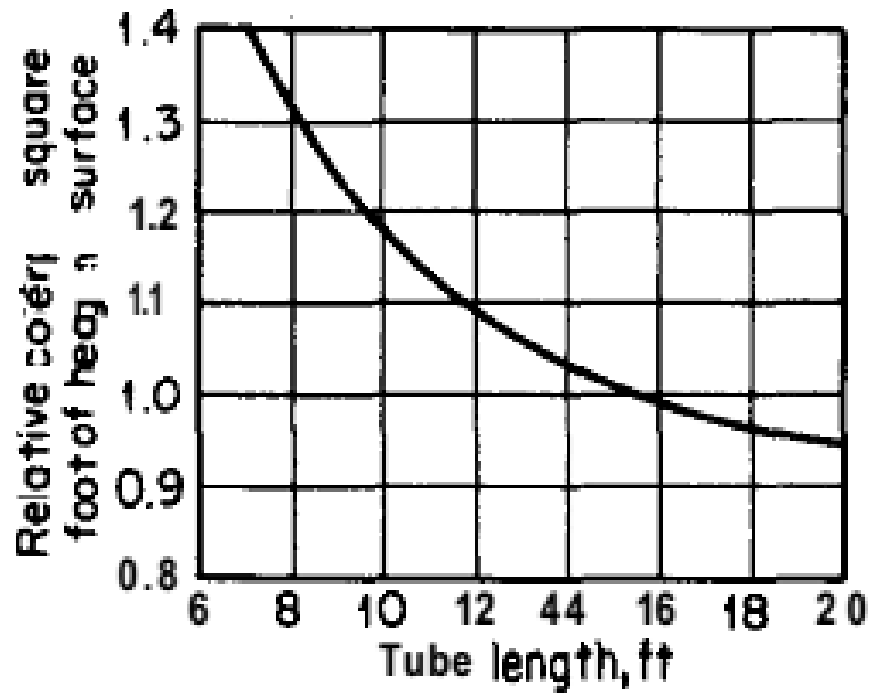


Fig 4.2 Effect of tube length on relative cost of evaporator¹⁶

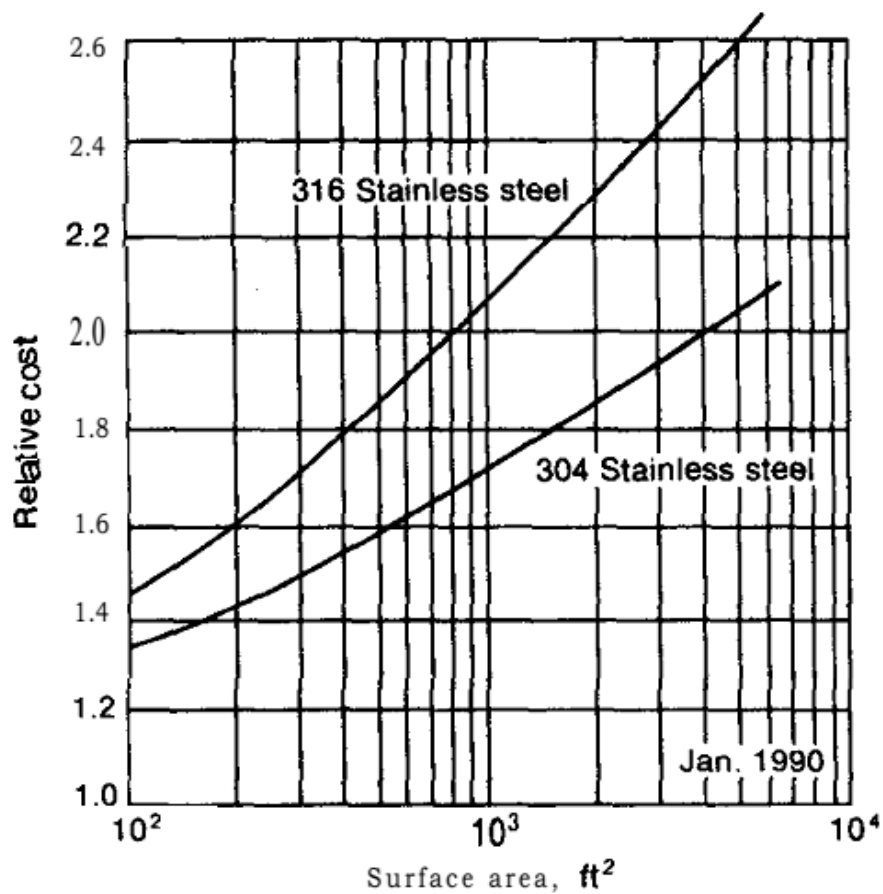


Fig 4.3:-Cost of heat exchangers with stainless-steel tubes relative to all-carbon-steel construction¹⁶

From the fig (4.1 to 4.3) the relative cost of the evaporator can be correlated

$$RI_{\text{tube diameter}} = 0.5128 * D^5 + 2.6923 * D^4 - 5.6457 * D^3 + 6.4108 * D^2 - 3.5874 * D^1 + 1.6451 \dots \text{eqn}$$

$$RI_{\text{tube length}} = -0.0003 * L^4 - 0.0095 * L^3 - 0.1122 * L^2 - 0.5836 * L^1 + 0.4037 \dots \text{eqn}$$

$$RI_{\text{heating area}} = 10^{(0.1154*A-0.0864)} \dots \text{eqn}$$

From the fig 4.1 & 4.2 the relative cost will increase when the diameter increase and decrease as the length increase therefore by equating equation 4.1 and 4.2 optimum length can be related to diameter as shown on the graph.

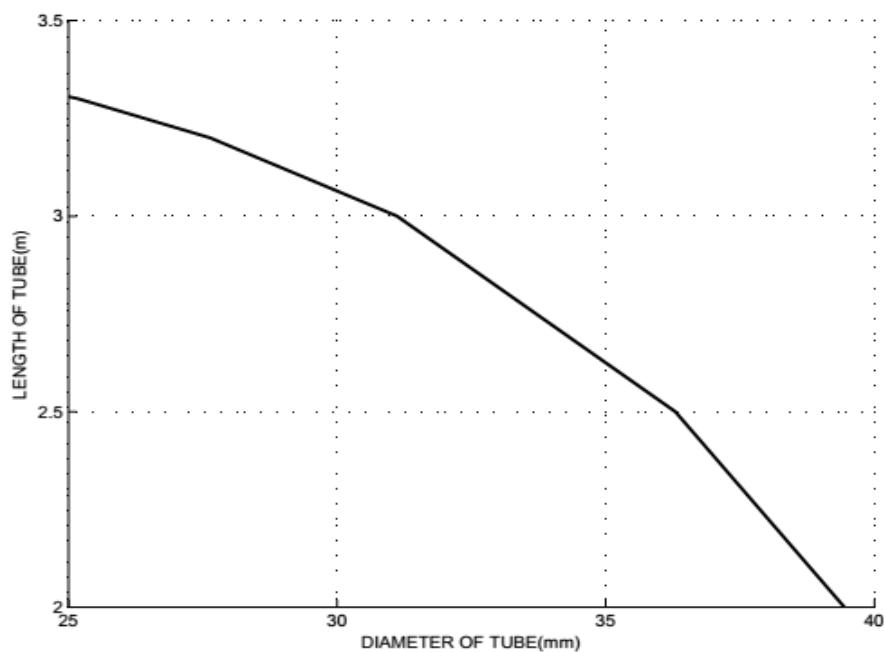


Fig 4.4:-diameter of tube to length for same relative cost

Using minimum heating surface from table 3.12 and relation of surface area to relative cost all-carbon-steel construction in equation 4.3

