FS-AVA-003

TECHNOLOGY FACT SHEETS
FOR EFFLUENT TREATMENT PLANTS
ON TEXTILE INDUSTRY

EVAPORATION

SERIES: ADVANCED TREATMENTS

TITLE	**EVAPORATION (FS-AVA-003)**
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INDITEX

EVAPORATION (FS-AVA-003)

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1.- INTRODUCTION

Wastewater evaporation is a technique used for a long time to reduce the percentage of water present in waste. Evaporation is being considered as an alternative process in a growing number of applications in wastewater treatment. In its simplest form, the evaporator converts the water present in the waste into steam, while leaving the contaminants in the residue in a higher concentration. This technique greatly reduces the amount of waste needed to be transported to a final destination.

Evaporation can be effective to concentrate or remove salts, heavy metals and a variety of hazardous materials from a solution. It can also be used to recover useful by-products from a solution, or to concentrate the liquid waste before further processing and final disposal. Most applications of the technology also produce a high quality distillate, which can be reused.

During evaporation a solution concentrates when part of the solvent, usually water, is vaporized, creating a saline liquor containing practically all of the dissolved solids, or solute, present in the original feed.

The evaporation process is generated by heat transferred from the condensing steam to a lower temperature solution through a metallic heat transfer surface. Absorbed heat causes solvent vaporization, usually water, and an increase in the solute concentration. The resulting vapor may be vented to atmosphere, or condensed for reuse.

In an ideal system one kilogram of condensing steam serves to evaporate one kilogram of water from the solution. Such a system would have an efficiency or economy of 1 (1 kg of water removed per kg of water vapor applied). A simple evaporator system usually has one evaporation chamber, and is said to be a *single effect* evaporator.

Given that evaporation is a separation system, the presence of three different fluids is found: cold feed, distilled and concentrated (CONDORCHEM ENVITECH, 2015):

Feed: The inflow to the evaporator. It is water contaminated with various inorganic or organic substances, suspended solids, etc. In some cases, feed pretreatment consisting of a gross solids filtration, settling, pH neutralization or adjustment, etc.

Distilled: The liquid obtained from the evaporation which has been transformed from vapor to liquid. It is more or less pure water, free of salt. It may be, however, contaminated by the presence of volatile substances to be evaporated together with water. Depending on the final destination of the condensate, it could be directly reused or it would need further treatment before discharge. This final water treatment could consist of an absorption-adsorption step, membrane separation or others, in order to achieve high quality water.

Concentrate: It is the final waste product. Generally, it is possible to reduce feed volume 10 or 15 times. With special equipment, dry residue can even be obtained. In some cases it is possible to recover the concentrate as a raw material; in other cases, it will be disposed to a waste manager. The enormous waste volume reduction turns the process into a profitable investment in terms of waste management savings.

2.- EVAPORATION PROCESSES

Enthalpy is a thermodynamic quantity, symbolized by the capital letter H, whose variation expresses the amount of energy measure absorbed or produced by a thermodynamic system; that is, the amount of energy exchanged by a system to its environment.

Enthalpy is a thermodynamic state function that can express the amount of heat introduced during an isobaric transformation, ie, at constant pressure in a thermodynamic system, considering that every object can be understood as a thermodynamic system. This is a transformation where energy can be received or supplied (for example that used for mechanical work). Accordingly, enthalpy is numerically equal to the heat exchanged with the environment of the system.

Within the International System of Units enthalpy is usually measured in joules that, in principle, it was introduced as a work unit.

The most typical enthalpy variable is called *thermodynamic enthalpy*. Additionally the Gibbs function corresponds to the *free enthalpy*, whereas the *molar enthalpy* is one that represents a mole of the constituent substance of the system.

In a chemical reaction at constant pressure, the change in enthalpy of the system is the heat absorbed or evolved in the reaction. In a phase change, i.e. from liquid to gas, the change in enthalpy of the system is the latent heat, in this case that related to vaporization. In a simple temperature change, the change of enthalpy variation degree corresponds to the heat capacity at constant pressure system.

Mathematically enthalpy H is equal to $U + pV$, where U is the internal energy, p is the pressure and V is the volume.

$$H = U + pV$$

When a system changes from initial conditions to other final ones, the enthalpy change (ΔH) can be measured.

$$\Delta H = Hf - Hi$$

The vaporization enthalpy or heat of vaporization is the amount of energy required per mass unit (kg, mol, etc.) of a substance that is in equilibrium with its own vapor at one atmosphere pressure to completely pass from liquid to gas state; It represented by ΔH_{vap}.The value decreases slowly with increasing temperature when it is far from the critical point, faster when the temperature is closer to it, and above the critical temperature the liquid and vapor phases no longer coexist. It is generally determined on the boiling point of the substance and corrected to tabulate value under normal conditions.

2.1.- Fundamentals of evaporation processes

Evaporation is the boiling method used to concentrate solutions. An evaporator for indirect heat transfer is only a modified heat exchanger. Since evaporation involves boiling, the gas sublayer in contact with the liquid phase in the liquid-vapor interface will be comprised of generated steam. Consequently, there will not be any resistance to mass transfer in the gas phase, hence this operation is controlled by the heat transfer rate and not by the corresponding mass transfer, and it can be studied under the principles of heat transfer (Martinez - Rus, 2004).

2.2.- Types of evaporators

The most common evaporators classification is according to the heat application method:

A) Equipment heated with fire or direct heat (solar heat).

B) Equipment heated through a double wall. They are characterized by low heat transfer rate. They can operate under vacuum. They are useful for the evaporation of liquids at small scale.

C) Equipment heated by steam with pipes as heat contact surface. The most important ones of this group are the tubular evaporators.

Tubular evaporators classification is based on the contact steps between the liquid feed to be evaporated and the heating tubes. They can be distinguished: single-effect evaporators and circulation evaporators:

One step evaporator: In the operation of a single effect evaporator the liquid feed passes once through heating tubes, steam emerges and leaves a liquid concentrate. They are especially useful for the treatment of heat-sensitive materials, operating at high vacuum they keep the liquid at low temperature during a short contact time. They also adapt well to multiple effect operation.

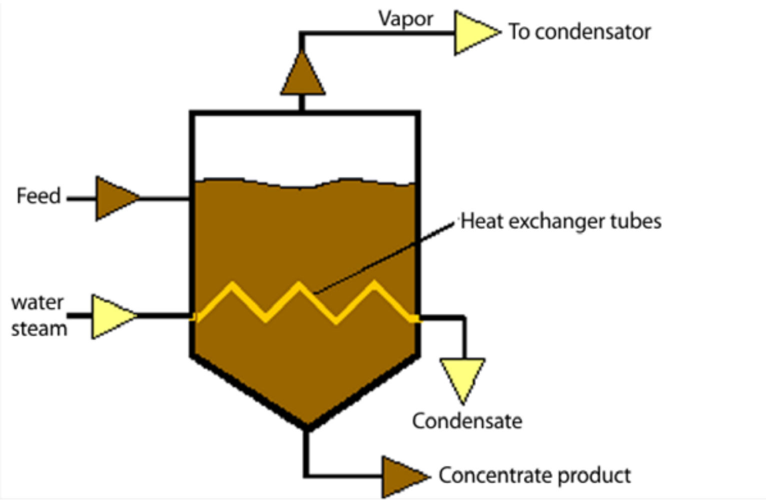

Figure 1.- Basic evaporator elements

Circulation evaporators: circulation evaporators operate with a liquid fraction inside the unit. The liquid feed mixes with the liquid hold inside the evaporator and subsequently the mixture passes through the tubes, so that, at each step, a portion of the total evaporation occurs. These types of evaporators are not suitable to concentrate heat sensitive fluids because even when working under vacuum, the liquid contacts with the hot tube surface several times. They adapt very well to evaporation in single direction, they can use natural circulation (due to density differences) or forced circulation (fluid is driven by a pump).

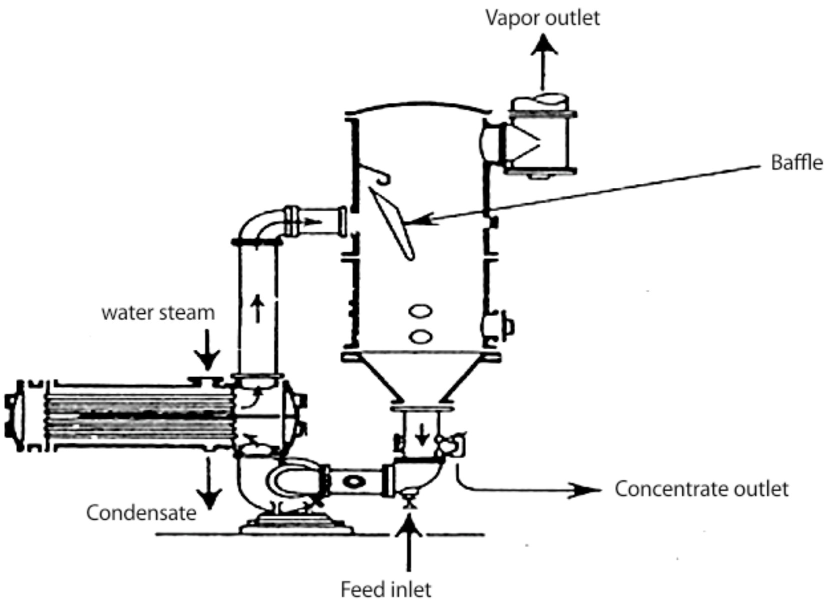

Figure 2.- Horizontal tubes evaporator with forced circulation (Pontiles, 2012).

