

APPLICATION OF MECHANICAL VAPOR RECOMPRESSION (MVR)
EVAPORATOR SYSTEM ON INDUSTRIAL WASTEWATER TREATMENT

by
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M.Sc. Chem. Eng.

Submitted to Institute of Environmental Sciences in partial fulfillment of
the requirements for the degree of
Doctor
of
Philosophy

Boğaziçi University
2005

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Dedication to my family....

ACKNOWLEDGEMENTS

I would like to thank Prof. Dr. Ömer Saygın my advisor, who supervised my Ph.D. studies and provided me valuable knowledge, insights, guidance and never ending helps to recognize my mistakes. I would also like to thank him for lending me adequate freedom and flexibility while working on this project. Furthermore, my experience would have been incomplete without Prof. Dr. Orhan Yenigün, Chairman of the Institute of Environmental Sciences; I thank him for his friendly, loving and supportive behavior throughout my stay of study. A special debt of thanks and acknowledgment goes to Prof. Dr. Ferhan Çeçen, Prof. Dr. Miray Bejbölet, Prof. Dr. Lütfl Akça and Assoc. Prof. Dr. Turgut T. Onay, my jury members, who devoted their valuable time for reading and commenting on the thesis and enabled me to improve the manuscript.

I am grateful to Saygın Limited for the financial support and provision of technical and manpower facilities during the length of this project. I also extend my deepest thanks to the staff of Saygın Limited for their whole hearted support and help.

Special thanks are offered to ABB firm for supplying valuable equipment (motor converter) which was highly essential for this project. I would like to show my appreciation to their engineers Mr. Levent Bütün and Mr. Sabri Demiryürek for their technical support in this regard.

Assoc. Prof. Dr. Ayşen Erdinçler has also been very supportive of me and has always tried to help me, as and when the need arose. I would like to thank her for her helps extended towards me. Furthermore, The Institute of Environmental Sciences and its laboratory staff deserve thanks for their cooperation, support and friendly behavior during my stay at the institute.

Finally, and most of all, I am deeply indebted to my family and my Pakistani and Turkish friends for their invaluable moral support, love and encouragement that I will always admire.

ABSTRACT

As a principle “recycling should be preferred over treatment wherever possible”. In line with this, a multipurpose Mechanical Vapor Recompression (MVR) evaporator pilot plant was designed, fabricated and tested at a pilot plant level with the aim of recovering water and valuable components from industrial wastewaters. A cost of 2.5-3.0 US\$ was found to be necessary for evaporation of one ton of wastewater. It was found with different wastewaters that generally the distillate was of a quality which is comparable to many raw water sources used today by the industry (200-500 $\mu\text{S}/\text{cm}$), which have a value of about 1.0 US\$. The experiments showed distillates are not of required quality in the presence of solvents or foaming detergents. Even if the distillate is marketed the total cost does not allow this technology to compete with classical wastewater treatment except in cases where classical methods fail (high organic, inorganic or toxic load).

Experiments with zinc-bath wastewaters showed that MVR technology can easily separate pure ZnSO_4 by fractionated crystallization from other constituents, the value of which is in order of magnitude greater than the evaporation costs. It is believed that this feasibility situation should be the rule for chemicals recovered from wastewater.

ÖZET

İlke olarak “geri kazanım mümkün olan her yerde arıtmaya tercih edilmelidir”. Bu doğrultuda, bu çalışmada endüstriyel atık sulardan suyun ve kimyasalların geri kazanılması amacıyla pilot ölçekte bir Mekanik Buhar Rekompresyonlu Evaporatör dizayn edilmiş, üretilmiş ve test edilmiştir. Bir ton atık suyun buharlaştırılabilmesi için 2.5-3.0 US\$ gibi bir masrafın gerektiği bulunmuştur. Değişik atık sularla yapılan deneylerde çıkan destilatın genelde bugün endüstrinin kullandığı ve değeri yaklaşık 1.0 US\$ olan ham su kaynaklarının kalitesi (200-500 $\mu\text{S}/\text{cm}$) ile karşılaştırılabileceği bulunmuştur. Ayrıca deneyler solvent veya köpüren maddelerin suda mevcudiyeti durumunda destilat kalitesinin yeterli olmadığını göstermiştir. Elde edilen distilat pazarlanabilse bile toplam evaporatör masrafları bu teknolojinin klasik arıtma ile bir çok misalde rekabet edemeyeceğini göstermektedir. Fakat klasik arıtma teknolojilerinin başarısız kaldığı örneklerde (yüksek organik, inorganik veya toksin yük) durum değişebilir.

Çinko giderme banyosu atık suları ile yapılan deneyler MVR teknolojisinin fraksiyonel kristalizasyon sayesinde sudaki diğer bileşiklerden temiz ZnSO_4 ayırabileceğini ve bunun değerinin buharlaştırma masraflarının on katından daha fazla olduğunu göstermiştir. Bu fizibilite durumunun genelde atık sudan herhangi bir kimyasal geri kazanıldığında da geçerli olacağı düşünülmektedir.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	Explanation	Unit used
BOD_5 / BOD	5-days Biochemical Oxygen Demand	(mg/L)
COD	Chemical Oxygen Demand	(mg/L)
DOC	Dissolved Organic Carbon	(mg/L)
h	Heat transfer coefficient	(W/m ² .K)
m	Mass flow rate	(kg/s)
$4M/\mu_l$	Reynolds number	-
M	Mass flow rate in the film, per unit of film width	(kg/m.s)
NTU	Nephelometric Turbidity Unit	-
q_s	Heat transfer from solid surface to liquid	(W)
TDS	Total Dissolved Solids	(mg/L)
TKN	Total Kjeldahl Nitrogen	(mg/L)
T_s	Condensing surface temperature	(°C)
T_{sat}	Saturation temperature	(°C)
$T_{v, \infty}$	Vapor temperature	(°C)
ΔT_e	Excess temperature difference	(°C)

δ	Thickness of film	(cm)
μ_l	Viscosity of liquid	(kg/m.s)

1. INTRODUCTION

The thermodynamic revolution in the eighteenth century completely changed the economic system of the world. The global economy prior to this was agrarian in nature but after this revolution a new era of industrial economies began. Irrational growth of the industries tainted beauty of the world with the ugly effects of environmental pollution. All the three spheres of the earth, i.e. air, water, and soil have been contaminated to an extent that the survival of animals and plants in their respective sphere has become threatened. Wastewater being one of the major culprits of environmental degradation has been a matter of grave concern since its discharge. Wastewater, whether domestic or industrial, contains pollutants ranging from pathogens to heavy metal ions and bio-refractory materials. Water borne diseases, the leading cause of infant mortality in human societies of the world is due to the water that has been polluted by coliform bacteria. Many of the organic halogen compounds from process industries are confirmed mutagens, carcinogens and causing problems in blood circulating systems. Heavy metal ions in the effluent of metallurgical industries and mining and toxic chemicals from pesticides are accumulating into the human body through a process of food chain and disturbing immune system and creating reproductive and nervous system disorders. Nutrients rich wastewater, if discharged untreated, converts a receiving body of fresh water into a dead mass through a phenomenon of eutrophication. Situation in under developed countries is certainly more alarming than the developed countries.

Water is an important constituent of this invaluable asset. The shortage of potable water is one of the main concerns of environment. Sustainable development and environmental protection requirements, as well as economic factors have caused the industry to solve treatment of effluents in a new way. The trend is clearly toward closed cycle systems with significant reductions or eliminations of many effluent streams. The idea is based upon trying to extract the water from already contaminant discharge of different industries. One of the most practical solutions for this is the process of evaporation.

Evaporation is one of the physical treatment processes, in which phase change occurs. It plays a critical role in the manufacture of a variety of products in the chemical process industries (CPI), including foods, pulp and paper, pharmaceuticals, specialty and fine chemicals, organic and inorganic chemicals, polymers and fertilizers. Evaporation differs from drying in that the residue is a liquid-sometimes a highly viscous one-rather than a solid; it differs from distillation in that the vapor usually is a single component, and even when the vapor is a mixture, no attempt is made in the evaporation step to separate the vapor into fraction; it differs from crystallization in that emphasis is placed on concentrating a solution rather than forming and building crystals. In certain situations, e.g. in the evaporation of brine to produce common salt, the line between evaporation and crystallization is far from sharp. Evaporation sometimes produces slurry of crystals in saturated mother liquor.

The use of evaporation for wastewater treatment is a new trend. Evaporation is, in fact, the most powerful means of water purification that nature has provided. Billions of cubic meters of water contaminated in different ways are evaporated every day from the earth's surface by solar power and subsequently recycled back as rain. Man has learned from nature to apply this in the industrial processes.

The process of evaporation can effectively separate the inorganic and non-volatile organic compounds dissolved in an aqueous stream into a clean water fraction of high purity and a concentrate containing all the compounds. Concentration of aqueous process liquids by evaporation is an old and widely used unit process in the industry. For several different types of evaporation, it is possible to concentrate the dissolved compounds into heavy syrups and also to crystallize out the dissolved compounds and recover them in a dry form. In most of these cases evaporation has shown to be the only useful tool.

Evaporation technology can be applied, for a variety of non-volatile chemicals present in the wastewater. Evaporation can be employed when the bulk wastewater stream contains a high concentration of solid or other phase-separable material. As a result, the reduced amount of bulk liquid can be easily disposed of. Evaporation has historically been the primary technology for liquid concentration in the process industry. Of all the concentration technologies, evaporation process is the least expensive due to the energy

recovery. Extremely high concentration can be achieved by evaporation technology. No other concentration technology can compete with evaporation in this sense as shown in Figure 1.1.

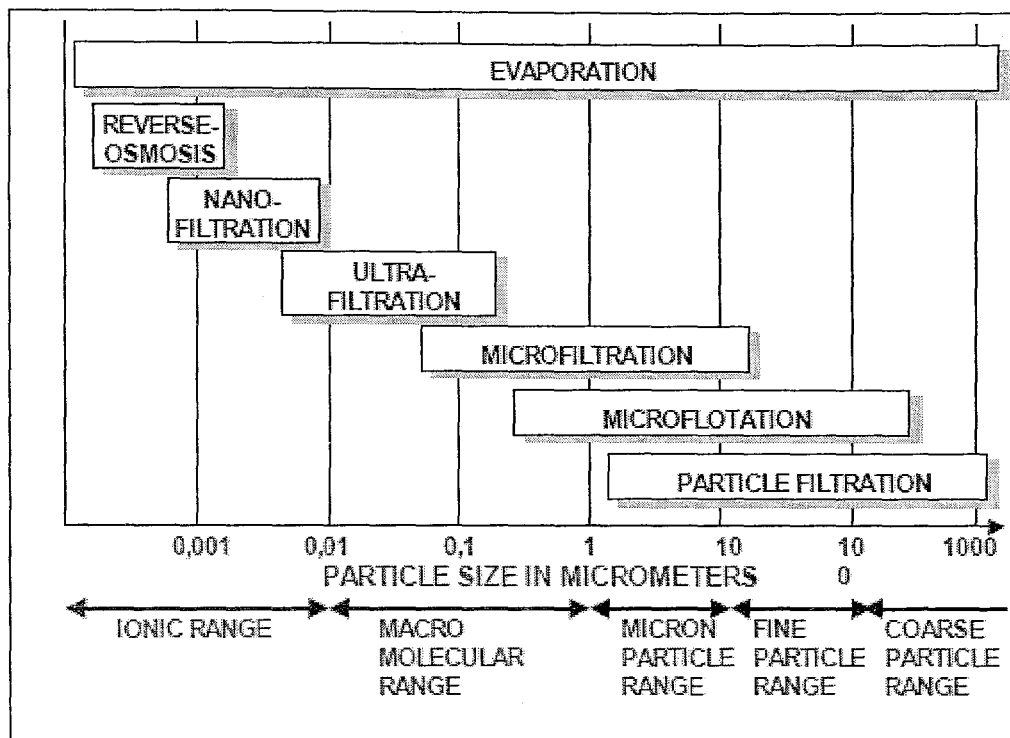


Figure 1.1. Filtration spectrum of separation methods (Petor, 1999).

Tightening wastewater discharge requirements and the increasing scarcity of fresh water is now a day forcing the industry to look for new methods to recycle process effluents. From a technical point of view, evaporation is an ideal method for purification of these streams for following reasons:

- All non-volatile substances can be completely separated.
- No chemicals use.
- Water recovered form the effluent stream is of high quality.
- Evaporated water can be re-used in process or discharged.
- Harmful solids can be concentrated to a manageable amount for appropriate disposal.
- Valuable solids can be recovered and re-used.
- Strict discharge limits can be met

Traditionally, evaporation is highly energy consuming and a lot of effort has, therefore, been done in order to reduce the energy consumption. Requirements for optimal evaporation include: (1) Rapid rate of heat transfer, (2) Low temperature operation, (3) Efficient vapor-liquid separation and (4) Efficient energy use and recovery.

One of the main advantages of evaporation technology is the range of options available for efficient energy use and recovery. Typically, one kg of steam can be used to generate a little less than one kg of vapor through evaporation. Using energy recovery technologies steam economy up to 10 to 20 (Macek, 1995) can be achieved in the Multiple Effect and Vapor Recompression techniques.

In this study, Mechanical Vapor Recompression (MVR) evaporator system is adopted for industrial wastewater treatment, this is the most economical and energy efficient technique. With the MVR evaporator system, all the vapors produced in the evaporator are compressed and recycled to the steam side of the calandria. For initial start-up an auxiliary steam supply or electric heater is required, but no on-site high-pressure steam source is needed. Since all vapor are condensed in the calandria, so no external condenser is needed and water costs are also saved along with high economy. These are the important advantages when compared with other kinds of energy recovery technique of evaporations. Mechanical Vapor Recompression is the best suited for the evaporation of dilute solutions that give lower viscosity product (McCabe and Smith, 1993).

For the study purpose, a pilot scale skid mounted multipurpose Mechanical Vapor Recompression (MVR) evaporator was designed, fabricated and trialed after streamline for different industrial wastewaters for achieving following objectives.

1.1. Aims and Scope of the Study

Study was performed for the treatment of industrial wastewater having several kinds of chemicals and metals, which is always a challenge for the environmental engineers. Followings are the aims of this study.

1.1.1. Volume Reduction

Using Mechanical Vapor Recompression (MVR) evaporator technology, effective volume reduction of wastewater is achieved. Effluents are concentrated before treatment or disposal, reducing costs. In most of the cases the condensate/distillate can be re-used in the process or discharged.

1.1.2. Water Re-uses

The condensate/distillate of MVR system is a water of high quality that can be re-used in the process. This will help saving costs relating to the raw water supply.

1.1.3. Re-use or Recovery of Valuable Components

In many industries process or wastewaters contain valuable components. In some cases it makes economically sense to re-use the concentrate economically in the process, thus saving on raw materials. In other cases, recovery of valuable components (e.g. proteins, metals) is economically interesting, because these components have a market value. Therefore, it was considered necessary to use MVR evaporator system to study of reuse/recovery of valuable components, present in industrial wastewaters.

1.1.4. Cost Analysis

Cost analysis for treatment of industrial wastewater was studied using MVR evaporator system.

2. LITERATURE REVIEW AND BACKGROUND

Reducing waste is one of the greatest challenges facing the industries today. Because water is one of industry's major waste products, the ability to reclaim wastewater for reuse would be a giant step toward overall waste reduction. In general, wastewater can be characterized based on its bulk organic parameters, physical characteristics and specific contaminants. In addition to knowing the characteristics of a specific wastewater, one must also understand the treatment requirements.

Wastewater treatment is generally classified into four levels: primary, secondary, tertiary and quaternary treatment. Each treatment level aims at removing a more specific class of contaminants. Primary treatment involves simple physical processes that remove suspended solids and entrained oil from a wastewater stream. Secondary treatment is designed to remove soluble material from waste streams that cannot be removed by simple physical means. There are numerous secondary treatment technologies available, depending on the constituents to be removed. Tertiary and quaternary treatments are used to polish an effluent to remove a specific contaminant that is not removed in the first and second treatment steps.

In addition to these four levels of treatment, there are four classes of treatment technologies; physical, chemical, thermal, and biological. The specific processes selected to remove contaminants from the bulk aqueous phase can be used either singularly or together in various combinations.

The physical treatment processes typically employed in industrial wastewater treatment are gravity separation, air flotation, oil coalescing, evaporation, filtration, activated carbon adsorption, air or stream stripping, and liquid/liquid extraction.

Chemical treatment processes manipulate the chemical properties of the contaminants to facilitate removal of the pollutant from the bulk wastewater stream or to decompose the compound within the waste stream. The end products of the chemical destruction process can then either be easily separated from the waste stream, or are

innocuous and pose no effluent problems if they are left in solution (such as carbon dioxide and water).