Table 4.6:- Relative cost based on minimum surface area

Vessels	Relative cost					Total
	1 st effect	2 nd effect	3 rd effect	4 th effect	5 th effect	
Triple effect	2.2718	2.2	2.0049	0	0	6.4767
Quadruple effect	2.1618	2.1286	2.0399	2.0371	0	8.3674
Quintuple effect	2.1804	2.1438	2.038	2.0675	2.0918	10.5215

The optimum diameter of the vessel and number of tube can be determined by using the relation between the diameter of tube and optimum length.

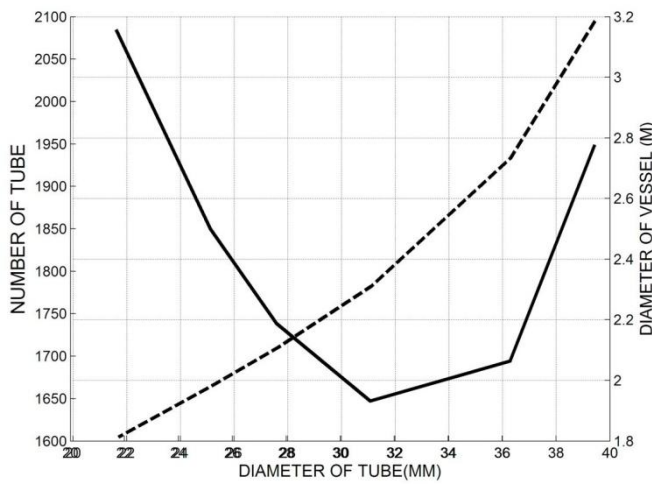


Fig 4.5(a)

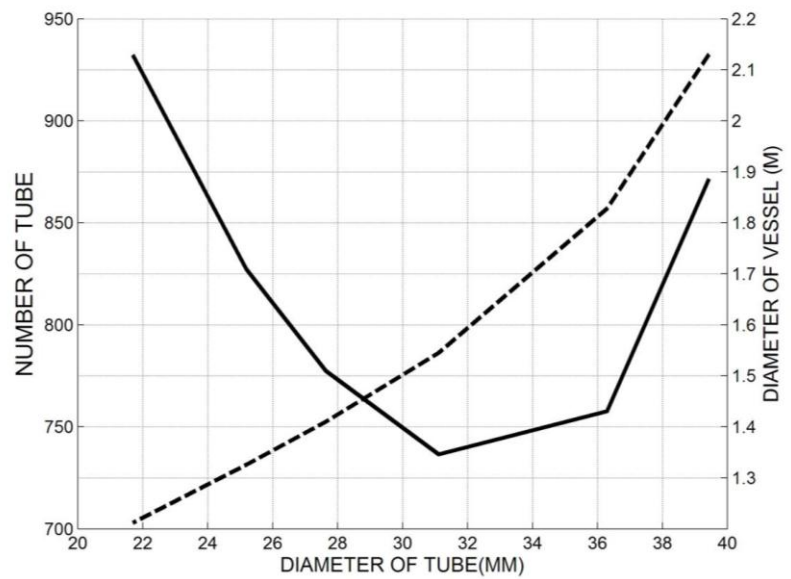


Fig 4.5(c)

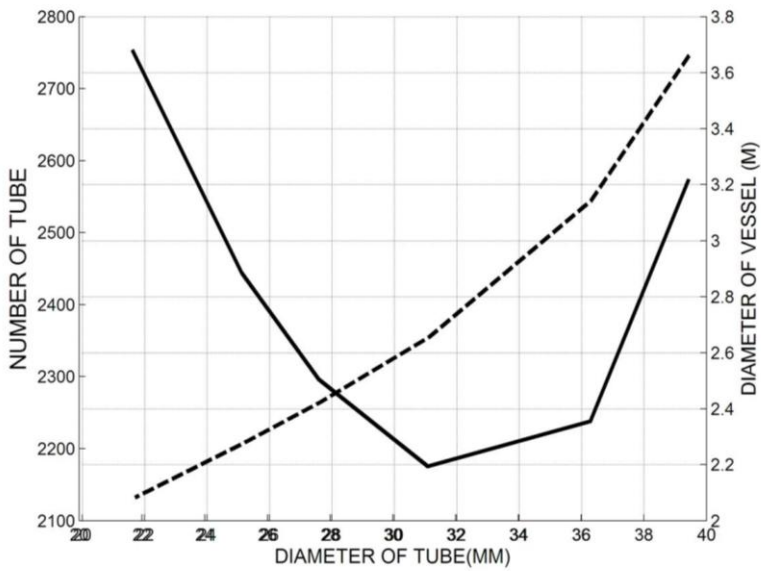


Fig 4.5(b)

Fig 4.5(a-c) diameter vessel and number of tube related to tube diameter for 1st, 2nd and 3rd effect respectively

----- vessel diameter
 _____ Number of tube

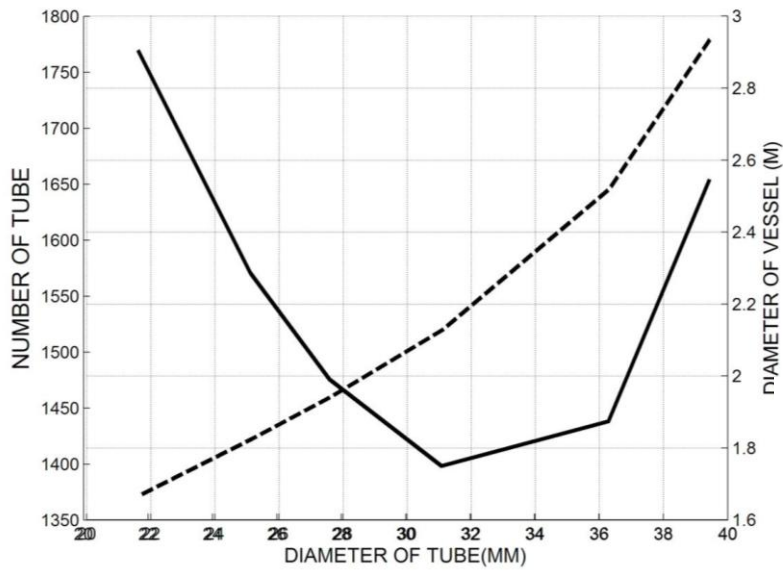


Fig 4.6(a)