Another classification of tubular evaporators is based on the configuration of the heating tubes (Bonsfills et al, 2007; Martinez - Rus, 2004;. Pontiles, 2012) .

- HORIZONTAL TUBES: Saturated heating steam transmits its condensation heat and exits the unit as a liquid at the same temperature and pressure as the water inlet. There can be no condensable vapor, which is removed by a purge. The evaporation chamber is formed by a vertical cylindrical body, closed at the base, with an outlet for the evaporated solvent at the top and another outlet for the concentrated solution at the bottom. These evaporators are usually made of steel or iron with a diameter between 2 and 3 meters high. The diameter of the tubes is commonly around 2-3 centimeters. They are relatively inexpensive, requiring low available height. The Installation of these evaporators is easy and provide good heat transfer. Liquid circulation is small and is not suitable for viscous liquids or fluids which crystallize. They can operate with natural circulation. The operation with non-viscous liquids and liquids that do not form crusts is good, with high heat transfer coefficients. They operate with a constant feed and output rate.

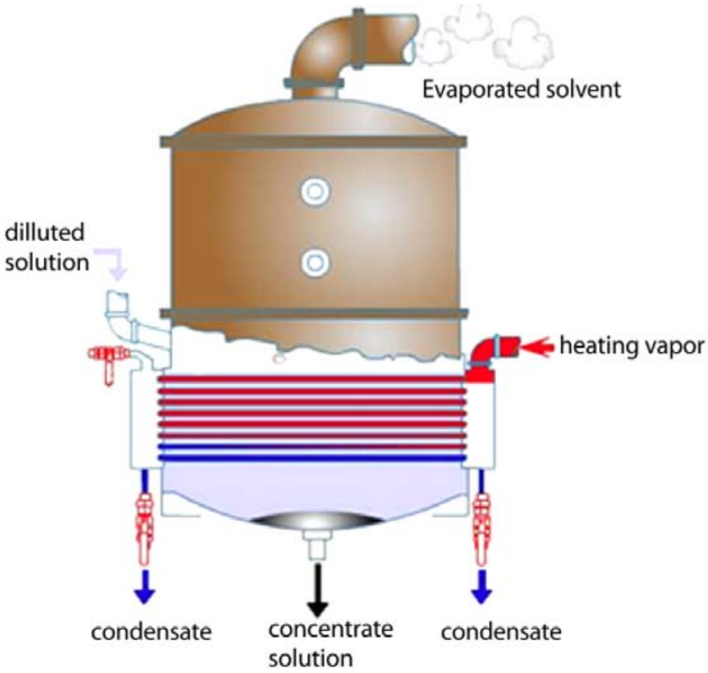

Figure 3.-Horizontal tubes evaporator (Bonsfills et alt., 2007).

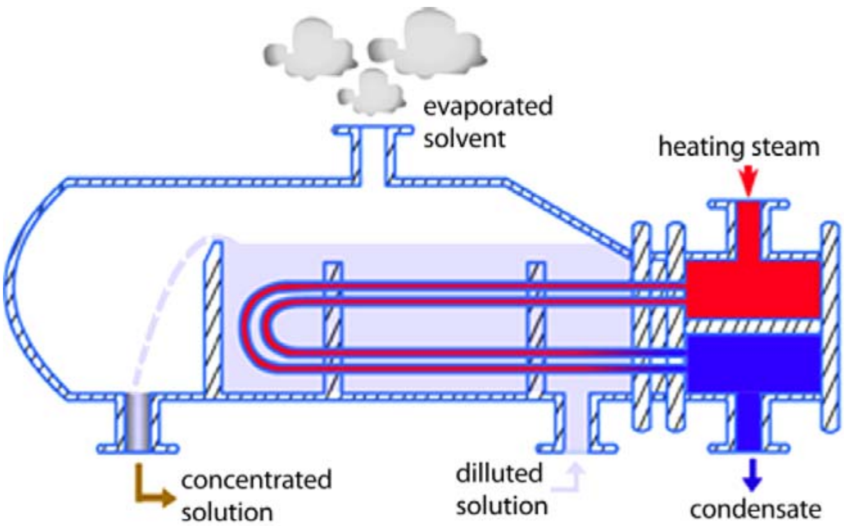

Figure 4.- Horizontal tubes evaporator (II) (Bonsfills et alt., 2007).

- VERTICAL TUBES: This equipment derives its name from the tube bundle arranged vertically inside the vessel. The liquid is inside the tubes and the steam gets condensed on the outside. The heater steam goes over the bundle of tubes and exits as condensate. Due to boiling and lower density, the fluid rises naturally through the tubes and flows upward. This natural circulation increases the heat transfer coefficient, though it is not useful with viscous liquids. There are of short tubes and long tubes, which may require forced circulation; under these conditions, vertical tubes can be used for viscous liquids because the heat transfer coefficient is improved. However, they are not suitable for dilute solutions, as the additional costs outweigh the benefits. Very different models appear, all consistent of a tubular exchanger with the liquid concentrate inside the tubes and steam outside, a vapor space to separate the vapor formed from the liquid, and return branch in upflow circulation systems. For heat sensitive products (fruit juices, blood plasma, vitamins, etc.) other variants comprising downflow through the tubes are used. In them, the vapor formed is entrained by the liquid, leaving the unit by a bottom valve.

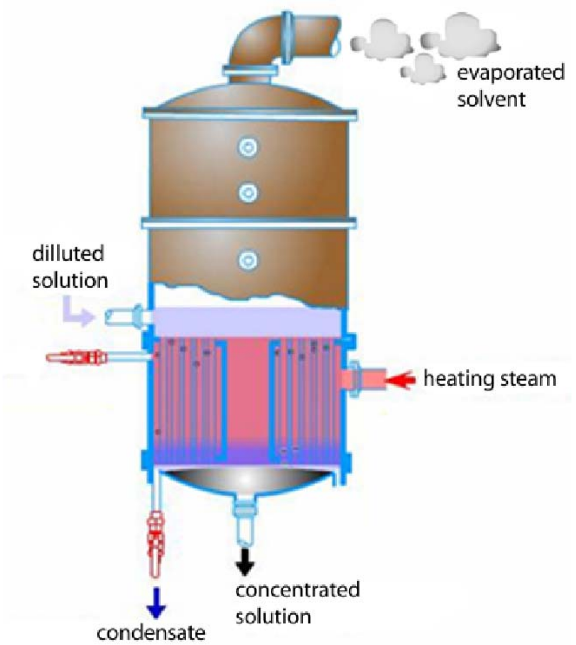

Figure 5.- Short vertical tube evaporator (Bonsfills et alt., 2007).

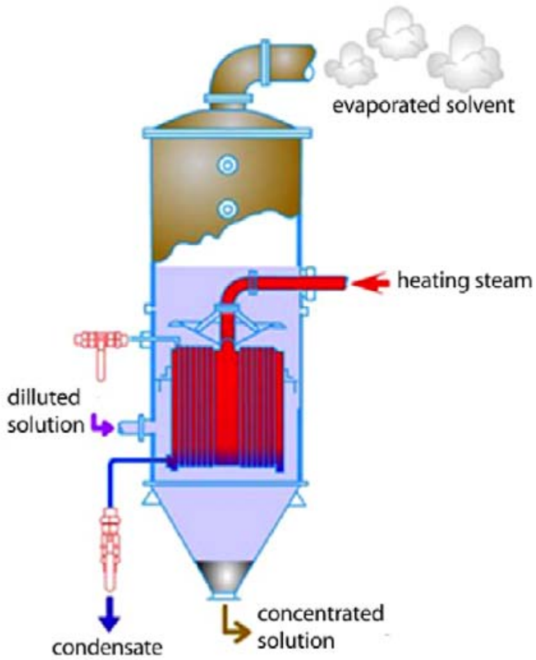

Figure 6.- Basket type vertical tubes evaporator (Bonsfills et alt., 2007).