Thermal treatment processes utilize elevated temperatures to bring about the decomposition of contaminants. Metallic species are decomposed to their elemental form either as ash or pure gases, while organic compounds are decomposed to carbon dioxide, water, and halides or halogen gases. Because the conditions of destruction of the contaminant are generally at or near the critical point of water, the entire bulk waste stream undergoes decomposition rather than separation of contaminants of concern.

Biological treatment processes utilize biological and biochemical mechanisms to bring about a chemical change in the properties of the contaminants of interest. The chemical properties are altered under the action of a wide variety of microorganisms to cause the decomposition of the compound within the bulk waste stream.

The research was mainly concerned with the physical treatment of wastewater and amongst those the process of evaporation is most suited for the wastewater of different kinds. Evaporator is the main device for achieving this objective. An unending research is being carried out continuously for improving the efficiency, performance and output of the different evaporators. This research is also one of them. The important types of evaporators are as under.

2.1. Types of Evaporators

In some parts of the world today, common salt is recovered from seawater by direct solar evaporation of seawater in shallow ponds. A variant of this is to heat the liquid in a pan over a fire. However, the simplest form of industrial evaporator is shown in Figure 2.1; it is a simple steam heated evaporator (sometimes called a "still"). In industrial evaporators the heating medium is very commonly process steam (as in Figure 2.1), but sometimes hot oil or special heating liquid is used.

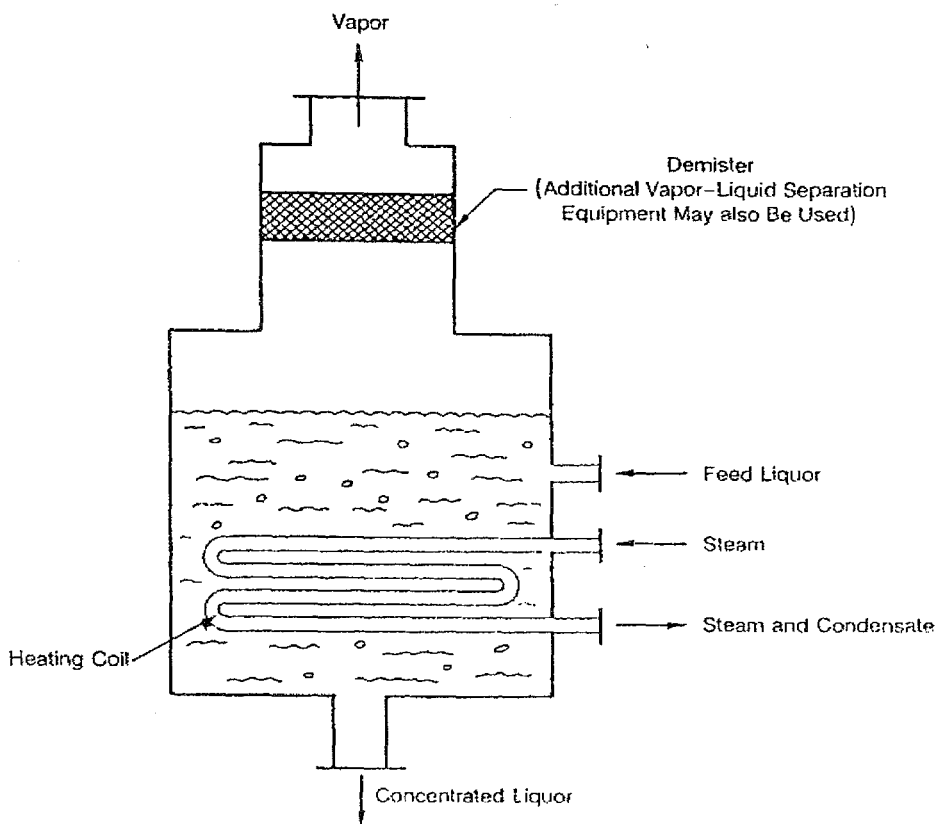


Figure 2.1. Typical pot-type evaporator (Sadik, 1991).

2.1.1. Horizontal Shell-Side Evaporator

The horizontal shell-side evaporator and the kettle reboiler are identical in construction. The horizontal shell-side evaporator is illustrated in detail in Figure 2.2. The heating fluid (usually steam) is supplied to the inside of the tubes in the bundle, and the liquid to be evaporated is on the outside of the tubes. These units are often used as boiler feed-water make-up evaporators, but are otherwise not much used as evaporators. Low entrainment of liquid drops into the vapor is a primary requirement for these evaporators, and the horizontal unit provides a large vapor-liquid surface area for separation in relation to the shell diameter. For economic reasons the shell diameter must be kept at high pressures both on the tube side and the shell side.

The advantages of horizontal shell-side evaporators are:

1. They give a relatively large vapor-liquid separation area.
2. They have a very low headroom requirement and can thus be fitted into confined spaces.
3. They are relatively cheap to construct, though the cost increases fairly rapidly with the shell-side pressure as the shell is relatively large. The large shell is necessary to provide the space for the disengagement of the liquid and the vapor.
4. They provide good heat transfer performance because there is a strong circulation induced within the shell and through the tub bundle.
5. As evaporators they can be used with hard waters; it has been found that the scale formed on the tubes can be removed by draining the shell and rapidly filling the hot tube bundle with cold water to create a thermal shock to crack off the scale.

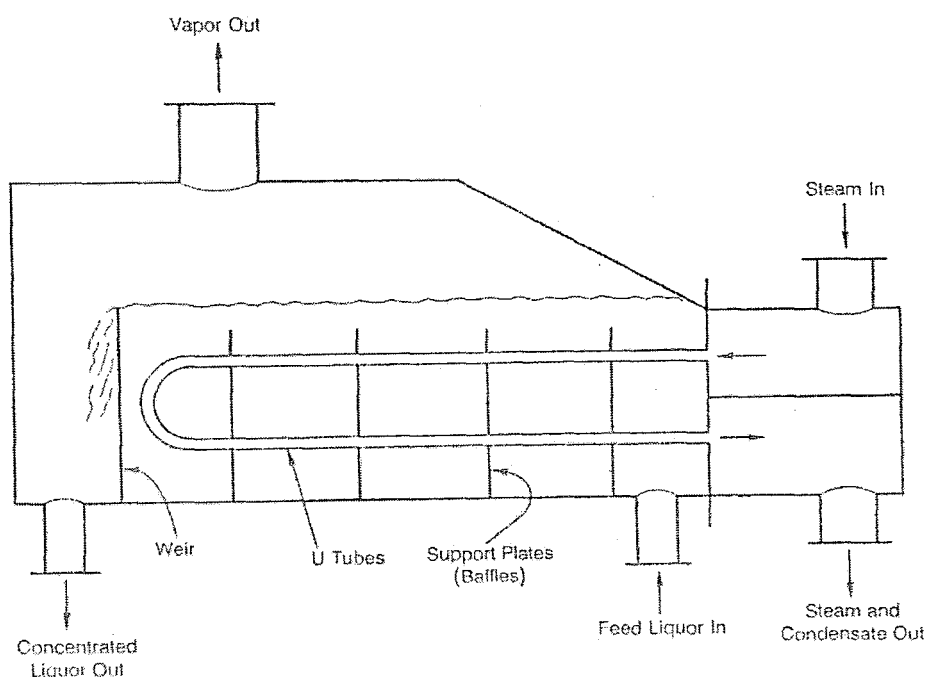


Figure 2.2. Horizontal shell-side evaporator (Charles, 1975).

In general, however, in spite of the comment about hard-water scale, these units are not best suited to the evaporation of fouling liquids. It is common for the most fouling stream to be placed inside the tubes as this surface can be mechanically cleaned. Also they are not suitable for foaming liquids.

2.1.2. Horizontal Falling-Film Evaporator

Falling-film evaporators are usually vertical units, where the liquid falls down inside of the tubes. However, horizontal falling-film evaporators have also been suggested (Figure 2.3). Here the liquid to be evaporated is sprayed on the outside of a horizontal tube bundle. The heating fluid flows inside the tubes. The liquid outside the tubes forms a thin film flowing around the tubes. When it reaches the bottom it drips off, either as drops or possibly as a sheet of liquid, onto the tubes below. The flow is very much like the traditional view of condensation in a horizontal tube bundle: indeed the main difference is that the flow rate of liquid falls going down through the bundle instead of rising.

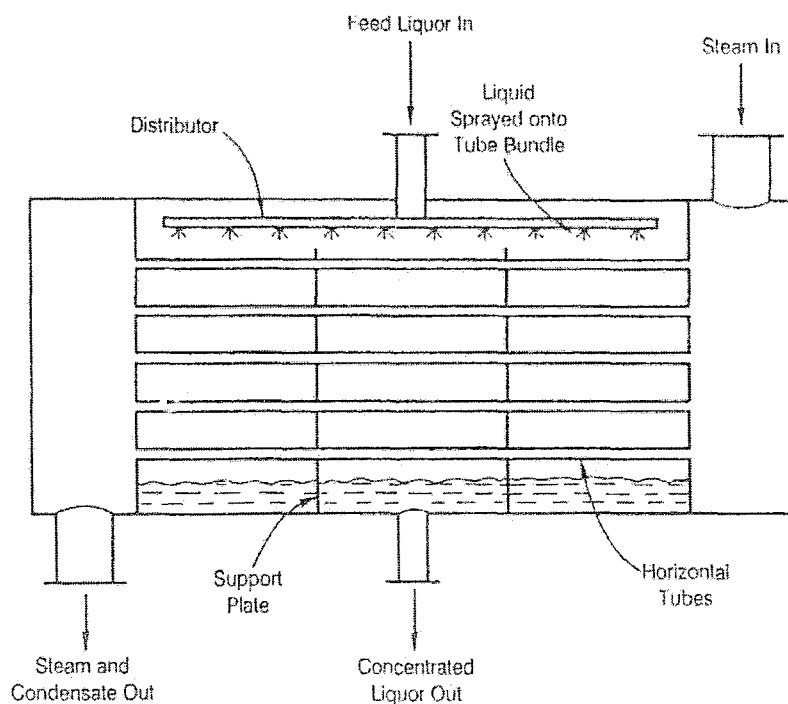


Figure 2.3. Horizontal falling-film evaporator (Othmer et al., 1978).

One particular advantage of these units over conventional film evaporators is that the problem of distributing the liquid is much simpler. In a vertical unit, ideally the same amount of liquid is fed to each tube and distributed uniformly around the periphery of each tube. In the horizontal unit, the distribution can be done as a spray onto the top face of the bundle. Like vertical falling-film evaporators horizontal units give high heat transfer coefficients because the liquid is in the form of a very thin film.

2.1.3. Horizontal Tube-Side Evaporator

This type of evaporator is shown in Figure 2.4, it is also sometimes called the submerged tube forced-circulation evaporator. It consists of a horizontal shell-and-tube heat exchanger with steam or other heating fluid on the shell side. The liquid feed flows on the tube side, it is heated but bulk boiling does not occur because the pressure is high.

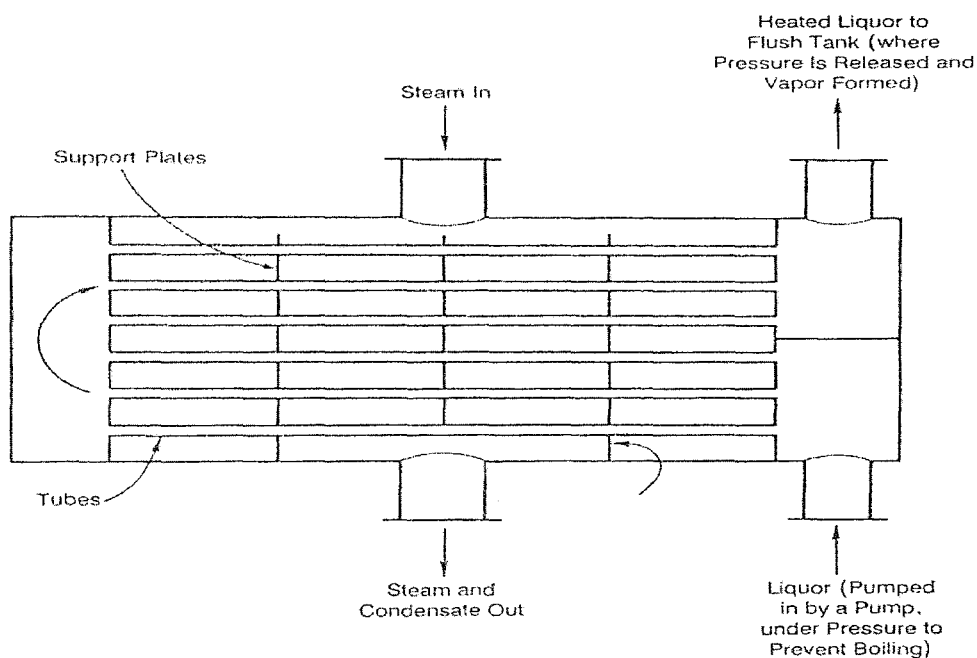


Figure 2.4. Horizontal tube-side evaporator (Othmer et al., 1978).

It should be noted that the prevention of boiling point inevitably means that the heat transfer is relatively poor, though possible some sub cooled boiling may occur if the temperature is only a few degrees below the boiling point. The heated solution flows through a throttle valve and into a separator. As the liquid flows into the separator, some of it flashes to form vapor. The liquid from the separator is recirculated via a pump to the evaporator. A pump is inevitably necessary because of the large pressure loss across the throttle valve. These evaporators are suitable for crystallization of, for example, common salt, and similar duties. They are suitable for such applications because the fact that boiling is prevented in the heat exchanger prevents crystallization on large-scale fouling occurring on the heat transfer surfaces.

2.1.4. Short Tube-Vertical Evaporator

This type of unit is shown in Figure 2.5. It was one of the first types of evaporator to be developed; it is also called "calandria" evaporator. It consists of a relatively squat vertical cylinder, and it has horizontal tube sheets that go right across the shell. The tubes are relatively large in diameter, in the range of 25 to 75 mm, but relatively short (only 1.5 to 2 m long). The tubes are expanded into tube sheets. The larger tube diameters are used for crystallizing evaporators. The evaporating liquid fills the lower part of the vessel and comes part way up the tubes. The tubes are heated from the outside, usually by condensing steam. The liquid boils in the tubes. As the liquid boils, it is carried upward by the steam. The liquid is then returned to the lower part of the evaporator through a large central hole (or "well"). This large hole typically has roughly the same cross-sectional area as that available for flow in all the tubes. This means, in practice, that the central hole has a diameter, which is about half the diameter of the tube sheet. Alternatively, down comers around the outside of the bundle can be used.

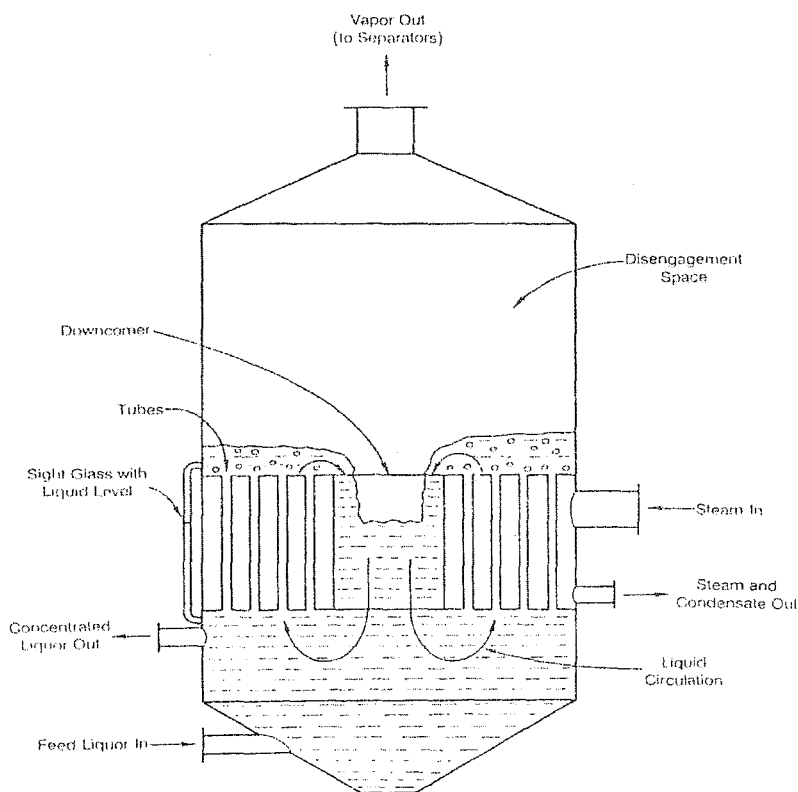


Figure 2.5. Short-tube vertical evaporator (Davinder, 1986).