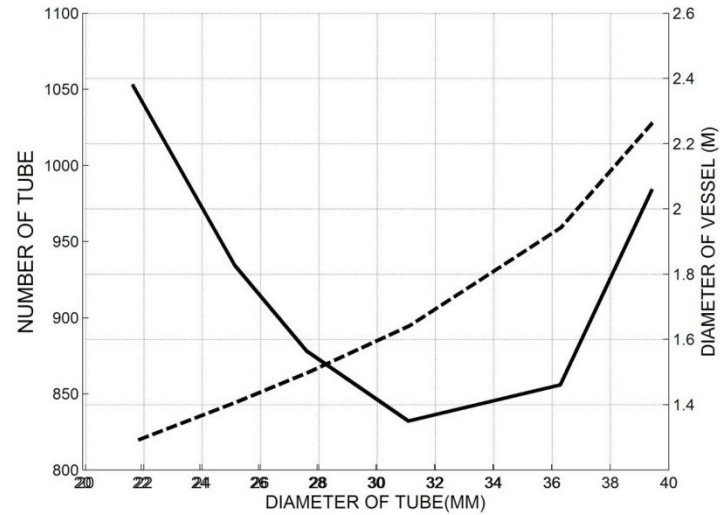


Fig 4.6(b)

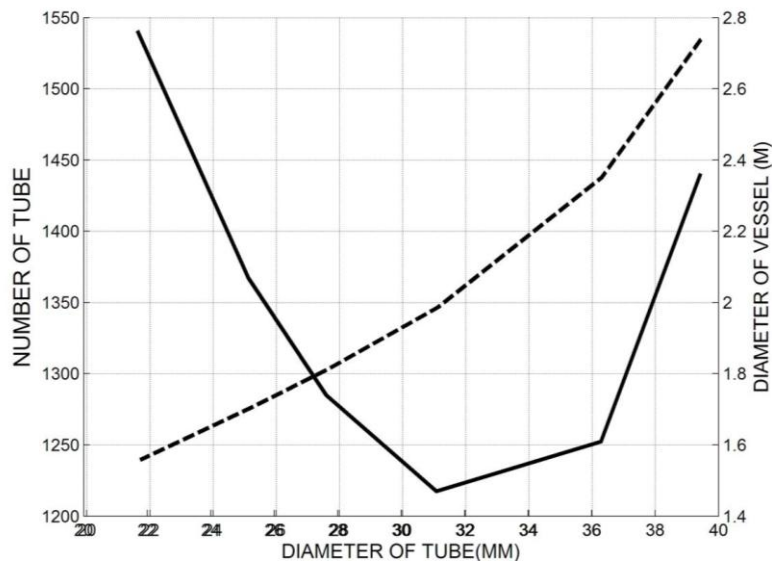


Fig 4.6(c)

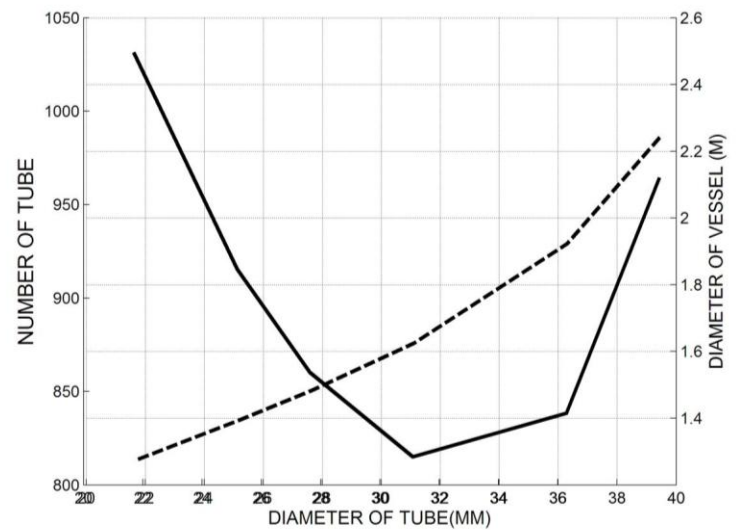


Fig 4.6(d)

Fig 4.6(a-d) diameter vessel and number of tube related to tube diameter for 1st, 2nd, 3rd and 3rd effect respectively

----- vessel diameter
 _____ Number of tube

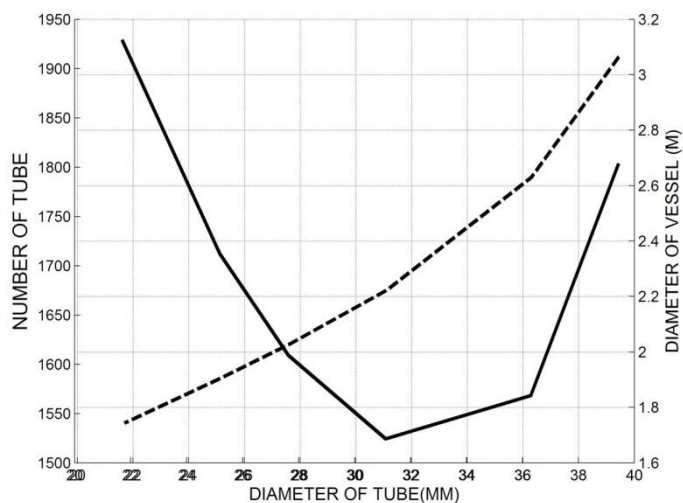


Fig 4.7(a)

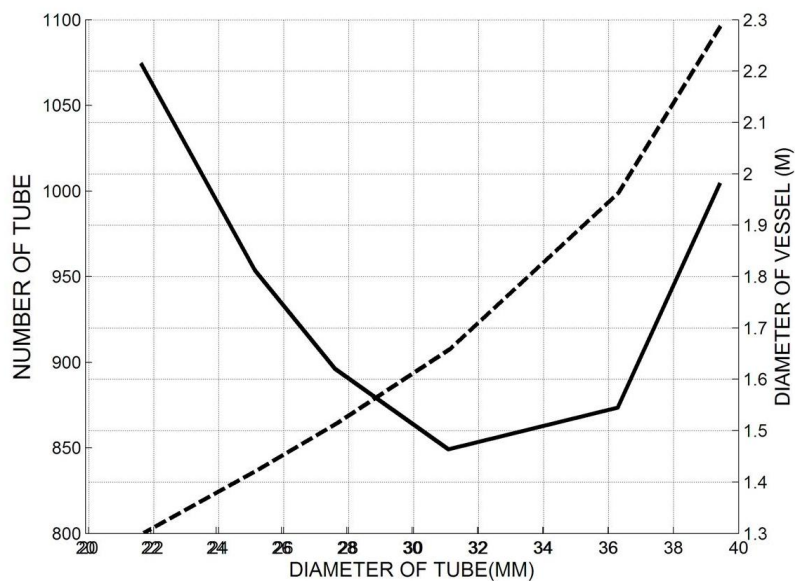


Fig 4.7(b)