Vertical tube evaporator variants:

a) **Short vertical tube evaporators (basket type evaporators):** This type of evaporator is use when the objective implies to evaporate all the solvent in the dilute and obtain crystals. Formed crystals are collected at the bottom. The heating device is a compact element that can be removed so as to be cleaned.

b) **Falling film evaporators:** The liquid is fed by the upper side of the tubes, flowing through their inner surface as a thin film. Vapor-liquid separation occurs at the bottom end. This type is commonly used to concentrate heat-sensitive materials with a high heat transfer coefficient.

c) **Agitated thin film evaporator:** In long tube evaporators, especially forced circulation ones, liquid turbulence degree and heat transfer coefficient are high. Another way to increase the turbulence is liquid film agitation. This is a modified falling film evaporator, with a single wall tube, supplied by an inner agitator. The liquid enters by the upper side of the tube, the concentrate is extracted by the bottom and the vapor passes to a separator flowing upwards to the outlet. It is a very efficient option for very viscous and heat sensitive products (gelatin, rubber latex, antibiotics, juices etc.). Conversely high cost, high maintenance of internal moving parts, and small capacity are disadvantages of this technology.

Other evaporator types:

- **Plates evaporator:** It consists of a series of plates mounted together in a frame. The evaporator operates with a single step, where each unit has a rising and falling films and two steam sections. The concentrated liquid and the vapor pass to a cyclone separator where both are separated. Vapor phase passes to a condenser or to the following effect. Different models have been developed depending on the characteristics of the liquid.

- **Serpentine evaporator:** A cylindrical vessel inside which steam passes through coils.

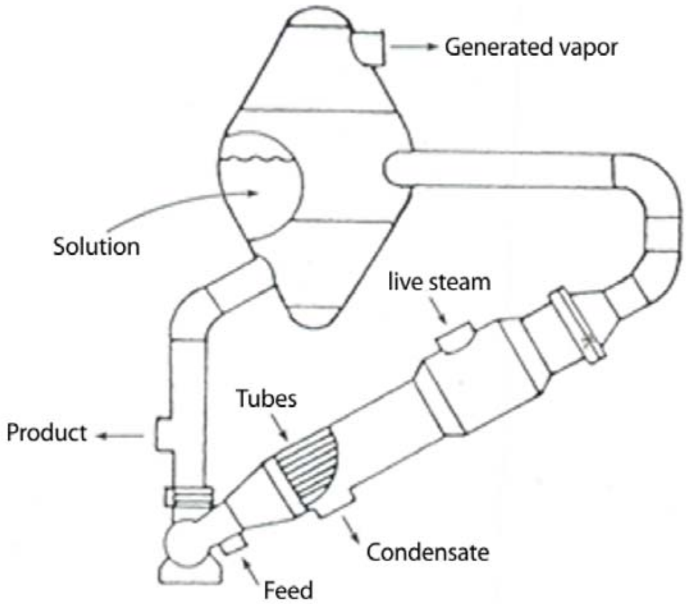

Figure 7.- Forced circulation inclined tubes evaporator. (it minimizes the height in big systems) (Martínez - Rus, 2004).

2.3.- Multiple effect evaporators configuration.

A multiple effect evaporator consists of a set of single direction evaporators, where each effect corresponds to an evaporator. During operation, the steam produced in the first effect is used as heating steam in the second effect, and so on. This configuration can increase the economy of the process. As the temperature decreases in each successive stage evaporation continues because the pressure and boiling point are also reduced.

The use of each additional effect increases the energy efficiency of the system. E.g. a double effect evaporator requires approximately 50 percent of the steam consumed by a single effect unit, having a theoretical 2 economy.

The advantages of multiple effect systems relative to single-effect, consist in heating fluid saving, due to a more effective thermal energy and cooling water use, since the liquid to evaporate contributes to a partial condensation of the vapor produced. To heat the first effect, 90° C water, superheated steam or superheated hot water is used. It is estimated that to evaporate 1 kg of water, 540 calories are required. If this vapor is used in a second stage it generates another kg of evaporated water without consuming more energy. If another effect is installed, again another kg of water can be evaporated. That is, with a triple effect evaporation 3 kg of water vapor can be obtained with 540 Kcal. This energy is typically produced by natural gas or diesel boilers. A very interesting possibility is to use the hot water circuit of a cogeneration equipment; thus the energy use efficiency is total. Multiple-effect evaporators are for sure the energy management low-cost option among all the possibilities to treat high flows.

Another great advantage of the multi-effect process is that, e.g. the system can be started with a double effect (two boilers) distillate production of 5000 L/day, and expand in the future by inserting a third module or boiler to produce 7,500 L/day, that is, a 50% additional production without higher energy costs and with low investment cost.

Feeding methods in multiple effect configurations (Pontiles, 2012; Bonsfills et alt., 2007):

Forward feed. The influent enters the first effect and follows the same flow direction as the vapor, leaving the product in the final effect. The liquid flows in decreasing pressures direction so it does not need to supply auxiliary energy to conduct the liquid between effects. It only requires two pumps, one to introduce the liquid into the first effect and another to remove the product from the latter effect.

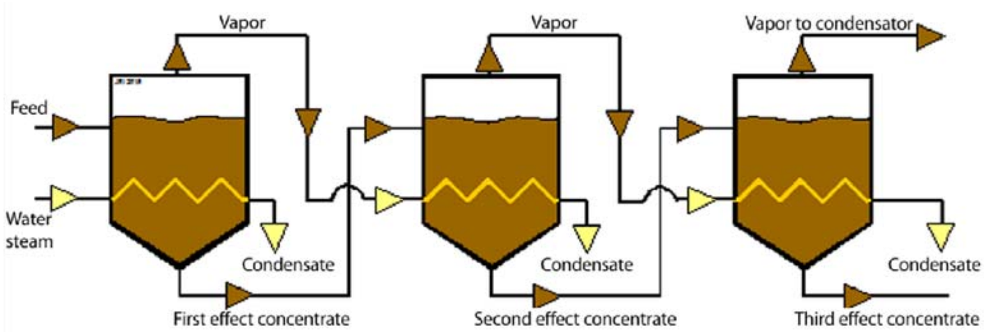

Figure 8.- Forward feed Multiple-effect evaporator configuration scheme.

Backward feed evaporator: The liquid feed is located in the latter effect and the outlet is in the first one. Thus, liquid concentrate and heating vapor circulate in opposite directions. Here the liquid flows in increasing pressures requiring the use of pumps after each effect. This is a considerable mechanical complication in addition to that of working with pumps at sub-atmospheric pressures. Therefore, if no other reasons, the forward feed system is preferred. When the solution is viscous this configuration allows a higher capacity than the forward feed configuration, but it may produce a smaller economy when the influent is cold.

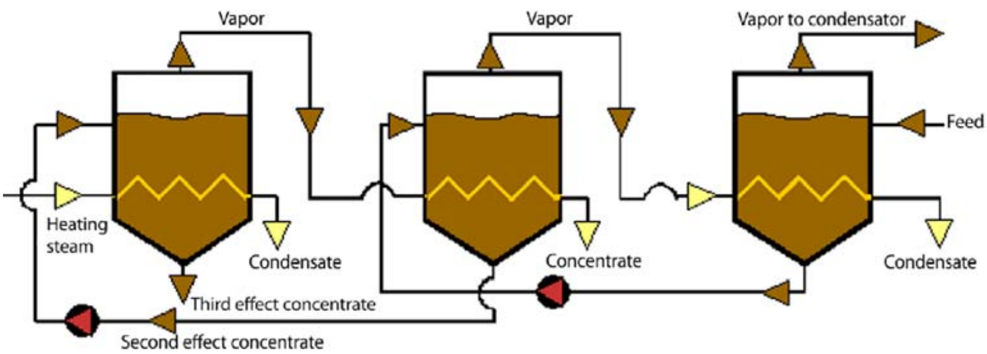

Figure 9.- Backward feed multiple-effect evaporator configuration.

Mixed feed: When the system has partial forward and backward feeding. This configuration is useful to work with very viscous solutions. If pure forward feed is used, the overall coefficient (U) decreases in the latter effect, where temperature is lower and the concentrated solution viscosity increases. To counter this phenomenon backward or mixed feed are used. The dilute solution enters the second effect and follows forward direction so it is conducted from the last effect to the first, to complete evaporation at high temperature.