The magnitude of the liquid velocity up the tubes has an effect on the heat transfer performance: the greater velocity, the higher the boiling heat transfer coefficients. The liquid velocity is influenced by the level of liquid within the whole unit. For the optimum operating level more often the rough rule is used that the liquid level (as indicated by a sight glass) should be between one-half and two-thirds the way up the calandria. If the level is too high, then the saturation temperature will be increased by the hydrostatic pressure effect. This will reduce the heat transfer and the circulation rate. If the level is too low, then there may be incomplete wetting of the upper part of the tube surfaces.

If these units are used as crystallizing evaporators, then it is important to keep the circulation rate high. Assisted circulation is used by putting a large impeller in the central down comer. Such a unit is shown in Figure 2.6. Crystallization is not wanted in the tubes, and so the liquid level is increased, as shown in the Figure 2.6. The pumping unit, if used to increase the liquid flow rate, should be installed at the bottom of the down comer to minimize the risk of cavitations.

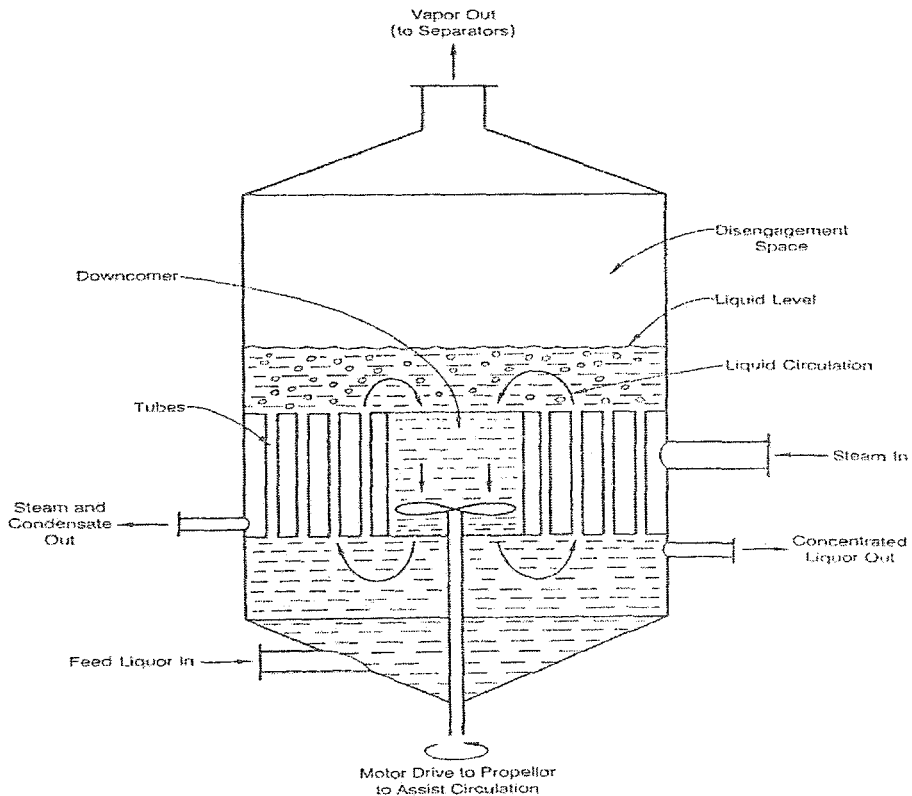


Figure 2.6. Short-tube vertical evaporator used as crystallizer (Davinder, 1986).

The advantages of short-tube vertical evaporators are:

1. They give good heat transfer performance particularly at large temperature differences because large temperature differences lead to high liquid velocities through the tubes.
2. They are relatively cheap to construct and can be built as large units.
3. They are suitable for crystallizing liquids if assisted circulation is used, as in Figure 2.6.
4. They require low headroom.
5. They often have large-diameter tubes and therefore the inside surface, in particular, is relatively easy to clean mechanically. They are thus suitable for fouling liquids.

2.1.5. Long-Tube Vertical Evaporator

The long tube vertical tube evaporator is very similar to the vertical thermosyphon reboiler. The main difference is that the vertical thermosyphon reboiler is, as its name implies, a natural-circulation device. The long-tube vertical evaporator is often equipped with a pump in the feed line as shown in the Figure 2.7. The unit consists of a vertical shell-and-tube heat exchanger. The tubes are usually smaller in diameter, longer, and fewer in number than in the short-tube version. Here the tube length may be up to six meter. Boiling takes place inside the tubes, which are usually heated by steam condensing on the shell side. The vapor-liquid separator may be integral, but is more usually carried out in a different vessel. From the separator liquid phase recirculates to the evaporator.

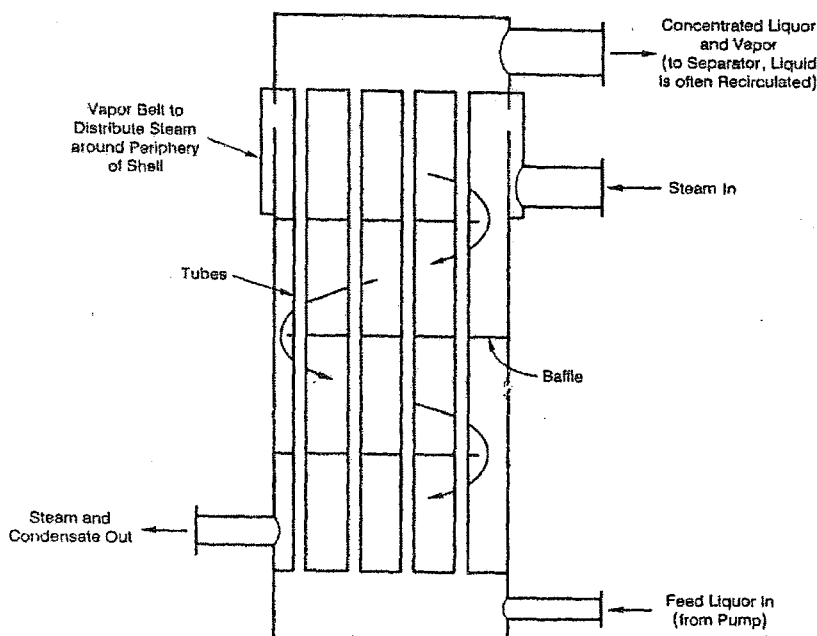


Figure 2.7. Long-tube vertical evaporator (Nicholas, 1993).

2.1.6. Climbing-Film Evaporator

A slight variant on the long-tube evaporator described above is the so-called "climbing-film evaporator". Here the flow into the tubes is relatively low and so a large fraction of the flow is vaporized fairly quickly. This has the result of producing a high vapor velocity which causes the "annular" vapor-liquid flow pattern to be formed. Here most of the liquid flows as a thin film on the walls of the tube, and the vapor flows up the center of the tube. The advantage of the annular flow pattern is that the liquid film is very thin and so high heat transfer coefficients are obtained. A climbing-film evaporator can be used, in some applications, as a once-through device. Here the required concentration is reached in one pass through the evaporator, and so no recirculation of the feed liquid is required.

The change in the saturation temperature due to the hydrostatic pressure effect can make this evaporator type difficult to analyze. If it is operating in a natural-circulation mode (as in a thermosyphon reboiler) without a pump, then calculation of the throughput is particularly difficult.

The advantages of climbing-film evaporators are:

1. They give excellent heat transfer performance.
2. They are generally inexpensive to manufacture.
3. They take up little floor space, but high headroom is needed.
4. The liquid hold-up and the liquid residence time are low. These units are therefore useful for evaporating heat-sensitive liquids, or where a low inventory of liquid is required for safety reasons.

2.1.7. Vertical Falling-Film Evaporator

This type of unit is shown in Figure 2.8. A down-flow evaporator is desirable because it does not suffer from problems brought about by the hydrostatic head effect in up flow evaporators. The feed liquid is arranged to fall as a thin film down the inside of the tubes. The heating fluid (condensing steam or hot liquid) is on the shell side of the exchanger. Because the film is very thin, the heat transfer coefficient for the evaporating film can be very high. The vapor usually flows downwards co-currently with the liquid and the vapor-liquid separator is arranged at the base of the unit.

If it is required to evaporate the liquid below its normal boiling point and vacuum operation is undesirable because the liquid would be oxidized by any leakage of air into the system, then the evaporation may be carried out in a stream of inert gas. For co-current down-flow the inert gas would enter at the top of the heat exchanger and be taken off at the bottom. In this type of unit there may be an advantage in having countercurrent operation as this gives a better concentration driving force for the mass transfer. This means having the inert gas and evaporated vapor flow upwards against the liquid flowing downwards. One danger of such an arrangement is that the flooding limit may be exceeded and the liquid film may no longer be able to flow downwards against the up flow of gas.

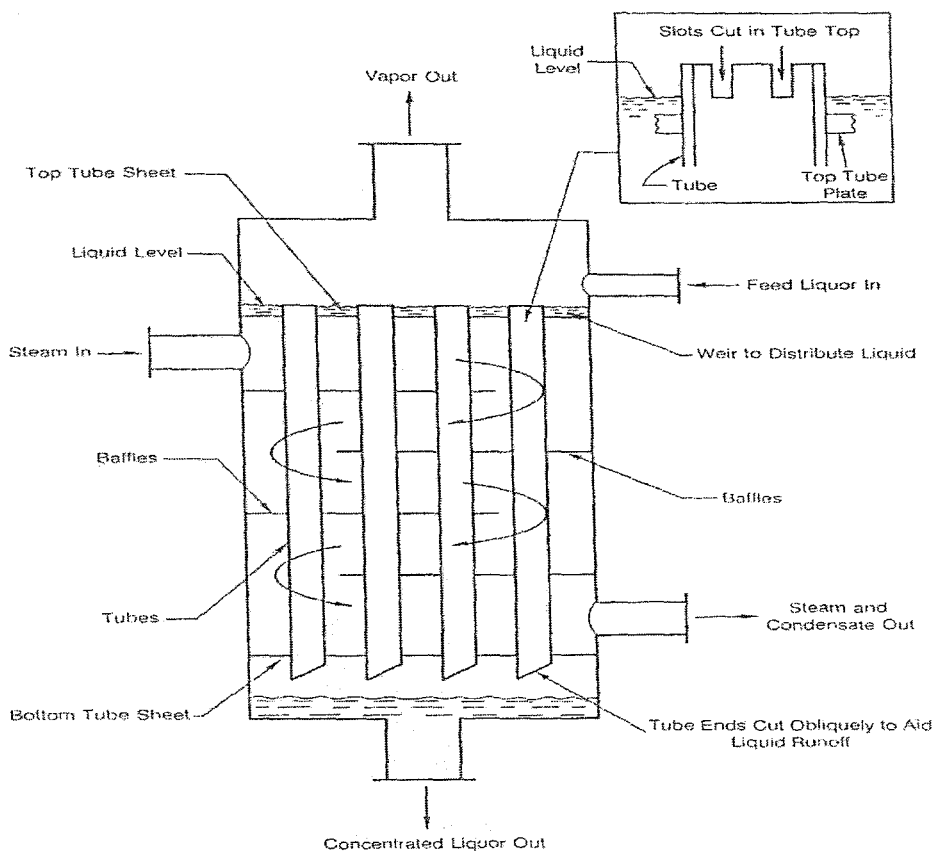


Figure 2.8. Vertical falling-film evaporator (Sadik, 1991).

The main problem with falling-film evaporators is that it is very important to have a good distribution of the liquid feed both uniformly to every tube and also around the circumference of each tube. If this is not achieved then some of the tubes will not be wetted over their entire length. A weir arrangement can work reasonably well provided that the top tube sheet is accurately flat and level; this arrangement is however sensitive to hydrostatic pressure gradients across large tube sheets. Distributors with orifices are often preferable to weirs in that they give a better-feed distribution; however the orifices can become blocked if the feed liquid is dirty. The equal distribution problem is not so severe in horizontal falling-film evaporators.

Both the vertical falling-film evaporator and the climbing-film evaporator produce very good heat transfer performance. However, the falling film unit has the inherent advantage that it is a down-flow device. The falling-film evaporator is, however, slightly larger than the climbing-film unit for a given evaporation duty and therefore more expensive to manufacture. The expense is increased even more because of the delicate

nature of the liquid distributors required. Falling-film evaporators are, however probably the type of evaporator able to operator most successfully at the lowest values of temperature difference between the hot and cold sides of the heat exchanger.

2.1.8. Agitated Thin Film Evaporator

This type of unit is shown in Figure 2.9. The falling film evaporator uses gravity to produce a thin film the climbing film evaporator uses shear stress produced by the vapor flow, and in this evaporator the thin film is produced mechanically; this is done by an integral rotor equipped with blades that spread out the liquid into a thin film (Salden, 1987).

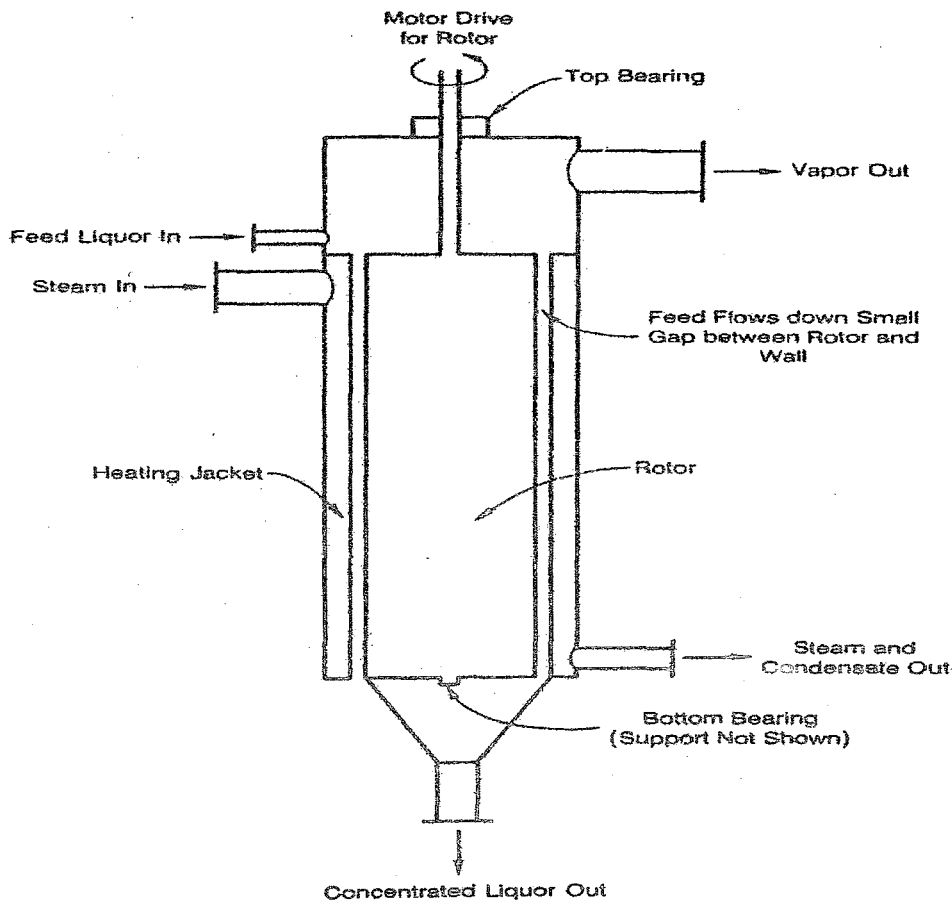


Figure 2.9. Agitated thin film evaporator (Sadik, 1991)

Thin films are of course desirable because they lead to high heat transfer coefficients. Such evaporators are used when the product is:

1. Heat sensitive, for example food products because the residence time on the heated surface is very low, typically in the range of 6 to 40 seconds. In addition the residence time distribution is very narrow so that there is only a small probability of a heat sensitive product being damaged.
2. Known to have a tendency to foam or to foul the heat transfer surface.
3. Highly viscous, as the mechanical action produces the thin film.

As well as producing high heat transfer coefficients under difficult circumstances these evaporators are able to operate at high evaporation ratios.

2.1.9. Plate Type Evaporator

This type of unit is shown in an exploded view in Figure 2.10 (Gray, 1984). Plate heat exchangers can often be used as an alternative to shell and tube exchangers. They are very commonly used in heat transfer to single phase liquids but their use with boiling and condensing flows is less well known. Normal evaporators usually involve condensation of the heating steam, as well as partial vaporization of the feed liquid. There are approaches to using a plate heat exchanger as an evaporator.

The first is to use the heat exchanger as a conventional single-phase heat exchanger by preventing the feed liquid from evaporating by increasing the pressure. When the pressure is released after the heat exchanger, the vapor is formed by flashing (Usher, 1970).

The second approach is to accept that changes of phase will take place in the plate heat exchanger and to modify the exchanger accordingly. Inevitably, a large change of volume occurs, so in the evaporation, for example, provision must be made for the large extra volume of vapor produced. Hence a novel arrangement and design of plates is needed (Figure 2.10). The plates are relatively widely spaced to allow sufficient flow area for the

two phase mixtures. The plate are grouped in sections of four plates as referring to Figure 2.10., and considering the plates from the left.