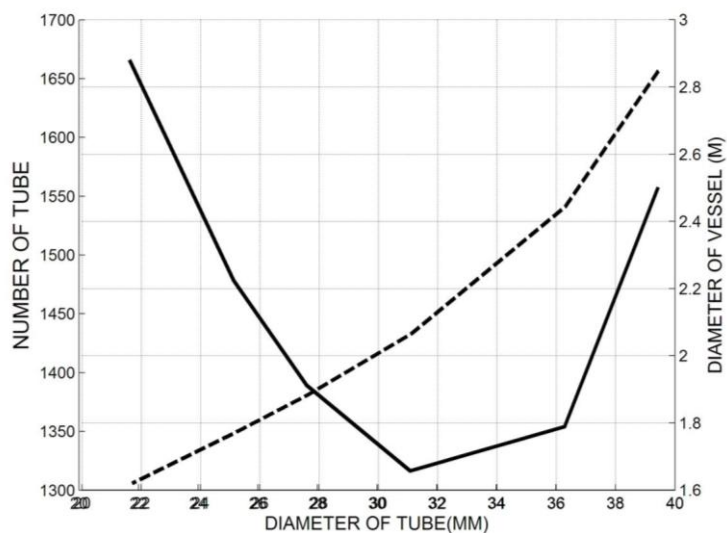


Fig 4.7(c)

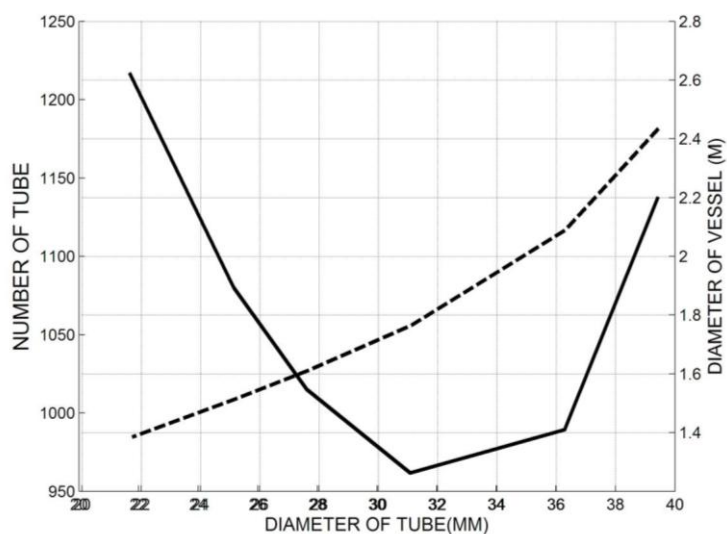


Fig 4.7(d)

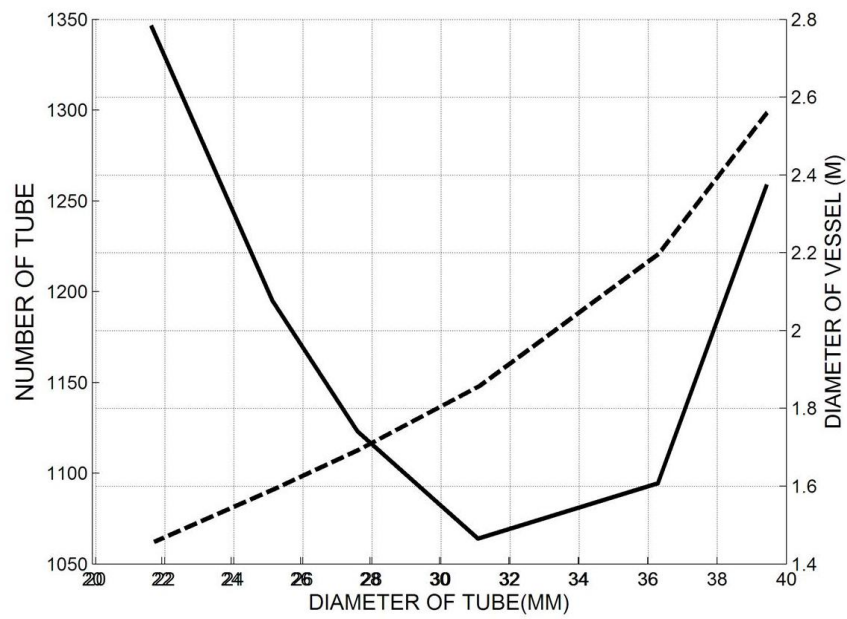


Fig 4.7(e)

Fig 4.7(a-e) diameter vessel and number of tube related to tube diameter for 1st, 2nd, 3rd, 4th and 5th effect respectively

----- **vessel diameter**
 _____ **Number of tube**

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusion

The relative cost will increase when the diameter of the tube increase and it decrease when the length of the tube increase. Climbing efficiency will increase when the diameter e increase and it will decrease when the length increase. By considering the efficiency and cost with changing diameter and length of tube the optimization for appropriate length of tube for changing the tube diameter will be selected.

The cost will increase when the heating surface increase and change in heating surface will affect the number of tube and diameter of vessel. With consideration the optimum number of tube and diameter of vessel will be

Vessel	Quintuple effect		Quadruple effect		Quintuple effect	
	Number of tube	Vessel diameter (m)	Number of tube	Vessel diameter(m)	Number of tube	Vessel diameter(m)
1	1254	2.2	1398	2.13	2176	2.66
2	1316	2.1	1218	1.99	1647	2.31
3	849	1.7	832	1.64	737	1.55
4	962	1.8	815	1.63	--	--
5	1064	1.9	--	--	--	--

Table 5.1:- Optimum number of tube and vessel diameter

5.2. Recommendation

By considering proportion diameter of vessel of evaporator for multiple effect and minimum number of tube in the system for minimum loss of pressure and scaling quadruple effect evaporator system will appropriate for multiple effect evaporation system.

Appendix 1: CORRELATION

The correlation applied in this paper work for determine the major properties of the solution are [8][9][15]:-

- Density by Waston (1986)

$$\rho = 1005.3 - 0.2255(T) - 2.4304 * 10^{-3}(T^2) + 3.7329(B) + 0.01781937(B)^2$$

- Viscosity by Steindl (1981)

$$\eta = 4.3 * 10^{-4} \exp \left[\frac{3.357(B - 0.3155(T - 50))}{1116.8} - (B - 0.3155(T - 50)) \right]$$

- thermal conductivity by Waston (1986)

$$K = 0.574 + 1.699 * 10^{-3}(T) - 3.608 * 10^{-6}(T^2) - 3.528 * 10^{-3}(B)$$

- Boiling point elevation, Peacock (1995)

$$T_{bpe} = 6.064 * 10^{-5} \left[\frac{((273.15 + T)^2 * B^2)}{(374.3 - T)^{0.38}} \right] * (584 * 10^{-7}(B - 40)^2 + 7.2 * 10^{-4})$$