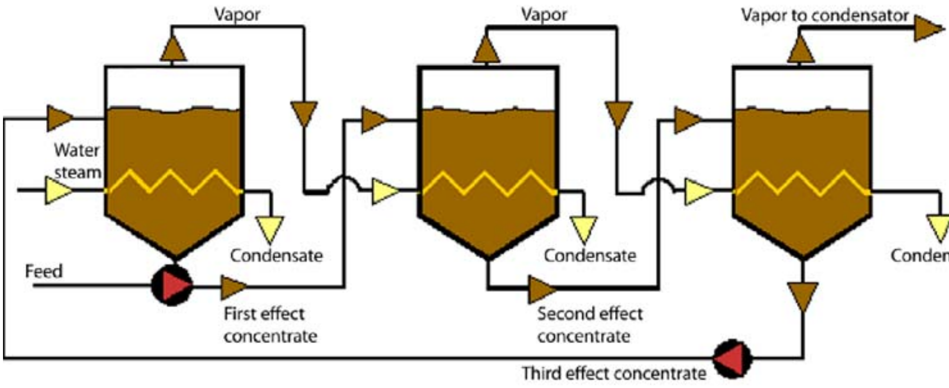

Figure 10.- Mixed feed multiple-effect configuration scheme.

This configuration eliminates any pumps requiring reverse configuration and allows the final evaporation at higher temperatures.

Parallel feed: When feed enters simultaneously in all the effects and the concentrated liquid is collected into a single stream. There is no liquid transport between effects. It is used in the crystallization evaporators where crystal suspensions and mother liquor are removed. It is a system used in the concentration of sodium chloride solutions, where the deposited crystals would complicate the forward feed arrangement.

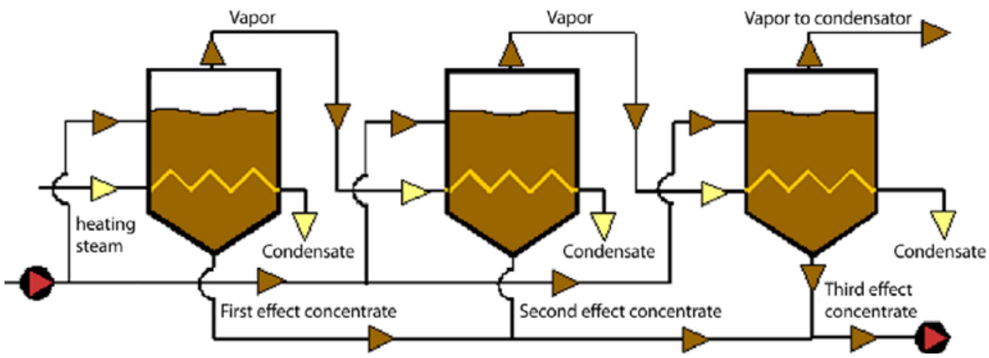

Figure 11.- Parallel feed multiple-effect configuration.

In general, to decide between feeding systems it is necessary to make a previous performance calculation evaporation for each system.

If the inlet feed temperature is well below the boiling point, the forward feed configuration will employ most part of the first effect's energy in liquid heating, instead of vapor generation, causing poor performance in the global process of multiple effect. In this case, backward feed is preferred.

In contrast, when the solution enters the system exceeding the latter effect boiling point temperature, forward feed configuration is more suitable, because the solution would enter the last effect partially vaporized, producing vapor without subsequent profits. Then, the solution would cool down until the latter effect boiling temperature, requiring further heat on each effect.

2.4.- Vacuum evaporation systems

The vacuum evaporation systems are one of the most efficient wastewater treatment technologies (CORDORCHEM ENVITECH, 2015).

Vacuum evaporation consist in the reduction of the evaporator's boiler inner pressure below atmospheric pressure. This reduces the boiling temperature of the liquid to evaporate, which reduces heat needed to be supplied/removed in the process of boiling and condensation. In addition, other technical advantages are the viability to distillate liquids with high boiling points or to prevent alteration of temperature sensitive substances.

Three main different types of vacuum evaporation systems can be observed:

- **Vacuum heat pump evaporation:** The refrigeration cycle of Freon gas is used. By the action of this compression gas condenses and transfers heat to the liquid to be evaporated by heat exchange. Then it proceeds to the gas expansion through a thermostatic valve and the action of a condenser that cools the evaporated liquid and the removed distillate. Freon flows into a closed and sealed circuit. As the evaporation reactor is under vacuum, it allows evaporation at temperatures around 40° C, so it does not need any other heating or cooling source becoming a very attractive process from the economy and management point of view. The energy absorbed in this process varies depending on the application and the fluid to be treated between 150 and 250 W per distillate liter. The system low evaporation temperature permits a wide variety of applications, even for highly corrosive liquids employing special alloys; evaporation systems to dry residue, hard fouling or crystallizing fluids, etc.

- **Vacuum evaporation by mechanical vapor compression:** This technology tries to recover the condensation latent heat of the distillate as a heating source for the liquid to evaporate. To this end, the generated steam temperature in the evaporation is increased by compressing the vapor phase. Thus, the superheated steam can be recycled through a heat exchanger inside the evaporator achieving two objectives: a) saving energy for evaporation and b) avoiding a condensation cooling device (cooling tower, etc.). Evaporation with a mechanical vapor compression is the most energy efficient evaporation system (min. 36 W per liter of distillate).
- **Vacuum evaporation with steam or hot water by multiple effect:** It consists on a series of evaporators inside which the pressure decreases progressively from first to last, whereby the steam produced in the first evaporator is used as heating medium on the following evaporator, while it condenses to liquid. The latter effect, requires an external cooling system. A wet bulb condenser is generally used, which is, in fact, a closed evaporative tower with low consumption compared to the open types.

2.5.- Applicability

The application of evaporation technology to treat industrial liquid waste at point source involves a number of advantages:

- It allows minimization of these wastes by concentration, which reduces significantly the management costs.
- Sometimes it is possible to value the concentrate for possible reuse in the same process or in alternative applications.
- The minimization at the point source reduces the storage need of hazardous waste large volumes in industrial enclosures.
- It reduces the likelihood of spills risk caused by accidents during transport from the source to the destination point of treatment.
- It reduce greenhouse gas emissions generated by this transport.

The treated water (distillate) that has been extracted from waste liquid has a quality that allows its recycling inside the plant for various applications (production, cooling, etc.), what reduces other water sources consumption. Most installations may produce a distillate below 10 mg/L in TDS concentration and, in some cases, lower than 2 mg/L.

In many industrial plants evaporators can be installed to achieve zero liquid wastewater discharge.

Vacuum evaporation is one of the most innovative and effective technologies for the minimization and treatment of liquid industrial wastewater-based. It is a clean, safe technology, with low maintenance, with a very low management cost. In many cases, moreover, a zero liquid discharge can be achieved with this technology.

Some of the most common applications are:

- Oily emulsions, lubrocoolers, separating agents
- Compressor purges; floor washing waters.
- Water from tanks and reactors washing (industry. Chemicals, pharmaceuticals, cosmetics, perfumes).
- Work baths and wash waters in electroplating and surface treatment processes.
- Penetrating liquids.
- Printing wastes (cleaning water, inks, etc.).
- Water treatment plants rejections (reverse osmosis, demineralizers, etc.).
- Urban solids residues leachates.

- Biogas generation plants digestates.
- Pickles.

3.- DESIGN

Dealing with an evaporator design, it is necessary to know the capacity, economy and heating steam consumption of the process unit, which are given by the following expressions:

$$Capacity = \frac{kilogram\ of\ evaporated\ solvent}{time}$$

$$Economy = \frac{kilogram\ of\ evaporated\ solvent}{kiogram\ of\ heating\ steam}$$

$$Heating\ steam\ consumption = \frac{capacity}{economy} = \frac{kilogram\ of\ heating\ steam}{time}$$

Evaporator characteristic parameters (Martinez-Rus, 2004):

- **Heating device or calandria:** It is the unit where the live steam stream enters with mass flow W_0^S and specific enthalpy H_0^S and the liquid condensate flow leaves with $W_0^S = W_1^C$ flow and h_1^C specific enthalpy.
- **Evaporation chamber.** In this chamber, the dilute liquid feed enters with W_0^L mass flow, and h_0^L specific enthalpy, and the concentrate solution leaves with W_1^L mass flow and h_1^L specific enthalpy. Besides, the generated vapor stream leaves it with W_1^V mass flow and H_1^V specific enthalpy.