Plate 1 is a condensing-steam plate. Steam condenses on this plate and heats the plates on each side. This plate has downwards flow, and the condensate is removed at the bottom of the plate. Plate 2 is an evaporation plate. The feed liquid enters at the bottom, and the liquid is partially evaporated as it rises. The plate is heated by the two adjacent condensing-steam plates. The liquid and the vapor are transferred to plate 4.

Plate 3 is another condensing-steam plate. Again the steam condenses in downwards flow, and the condensate is removed at the bottom of the plate. Plate 4 is another evaporation plate that receives the liquid and vapor from plate 2. The liquid flows downwards on this plate, further evaporation taking place as it falls. The remaining liquid and the vapor are removed through the large rectangular port at the bottom of the plate and flow into the separation vessel. Again this plate is heated by the two surrounding steam plates. Plate 5 is the first plate of another group of four.

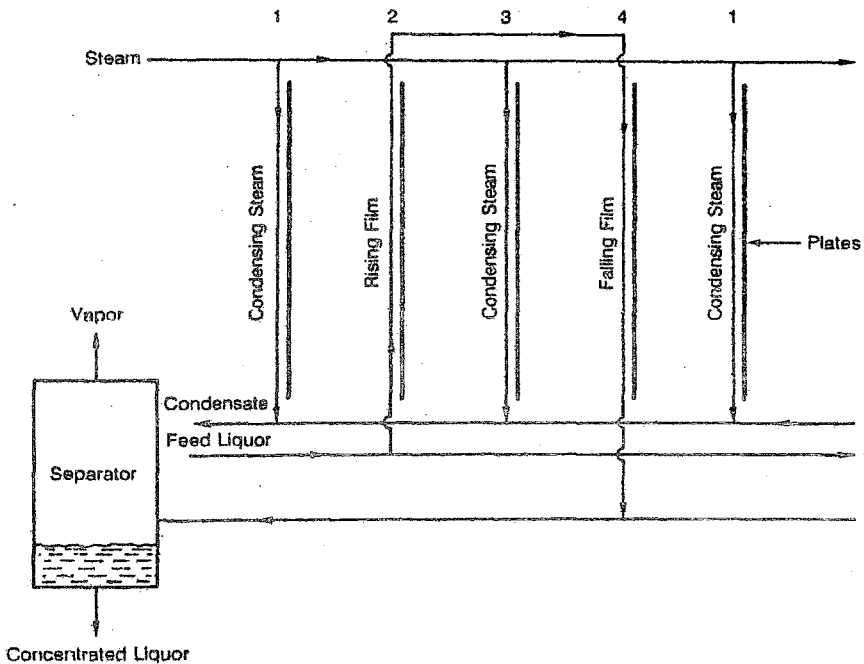


Figure 2.10. Plate and frame type evaporator (Sadik, 1991).

The advantages of these plate-type evaporators are:

1. They can be used with very heat sensitive products, as the residence time is short. In addition, the liquid hold-up on the plates is low.
2. They do not require much headroom typically 3 meter.
3. They give high heat transfer rate. Once again this is a consequence of the liquid being in the form of a thin film.
4. They can be arranged in very flexible group. For example, plate evaporators can be arranged as multiple-effect evaporators. Another consequence of this flexibility is that a number of units can easily be arranged to handle large flow rates.

2.1.10. Submerged-Combustion Evaporator

The primary example of a direct-contact evaporator is the submerged-combustion evaporator as shown in Figure 2.11. Submerged combustion is the combustion of hydrocarbon fuel so that either the combustion itself takes place under liquid, or the hot combustion product gases are released under the surface of the liquid. In either case the energy released by the combustion process is transferred by direct contact with the liquid. Submerged-combustion systems are unusually efficient in that the maximum possible energy is transferred to the liquid.

As indicated previously the burner itself can be submerged in the liquid; however, this is relatively unusual. It has the advantage, however, that the burner is very efficiently cooled by the surrounding liquid. This may mean that refractory material or special steel is not needed for the burner.

The exhaust gas to the stack from any type of submerged-combustion unit will be unusually cool and wet. This of course is a necessary consequence of the efficiency of combustion process. It does mean, however, that the stack gas will be unusually corrosive, and this fact leads to a tendency to use very clean fuels in this type of evaporator.

In the submerged exhaust system, the exhaust gas is released into the annulus between the down comer and draft tube. This has the effect of producing a strong

circulation of the liquid in the tank and so gives good mixing between the hot exhaust gas and the liquid.

Submerged-combustion evaporators have found two main uses. They are used to revaporize liquefied gases. This is done in a submerged-combustion units in two stages. First, the combustion product gases are used to heat water in a tank. Then the hot water in the tank is used to vaporize the liquid that flows through coiled tubes immersed in the liquid. This can be done safely when the direct vaporization of the liquefied gases might be hazardous. Submerged-combustion evaporators are also commonly used in the concentration of corrosive form of chemicals such as sulfuric acid, phosphoric acid, or various forms of chemical waste.

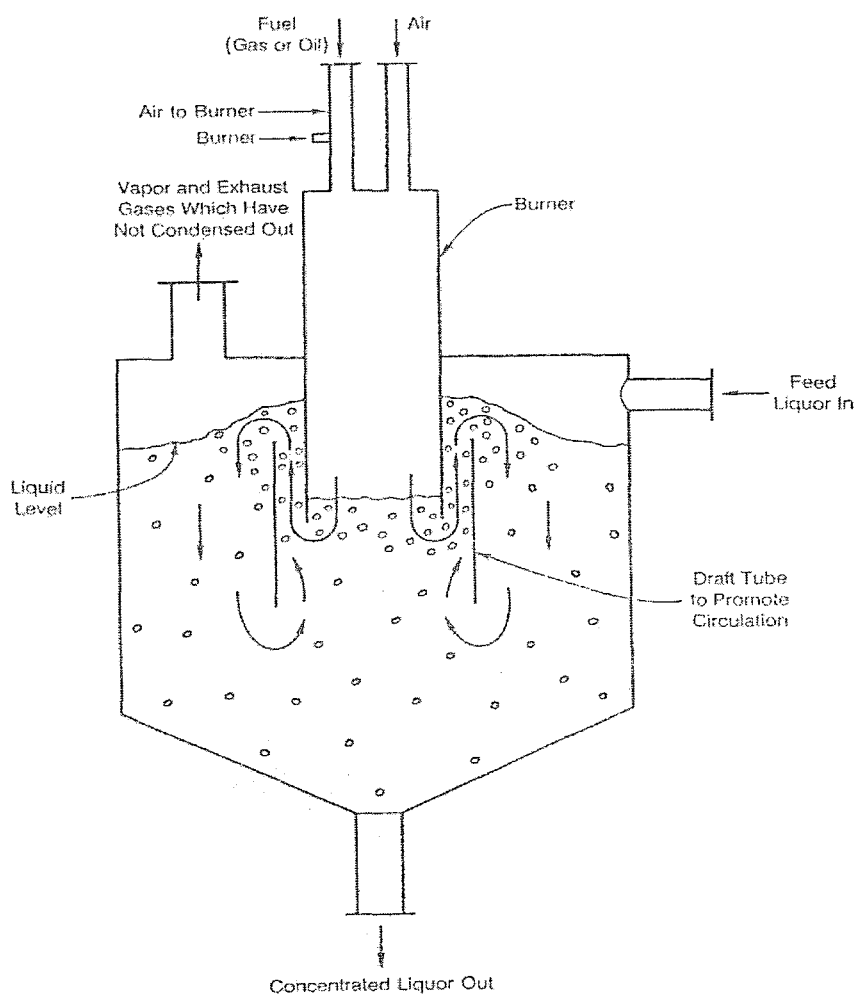


Figure 2.11. Submerged-combustion evaporator (Sadik, 1991).

The main disadvantages of these submerged-combustion units come from the absence of any fixed heat transfer surface, so there can be no corrosion or fouling. They can also handle viscous liquids, very corrosive liquids, and liquid with dissolved solids. The disadvantage, as mentioned before, is the contamination of the liquid by the combustion product.

The application of evaporation technology for the wastewater can be seen from the following Figure 2.12.

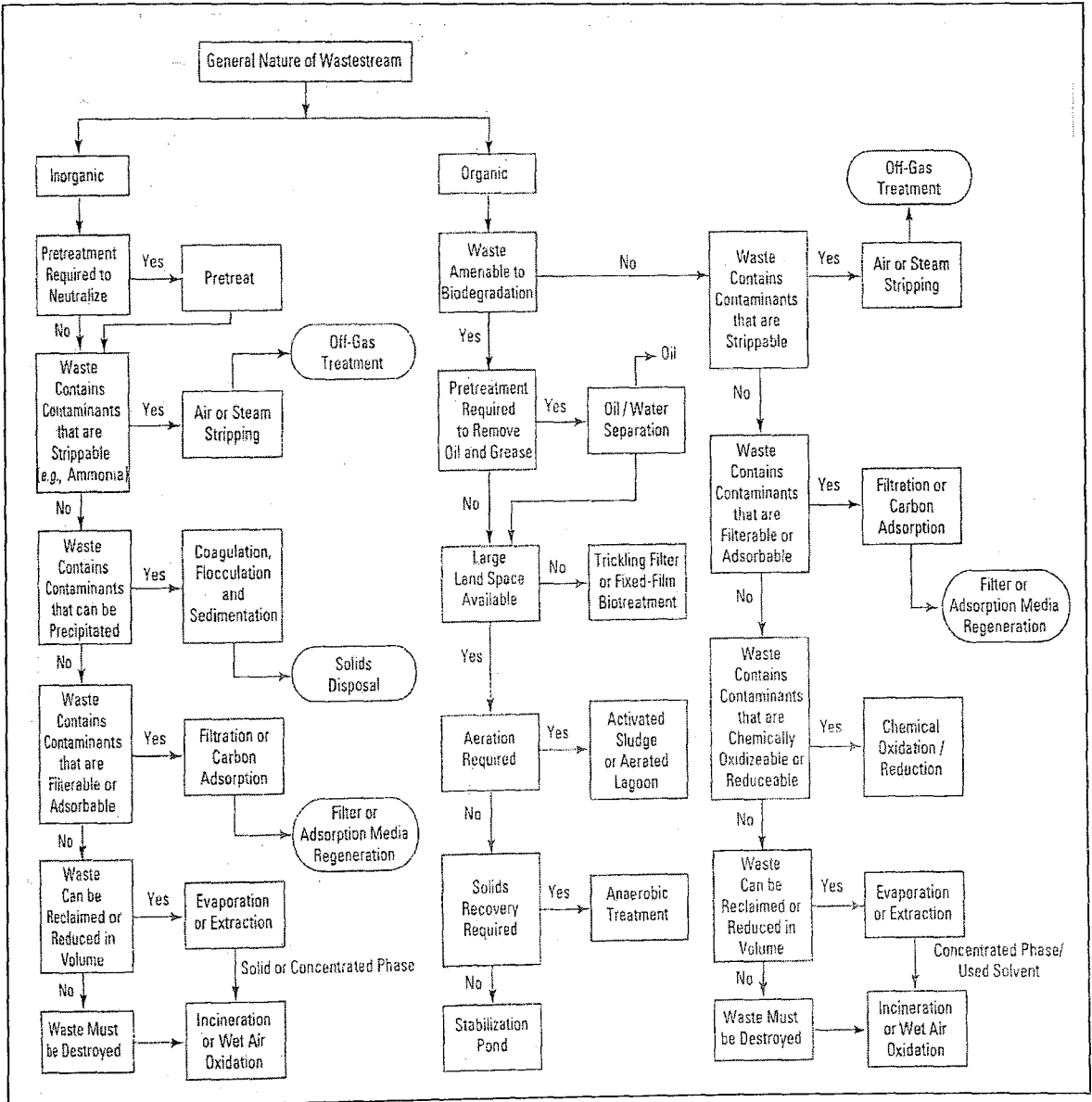


Figure 2.12. Flow chart to select the appropriate wastewater treatment technologies (Dannele, 1995).

2.2. Energy Conservation in Evaporators

Heat extracted from the steam supplied to an evaporator must be sufficient to heat the feed solution to the boiling temperature, supply any heat required to separate liquid solvent from the solution (the opposite of the heat of mixing), and evaporate the solvent (which is normally water). Usually, the last of these is by far the largest, requiring 80-100 percent of the total. Thus, the vapor given off is steam in an amount approximating the amount of steam condensed, only somewhat lower in temperature due to temperature difference required to accomplish heat transfer. This steam given off is usually termed "vapor" to distinguish it from the prime steam, which may be compressed to serve as part or all of the prime steam (thermo compression operation), or may be used to heat another unit boiling at lower temperature (multiple effect operation). These means of conserving energy require a more expensive evaporator than would otherwise be needed but sometime save enough in other investment costs to justify their use on the basis of capital cost alone. Multiple-Effect operation reduces the amount of prime steam needed and hence the cost of boiler. It also reduces the amount of cooling water needed to condense the final vapor and hence the cost of the condenser and water supply system. Thermo compression operation eliminates the need for condenser water entirely and also either eliminates or greatly reduces the size of steam boiler needed.

2.2.1. Multiple-Effect Evaporators

As indicated before in Multiple-Effect evaporation, the basic idea is to make use of the steam generated in one evaporator to act as the heating medium in a second evaporator, and so on. Of course, it is obvious that the second evaporator must be at a lower pressure than the first so that the saturation temperature of the solvent is reduced. Because over the working pressure range of a Multiple-Effect system the latent heat of vaporization varies comparatively little, the steam usage can be reduced by the factor that is almost equal to the number of "effects" in series. The word "effect" in this context simply means an evaporation stage.

Smith (1986) identifies a number of important points that need careful attention if Multiple-Effect evaporation is to produce satisfactory results.

1. Noncondensable gases may be present due to gas coming out of solution as the evaporation proceeds or due to in-leakage of air to effects working at below atmospheric pressure. Such gas means that there is no longer the expected simple relationship between the pressure and the saturation of the liquid.
2. The feed must be heated to as near its initial saturation temperature as possible. If this is not done, then some of the heating in the Multiple-Effect system will be required merely due to this heating.
3. The vapor must be efficiently separated from the vapor. If this is not done then the liquid droplet carry-over will occur, and as the liquid is certainly not pure solvent, scale may be formed on the heating surface of the next effect.

In Multiple-Effect evaporator, the actual reduction in energy input, R , and the number of stages, n , is almost equal. R is defined as the energy input required per kilogram of product in a single-stage evaporator. It is also known as the performance ratio as it defined the energy advantage to be gained by using a multistage process. What then limits the number of stages since it appears that this should be as large as possible? The important variable is the minimum temperature difference between the evaporating and the condensing liquids. In a short-tube vertical evaporator, a minimum temperature difference of about $8\text{ }^{\circ}\text{C}$ in each effect is needed. In addition, in large units the effects of hydrostatic head increasing the boiling point can be relevant. In practice the number of stages, n , and the performance ratio, R , are limited to about 6. An improvement can be made if an evaporator capable of operating at lower value of temperature difference is used. A falling-film evaporator, in which there is also no hydrostatic head effect, can mean that n and R is increased to 10 or even 12. For some applications, a Multiple-Effect evaporator gives a very useful energy saving,

2.2.1.1. Forward Feed. The feed to Multiple-Effect evaporator is usually transferred from one effect to another in series so that the final product concentration is achieved in only one effect. In forward feed operation, raw feed is introduced in the first effect and passed from effect to effect parallel to the steam flow. The concentration of the liquid increases from the first effect to the last and product is withdrawn from the last effect as shown in Figure 2.13.

Forward feed operation is advantageous when the feed is hot or when the concentration product would be damaged or foul at high temperature. Forward feed is the simplest arrangement when liquid can be transferred by pressure difference alone, removing the need for pumping between effects. When a feed is cold, forward feed has a lower energy economy because some steam must be used to provide sensible heat to heat the cold feed to the liquid temperature of the first effect. If forward feed is required and the feed is cold, energy economy can be improved by preheating the feed in stages with vapor from intermediate evaporator effect. This usually requires little increase in total heat transfer surface since the feed must be heated anyway. Further, heat exchangers are usually less expensive than evaporator, especially if gasketed plate exchangers can be used.