Appendix 2 : MATLAB SIMULATION CODE

```
clear;
clc ;
%.....
% Ps1    pressure of steam at 120oc in kg/cm2
% Ps2    pressure of steam at 52.17oc in kg/cm2
% DP      total change of pressure in multiple effects
% b       brix of concentrated juice for equal pressure drop
% q       Steam evaporated in each effect (kg/hr)
% c       specific evaporation rate
% s       heating surface area
% pt      pressure distribution for triple effect
% pq      pressure distribution for quadruple effect
% pqt     pressure distribution for quintuple effect
% bpe     boiling point elevation
% Dt      total temperature drop
% nt      number of tube
% Dv      diameter of vessel
% tarea   cross-sectional area of vessel
%.....

%..... initial input data

datasave31=[];
datasave41=[];
datasave51=[];
datasave3=[];
datasave4=[];
datasave5=[];
Ps1=2;
Ps2=0.14;
DP=Ps1-Ps2;

b=[0.2736 0.4002 0.5601 0 0;0.2669 0.3662 0.4662 0.5672 0;0.263 0.3482 0.4228
0.4874 0.582];
q=[42400 32700 1700 0 0;38100 28400 12500 13300 0;35400 25700 9700 10200 10900];
c=[5.28 3.85 2.12 0 0;5.28 4.16 2.85 1.58 0;5.28 4.31 3.27 2.31 2.06];
s=[638 483 216 0 0;934 639 303 274 0;946 720 292 301 196];

pt=triplepressure(DP,Ps1);
pq=quadruplepressure(DP,Ps1);
pqt=tquintuplepressuere(DP,Ps1);

%----- TRIPLE EFFECT -----

Ts=temprature(Ps1,1);
T3=temprature(Ps2,1);
T1=temprature(pt(1,1),1);
T2=temprature(pt(1,2),1);

b1=b(1,1);
b2=b(1,2);
b3=b(1,3);
```

```

c1= c(1,1);
c2= c(1,2);
c3= c(1,3);

bpe1=(6.064*(10^-5)*((273.15+T1)^2*(b1^2)))/((374.3-T1)^0.38)*(584*(10^-
7)*(b1-40)^2+(7.2*(10^-4)));
bpe2=(6.064*(10^-5)*((273.15+T2)^2*(b2^2)))/((374.3-T2)^0.38)*(584*(10^-
7)*(b2-40)^2+(7.2*(10^-4)));
bpe3=(6.064*(10^-5)*((273.15+T3)^2*(b3^2)))/((374.3-T3)^0.38)*(584*(10^-
7)*(b3-40)^2+(7.2*(10^-4)));

q1=q(1,1);
q2=q(1,2);
q3=q(1,3);

s31(1)=s(1,1);
s32(1)=s(1,2);
s33(1)=s(1,3);

Dt=Ts-T3 + (bpe1+bpe2+bpe3);

for i=2:1:100

    %----- evaporatio capacity -----
    t1=q1/c1;
    t2=q2/c2;
    t3=q3/c3;

    %----- calculation of recurrence quotient -----
    r3=sqrt(t2/(2*t3));
    r2=sqrt(((1+(1/r3))*t1)/(2*(t2+(t3*r3))));
    r1=1+(1/r2)+(1/(r2*r3));

    %----- calculatio of new theoretical temprature ----

    dt1=Dt/r1;
    dt2=dt1/r2;
    dt3=dt2/r3;

    dt1=dt1+(Dt*0.008);
    dt2=dt2+(Dt*0.006);
    dt3=dt3+(Dt*0.003);

    a1=T1;

    T1=Ts-dt1-bpe1;
    T2=T1-dt2-bpe2;
    T3=T2-dt3-bpe3;

    datasave3=[datasave3; T1 T2 T3 ];

    %----- calclation of new surface area -----

    s31(i)=fix(q1/(c1*dt1));
    s32(i)=fix(q2/(c2*dt2));
    s33(i)=fix(q3/(c3*dt3));

```

```

        datasave31=[datasave31; s31(i) s32(i) s33(i)];

%----- calculation of the change in surface area-----
        count1=a1;
        count2=T1;
        error=count1-count2;

%----- calculation of new specific heat coefficient ----
bpe1=6.064*(10^-5)*(((273.15+T1)^2*(b1^2)))/(374.3-T1)^0.38)*(584*(10^-7)*(b1-40)^2+(7.2*(10^-4)));

bpe2=6.064*(10^-5)*(((273.15+T2)^2*(b2^2)))/(374.3-T2)^0.38)*(584*(10^-7)*(b2-40)^2+(7.2*(10^-4)));

bpe3=6.064*(10^-5)*(((273.15+T3)^2*(b3^2)))/(374.3-T3)^0.38)*(584*(10^-7)*(b3-40)^2+(7.2*(10^-4)));

        Dt=dt1+dt2+dt3;
        c1=0.001*(100-b1)*(Ts-54);
        c2=0.001*(100-b2)*(T1-54);
        c3=0.001*(100-b3)*(T2-54);

%----- check the difference -----

        if (error < 0.001 | T3 < 52)

                surface31=s31(i-1);
                surface32=s32(i-1);
                surface33=s33(i-1);

                [nt31 Dv31]=relation2(surface31);
                [nt32 Dv32]=relation2(surface32);
                [nt33 Dv33]=relation2(surface33);

                break
        end
end

```

```

%----- QUADRUPLE EFFECT -----

```

```

Ts=temperature(Ps1,1);
T4=temperature(Ps2,1);
T1=temperature(pq(1,1),1);
T2=temperature(pq(1,2),1);
T3=temperature(pq(1,3),1);

b1=b(2,1);
b2=b(2,2);
b3=b(2,3);

```

```

b4=b(2,4);

c1= c(2,1);
c2= c(2,2);
c3= c(2,3);
c4= c(2,4);

bpe1=(6.064*(10^-5)*((273.15+T1)^2*(b1^2)))/((374.3-T1)^0.38)*(584*(10^-7)*(b1-40)^2+(7.2*(10^-4)));
bpe2=(6.064*(10^-5)*((273.15+T2)^2*(b2^2)))/((374.3-T2)^0.38)*(584*(10^-7)*(b2-40)^2+(7.2*(10^-4)));
bpe3=(6.064*(10^-5)*((273.15+T3)^2*(b3^2)))/((374.3-T3)^0.38)*(584*(10^-7)*(b3-40)^2+(7.2*(10^-4)));
bpe4=(6.064*(10^-5)*((273.15+T4)^2*(b4^2)))/((374.3-T4)^0.38)*(584*(10^-7)*(b4-40)^2+(7.2*(10^-4)));

q1=q(2,1);
q2=q(2,2);
q3=q(2,3);
q4=q(2,4);

s41(1)=s(2,1);
s42(1)=s(2,2);
s43(1)=s(2,3);
s44(1)=s(2,4);

Dt=Ts-T4+(bpe1+bpe2+bpe3+bpe4);

for i=2:1:100

    %----- evaporatio capacity -----
    t1=q1/c1;
    t2=q2/c2;
    t3=q3/c3;
    t4=q4/c4;

    %----- calculation of recurrence quotient -----
    r4=sqrt(t3/(2*t4));
    r3=sqrt(((1+(1/r4))*t2)/(2*(t3+(t4*r4))));
    r2=sqrt(((1+(1/r3))+1/(r3*r4))*t1)/(2*(t2+(t3*r3)+(t4*r4*r3)));
    r1=1+(1/r2)+(1/(r2*r3))+1/(r2*r3*r4);

    %----- calculatio of new theoretical temprature ----

    dt1=Dt/r1;
    dt2=dt1/r2;
    dt3=dt2/r3;
    dt4=dt3/r4;

    dt1=dt1+(Dt*0.008);
    dt2=dt2+(Dt*0.006);
    dt3=dt3+(Dt*0.003);
    dt4=dt4-(Dt*0.017);

    a1=T1;

    T1=Ts-dt1-bpe1;