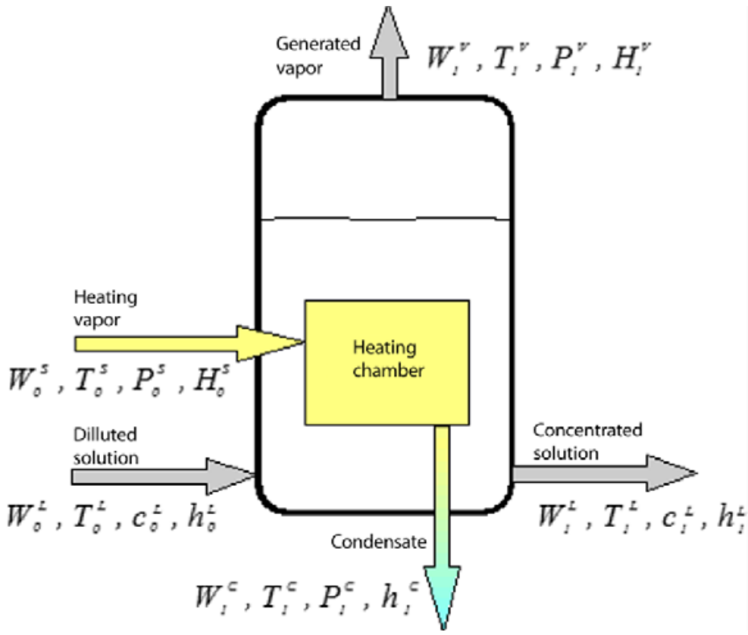

Figure 12.- Basic evaporator elements (Martínez-Rus, 2004).

Where:

W = Mass flow.
Subscript 0 = Inlet flow.
Subscript 1 = Outlet flow.
P = Pressure.
T = Temperature.
C = Concentration.
H = Gas phase enthalpy per unit mass.
h = Liquid phase stream enthalpy per unit mass.
Superscript S = Live steam.
Superscript C = Condensate.
Superscript V = Generated vapor.
Superscript L = Liquid stream.

The mathematical analysis of the evaporator requires to perform mass and enthalpy balances and to use the heat transfer equation (Martinez - Rus, 2004):

Mass and enthalpy balances:

Global mass balance:

$$W_0^L = W_1^L + W_1^V$$

$$W_0^S + W_0^L = W_1^C + W_1^L + W_1^V$$

Volatile component mass balance:

$$W_0^L . c_0^L = W_1^L . c_1^L + W_1^V$$

Energy balance:

$$W_0^S . H_0^S + W_0^L . h_0^L = W_1^C . h_1^C + W_1^L . h_1^L + W_1^V . H_1^V$$

$$Q = W_0^S . H_0^S - W_1^C . h_1^C = W_0^S . (H_0^S - h_1^C)$$

Where Q is the transferred heat across the evaporator heating surface.

Vapor energy recovery:

Considering that the liquid streams enthalpies are much lower than those of generated vapor, the following was concluded:

$$W_0^S . H_0^S \cong W_1^V . H_1^V$$

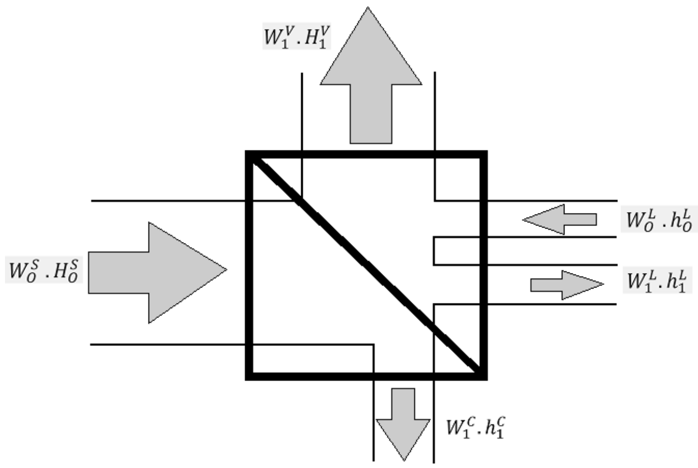

Figure 13.-Basic scheme of evaporator entalphy streams.

In the figure above, the flow and energy split of various incoming and outgoing evaporator flows are showed, being possible to observe how the energy transmitted from the heating steam leaves the evaporator in the generated vapor.

It is evident, therefore, that the energy recovery of the vapors in the processes of evaporation becomes necessary. The methods to be followed are (Martinez - Rus, 2004):

- Use of multiple effect systems.
- Re-compression of the generated vapor: mechanically or thermally.
- Use of a heating secondary fluid.

Heat transfer:

As inside a heat exchanger, the transmitted heat flow, *Q*, in the evaporator may move following the heat transfer equation, which can be expressed as follows:

$$Q = U \cdot A \cdot \Delta T = \begin{Bmatrix} Q = U_{ap} \cdot A \cdot \Delta t_{ap} \\ Q = U_C \cdot A \cdot \Delta t_C \end{Bmatrix}$$

where ***U*** is the **global heat transfer coefficient** in the evaporator, which may take the form U_{ap}, apparent coefficient, or U_G, corrected coefficient, depending on the solution boiling point determination criterion, and ***A*** is the heat transfer area.

Δt_{ap} value is given by the difference between the steam condensing temperature T_0^S and the boiling temperature of the liquid in the evaporation chamber. This temperature is measured from the chamber's pressure, which implies not considering the boiling point rise due to the solute effect in the solution or due to any hydraulic gradient. Similarly, in Δt_C calculation all possible corrections in determining the boiling temperature of the liquid in the evaporation chamber should be considered.

Enthalpy data:

It is necessary to know the specific enthalpies of both the liquid and vapor streams flowing across an evaporator. In the case where the stream was constituted by a pure component, e.g. W_0^S, W_1^C and W_1^V, streams (normally water vapor streams, liquid water or generated vapor), the specific enthalpies can be easily found in the literature. When the fluid flows comprise more than one component, an experimental determination is required. These determinations can be expressed graphically, as in the figure below, where the specific enthalpy of the solution es represented as a function of the concentration, at different temperatures (Dühring diagram).

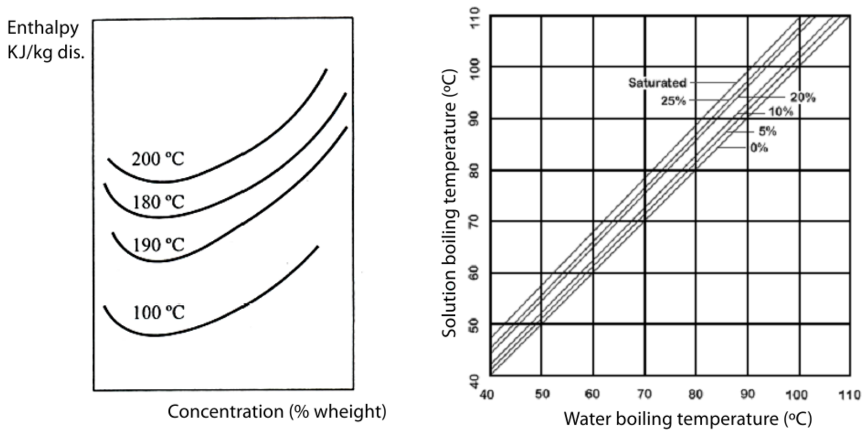

Figure 14.- Enthalpy vs concentration diagram example (left) (Martínez - Rus, 2004) and sodium chloride Dühring diagram (right).

In the event that there were no available test data, it will be necessary to simplify the specific enthalpies calculation on the base of the solution components.

The change of state latent heat determination for water is often extracted from the following empirical formula, called Regnault equation:

$$r = 606.5 - 0.695\ T$$

Where:
r = Change of state latent heat for water (kcal/kg).
T = Temperature (ºC).

Table 1.- Comparison between the residence time and heat transfer coefficients of some evaporators (Mannheim and Passy, 1974, and Earle, 1983).

EVAPORATOR TYPOLOGY	EFFECT NUMBER	APPROX. RESIDENCE TIME	U (W/m².ºK) (*OHTC, overall heat transfer coefficient*)	
			Low viscosity	High viscosity
Open	Single	30 min	500 – 1000	< 500
Short vertical tubes	Single		570 – 2800	-
Rising film	Single	10 – 60 s	2250 – 6000	< 300
Falling film	Single	5 – 30 s	2000 – 3000	-
Plates	3 stages	2 – 30 s	2000 – 3000	-
Expanded flow	2 stages	0.5 – 30 s	2500	-
Agitated film	Single	20 – 30 s	2000 - 3000	1700

4.- PERFORMANCE

The evaporator produces a distillate that can be recycled as it is free of dissolved solids, and a concentrated solid or semisolid with a water content lower than 15%

In most part of the wastewaters, which typically present a 1%-5% in dissolved solids content, it is relatively easy to evaporate between 75%-95% of the water in a falling film evaporator. In case that the feed flow contains very soluble salts, the latter 5%-25% of water can be difficult to evaporate.

5.- SPECIFICATIONS AND REFERENCES IN TEXTILE INDUSTRY APPLICATIONS

Praneeth, K., et al. (2014) developed a study on a pilot scale textile ETP. Although it was focused on the use of electrodialysis processes, they used an evaporation step to treat the rejection of the membrane filtration processes. The aim of the study was to determine the electrodialysis (ED) stage performance in the concentration of the rejection of a reverse osmosis unit. The evaporator could pass concentrations from 4.35% to 24%.