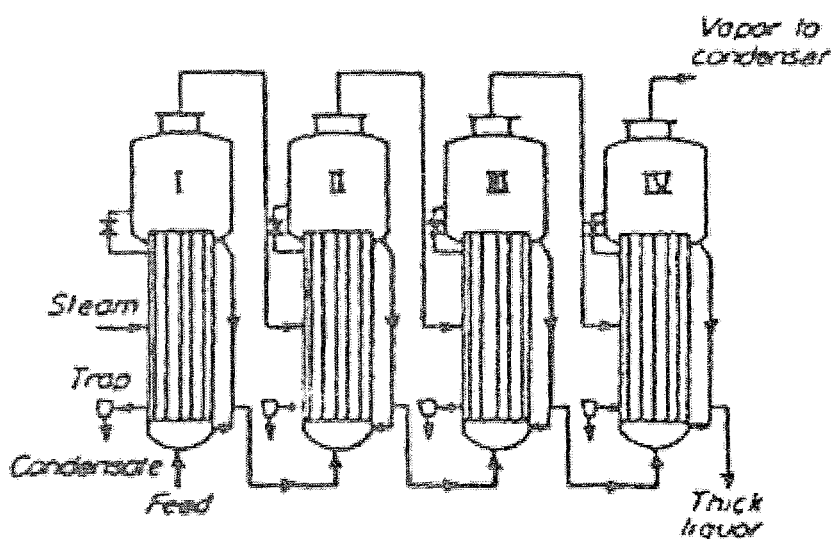


Figure 2.13. Pattern of liquor flow in Multiple-Effect evaporators as forward feed (Minton, 1986).

2.2.1.2. Backward Feed. In backward feed operation the raw feed enters the system at the last (coldest) effect and product is withdrawn from the first effect as shown in Figure 2.14. Pumps must be used to transfer liquid from lower pressure effects to higher pressure effects. This method of operation can be used to advantage when feed is cold since the entering liquid needs to be heated to a lower temperature than in forward feed operation. Backward feed is also used when products are viscous and higher temperature increases the rate of heat transfer. When the product is viscous but a hot product is not needed, the liquid from the first effect is some times flashed to lower temperature in one or several stages and the flashed vapor added to the vapor from one or more later evaporator effects.

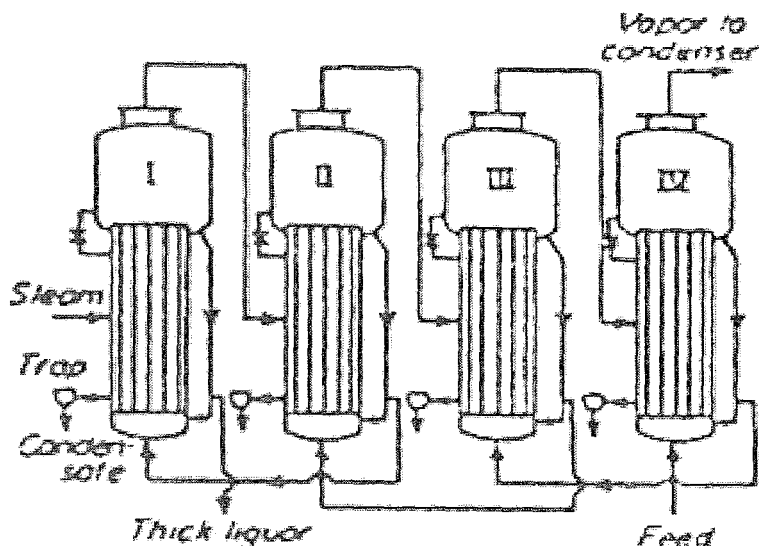


Figure 2.14. Pattern of liquor flow in Multiple-Effect evaporators as backward feed (Minton, 1986).

2.2.1.3. Mixed Feed. In mixed feed operation the feed enters as intermediate effect, flows in forward feed through the later effects, and is then pumped back to the earlier effect for further concentration as shown in Figure 2.15. Operation in the earlier effect can be either backward feed or forward feed. This eliminates some of the pumps needed in backward feed and permits final evaporation at the highest temperature. Mixed feed operation is used only for special application. Sometime liquid at an intermediate concentration and certain temperature is required for additional processing. The feed temperature may be close to that of an intermediate stage and mixed feed may result in greater energy economy.

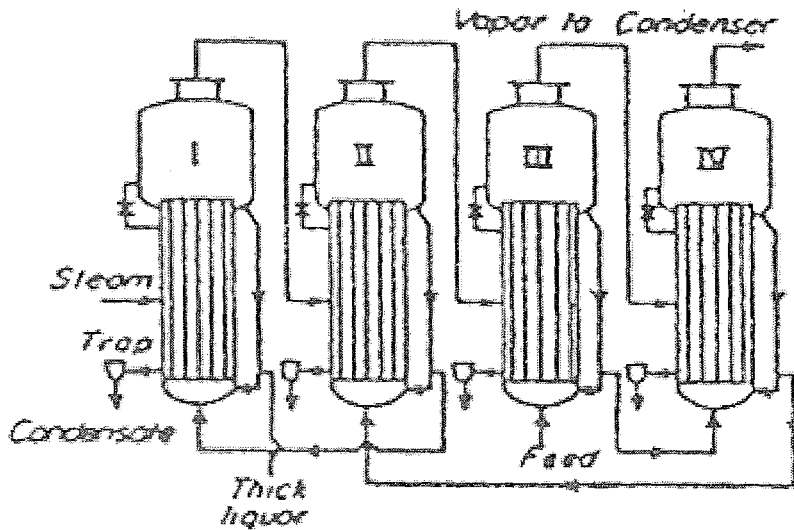


Figure 2.15. Pattern of liquor flow in Multiple-Effect evaporators as mixed feed (Minton, 1986).

2.2.1.4. Parallel Feed. Parallel feed operation requires the introduction of raw feed and the withdrawal of product from each effect as shown in Figure 2.16. In parallel feed there is no transfer of liquid from effect to effect. It is used primarily when the feed is saturated and the product is solid. All effects may operate at the desired product concentration or they may operate at different concentrations and final product obtained by blending.

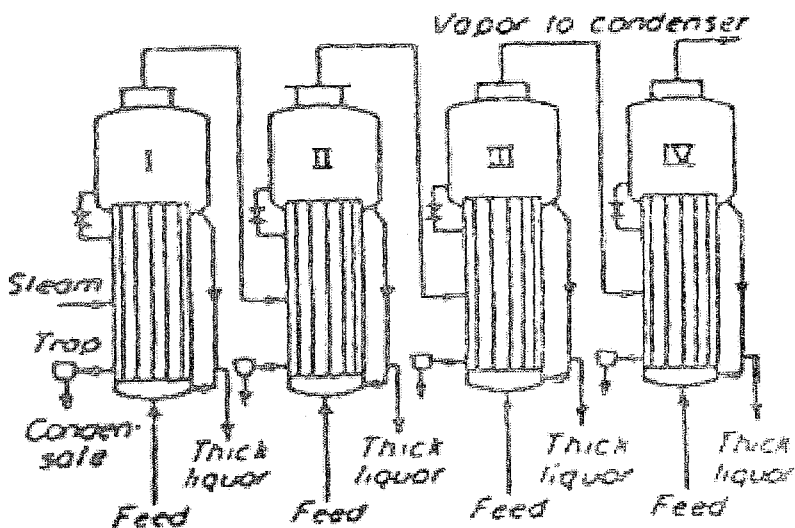


Figure 2.16. Pattern of liquor flow in Multiple-Effect evaporators as parallel feed (Minton, 1986).

2.2.2. Vapor Recompression Evaporator

In this method of energy conservation, water vapor from an evaporator is compressed and returned to the calandria at a pressure, which makes it suitable for reuse as a heating medium. These systems can result in considerable savings in overall energy requirements when compared with Multiple-Effect evaporation.

Two methods of recompression are available:

1. Thermal Vapor Recompression or steam jet (TVR), in which a steam jet compressor is used to compress the vapor.
2. Mechanical Vapor Recompression (MVR), where a mechanical compressor is employed.

2.2.2.1. Thermal Vapor Recompression (TVR) Evaporator. With this method only part of the vapor from the separator of the evaporator is exhausted to the condenser. The other part enters a steam jet compressor, fed with boiler house steam at a pressure of about 10 bar (Bernnan et al., 1990). It has no moving parts. A single-effect evaporator with a thermal vapor recompression system has a steam usage comparable to that of a double-effect evaporator operating under the same conditions with vapor recompression. The thermo-compressor is specifically designed so that the resulting steam mixture leaves at the pressure-temperature conditions required on the steam side of the calandria. This means that thermal vapor recompression system lack flexibility though they are quite efficient when working at, or very near, their specific design condition. For maximum economy they require low temperature differences across the calandria.

Steam jet thermo compression is advantageous when steam is available at a pressure appreciably higher than can be used in the evaporator. The steam jet can serve as a reducing valve while doing some useful work. The efficiency of a steam jet is quite low and falls off rapidly when the jet is not used at the vapor-flow rate and terminal pressure condition for which it was designed. Consequently multiple jet are used when wide variations in evaporation rate are expected. Because of the low first cost and the ability of handle large volumes of vapor, steam-jet thermo compressors are used to increase the

economy of the evaporators that must operate at low temperature and hence can not be operated in multiple effects. The steam-jet thermo compression evaporator has a heat input larger than that needed to balance the system, and some heat must be rejected. This is usually done by venting some of the vapor at the suction of the compressor.

2.2.2.2. Mechanical Vapor Recompression (MVR) Evaporator. Mechanical Vapor Recompression (MVR) is a modern concept for high-volume evaporation. Due to the need to operate on low temperature differences, it is desirable for mechanical recompression that high heat transfer coefficients should apply and this in turn leads to the use of film type evaporators. Since low temperature difference is a necessity, boiling point rise or hydrostatic head effects should be avoided, as both will reduce the temperature difference still further. Moreover, electrically operated, direct fans, which are simpler and much cheaper than turbo-compressor can be used. They give lower compression ratios and correspondingly lower temperature elevations than thermo-compressors, i.e. 4-7 °C as compared to 10-15 °C.

2.3. Pragmatic Comparison of MVR Evaporation System with Contemporary Techniques

A great many industries have adopted process technologies to minimize effluent loads. To achieve zero discharge status, contaminants must be removed from the effluent, producing clean water suitable for reuse in the process. For example for the paper industries processes with potential applications include various concentration and separation processes such as freeze crystallization, evaporation, ultra filtration, flotation, distillation, and reverse osmosis to separate contaminants from the water. These are commercial technologies, but their application to effluents from mechanical pulp mills was relatively unproven until the 1990s. To date, two basic approaches have been tried to achieve zero discharge. In one approach, steam driven evaporation is used to concentrate contaminants, which are then incinerated. The other approach uses freeze crystallization as the primary technology, followed by evaporation. Currently, all zero discharge mills utilize evaporation as the primary separation method. Some of them are as under.

1. Makeup freshwater treatment of *Millar Western Pulp (Meadow Lake) Ltd.* – *Meadow Lake, Saskatchewan, Canada*, includes clarification, filtration, reverse osmosis, and zeolite softening. Process wastewater, which carries wood waste and chemicals, is sent to a flotation clarifier, where suspended solids are removed. It is then concentrated in a three-stage Mechanical Vapor Recompression (MVR) evaporation system and steam-driven liquor concentrator. Strong liquor is combusted in a small recovery furnace. A portion of the smelt is recycled and the remainder is stored for future use in a lined landfill. Ninety percent of the distillate is reused directly in the pulp mill as freshwater makeup, with the remainder sent to a biological treatment pond and storage reservoir until needed as process water. Mechanical vapor recompression evaporation instead of multiple effect evaporation was selected in part because lower shell-side temperatures reduce scaling tendencies. Silica containing scales are minimized by controlling chemical additions and are removed by caustic washing. Organic acid washing is used to remove carbonate scales. To date, silicate scaling has not been an issue and the evaporators operate at 90 percent of design capacity.
2. The freeze crystallization process was selected by *Tembec (formerly Louisiana-Pacific) Chetwynd British Colombia, Canada* paper mill. But, later on, a number of difficulties were encountered and the plant could not operate at the rate and quality required. So, the system converted to an evaporation-based system, the mill sought to reuse existing equipment. The crystallizer bodies were converted into Mechanical Vapor Recompression (MVR) evaporators. Pre and post-evaporator treatments were improved, a process stage to deactivate scale-forming (calcium) material was added, and a recovery boiler to combust concentrate was added. The evaporation system was successfully started up and operated from 1993 to 2001. Excellent water quality was obtained from the evaporation system. The power consumption was 18 to 22 kWh/ton of water. In 1997 the MVR evaporators had some scaling issues, and were being taken out of service for 24 hours every 60 days for pressure cleaning.
3. To application of IPPC (integrated pollution and prevention control) regulation, Andritz has formed an alliance with the Finnish company, Hadwaco, to combine

improved pulp washing with a process (evaporation) that can concentrate the wash water stream even further, generating clean water for re-use and a concentrate for disposal. Using Mechanical Vapor Recompression (MVR) evaporation, pilot scale tests have been carried out at two mills so far, one of them being the stone ground wood mill of Stora Enso at Kabel in Germany. This process stream has an appreciable concentration of suspended solids as well as of dissolved organics and dissolved salts, so pre-treatment with flotation/filtration was necessary. At a concentration factor of 20 to give a concentrate with 11 percent total solids, the evaporator removed about 95 percent COD (chemical oxygen demand) and 99 percent salts. The residual COD included a contribution from methanol in the first stage condensate, which could be separated to improve the quality of condensate for re-use. A further concentration to 50 percent total solids was achieved in a steam driven, forced circulation evaporator so that it could be burnt in an incinerator such as the pressurized, oxygen-based Conox unit. Projected costs for COD removal are favorable compared to conventional aerobic biological treatment (Webb, 2001)

4. Debarking effluent of *Stora Enso Oyj, Fine Paper – Varkaus Mill, Finland* is concentrated by evaporation and added into the black liquor. The debarking plant, operated in two shifts, consists of three wet debarking drums. The plant has been operated with a closed water loop since 1996. A Mechanical Vapor Recompression (MVR) evaporator is fed 24 h/d with 1000 m³/d filtrate from the bark presses. All the condensate is fed into the debarking drums and is blended into the weak black liquor at 20 percent solids. The combusted COD varies between about 10 (summer) and 20 (winter) tons/day. The total energy consumption is 17 kWh/m³ of water evaporated. Scaling is controlled by adding alkali to the feed and manually cleaning the heat transfer surfaces once a year.
5. Bowater Inc., in USA, manufactures market pulp, newsprint, and coated magazine paper. During the processing of green wood chips, which are half water and half fiber, the water is converted to steam as the fibers are separated, processed, and pumped to paper machines to be converted to paper stock. The company wanted to capture the energy lost in this low-pressure steam it vented

from its seven thermo mechanical pulping (TMP) refiner lines. To convert the steam to energy, Bowater installed two Mechanical Vapor Recompression (MVR) evaporator that efficiently converted the 1.31 bar steam at 121.11 °C to 3.93 bar steam at 243.33 °C. The converted steam could then be used to power the drying stage of the paper production operations. The MVR compressor also has a turndown of 50 percent, allowing it to adapt to changing amounts of steam, which optimizes energy use.

Achievements:

- Annual energy savings of one million US\$ paid back the 1.5 US\$ million investment in 1.5 years.
- About 200 gallons of turpentine (a TMP byproduct) is recovered daily for re-sale, reducing atmospheric emissions and providing additional income.
- By preventing steam from escaping, 100 gallons of water per minute is saved, which saves about 144 US\$ per day.
- Controlling the steam vapor once it is released into the atmosphere reduces the plant's noise level.

2.4. Types of Wastewater

2.4.1. Oily Wastewater

Oil and grease in wastewaters pose a vexing problem for wastewater treatment facilities attempting to recycle water and staying compliance with permissible discharge limits. Their removal is necessary for prevention of their deposition on pipes and fouling filtration media. Furthermore, because of their flotation on surface as a film they cause reduced re-aeration and reduced light penetration in natural waters consequently causing depletion of dissolved oxygen and reduction in photosynthesis respectively (George, 1998).

There are numerous reports concerning separation of oil from effluents. The difference in the characters of the wastewater may lead to the selection of a single or combinations of the following methods.

Oil is removed usually from wastewater mainly by using the dissolved air flotation technique. Dissolved air flotation uses air to increase the buoyancy of smaller oil droplets and enhance separation of oil droplets with size greater than 40 μm can be effectively removed by applying DAF units. However, the flotation rate occasionally would be smaller than predicted. DAF units typically employ chemicals to promote coagulations and increase floc size to facilitate separation (Cheryan and Rajagopalan, 1998).

The increased temperature reduces the viscosity of the oil and heating that often changes the solubility relationships of the natural emulsifiers in the oil so that the emulsion is broken and the water can be removed (Lissant, 1983). Due to economic considerations, heating is normally combined with other methods such as chemical method.

Ambler (1961) described the performance of a centrifuge in equilibrium with the external force supplied by the centrifuge under stoke's region. The centrifuge acts to increase the effective gravitational force and the rate of settling. Centrifugation is normally applied to oily sludge though it might be employed for small volumes of dilute oily wastes in special cases (Nebolsine, 1970). Benitto et al., (2002) explained that splitting of the oil and water faces required the addition of chemicals at a certain concentration before the application of centrifugation to oily wastewater.