```

```

T2=T1-dt2-bpe2;
T3=T2-dt3-bpe3;
T4=T3-dt4-bpe4;

datasave41=[datasave41; T1 T2 T3 T4];

%----- calculation of new surface area -----

s41(i)=fix(q1/(c1*dt1));
s42(i)=fix(q2/(c2*dt2));
s43(i)=fix(q3/(c3*dt3));
s44(i)=fix(q4/(c4*dt4));

datasave4=[datasave4; s41(i) s42(i) s43(i) s44(i)];

%----- calculation of the change in surface area-----
count1=a1;
count2=T1;
error=count1-count2;

%----- calculation of new specific heat coefficient -----
bpe1=6.064*(10^-5)*(((273.15+T1)^2*(b1^2)))/(374.3-T1)^0.38)*(584*(10^-7)*(b1-40)^2+(7.2*(10^-4)));

bpe2=6.064*(10^-5)*(((273.15+T2)^2*(b2^2)))/(374.3-T2)^0.38)*(584*(10^-7)*(b2-40)^2+(7.2*(10^-4)));

bpe3=6.064*(10^-5)*(((273.15+T3)^2*(b3^2)))/(374.3-T3)^0.38)*(584*(10^-7)*(b3-40)^2+(7.2*(10^-4)));

bpe4=6.064*(10^-5)*(((273.15+T4)^2*(b4^2)))/(374.3-T4)^0.38)*(584*(10^-7)*(b4-40)^2+(7.2*(10^-4)));

Dt=dt1+dt2+dt3+dt4;
c1=0.001*(100-b1)*(Ts-54);
c2=0.001*(100-b2)*(T1-54);
c3=0.001*(100-b3)*(T2-54);
c4=0.001*(100-b4)*(T3-54);

%----- cheak the difference -----

if (error < 0.001 | T4 < 52)

    surface41=s41(i-1);
    surface42=s42(i-1);
    surface43=s43(i-1);
    surface44=s44(i-1);

    [nt41 Dv41]=relation2(surface41);
    [nt42 Dv42]=relation2(surface42);
    [nt43 Dv43]=relation2(surface43);
    [nt44 Dv44]=relation2(surface44);

    break
end
end

```

```

%----- QUINTUPLE EFFECT -----

Ts=temperature(Ps1,1);
T5=temperature(Ps2,1);
T1=temperature(pqt(1,1),1);
T2=temperature(pqt(1,2),1);
T3=temperature(pqt(1,3),1);
T4=temperature(pqt(1,4),1);

b1=b(3,1);
b2=b(3,2);
b3=b(3,3);
b4=b(3,4);
b5=b(3,5);

c1= c(3,1);
c2= c(3,2);
c3= c(3,3);
c4= c(3,4);
c5= c(3,5);

bpe1=(6.064*(10^-5)*((273.15+T1)^2*(b1^2)))/((374.3-T1)^0.38)*(584*(10^-
7)*(b1-40)^2+(7.2*(10^-4)));
bpe2=(6.064*(10^-5)*((273.15+T2)^2*(b2^2)))/((374.3-T2)^0.38)*(584*(10^-
7)*(b2-40)^2+(7.2*(10^-4)));
bpe3=(6.064*(10^-5)*((273.15+T3)^2*(b3^2)))/((374.3-T3)^0.38)*(584*(10^-
7)*(b3-40)^2+(7.2*(10^-4)));
bpe4=(6.064*(10^-5)*((273.15+T4)^2*(b4^2)))/((374.3-T4)^0.38)*(584*(10^-
7)*(b4-40)^2+(7.2*(10^-4)));
bpe5=(6.064*(10^-5)*((273.15+T5)^2*(b5^2)))/((374.3-T5)^0.38)*(584*(10^-
7)*(b5-40)^2+(7.2*(10^-4)));

q1=q(3,1);
q2=q(3,2);
q3=q(3,3);
q4=q(3,4);
q5=q(3,5);

s51(1)=s(3,1);
s52(1)=s(3,2);
s53(1)=s(3,3);
s54(1)=s(3,4);
s55(1)=s(3,5);

Dt=Ts-T5+(bpe1+bpe2+bpe3+bpe4+bpe5);

for i=2:1:100

%----- evaporatio capacity -----
    t1=q1/c1;
    t2=q2/c2;
    t3=q3/c3;
    t4=q4/c4;
    t5=q5/c5;

```

```

%----- calculation of recurrence quotient -----

r5=sqrt(t4/(2*t5));
r4=sqrt(((1+(1/r5))*t3)/(2*(t4+(t5*r5))));
r3=sqrt(((1+(1/r4)+(1/(r4*r5)))*t2)/(2*(t3+(t4*r4)+(t5*r5*r4))));

r2=sqrt(((1+(1/r3)+(1/(r3*r4)))+(1/(r3*r4*r5)))*t1)/(2*(t2+(t3*r3)+(t4*r4*r3)+(t5*r5*r3*r4)));
r1=1+(1/r2)+(1/(r2*r3))+(1/(r2*r3*r4))+(1/(r2*r3*r4+r5));

%----- calculatio of new theoretical temprature ----

dt1=Dt/r1;
dt2=dt1/r2;
dt3=dt2/r3;
dt4=dt3/r4;
dt5=dt3/r5;

dt1=dt1+(Dt*0.008);
dt2=dt2+(Dt*0.006);
dt3=dt3+(Dt*0.003);
dt4=dt4-(Dt*0.017);
dt5=dt5-(Dt*0.017);

a1=T1;

T1=Ts-dt1-bpe1;
T2=T1-dt2-bpe2;
T3=T2-dt3-bpe3;
T4=T3-dt4-bpe4;
T5=T4-dt5-bpe5;
datasave51=[datasave51; T1 T2 T3 T4 T5];

%----- calclation of new surface area -----

s51(i)=fix(q1/(c1*dt1));
s52(i)=fix(q2/(c2*dt2));
s53(i)=fix(q3/(c3*dt3));
s54(i)=fix(q4/(c4*dt4));
s55(i)=fix(q5/(c5*dt5));
datasave5=[datasave5; s51(i) s52(i) s53(i) s54(i) s55(i)];

%----- calculatio of the change in surface area-----

count1=a1;
count2=T1;
error=count1-count2;

%----- calculation of new specific heat cofficent -----
bpe1=6.064*(10^-5)*(((273.15+T1)^2*(b1^2)))/(374.3-T1)^0.38)*(584*(10^-7)*(b1-40)^2+(7.2*(10^-4)));
bpe2=6.064*(10^-5)*(((273.15+T2)^2*(b2^2)))/(374.3-T2)^0.38)*(584*(10^-7)*(b2-40)^2+(7.2*(10^-4)));
bpe3=6.064*(10^-5)*(((273.15+T3)^2*(b3^2)))/(374.3-T3)^0.38)*(584*(10^-7)*(b3-40)^2+(7.2*(10^-4)));
bpe4=6.064*(10^-5)*(((273.15+T4)^2*(b4^2)))/(374.3-T4)^0.38)*(584*(10^-7)*(b4-40)^2+(7.2*(10^-4)));
bpe5=(6.064*(10^-5)*(((273.15+T5)^2*(b5^2)))/((374.3-T5)^0.38)*(584*(10^-7)*(b5-40)^2+(7.2*(10^-4))));