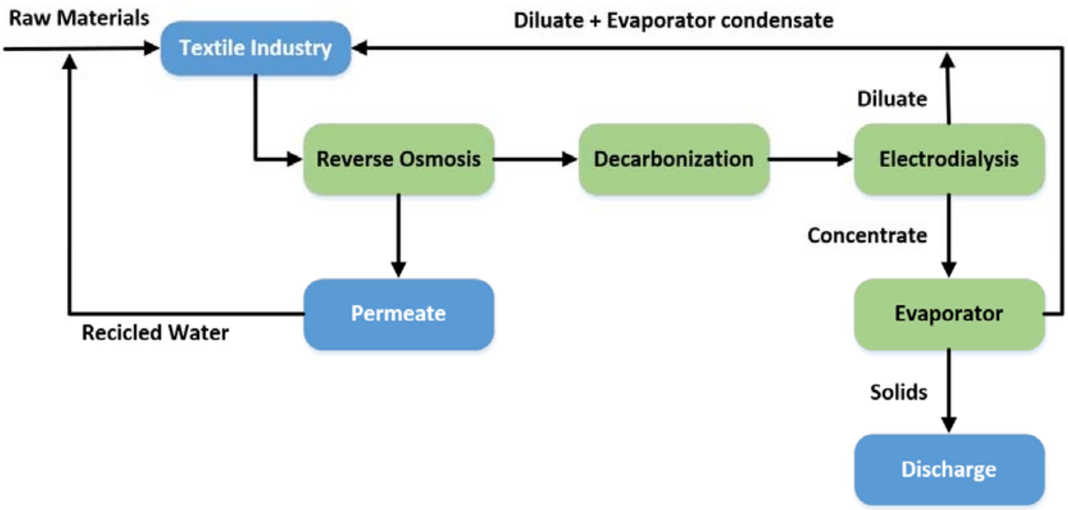

Figure 15.- Evaporator position in the process configuration diagram (Praneeth et alt.,2014).

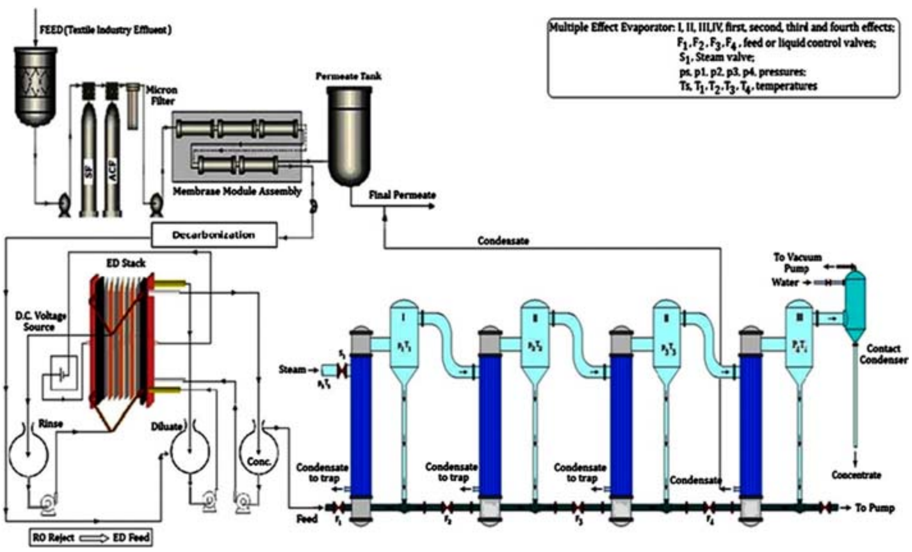

Figure 16.- Process diagram where a multiple effect evaporator is located.

Ranganathan et al. (2007) describe and assess specific cases of dyeing and washing effluent's advanced treatment with water reuse objective. These are industries in Tirupur and Karur (Tamil Nadu, India). A brief reference to these systems is referred below:

- *M/s. Siva Sakthi textile Processes (Mangalam, Tirupur)*: This mill generates dyeing and washing effluents. The washing line effluent is collected in tanks and pumped to a physical-chemical primary treatment (with ferrous sulfate and lime) comprised of coagulation-flocculation and sedimentation. In order to recycle this effluent water, it is introduced into pressure sand filter, passed through a filter to remove iron and other ion exchange filter. Finally the water passes through a reverse osmosis (RO) unit (two stage, pressures of 21.2-28.2 kg/cm^2). The rejection of the first RO is sent to the second; and the final rejection is 20% in volume. This final rejection is sent to a multiple effect evaporator and to evaporation ponds. The condensed water is used in cleaning operations. In the evaporation step concentrations of about 100 g/L are achieved, and furtherly undergo solar evaporation. The permeate water from the RO is used in the process. The waste water generated in dyeing processes is sent to a pre-filtration and subsequently to nanofiltration (NF) process, with a rejection in the order of 30% that is sent to a multiple-effect evaporator and the solar evaporation system. The NF permeate is used to prepare solutions for dye baths.

- *M/s. Renaissance creations processing division (Kupanda Palayam, Tirupur)*: This mill activity is mainly conducted to washing and dyeing processes. The washing line effluent is homogenized in a tank and sent to a physical-chemical primary treatment (coagulation-flocculation with ferrous sulfate and lime) and a biological treatment based on trickling filters. Subsequently, the water is chlorinated. The effluent is passed through an activated carbon filter before entering a two-stage reverse osmosis process. The RO has a 12-15% rejection (in volume), which is sent to a multiple-effect evaporator. The RO permeate is passed through a degassing tower. Dyeing line process effluent is first treated with lime and ferrous sulfate to coagulate and flocculate, to remove color. This flow, with a light color, is mixed with the rejects of the RO system and sent to evaporation. Condensed water is recycled in the process and the concentrate is conducted to crystallization system for salt recovery.

- *M/s. Leeds spinning mills Ltd*: Dyebath's effluent is first subjected to a settling process and subsequently to nanofiltration. The collected permeate contains NaCl. The rejection is sent to solar evaporation ponds. Washing line effluent, after a physical-chemical treatment (lime and ferric chloride), is conducted to a sand filtration and subsequently to an iron removal filtration. The flow then passes to a dual stage RO system whose permeate (80%) is used in the industrial process and the rejection is sent to nanofiltration and solar evaporation.

- *M/s. Karur Amaravathi textiles industry*: Dyeing and washing effluents are collected together in a tank and subjected to advanced treatment. The wastewater is sent directly to a reverse osmosis system; without any BOD, color or other impurities removal. It has a four stage RO. All the permeate flows are collected together and sent to industrial process. Finally, rejects undergo nanofiltration process and the permeate is used to make dye solutions. NF rejection is sent to evaporation line.

Table 2.- Characteristics of the effluents on each treatment step in M/s. Shivasakthi Textile Processors, Tirupur. Ranganathan et al. (2007).

PARAMETER	WASHING LINE EFFLUENT				DYEING LINE EFFLUENT	
	ETP INLET	PHYSICAL-CHEMICAL TREATMENT OUTLET	REVERSE OSMOSIS PERMEATE	REVERSE OSMOSIS REJECT	DYEING EFFLUENT	NANOFILTRATION OUTLET
pH	9.76	9.78	7.52	8.21	10.42	8.21
Conductivity (mS/cm)	6.80	6.63	0.77	32.1	53.9	63.55
Total suspended solids (mg/L)	47	26	*BLD*	46	76	60
Total dissolved solids (mg/L)	4280	3620	474	21670	39179	48294
BOD_5 (mg/L)	80	63	10	450	180	100
COD (mg/L)	317	204	24	1143	909	402
Total hardness (mg/L) as $CaCO_3$	320	141	3	728	88	45
Temporal hardness (mg/L) as $CaCO_3$	272	104	3	687	68	22
Sulfates (mg/L)	75	116	8	328	174	362
Chlorides (mg/L)	1912	1771	184	10756	19179	26432
Sodium (mg/L)	1600	–	–	9280	–	20480
Potassium (mg/L)	38	–	–	208	–	10062
% sodium	90	–	–	95	–	100
Sodium absorption rate (SAR)	39	–	–	146	–	1329

Note: BLD, below limit detection. –, not analyzed.

Vishnu et al. (2007) presented a study in Tirupur (India) about three dyeing units whose effluent receives a treatment that consists of the following stages: physical-chemical, biological treatment, ozonation, reverse osmosis (RO), nanofiltration (NF), multiple effect evaporator, crystallizer and solar evaporation. Composite samples of color, pH, SST, SDT, chlorides, sulfates, COD, total iron, silica, SDI, LSI and total hardness were analyzed. The results indicated that the physical-chemical treatment alone is insufficient to achieve the feed water quality for RO membranes. It is recommended that RO feed preparation incorporate a biological treatment and ultrafiltration to reduce COD and SDI in water. RO and NF performance using salt recovery were 87% and 71%, respectively.