Hydrocyclone separation is similar to centrifugal separation except that two liquids with different densities (oil and water) form a mixture (Bokotko et al., 1996).

A series of studies on the separation of oils from water emulsions by using hydrocyclone have been reported (Beeby and Nikol, 1997). Using turbidity as a measure of concentration for emulsified oil in water, a 96 percent removal was obtained from the under flow of a feed oil of concentration of 440 mg/L (Beeby and Nikol, 1996).

Coalescers and precoat filtration are effective in reducing high level of oil and grease in the appropriate particle size range. Typically, precoat filtration and coalescers and precoat filtration and coalescers are used for separating particles in the 20-100 μm size range. This method is not suitable for the treatment emulsified oil, since emulsified oil has droplets typically less than 20 μm (Cheryan and Rajagopalan, 1998).

Electrical coalescence is one of the most extensively used methods for the de-emulsification of oily wastewater (Hendricks and Sadek, 1977 ; Sadek and Hendricks, 1974).

Although using an electrical field can achieve high separation rates in many cases, its high energy consumption and problem of industrial safety are still causing severe limitations. Tirmizi et al. (1996) applied a combination of electrical fields and microfiltration by hollow-fiber membrane. This method is particularly suitable for emulsions with high concentrations.

The chemical emulsion break is based on introducing a chemical agent which counteracts the stabilizing influence of naturally present emulsifying agents. Inorganic chemical agents are used as well as polyelectrolytes for the destabilization of oil droplets. Wastes containing emulsified oils can be clarified by coagulation (Eckenfelder, 2000).

Evaporation and incineration is more universal and perhaps more suitable for many types of oily wastewaters. The combustion (incineration) method is based on the fact that organic impurities are fully oxidized (burned) at high temperature with production of non-toxic gaseous combustion products and solids (Pushkarev et al., 1983).

2.4.2. Chrome–Laden Wastewater

Industrial wastewaters often contain considerable amounts of heavy metals that endanger public health and the environment, if discharged without adequate treatment. Heavy metals such as Pb, Hg, Cr, Ni, Cd, Cu, and Zn, which are usually associated with toxicity (Alloway and Ayers, 1993). Major anthropogenic sources of heavy metals in the environment include metal extraction, metal fabrication and surface finishing, paints and pigments, as well as the manufacture of batteries. Chromium in industrial waste is primarily present in the form of hexavalent Cr (VI) as chromate (CrO_4^{2-}) and dichromate ($\text{Cr}_2\text{O}_7^{2-}$). Chromium has widespread industrial applications; hence, large quantities of chromium are discharged into the environment. The major industries that contribute to water pollution by chromium are mining, leather tanning, textile dyeing, electroplating, aluminum conversion coating operations, plants producing industrial inorganic chemicals and pigments, and wood preservatives (Udy, 1956).

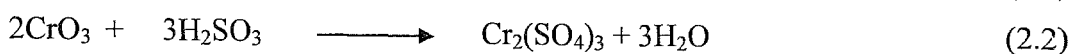
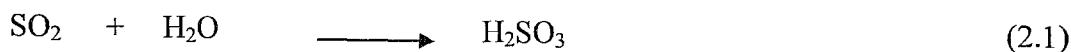
The effluent from the industries may contain chromium at concentrations ranging from tenths to hundreds of mg/L. Chromium is considered by the IARC (1982) as a powerful carcinogenic agent that modifies the DNA transcription process causing important chromosomal aberrations (Benoit, 1976 ; Marshall, 1979 ; Nandy et al., 1990). Moreover, the presence of chromium in water causes serious environmental problems as mentioned by Muir (1977). The National Institute for Occupational Safety and Health (NIOSH) recommends that the levels of chromium in water should be reduced to 10^{-3} mg/m³. The metal is reported to be bioaccumulated into flora and fauna, creating ecological problems (Bharti et al., 1979 ; Knocke and Kelley 1987). Chromium toxicity to mammals and aquatic organisms appears to be lower compared to other heavy metals, due to the general low solubility of Cr (III) compounds, low mobility in the environmental compartments and limited availability to living organisms. However, the possibility that organic ligands and/or acidic conditions in the environment increase Cr (III) mobility, that MnO₂ oxides, present in soils, favor the oxidation of Cr (III) to the more toxic and mobile Cr (VI) forms cannot be excluded (Tiravanti et al., 1997).

The level of chromium in discharged wastewater should be reduced, or recycled if possible. Previous researchers reported reasonable methods, from the economical and technological point of view, to remove heavy metals in general from superficial waters, with the aim of the preservation of the entire ecosystem from the damages due to their accumulation (Chiarle et al., 2000).

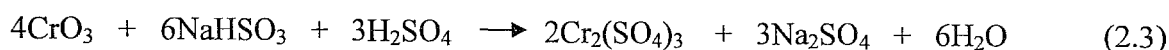
Several methods are utilized to remove chromium from industrial wastewater. These include: reduction followed by chemical precipitation (Zhou et al., 1993); ion exchange (Tiravanti et al., 1997); reduction (Seaman et al., 1999); adsorption (Dahbi et al., 1999); electrochemical precipitation (Kongsricharoern and Polprasert, 1996); solvent extraction (Pagilla and Canter, 1999); membrane separation (Chakravarti et al., 1995); cementation (Lin et al., 1992) etc. Among them reduction of Cr (VI) to Cr (III) is used more commonly than others.

2.4.2.1. Reduction and Precipitation. Reduction of hexavalent chromium from a valence state of plus six to plus three, and subsequent precipitation of the trivalent chromium ion is the most common method of hexavalent chromium disposal. Methods of reduction of

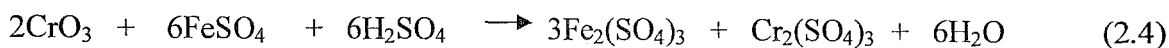
hexavalent chromium vary with each particular plant. Common reducing agents are gaseous sulfur dioxide, sodium bisulfite, metabisulfite, hydrosulfite or ferrous sulfate. During reduction sulfuric acid is normally added to maintain an acid solution with a pH range of 2.0 to 3.0, which is more important. Under these conditions, the reactions that occur are:



The reaction with bisulfite is



The reaction with ferrous sulfate is



With ferrous sulfate, however large quantities of sludge are produced than with sulfur dioxide or bisulfites.

After reduction, the acid solution is neutralized by sodium hydroxide or hydrated lime. As a result metals converted in to hydroxide form and settled easily. Shink (1968) achieved an effluent containing less than 1.0 mg/L hexavalent chromium and 2.0 mg/L total heavy metals, via the reduction-neutralization-precipitation treatment sequence.

These methods suffer from some drawbacks such as high capital and operational costs or the treatment and disposal of the residual metal sludge.

2.4.3. Zinc Galvanizing Wastewater

Electroplating processes are one of the major industrial contributors of heavy metal-laden effluents into the environment. Zinc is most often found in plating, galvanizing and roller coating operations. As only 30 to 40 percent of all metals used in plating processes

are effectively utilized (plated on the articles), waste effluents from acid- Zn^{2+} -plating lines are responsible for high amounts of Zn^{2+} encountered in electroplating discharges (Grebenyuk et al., 1996). Zinc is the fourth largest metal consumed in the world (behind iron, aluminum and copper). Zinc is highly toxic like some other heavy metals as it is carcinogens and mutagens in nature (Moore and Ramamoorthy, 1984). The removal of toxic metal ions is a very difficult task due to the high cost of treatment methods especially for underdeveloped countries (Weng and Huang, 1995). A number of methods are available for the removal of metal ions from aqueous solutions. These include ion exchange, solvent extraction, reverse osmosis, precipitation, coprecipitation and adsorption.

Chemical precipitation with lime or caustic soda is one of the common conventional treatments, where recovery of metals or water is not a consideration. However, to effectively decrease metals to acceptable levels require a large excess of chemicals, which generates volumetric sludge and increases the costs (Spearot and Peck, 1984). Other available treatments such as ion exchange, electrolysis and reverse osmosis require high capital investment and running costs.

The characteristics of zinc coatings that determine their corrosion performances are their intrinsic resistance to corrosion and their ability to protect the basis metal. Zinc coatings are unique among corrosion-protective measure since they not only protect by simple coverage with a sheath of rust-resistant metal to seal out corrosive moisture, but they also provide added protection through galvanic action, sacrificing themselves slowly in the course of saving the basis metal from rust. Zinc is much more resistant to corrosion than steel, especially in very dry climates where the rate of attack is very extremely slow. The behavior comparisons show that the corrosion rate of iron versus zinc is 25 to 1 in marine atmospheres and 15.7 to 1 in industrial areas (Willam, 1964).

Zinc is absolutely essential for the normal healthy growth and reproduction of all higher plants, animals and humans and is therefore called an "essential trace element" or a "micronutrient". Even where optimum amounts of manures and/or fertilizer nutrients (N, P and K) and water requirements have been satisfied, a crop will not achieve its full potential yield if its supply of zinc is inadequate. A very wide range of crops are affected by zinc

deficiency, including: cereals (rice, wheat and maize), fodder crops (sorghum and sudangrass), pulses (beans, chickpeas and soybeans), bush and tree fruits (apples, citrus, peaches), nuts (pecans), vegetables (potato, onion and sugarcane) and non-food crops such as cotton and tobacco.

Zinc is applied to crop normally in the form of zinc sulfate and it is basically used as a soil nourisher. It has numerous pleasant effects on the crop and soil such as:

- Increases fertility of the soil.
- Plant remains healthy and evergreen. Leaves do not turn yellow or brown prematurely.
- Growth rate of new shoots is high, due to which quantity of produce is high.
- Resistance power of the plant to various diseases is enhanced.
- Capacity of the plant to absorb other nutrients increases.
- Protects maize crop from "White Bud disease", Cotton from scorching of new leaves and therefore stunted growth and other crops from various other diseases.
- Yield increases by 25 percent and the farmer gets 4-5 times return on the sowed crop.
- In fruit trees there are no symptoms of clustering of leaves or drying of branches

Zinc sulfate is used in fertilizers, sprays and animal feeds in which it serves as a valuable trace element and disease-control agent. In the manufacture of rayon, it is a crenulating agent in the precipitation bath. It is also the starting material for the manufacture of many zinc chemicals and is used in textile dyeing and printing, flotation reagents, electrogalvanizing, paper bleaching, and glue (Othmer et al., 1978).

2.4.4. Textile Wastewater

The textile industry is one of the most complicated industrial chains in manufacturing industry because of its fragmented and heterogeneous character. Raw natural or man-made fibers are converted into finished apparel and non apparel textile products. Textile establishments receive and prepare fibers, transform fibers into yarn, thread, or webbing, convert the yarn into fabric or related products and dye and finish these materials at various stages of production. Established patterns of activity exist, with

finishing mills tending to concentrate on particular kinds of make-up or end-product, rather than the fiber type used.

The main environmental impacts of the textile chain derive from the so called "wet processes", mainly implemented by the textile finishing industry. Finishing processes aim at giving fabrics the visual, physical and esthetic properties demanded by consumers and includes four main stages: fabric preparation, dyeing, printing, and special finishing. The combination of unit processes applied varies greatly in function of the end-products, applications and site-specific manufacturing practices. Water is used as the principal medium to remove contaminants and to apply dyes and finishes. On average, 90 percent of the water input in textile finishing operations needs to be treated at the end-of-pipe and 1 kg of chemicals and auxiliaries is processed per kg of textile products. The brief textile processes flow diagram is shown in Figure 2.17. In almost all of these steps, wastewater is generated. The amount and composition of these wastewaters depend on many different factors, including the processed fabric and the type of process. Changes in machines, used chemicals or other characteristics of the processes also change and affect the nature of the generated wastewater.

The wastewater of textile industry is characterized primarily by measurements of BOD, COD, color, heavy metals, and total dissolved and suspended solids. BOD, or biochemical oxygen demand, is the measure of the oxygen consuming capabilities of organic matter. Water with high BOD indicates the presence of decomposing organic matter and subsequent high bacterial counts that degrade its quality and potential uses. COD, or chemical oxygen demand, measures the potential overall oxygen requirements of the wastewater sample, including oxidizable components not determined in the BOD analysis. Color is defined as either true or apparent color. True color is the color of water from which all turbidity has been removed. Apparent color includes any color that is due to suspended solids in the water sample. Color and turbidity both cause an aesthetic and real hazard to the environment. The aesthetic value considers the discoloration of recreational streams and waterways. The real hazards caused by color and solids in waste are dye toxicity and the ability of the coloring agents to interfere with the transmission of light through the water, thus hindering photosynthesis in aquatic plants.

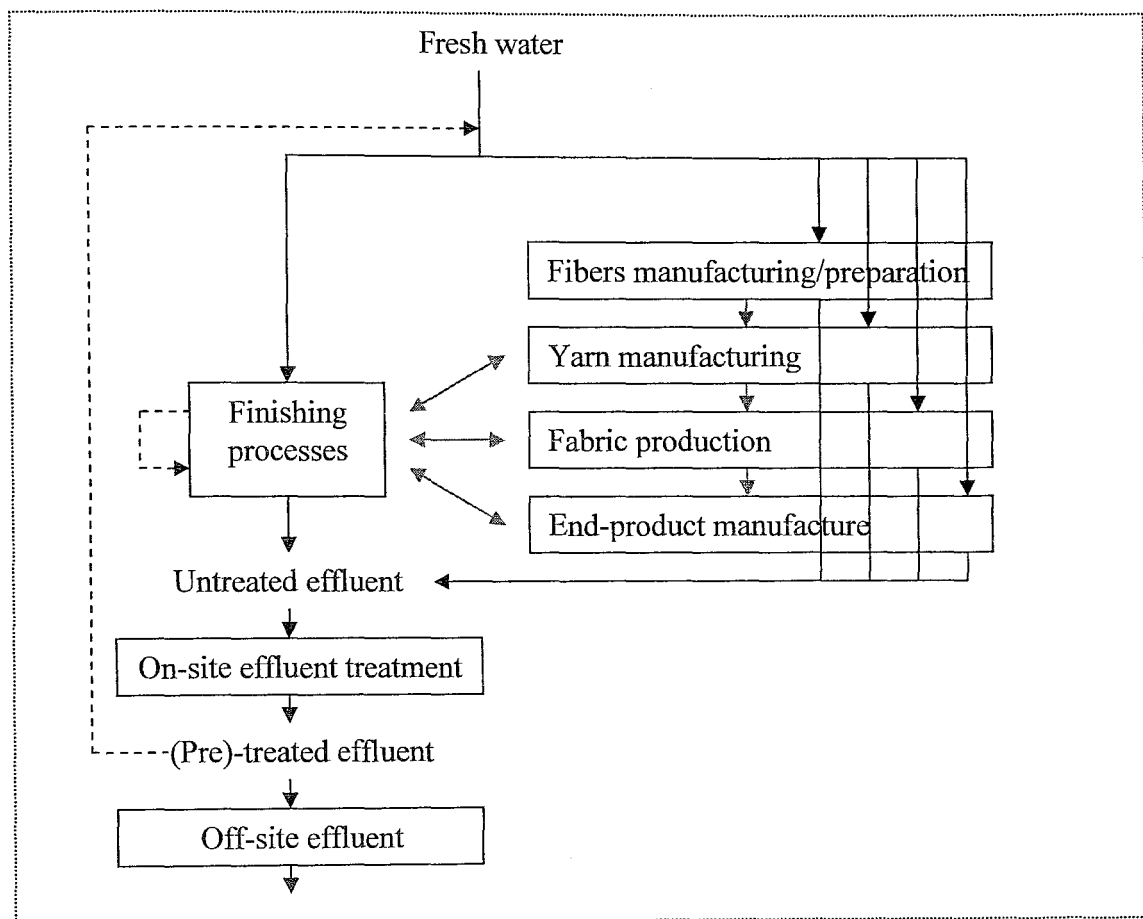


Figure 2.17. General diagram of the textile chain.

Heavy metals, typically chromium and copper, are very hazardous to human and aquatic life at relatively low concentrations. Heavy metals are introduced into the wastewater of textile manufacturing through the use of premetalized dyes and heavy metal after washes, which are used to increase the light fastness of the finished product. Heavy metals concentrations in dye bath effluents, typically in the range of 1 to 10 mg l⁻¹, were reviewed by Correia et al., (1994). Total dissolved solids, or TDS, characterize the general purity of water and is often largely due to soluble ions such as sodium, chloride, and sulfate. Obviously, high TDS is detrimental to fresh water aquatic life (Timothy, 1988).

There are many technologies currently available for treating wastewater from the textile industry including are: (1) biological treatment, (2) chemical precipitation, (4) ultra filtration, (3) carbon adsorption, and (5) oxidation with ozone.

Conventional methods for treating textile wastewaters are insufficient because of non-biodegradable, potentially toxic dyestuffs, and a variety of other chemicals (Lin and Peng, 1996). Some carrier chemicals used in dyeing, such as phenol, may be toxic and add odor. If organic substances such as dyes, starches and detergents in textile effluent are improperly processed they not only deteriorate the aesthetics of receiving waters, but also threaten aquatic life forms via hydrolysis and reduction reactions of some dyes to form toxic and carcinogenic end products (Gokçe, 2003).