```

```

Dt=dt1+dt2+dt3+dt4+dt5;
c1=0.001*(100-b1)*(Ts-54);
c2=0.001*(100-b2)*(T1-54);
c3=0.001*(100-b3)*(T2-54);
c4=0.001*(100-b4)*(T3-54);
c5=0.001*(100-b5)*(T4-54);

%----- cheak the difference -----

if (error < 0.001 | T5 < 52)

    surface51=s51(i);
    surface52=s52(i);
    surface53=s53(i);
    surface54=s54(i);
    surface55=s55(i);

    [nt51 Dv51]=relation2(surface51);
    [nt52 Dv52]=relation2(surface52);
    [nt53 Dv53]=relation2(surface53);
    [nt54 Dv54]=relation2(surface54);
    [nt55 Dv55]=relation2(surface55);

    break
end
end

```

1. Functions

```

%.....

% function for determine pressure distribution for triple effect
% Dp total pressure distribution
%.....

function P = triplepressure(DP,Ps1)
P(1,1) = Ps1-((11/30)*DP);
P(1,2) = P(1,1)-((10/30)*DP);

%.....

% function for determine pressure distribution for quadruple effect
% Dp total pressure distribution
%.....

function P = quadruplepressure(DP,Ps1)
P(1,1) = Ps1-((11/40)*DP);
P(1,2) = P(1,1)-((10.3/40)*DP);
P(1,3) = P(1,2)-((9.7/40)*DP);

```

```

%.....
% function for determine pressure distribution for quintuple effect
% Dp total pressure distribution
%.....

function P = tqintuplepressuere(DP,Ps1)
P(1,1) = Ps1-((11/50)*DP);
P(1,2) = P(1,1)-((10.5/50)*DP);
P(1,3) = P(1,2)-((10/50)*DP);
P(1,4) = P(1,3)-((9.5/50)*DP);


%.....
% function for determine the value of temperature for given pressure
% a temperature of solution at i-1 step
% b temperature of solution at i step
% c corresponding pressure at i-1 step
% d corresponding pressure at i step
% temp inter polluted temperature for given pressure (p)
%.....

function Temp = temperature(p,n)
load prosteam1.dat
for i=2:1:139
    a=prosteam1(i-1,2)./100000;
    b=prosteam1(i,2)./100000;
    if ((a <= p) && (b >= p))
        c=prosteam1(i-1,n);
        d=prosteam1(i,n);
        Temp= c-((a-p)*((c-d)/(a-b)));
        break
    end
end

end

```

```

%.....
% function for determine number of tube as well as diameter of the vessel
% nt number of tube
% pt pitch between tubes
% area crosectional area of vessel occupied by tube
% tarea total crosectional area of vessel
% Dv diameter of vessel
%.....

function [nt Dv]=relation2(surface)
x=[39.43953828 36.29433399 31.11200038 27.63563993 25.18408375 21.69007056 ];
yd=[2.0000 2.5000 3.0000 3.2000 3.3000 3.4000];
for d=1:1:6
    dd=x(d)/1000;
    nt(d)=surface/(pi*(dd)*yd(d));
    pt=1.35*(dd);
    area=(nt(d)*(pt)*(pt*(sin(pi*(60/180)))))/0.8;
    tarea=(4/3)*(area);
    Dv(d)=sqrt((tarea*4)/(pi));

end
clf
h11 = line(x,nt,'Color','k','LineStyle','-','LineWidth',3);
ax1 = gca;
set(ax1,'XColor','k','YColor','k','FontSize',12)
xlabel('DIAMETER OF TUBE (MM)','FontSize',14)
ylabel('NUMBER OF TUBE','FontSize',16)
ax2 = axes('Position',get(ax1,'Position'),...
    'XAxisLocation','Bottom',...
    'YAxisLocation','right',...
    'Color','none',...
    'FontSize',12,'XColor','k','YColor','k');
h12 = line(x,Dv,'Color','k','LineStyle','-','LineWidth',3,'Parent',ax2);
ylabel('DIAMETER OF VESSEL (M)','FontSize',14)
grid on
pause
print
clf;

```

2. steam property table (prosteam1.dat)

0	623	99987	0	597.2	597.2	485	206.3
5	889	99999	5	594.4	599.4	680	147.2
10	1251	99973	10	591.6	601.6	940	106.4
15	1738	99913	15	588.8	603.8	1282	77.99
16	1853	99897	16	588.3	604.3	1363	73.39
17	1975	99880	17	587.7	604.7	1447	69.1
18	2103	99862	18	587.1	605.1	1536	65.1
19	2239	99843	19	586.6	605.6	1630	61.35
20	2383	99823	20	586	606	1729	57.84
21	2534	99802	21	585.5	606.5	1833	54.56
22	2694	99780	22	584.9	606.9	1942	51.49
23	2863	99732	23	584.3	607.3	2056	48.63
24	3041	99707	24	583.8	607.8	2177	45.94
25	3229	99681	25	583.2	608.2	2304	43.41
26	3426	99654	26	582.6	608.6	2457	41.04
27	3634	99626	27	582.1	609.1	2576	38.82
28	3853	99597	28	581.5	609.5	2723	36.73
29	4083	99567	29	581	610	2876	34.77
30	4325	99537	30	580.4	610.4	3036	32.93
31	4580	99505	31	579.8	610.8	3204	31.2
32	4847	99463	32	579.3	611.3	3380	29.58
33	5128	99440	33	578.7	6117	3565	28.05
34	5423	99406	34	578.1	612.1	3758	26.61
35	5733	99371	35	577.5	612.5	3960	25.25
36	6057	99336	36	577	613	4171	23.97
37	6398	99299	37	576.4	613.4	4392	22.77
38	6755	99299	38	575.9	613.9	4622	21.63
39	7129	99262	39	575.3	614.3	4863	20.56
40	7520	99224	40	574.7	614.7	5114	19.55
41	7930	99186	41	574.2	615.2	5377	18.6
42	8360	99147	42	573.6	615.6	5650	17.7
43	8809	99107	43	573	616	5935	16.85
44	9279	99066	44	572.4	616.4	6233	16.04
45	9771	99024	45	571.8	616.8	6544	15.28
46	10284	98982	46	571.2	617.2	6867	14.56
47	10821	98940	47	570.7	617.7	7203	13.88
48	11382	98896	48	570.1	618.1	7553	13.24
49	11967	98852	49	569.5	618.5	7918	12.63
50	12578	98807	50	569	619	8298	12.05