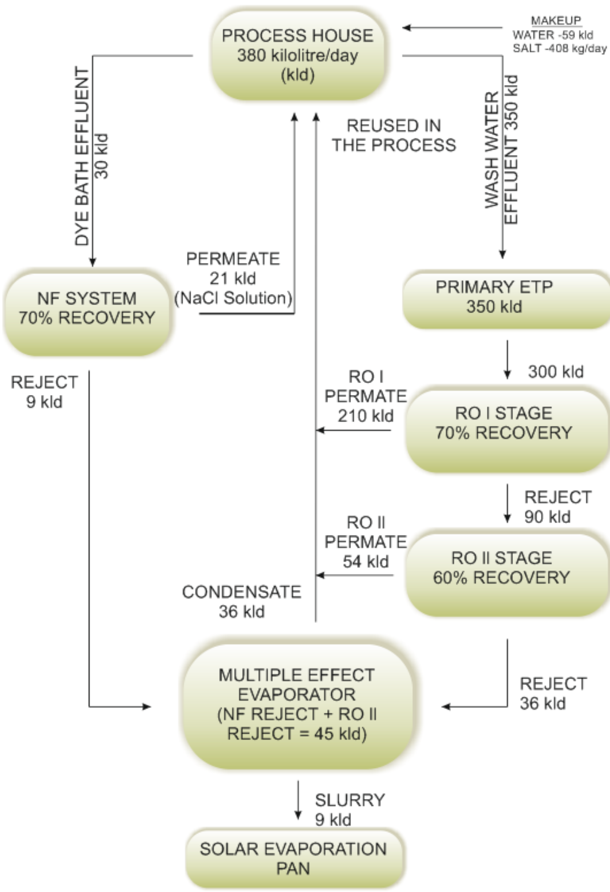

Figure 17.- Flows and balances scheme in treatment and recycling system Unit 1 (Vishnu, 2007).

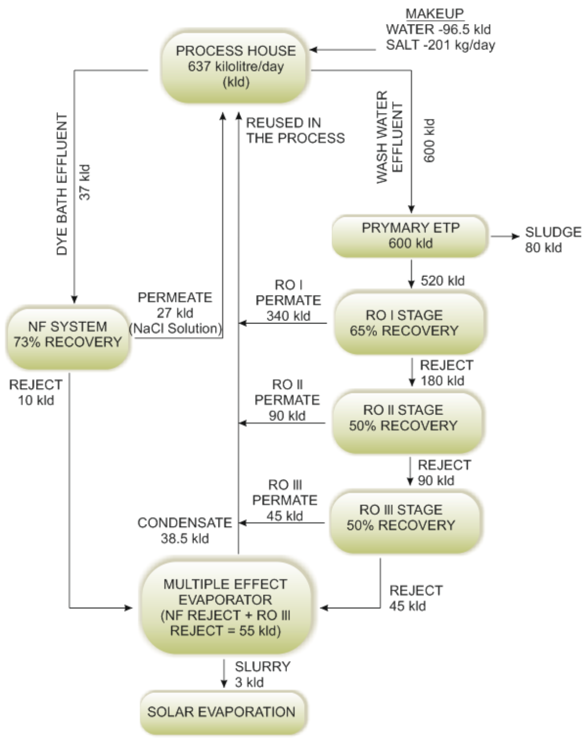

Figure 18.- Flows and balances scheme in treatment and recycling system Unit 2 (Vishnu, 2007).

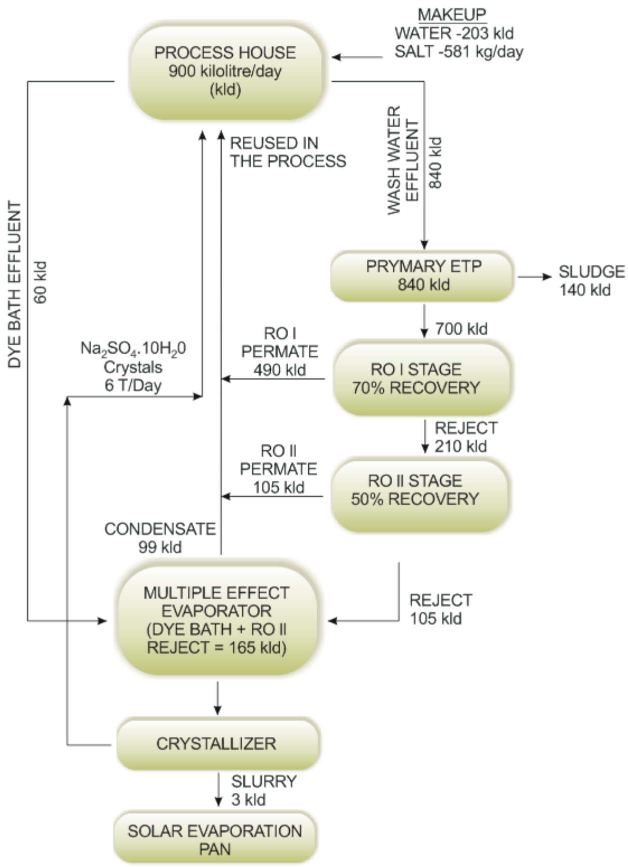

Figure 19.- Flows and balances scheme in treatment and recycling system Unit 3 (Vishnu, 2007).

Table 3.- Descriptive parameters on the evaporation units (Vishnu et al, 2007).

PARAMETER	Unit 1	Unit 2	Unit 3
Stages of evaporation	3	4	4
Rate of evaporation (kg steam:L of effluent)	1:3.5	1:5	1:5
Feed flow rate (m^3/h)	3.5	5	10
Feed TDS (mg/L)	23600 – 36500	11900 – 12800	39200-42550
Condensate TDS (mg/L)	64 – 85	38 – 53	67-48
Concentrate TDS (mg/L)	47400 – 77500	104100 - 109400	113800 - 119200
Condensate recovery (%)	76.6	70.0	60.0

6.- PARAMETERS AND CONTROL STRATEGIES

During evaporation, the physical and chemical properties (characteristics) of the solution (feed) that is being concentrated and the generated vapor have a great influence on the process. They develop a considerable effect on the type of suitable evaporator and on the process pressure and temperature.

- **Liquid concentration.** Typically, an evaporator liquid feed is rather diluted, with properties similar to those of water. As the evaporation progresses, the solution gets concentrated and its viscosity and density considerably arise. The solution becomes saturated or appears unsuitable for heat transfer so additional mechanisms are required in order to avoid a significant decrease of the evaporation coefficient.

- **Solubility**. As a solution evaporates and increases the concentration of solute or salt, the solubility limit of the material in solution can be exceeded, generating crystals. Also, when a hot solution is cooled at room temperature, crystallization phenomena may occur.

- **Materials thermal sensitivity.** Many products, particularly food and other biological materials, are damaged when heated to moderate temperatures for relatively short times. The degradation extent is a function of temperature and time. In these materials concentration, special techniques are used to reduce both the temperature of the liquid and the heating time.

9.- OPERATION AND MAINTENANCE TROUBLESHOOTING

Operation concerns:

- **Foaming**. Some materials, especially organic substances generate foam during boiling. This foam is dragged by the vapor flowing out the evaporator and can produce material losses. In extreme cases, the entire liquid mass can flow out with the vapor and be lost.

- **Crusting (deposits).** Some solutions deposit crusts on the heating surfaces. These deposits are formed as decomposition products or due to a solubility decrease. As the water evaporates from a solution and the liquid becomes more concentrated, it is possible to reach the precipitation point of solved salts. These precipitates (calcium, magnesium, or silica) strongly reduce the heat transfer coefficient, reducing evaporation and thermal efficiency. They cause a progressive decrease of the global evaporation coefficient until it is necessary to interrupt the operation and clean the tubes. When the crusts are hard and insoluble, cleaning operation is difficult and costly.

- **Materials composition.** The selection of evaporator production materials is important in order to prevent corrosion.

- **Pressure and temperature.** The rise of the boiling point of a substance is a function of the pressure and the concentration. Pressures below 1 atm (vacuum pressures) are normally recommended so as to operate at low materials temperature.