Effluent characteristics vary largely between processes and materials. Water usage entirely depends on the used equipment and fabric, and varies greatly between processes and materials. Some processes hardly generate wastewater, such as yarn manufacturing, weaving (some machines use water), and singeing (just some lightly polluted cooling water). The amount of wastewater produced in a process like sizing is small, but very concentrated. On the other hand, processes like scouring, bleaching and dyeing generate large amounts of wastewater, varying much in composition. Table 2.1 gives an overview of parameter values for various textile processes (Zhang et al., 1999).

Table 2.1. Characterizations values for different textile wastewaters (all values are in mg/L unless stated otherwise) (Bisschops and Spanjers, 2003).

Parameter	Fabric type	Desizing	Scouring	Bleaching	Dyeing	Printing
COD	Wool	-	5000-90000	-	7920	-
	Cotton	950-20000	8000	288-13500	1115-4585	-
	Synthetic -	-	-	620	1515	-
	Not specified	10000-12000	-	-	-	785- 49170
BOD ₅	Wool	-	2270-60000	400	400-2000	-
	Cotton	-	100-2900	90-1700	970-1460	-
	Synthetic -	-	500-2800	-	530	590
	Not specified	200-5200	-	-	-	600-1800
Color (ADMI)	Wool	-	2000	-	2225	-
	Cotton	64-1900	694	153	1450-4750	-
	Synthetic -	-	-	1750	-	-
	Not specified	-	-	-	-	1450
Total Solids	Wool	-	28900-49300	910	-	-
	Cotton	-	-	2300-14400	-	-
	Synthetic -	-	-	-	-	150-250
	Not specified	7600-42900	-	-	<50000	-

Table 5.12 Continued

Total Suspended Solids	Wool	-	1000-26200	900	-	-
	Cotton	18-800	184-17400	130-25000	120-190	-
	Synthetic	-	600-3300	-	140	-
	Not specified	400-4000	-	-	-	125-9500
Total Dissolved Solids	Cotton	530-6900	-	4760-19500	-	-
	Not Specified	-	-	-	55	-
DOC	Wool	-	5800	-	-	-
	Cotton	250-2750	-	320	-	-
Total Kjeldahl N	Cotton	70	-	40	-	-
	Synthetic -	-	-	-	-	164
	Not specified	-	-	-	-	30-1765
NH ₄ -N	Wool	-	604	-	-	-
	Cotton	9-19	-	8-19	-	-
	Synthetic	-	-	-	-	129
	Not specified	-	-	-	-	20-370
Total P	Cotton	4-10	-	6-60	-	-
	Synthetic	-	-	-	-	21
PO ₄ ⁻³	Wool	-	89.3	-	-	-
Sulphide	Wool	-	0.2	-	-	-
	Cotton	-	-	-	325-900	-
Sulphate	Cotton	-	-	-	1750-2690	-
Cl ⁻	Not specified	-	-	90-100	26000	-
Oil & Grease	Wool	-	580-55000	-	-	-
Cr ⁺³	Wool	-	50	-	-	-
pH	Wool	-	7.6-10.4	6	4.6-8	-
	Cotton	8.8-9.2	7.2-13	6.5-13.5	9.2-10.1	-
	Synthetic	-	8-10	-	11.7	-
	Not specified	6-8	-	-	-	5-8.5
Turbidity NTU	Not specified	930	-	-	-	-
Water usage (Lkg ⁻¹ fabric)	Wool	-	4-77.5	-	40-150	280-520
	Cotton	-	2.5-43	30-50	38-143	-
	Synthetic	-	17-67	-	38-143	-
	Not specified	12.5-35	-	-	-	20-300

3. THERMODYNAMICS OF MVR EVAPORATOR SYSTEM, CONDENSATION, BOILING AND COMPRESSORS

3.1. The MVR System

Simply stated, with Mechanical Recompression the water vapor boiled off in the evaporator is passed to an electrically powered compressor and is compressed through 1-3 bars. This raises the temperature of the vapor, which then is used as the heating medium. The difference in enthalpy between the vapors on the heating and process sides is comparatively small, with a resultant reduction in energy consumption and, depending on regional steam and power cost, an operating cost equivalent to at least eight to thirty effect evaporator. Theoretical thermal efficiency may exceed that of a 60-effect steam evaporator (Hui, 1992). Typically, a single-effect steam evaporator operating at atmospheric pressure (1 bar) with vapor being produced at 100 °C and is sent to a condenser. The heat source for this system is steam at 1.19 bar, condensing at 117.22 °C. If the same evaporator is operated with Mechanical Vapor Recompression, then the vapor at 100 °C, 1 bar, is sent to a compressor, where its pressure is raised to 1.19 bars. It is then charged to the steam side of the evaporator as the heating medium, condensing at 117.22 °C. Savings are realized in two areas: no steam is required for evaporation, although nominal amounts of steam are required for start up and compressor seals, and since the vapor from the evaporators is not sent to a condenser, cooling water requirements are dramatically reduced.

To a large extent, the design of MVR evaporators has been dictated by the capabilities of the compressor available at the time. The primary limitation has been the compression ratio (absolute discharge pressure divided by absolute suction pressure) that can be achieved since this determines the temperature difference available for the evaporator. For example if evaporator is run at 100 °C and atmospheric pressure and a compression ratio of 1.4 is used, then the steam at the discharge of the compressor is 1.4 x 1 bar or 1.4 bars. Since water vapor at 1.4 bars condenses at 109.72 °C, the allowable temperature difference ΔT for the evaporator is 9.72 °C before losses are considered. Table 3.1 shows the total temperature differences for a number of conditions.

Table 3.1. Saturated ΔT at Various Compression Ratios, °C

Compression Ratio	Boiling Temperatures 100 ° C
1.2	5.17
1.4	9.72
1.6	13.72
1.8	17.33
2.0	20.67

3.1.1. Operation

Mechanical Vapor Recompression (MVR) evaporator system employs conventional lower ΔT evaporators such as falling-film, forced circulation, and horizontal-tube falling-film types. Others such as rising-film, calandria and submerged-tube evaporators seldom are used in the MVR process, since they normally require a higher ΔT , and thus are less economical.

Mechanical Vapor Recompression (MVR) evaporator systems normally use single-stage centrifugal compressors or rotary Roots-type blowers. Such devices are better because they offer a high volumetric flow rate and high compressor ΔT at a reasonable cost. They also are quite reliable, when specified properly. A single effect evaporator transfers heat from condensing steam to aqueous solution across a heat-transfer surface. Water vapor flows to a barometric or surface condenser where it releases its latent heat to cooling water at a lower temperature.

Evaporation rate in a MVR system depends upon the ΔP (where P is pressure) established by the compressor. Capacity turndown requires some method of throttling the compressor. The two most common ones for centrifugal compressors are using (1) butterfly damper valves in the compressor’s suction line and (2) inlet guide vanes (IGV).

IGVs swirl the vapor entering the compressor and change the aerodynamic performance. Because of this, systems with IGVs use less power at part load than do systems with suction throttle valve (Yundt 1984). Throttle valves have a pressure drop, rather than changing the aerodynamics, and thus use more energy. A third technique for capacity turndown is varying the compressor speed (rpm). Though this technique offers lowest part-load power consumption, it is used mainly for steam-turbine-driven system. Variable-speed motors are expensive in the sizes required for MVR compressors.

3.1.2. Thermodynamics

MVR evaporators involve a thermodynamic process and they operate in a manner similar to that of a heat pump. In fact, the MVR evaporator functions like an open cycle heat pump, where the working fluid is water (or another solvent) in the form of vapor that will be condensed in order to transfer its energy (Raynald and Normand, 2004). To fully comprehend the potential of Mechanical Vapor Recompression (MVR) evaporation system, it is important that the thermodynamics of this technique be examined. The first two columns of Table 3.2 give the properties of saturated water vapor 1 bar, 100 °C and at 1.19 bar, 104.44 °C. These values can be used to estimate the energy requirements for an evaporator operating at these conditions. Considering first normal steam evaporator (with out MVR system) water at 1.19 bar, 104.44 °C has an enthalpy of 437.75 KJ/kg while steam at the same conditions has an enthalpy of 2682.80 KJ/kg. The difference between the vapor and the liquid is the latent heat or 2245.05 KJ/kg. In other words, in order to produce one pound of steam at 104.44 °C, 1.19 bar, from water at 104.44 °C, 1.19 bars and the addition of 2245.05 KJ/kg of energy is required.

Table 3.2. Properties of water vapors

State	Saturated	Saturated	Superheated
Pressure, Bar	1	1.19	1.19
Temperature, °C	100	104.44	117.2
H – Enthalpy Vapor, KJ/kg	2676	2682.80	2708.86
Latent Heat, KJ/kg	2256.9	2245.05	–
H – Enthalpy liquid, KJ/kg	419.1	437.75	–
S – Entropy, KJ/kg.K	7.3545	7.3026	7.3671

In the case Mechanical Vapor Recompression (MVR) evaporator, however, the vapor at 1.19 bar, 104.44 °C (enthalpy 2682.80 KJ/kg) is produced from vapor at 100 °C, 1 bar (enthalpy 2674.90 KJ/kg). Theoretically, only 6.74 KJ/kg of energy must be added.

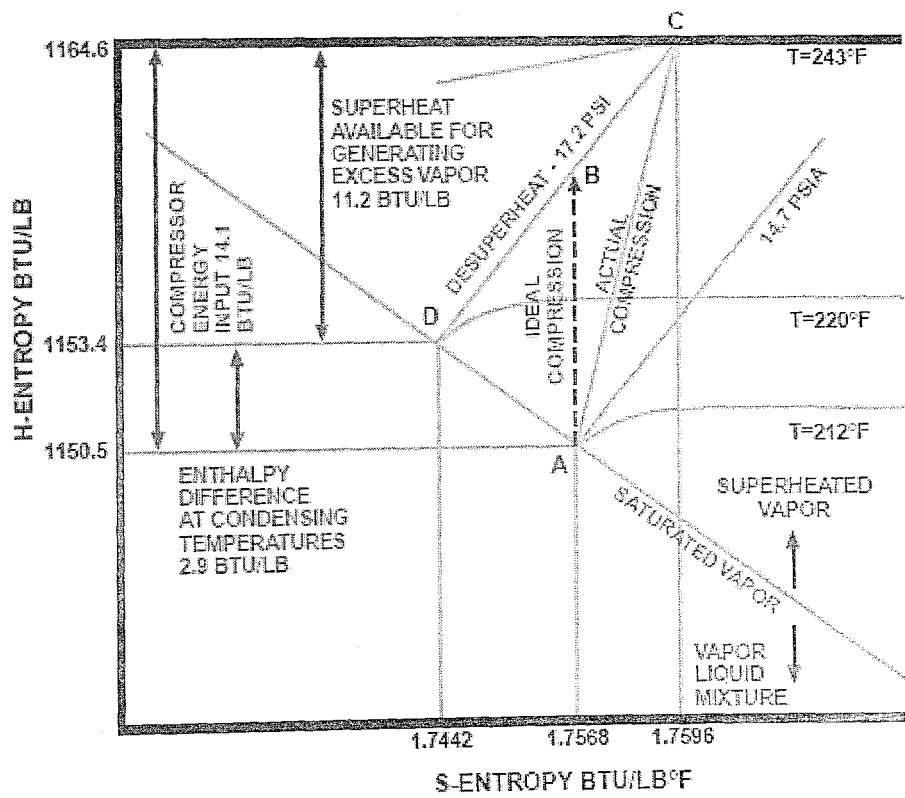


Figure 3.1. Enthalpy-Entropy diagram (Hui, 1992).

The compressor operates such that the entropy of the discharge vapor is at least as high as the entropy of the inlet vapor. Since inefficiencies in the compression cycle will result in an exit entropy above that of the inlet entropy, the temperature of the existing vapor and energy input to the compressor must be increased. The vapor at 1 bar, 100 °C, is shown Figure 3.1., at point A, during compression the entropy remains constant (ideally) or increases (actually). With typically efficiencies for this duty, the discharge temperature may be expected to rise to 117.22 °C where the enthalpy is 2708.86 KJ/kg. The energy input from the compressor is 32.8 KJ/kg.

In order to cool the vapor to its condensing temperature of 104.44 °C, 26.06 KJ/kg of heat is removed. This can be done by introducing condensate at 104.44 °C from the steam side of the evaporator. The 26.06 KJ/kg of heat removed from the vapor is absorbed into the condensate, some of which will vaporize and give off what is known as “excess vapor”. For every pound of vapor cooled, 11.81 KJ of heat is absorbed in the condensate, which requires 2245.05 KJ/kg to boil. Therefore for each point of vapor leaving the compressor, $11.81/2245.05$ or 5.26 g of excess vapor is available.

This excess vapor is used in several ways. Since there is a slight difference in latent heat between the steam and the vapor, slightly more steam is required than the vapor generated. Other excess vapor is used to cover losses due to radiation and venting, is made available in some instances for preheating, or is sent to a condenser. It is significant to note that the condenser on a Mechanical Vapor Recompression (MVR) evaporator is responsible only for vent and excess vapor. This results in a much lower cooling requirement than is necessary for steam evaporators. It is possible to calculate an equivalent steam economy for a Mechanical Vapor Recompression (MVR) evaporator system. In this example, for every kilogram of water evaporated, 1024.51 KJ is absorbed. The compressor supplies 14.88 KJ but with motor and gear losses, probably requires 15.30 KJ of energy. The equivalent economy ($1024.51/15.3$) is 67 to 1.

3.2. Condensation

The process of condensation of vapor is usually accomplished by allowing it to come in contact with a surface, the temperature of which is maintained at a value lower than the saturation temperature of the vapor for the pressure at which it exists. The removal of thermal energy from the vapor causes it to release its latent heat of vaporization and, hence, to condense onto the surface.

The appearance of the liquid phase on the cooling surface, either in the form of individual drops or in the form of a continuous film, offers a greater thermal resistance to the further removal of heat from the remaining vapor. In most cases of condensation, the condensate is removed by the action of gravity. Naturally, then the rate of removal of condensate, and with it the rate of heat removal from the vapor, is greater for vertically placed surfaces than for horizontal surfaces. In order to avoid the accumulation of large amounts of liquid at the lower end of a condensing surface it should be short; hence, horizontal cylinders are particularly applicable for such purposes. Thus, most condensing equipment consists of assemblies of horizontal tubes around which the vapor to be condensed is allowed to flow. The cool temperature of the outer tube surface is maintained by circulating a colder medium; usually water, through the inside of the tube.

Two general types of condensation have been observed to occur in practice. The first called film condensation, usually occurs when a vapor, relatively free of impurities, is allowed to condense on a clean surface. Under these conditions, it is found that the condensate will appear as continuous film all over the surface and it will flow off the surface under the action of gravity.

The second type of condensation, less frequently observed, is known as drop-wise condensation, and has been observed to occur either on highly polished surfaces or on surfaces contaminated with certain fatty acids. In this case, the condensate is found to appear in the form of individual drops. These drops increase in size and combine with one another until their size is great enough such that their weight causes them to run off the surface, leaving the surface exposed for the formation of a new drop.

Since there will be much less of a liquid barrier between the condensing surface and the vapor, it should not be surprising to know that heat transfer rates are five to ten times greater for drop-wise condensation than for film condensation. Hence, it would appear that drop-wise condensation would be preferred for commercial applications.

3.2.1. Film-wise Condensation on a Vertical Plate or Tube

The film originates at the top of the plate or tube and flows downward under the influence of gravity as shown in Figure 3.2. The thickness δ and the condensate mass flow rate m' increase with increasing x because of continuous condensation at the liquid-vapor interface, which is at T_{sat} . There is then heat transfer from this interface through the film to the surface, which is maintained at $T_s < T_{\text{sat}}$. In the most general case vapor may be superheated ($T_v, \infty > T_{\text{sat}}$) and may become part of a mixture containing one or more non-condensable gases. Moreover, there exists a finite shear stress at the liquid-vapor interface, contributing to a velocity gradient in the vapor, as well as in the film (Sparrow and Greeg, 1959 ; Koh et al., 1961). Temperature profile for the down flow evaporator is shown in Figure 3.2.

Despite the complexities associated with film condensation, useful results may be obtained by making assumptions that originated with an analysis by Nusselt (1916).