51	13220	98762	50.9	568.4	619.3	869	11.5
52	13880	98715	51.9	567.8	619.7	910	10.98
53	14570	98669	52.9	567.3	620.2	953	10.49
54	15300	98621	53.9	566.7	620.6	997	10.02
55	16050	98573	54.9	566.1	621	1043	9.584
56	16840	98524	55.9	565.6	621.5	1091	9.164
57	17650	98478	56.9	565	621.9	1141	8.764
58	18500	98425	57.9	564.4	622.3	1193	8.385
59	19390	98375	58.9	563.8	622.7	1247	8.025
60	20310	98324	59.9	563.3	623.2	1302	7.682
61	21270	98272	60.9	562.7	623.6	1359	7.356
62	22270	98220	61.9	562.1	624	1419	7.046
63	23300	98167	62.9	561.5	624.4	1481	6.752
64	24380	98113	63.9	560.9	624.8	1545	6.473
65	25500	98059	64.9	560.3	625.2	1611	6.206
66	26660	98005	65.9	559.7	625.6	1680	5.951
67	27870	97950	66.9	559.1	626	1752	5.709
68	29120	97894	67.9	558.5	626.4	1826	5.478
69	30240	97838	68.9	558	626.9	1902	5.258
70	31770	97781	69.9	557.4	627.3	1981	5.049
71	33170	97723	70.9	556.8	627.7	2062	4.849
72	34630	97666	71.9	556.2	628.1	2146	4.658
73	36130	97607	72.9	555.6	628.3	2234	4.476
74	37690	97548	73.9	555	628.9	2324	4.302
75	39310	97489	74.9	554.4	629.3	2418	4.136
76	40980	97429	75.9	553.8	629.7	2514	3.977
77	42720	97368	76.9	553.2	630.1	2614	3.826
78	44510	97307	77.9	552.6	630.5	2717	3.681
79	46370	97245	78.9	552	630.9	2823	3.543
80	48290	97183	80	551.3	631.3	2933	3.41
81	50280	97121	81	550.7	631.7	3046	3.283
82	52340	97057	82	550.1	632.1	3162	3.162
83	54470	96994	83	549.5	632.5	3282	3.047
84	56670	96930	84	548.8	633.2	3406	2.936
85	58940	96865	85	548.2	633.6	3534	2.83
86	61290	96800	86	547.6	634	3666	2.728
87	63720	96734	87	547	634.4	3802	2.63
88	66230	96668	88	546.4	634.7	3942	2.537
89	68820	96601	89	545.7	635.1	4086	2.447
90	71490	96534	90	545.1	635.5	4235	2.361
91	74250	96467	91	544.5	635.9	4388	2.279

92	77100	96399	92	534.9	636.3	4545	2.2
93	80040	96330	93	543.3	636.7	4707	2.124
94	83070	96261	94	542.7	637	4873	2.051
95	86190	96192	95	542	637.4	5045	1.981
96	89420	96122	96	541.4	637.8	5221	1.914
97	92740	96051	97	540.8	638.2	5402	1.851
98	96160	95981	98	540.2	638.5	5588	1.789
99	99690	95909	99	539.5	638.5	5780	1.73
100	103320	95838	100	538.9	638.9	5977	1.673
101	107070	375	101	538.3	639.3	6179	1.618
102	110920	760	102	537.6	639.6	6387	1.565
103	114890	1157	103.1	636.9	640	6601	1.515
104	118980	1566	104.1	536.2	640.3	6820	1.466
105	123180	1986	105.1	532.6	640.7	7045	1.419
106	127510	2419	106.1	535	641.1	7276	1.374
107	131960	2864	107.1	534.3	641.4	7514	1.331
108	136540	3322	108.1	533.6	641.7	7758	1.289
109	141250	3793	109.1	533	642.1	8008	1.249
110	146090	4277	110.1	532.4	642.5	8265	1.21
111	151060	4774	111.1	531.8	642.9	8528	1.173
112	156180	5286	112.1	531.1	643.2	8798	1.137
113	161440	5812	113.2	530.4	643.6	9075	1.102
114	166840	6352	114.2	529.7	643.9	9359	1.068
115	172390	6907	115.2	529.1	644.3	9650	1.036
116	178090	7477	116.2	528.4	644.6	9947	1.005
117	183940	8062	117.2	527.8	645	10260	0.9752
118	189950	8663	118.2	527.1	645.3	570	0.9462
119	196120	9280	119.2	526.4	645.6	10890	0.9183
120	202450	9913	120.3	525.7	646	11220	8914
121	208950	10563	121.3	525.1	646.4	11560	0.8655
122	215610	11229	122.3	524.4	646.7	11000	0.8404
123	222450	11913	123.3	523.7	647	12250	0.8161
124	229470	12615	124.3	523.7	647.4	12620	0.7927
125	236660	13334	125.3	522.4	647.7	12990	0.7701
126	244040	14072	126.4	521.6	648	13370	0.7482
127	251600	14828	127.4	520.9	648.3	13760	0.7271
128	259350	15603	128.4	520.3	648.7	14150	0.7068
129	267300	16398	129.4	519.6	649	14550	0.6871
130	275440	17212	130.4	518.9	649.3	14960	0.668
131	283780	18046	131.4	518.2	649.6	15390	0.6496
132	292330	18901	132.5	517.4	649.9	15830	0.6318

133	301100	1978	133.5	516.7	650.2	16280	0.6146
134	310100	2068	134.5	516	650.5	16730	0.5979
135	319200	2159	135.5	515.3	650.8	17190	0.5817
136	328600	2253	136.6	514.6	651.2	17670	0.5661
137	338200	2349	137.6	513.9	651.5	18150	0.551
138	348100	2448	138.6	513.3	651.9	18640	0.5363
139	358200	2549	139.6	512.6	652.2	19150	0.5221
140	368500	2652	140.6	511.9	652.5	19670	0.5084
141	379000	2757	141.7	511.1	652.8	20200	0.4951
142	389800	2865	142.7	510.4	653.1	20740	0.4823
143	400900	2976	143.7	509.7	653.4	21290	0.4698
144	412200	3089	144.8	508.9	653.7	21850	0.4577
145	423700	3204	145.8	508.2	654	22430	0.4459
146	435500	3322	146.8	507.3	654.3	23020	0.4345
147	447600	3443	147.8	506.8	654.6	23620	0.4235
148	455900	3566	148.9	506	654.9	24230	0.4128
149	472500	3692	149.9	505.3	655.2	24850	0.4024
150	485400	3821	150.9	504.6	655.5	25	

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