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ANNEX 1.- DESIGN CRITERIA COMPARISON

Table.- Comparison between evaporator tipologies (http://datateca.unad.edu.co/contenidos/301219/exe_calor/calor_3_2010/leccin_35_evaporadores.html)

EVAPORATOR TYPE	ADVANTAGES	DISADVANTAGES	BEST APPLICATIONS	DIFFICULTIES
FORCED CIRCULATION	High heat transfer coefficients Positive circulation Relatively free from contamination	Elevated cost Circulation pump energy need Residence time relatively high	Crystal products Corrosive solutions Viscose solutions.	Tube entry clogging due to salt deposition Difficult circulation due to losses higher than expected Salt deposition due to boiling in the tubes Erosion and corrosion.
SHORT VERTICAL TUBES	High heat transfer coefficient at elevated temperatures Low Upper space Relatively free from contamination Simple mechanic scaling removal Relatively low cost.	Bad heat transfer coefficient with low temperature changes and at low temperatures High floor surface and big weight Relatively high retention. Poor heat transfer with viscous liquids.	Clean liquids. Crystalline products. Relatively non-corrosive liquids, since the unit is large and expensive, if constructed of materials other than cast iron or steel. Solutions with slight scaling, require mechanical cleaning, because the tubes are short with big diameters.	
LARGE VERTICAL TUBES	Low cost. Large heating surface in one unit. Low retention. Need little floor surface Good heat transfer coefficients with reasonable temperature differences (Rising Film) Good heat transfer coefficients all temperature differences (falling film)	High headspace. They are not suitable for liquids forming deposits of salts or scales. Falling film variant requires recirculation.	With clean fluids. With scummy liquids. With corrosive solutions. With large loads of evaporation. With considerable high temperature (Rising film) low temperature differences (Falling film)	Rising film units are sensible to changes in operating conditions. Poor distribution of the feed material in falling film units.
HORIZONTAL TUBES	Very low headspace Good heat transfer coefficients.	They are not suitable for liquids with a tendency to salt deposition Unsuitable for liquid scales. High cost.	High headspace. Small capacity. Liquids without salt or scales deposition.	

ANNEX 2
REQUIRED SURFACE ESTIMATION

EVAPORATOR UNITS REQUIRED SURFACE

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ANNEX
GRAPHICAL DESCRIPTION OF UNIT PROCESSES

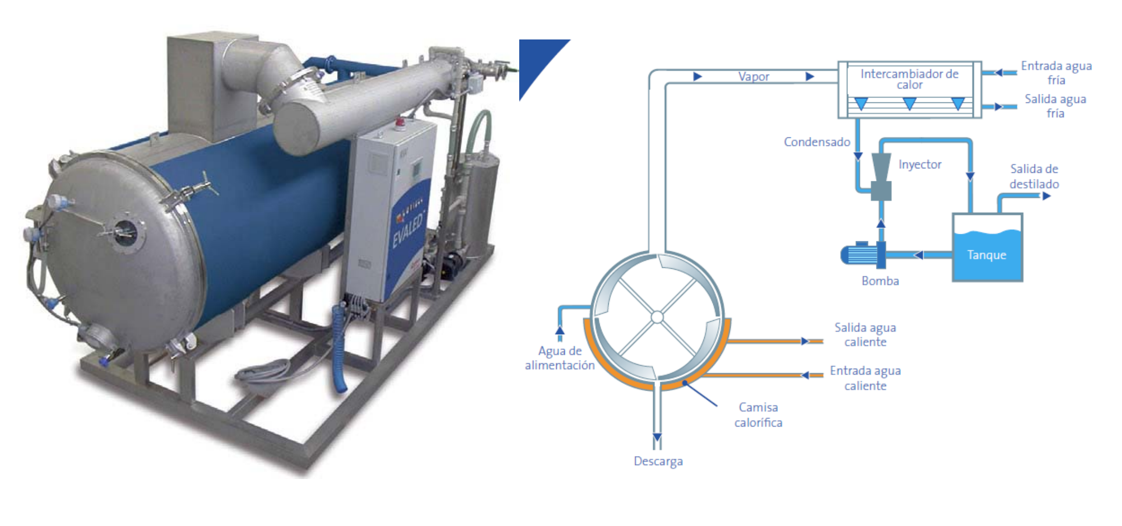

Figure 1.- Evaporator EVALED™ AC – RW. It variates from 3.000 until 12.000 distillate litres per day at a boiling temperature of 40º C (104º F) and with a vacuum of 5 kPa (approx..). Veolia Water- Solutions & Technologies. (September 2015).

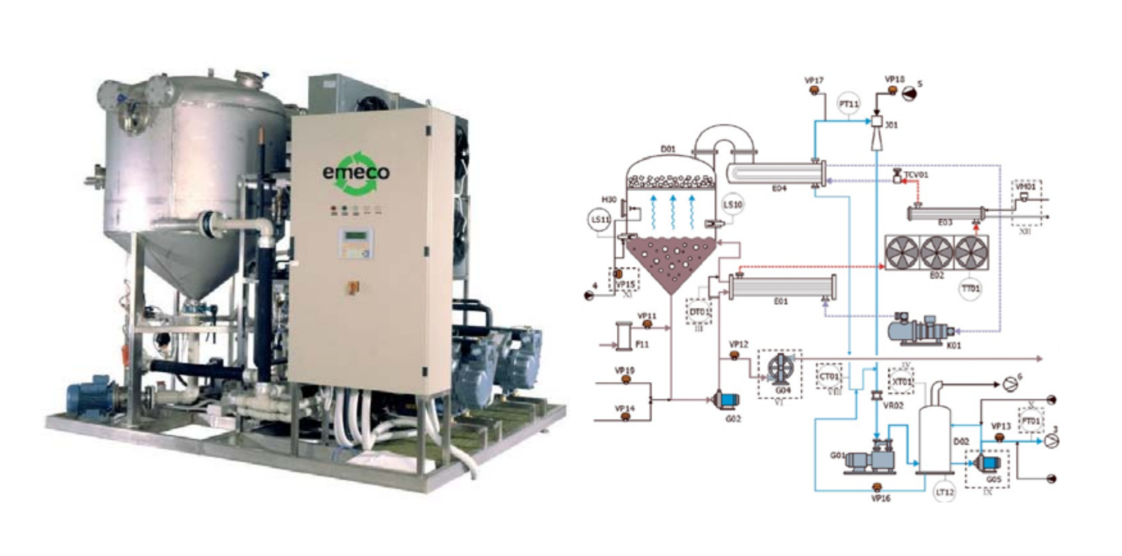

Figure 2.- Vacuum evaporator E 6000. EMECO S.A. Emeco, S.A. (Ingeniería de Aguas Residuales). (September 2015).

MODELOS DE EVAPORADORES					
Modelo	Producción	Consumo	APC	CLEAR CAT	Dimensiones
	L / h - L / Día	KW			Ancho x Fondo x Alto(mm)
VDT 20	20 – 480	2.5	-	-	1230x 600 x 1335
VCT 30	30 – 720	2.7	-	-	1230x 600 x 1335
VCT 40	40 – 960	3.4	-	-	1230x 600 x 1335
VCT 60	60 - 1440	4.5	-	-	1230x 600 x 1335
VCT 75	75 - 1800	5.9	●	opcional	1350x 920 x 1855
VCT 100	100 - 2400	7.2	●	opcional	1350x 920 x 1855
VCT 175	175 - 4200	11.7	●	opcional	1550x 1220 x 2300
VCT 250	250 - 6000	15.3	●	opcional	1550x 1220 x 2300
VCT 350	350 - 8400	21	●	opcional	2500x 1100 x 2800
VCT 500	500 - 12000	30	●	opcional	2500x 1100 x 2800
VCT 750	750 - 18000	41.3	●	opcional	3035x 1400 x 3060
VCT 1000	1000 - 24000	50	●	opcional	3035x 1400 x 3060
VCT 1500	1500 - 36000	83	●	opcional	3035x 1400 x 3060
VCT 2000	2000 - 48000	100	●	opcional	3035x 1400 x 3060

Figure 3.- TOTAGUA Evaporators. www.totagua.com. (September 2015).

EVALED PC-R

EVALEC PC-E

Figure 4.- Heat pump vacuum evaporators
http://www.veoliawatertechnologies.es/tecnologias/evaled/. (September 2015).

Figure 5.- VNT industrial vertical evaporator for printing line process effluent treatment. 90% of the water is recovered.
http://www.controlgraf.com/famreciclaje.htm. (September 2015).

Figure 6 – Industrial evaporators.
Veolia EVALED equipment. (September 2015)

Figure 8.- Brine crystallization
Condorchem Envitech. http://blog.condorchem.com/tag/evaporadores-al-vacio/page/8/. (September 2015)

Figure 8.- General view of an evaporation installation.
JINZHOU GROUP CO., LTD. http://www.jzmachinery.com/IndustrialEvaporator.html (September 2015)

Figure 8.- Falling film evaporator
JINZHOU GROUP CO., LTD. http://www.jzmachinery.com/IndustrialEvaporator.html (September 2015)

Figure 8.- Forced circulative evaporator
JINZHOU GROUP CO., LTD. http://www.jzmachinery.com/IndustrialEvaporator.html (September 2015)