1. Laminar flow and constant properties are assumed for the liquid film.
2. The gas is assumed to be a pure vapor and at a uniform temperature equal to T_{sat} . With no temperature gradient in the vapor, heat transfer to the liquid-vapor interface can occur only by condensation at the interface and not by conduction from the vapor.
3. The shear stress at the liquid-vapor interface is assumed to be negligible. With this assumption and the foregoing assumption of a uniform vapor temperature, there is no need to consider the vapor velocity or thermal boundary layers.
4. Momentum and energy transfer by advection in the condensate film are assumed to be negligible. This assumption is reasonable by virtue of the low velocities associated with the film. It follows that heat transfer across the film occurs only by conduction, in which case the liquid temperature distribution is linear

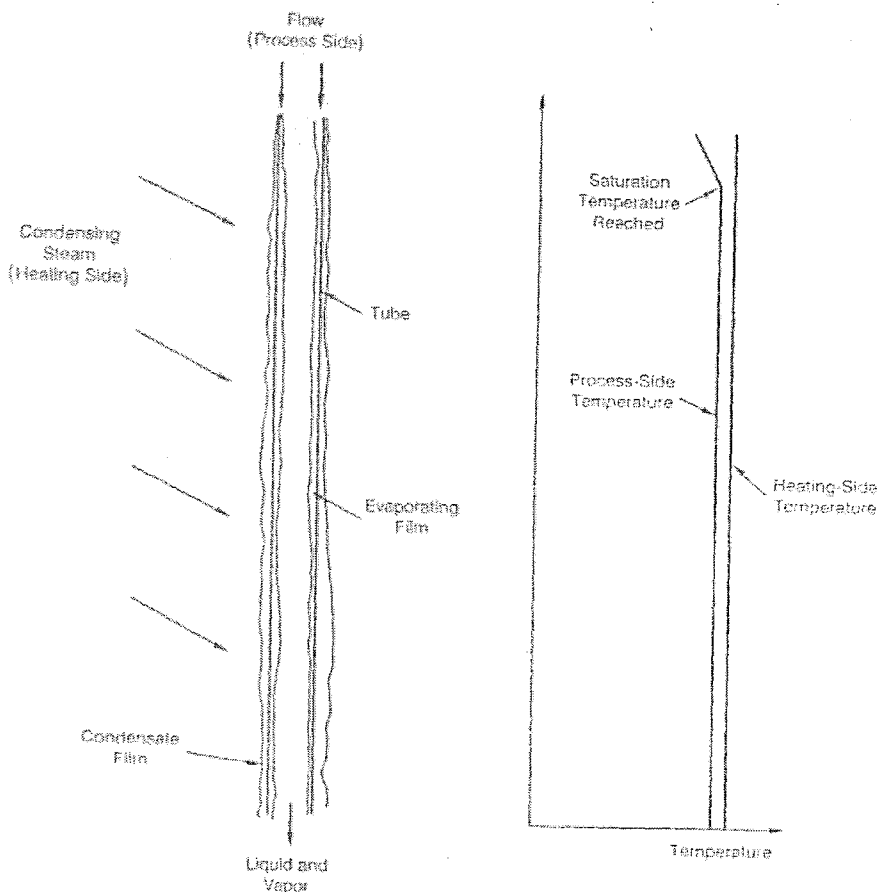


Figure 3.2. Down flow in an evaporator: typical temperature profile in the boiling liquid (Sadik, 1999).

3.2.2. Drop-wise Condensation

As two basic types of condensation are observed to occur, film and drop-wise. It has been observed that when traces of oil, or other similar substances, are present on the condensing surface so that the liquid does not readily wet it, the condensate breaks into droplets-forming what is known as "drop-wise condensation". The drops thus formed grow as condensation progresses and either coalesce with neighboring drops or run off the surface after their weight overcomes the restraining forces of surface tension. As the drops run off, a greater fraction of the condensing surface is left free of liquid, thus enhancing the heat transfer process.

Since the entire surface is not covered with a continuous liquid film, heat transfer in the drop-wise condensation mode is observed to be five to ten times as great as in the film

mode. Thus, if drop-wise condensation could be maintained in industrial condensing equipment, significant savings in the size of such devices could be realized. Consequently, a great deal of time and effort has been devoted to the study of this mechanism and in seeking ways to promote its occurrence. The results of studies to date indicate that drop-wise condensation is promoted by the use of highly polished surfaces or by injection of various fatty acids such as oleic or stearic acids. However, the effectiveness of additives last for only a few hundred hours, due to the cleansing effects of steam. Consequently, the use of drop-wise promoters may require continuous injection, which would become expensive or incur undesired effects in the test of the plant, or cycle, using the condenser.

As a result of all the above, most industrial condensing equipment is still designed on the presumption that film condensation will be present.

3.2.3. Real Condensation

Real condensation differs from the analysis in a number of ways (Nusselt, 1916).

1. The film is almost never smooth. Ripples on the surface increase the surface area and stir up the film. These effects can increase the heat transfer coefficient by about 20 percent.
2. There is a shear force exerted by the flowing vapor on the liquid film. Normally, this is arranged to make the film thinner and so to increase the heat transfer coefficient.
3. The film may become turbulent. This happens at value of the film Reynolds number ($4M/\mu_l$) in the range 1000 to 2000. Again, turbulence increases the heat transfer coefficient as compare to the laminar flow values. The effect of the turbulence is to increase the effective viscosity of the liquid: this makes the liquid film thicker. This effect is, however, more than counteracted by the increased heat transfer due to convection effects in the liquid.
4. Multi-component effects. The simplest of these is the effect of an "incondensable" gas (such as, for example, air) on the condensation of steam. However, it can be noted here, that in many cases the presence of an incondensable gas can give rise to condensation heat transfer coefficients, which are far less than expected.

In contrast to the large effects of an incondensable gas, the first three effects lead to fairly modest increases in the condensation heat transfer coefficient.

3.2.4. Effects of Non-Condensable Gases

The liquid-vapor interfacial temperature was taken to be t_{sat} at the pressure of the bulk vapor. When a noncondensable gas, such as air, is also present, the saturation pressure in the bulk gas-vapor medium is that corresponding to the partial pressure of the vapor in this mixture. In addition, the vapor, in moving toward the condensing surface, must diffuse through the noncondensable component. Thus, a decreasing gradient in the partial pressure of the vapor component must exist as the interface is approached. Consequently, the saturation temperature at the interface will be lower than that in the bulk mixture. The diffusion process and the lowered saturation temperature reduces the condensation rate and, hence, the observed heat transfer coefficient (Rohsenow et al., 1998). Typical calculations show that the noncondensing heat transfer coefficient for steam may be reduced by as much as 50 percent when air in amounts as low as 1 percent, by mass, is present. Consequently, it is customary practice in steam condenser design to provide means of removing as much of the noncondensable gases as possible through venting or the use of ejectors.

The simplified Nusselt (1916) analysis presumed no shear stress at the liquid-vapor interface. In some applications, particularly for flows inside tubes, the ambient vapor may be flowing with a significant velocity relative to the liquid film. This vapor velocity may be accompanied by significant shear stresses at the interface. Obviously, profoundly different results may occur between the cases when the vapor flows in the same direction as the liquid or in the opposite direction.

3.3. Boiling

When evaporation occurs at a solid-liquid interface, it is termed boiling. The process occurs when the temperature of the surface T_s exceeds the saturation temperature T_{sat} corresponding to the liquid pressure. Heat is transferred from the solid surface to the liquid, and the appropriate form of Newton's law of cooling is

$$q_s = h (T_s - T_{\text{sat}}) = h\Delta T_e \quad (3.1)$$

Where $\Delta T_e = T_s - T_{\text{sat}}$ is termed the excess temperature. The process is characterized by the formation of vapor bubbles, which grow and subsequently detach from the surface. Vapor bubble growth and dynamics depend, in a complicated manner, on the excess temperature, the nature of the surface, and thermo-physical properties of the fluid, such as its surface tension. In turn, the dynamics of vapor bubble formation affect fluid motion near the surface and therefore strongly influence the heat transfer coefficient.

Boiling may occur under various conditions. For example, in pool boiling the liquid is quiescent and its motion near the surface is due to free convection and to mixing induced by bubble growth and detachment. In contrast, for forced convection boiling, fluid motion is induced by external means, as well as by free convection and bubble-induced mixing. Boiling may also be classified according to whether it is sub cooled or saturated. In sub cooled boiling, the temperature of the liquid is below the saturation temperature and bubbles formed at the surface may condense in the liquid. In contrast, the temperature of the liquid slightly exceeds the saturation temperature in saturated boiling. Bubbles formed at the surface are then propelled through the liquid by buoyancy forces, eventually escaping from a free surface.

3.3.1. Types of Boiling

Boiling can be divided into categories according to the mechanism occurring and according to the geometric situation. The three mechanisms of boiling are:

1. Nucleate boiling, where vapor bubbles are formed (usually at a solid surface).
2. Convective boiling, where the heat is conducted through a thin film of liquid-the liquid then evaporates at the vapor-liquid interface with no bubble formation; and
3. Film boiling, where the heated surface is blanketed by a film of vapor-the heat is conducted through the vapor, and the liquid vaporizes at the vapor-liquid interface.

The two main geometric situations are:

Pool boiling, where the boiling occurs at a heated solid surface in a pool of liquid which, apart from any convection induced by the boiling, is stagnant; and flow boiling, where the liquid is pumped through a heated channel, typically a tube.

Nucleate boiling and film boiling occur in both pool boiling and flow boiling but convective boiling usually only occurs in flow boiling.

3.3.1.1 Forced Convection Boiling. Forced convection boiling is most often encountered in the case of forced flow of a liquid through a tube with boiling occurring at the inner surface. Bubble growth and the influence of the bubble dynamics on the heat transfer mechanism are strongly influenced by the forced velocity of the flow. If a sub-cooled liquid enters a tube maintained at a surface temperature in excess of t_{sat} , the heat transfer is initially accomplished by forced convection. However, boiling is soon initiated, and bubbles begin to appear on the surface as the fluid moves down the tube. The bubbles grow, break away from the surface and are taken into the mainstream of the liquid. This is known as the bubbly-flow regime and is associated with a sharply increased heat transfer coefficient. As the flow continues down the tube, the fraction of vapor becomes so large that slugs of vapor are formed, separated by slugs of liquid. This slug-flow regime is followed by the annular-flow regime, in which so much vapor exists that it flows in the central core of the pipe with liquid in annular film at the surface. The heat transfer rate continues to begin to occur on the surface, and the heat transfer coefficient drops as the flow passes into the mist-flow regime. In this latter regime, the flow is mainly vapor with the liquid phase suspended in it in a mist of liquid droplets. Eventually all the mist evaporates, and the vapor begins to superheat.

Needless to say that the above description of the forced boiling process is sufficiently complicated to preclude the presentation of the many correlations which have been developed for the various flow regimes. As a general simple rule, Rohsenow and Griffith (1955) suggest that forced convection boiling be treated by superimposing the two effects of forced convection and nucleate boiling, at least up to the slug-flow regime.

3.4. Compressor

Ferguson (1963) defines the function of a compressor as: “It is the function of a compressor to raise the pressure of a specified mass flow of gas by a prescribed amount using the minimum power input”.

The purpose of compression is simply to increase the pressure of a gas from one level to another. Depending on a host of circumstances and situations, the pressure increase imparted to a gas will be from a fraction of a pound per square inch (psi) (or a few Pascals) in laboratory equipment to literally tens of thousands of psi in hyper compressors used for the manufacture of polyethylene.

Compressors are used in a wide variety of applications. These includes turbo jet engines used in aerospace propulsion, power generation using industrial gas turbines, turbo charging of internal combustion engines, pressurization of gas and fluids in the process industry, transport of fluids in pipelines and so on.

Two principal methods are used to compress gases. The first method is to trap a volume of gas and displace it by the positive action of a piston or rotating member; we call these machines positive-displacement compressors. The second method uses dynamic compression; it is accomplished either by the mechanical action of contoured blades, which impart velocity and hence pressure to the flowing gas, or by the entrainment of gases in a high velocity jet of the same or another gas (e.g. steam). The entrainment principle is generally found in ejectors that operate with inlet pressures below atmospheric pressure.

The two major groupings of compression machinery, positive displacement and dynamic, can be further subdivided. *Positive-displacement* units are those in which successive volumes of gas are confined within a closed space and elevated to a higher pressure. *Reciprocating compressors* are positive-displacement machines in which the compressing and displacing element is a piston that moves back and forth within a cylinder. *Rotary positive-displacement compressors* are machines in which compression and displacing element by the close meshing of rotating elements. *Sliding-vane*

compressors are rotary positive-displacement machines in which axial vanes slide radially in a rotor. This rotor is eccentrically mounted in a cylindrical casing. Gas trapped between the vanes is compressed and displaced. *Liquid-piston compressors* are rotary positive-displacement machines in which water or other liquid is used as the piston to compress and displace the gas handled. *Roots-type straight-lobe compressors* are rotary positive-displacement machines in which two mating lobed impellers trap gas and displace it from intake to discharge. There is no internal compression. *Helical or spiral-lobe compressors* are rotary positive-displacement machines in which two intermeshing rotors, each with a helical form, compress and displace the gas.

Dynamic compressors are continuous-flow machines in which either the rapidly rotating element or ejector nozzle accelerates the gas it passes through the element. The velocity head is converted into pressure, partially in the rotating element and partially in stationary diffusers or blades. *Centrifugal compressors* are dynamic machines in which one or more rotating impellers, usually shrouded on the sides, accelerate the gas. Main gas flow is radial. *Axial compressors* are dynamic machines in which gas acceleration is obtained by the action of the bladed rotor shrouded on the blade ends. Main gas flow is axial. *Mixed-flow compressors* are dynamic machines with an impeller form combining some characteristics of both the centrifugal and axial types.

3.4.1. Types of Compressors

The type of compressor best suited depends on the operating conditions relevant to the application. Key parameters are the required pressure rise and the flow rate of the vapor to be compressed. As evaporation plants are frequently operated in the vacuum range at medium heating surface loads and with small temperature differences, centrifugal recompressors are often used. These are mainly high pressure centrifugal fans single-stage centrifugal compressors. These machines are capable of a wide range of flow rates (e.g. 3,000 to 500,000 m³/h), at pressure ratios of 1.1 to 2.5.

3.4.1.1. Reciprocating Compressors. Operate in similar fashion to the principle of the internal combustion engine. The crankshaft moves the piston in a straight oscillating motion via the connecting rod and the piston rod running on the crosshead. The gas in the

working chambers above and below the piston is displaced through valves actuated by the gas pressure. In order to avoid thermal stress at the sealing faces, the cylinder shell and the gland pocket may be heated with steam.

3.4.1.2. Rotary Compressors. Rotary compressors are of little importance for the compression of water vapor. They are frequently used for the compression of cooling agents.

3.4.1.3. Screw Compressors. The working elements of the screw compressor are the primary rotor and the secondary rotor. Compartments are formed by the rotors between their intermeshing screw profiles and the casing. As the rotors turn, the compartments become progressively smaller. The installed pressure ratio is determined by the position of the outlet port and rotor dimensions.

3.4.1.4. Roots Compressors. Rotary piston, or lobe-type, blowers derive from the Roots compressor principle and have been built since 1864. They are used in a large variety of process plant applications, including pneumatic conveying of bulk materials, pressurized aeration of water at treatment plants, creation of vacuum, and gas movement in the petrochemical, pharmaceutical, and metallurgical industries. They range in size from fractional horse power to literally hundreds of kilowatts. This kind of compressor is used in the Mechanical Vapor Recompression (MVR) evaporator of this study.

Rotary piston blowers are twin-shaft rotary machines. The two rotors are axially parallel to one another and located centrally inside the casing. The timing gears ensure that the rotors turn without contact. The rotors are supported on ball and roller bearings. The clearance between the rotors is kept to a minimum and selected for the expected pressure differential and thermal load under working conditions. Smaller rotors are adjusted in such a manner as to enable them to be run in either flow direction. Large blowers and gas blowers of special design are suitable for flow in one direction only, since in this case the clearances between the rotors and the casing must be kept larger on the low-pressure side to compensate for shaft deflection and bearing clearances. Axial thermal expansion of the free bearing end, i.e., at the bearing that is permitted to slide so as to accommodate thermal growth.

The shaft diameter is a very important factor in the evaluation of rotary lobe blower quality. It determines the amount of deflection and thus the magnitude of clearance and volumetric efficiency under load. Adequate bearing span provides space for proper sealing components between compression chamber and bearing housings. Needless to say, well-designed seals prevent contamination of gas by the lube oil and vice versa. This extends the life of bearings and gears. The principal construction features of rotary piston blowers include driving and driven rotors, timing gears, bearings, and seals.

3.4.1.5. Axial Compressors. Axial compressors are used for very large volumetric flow rates. They are nearly always designed as multi-stage systems. In a single axial stage, only a fraction of the pressure increase of a single centrifugal stage can be achieved. The efficiency of multi-stage axial compressors is however higher than that of multi-stage centrifugal compressors. Compared with the centrifugal compressor, a much smaller sized axial compressor can be used for the same type of compression work.

3.4.1.6. Centrifugal Fans. Centrifugal fans can be used for low pressure ratios of up to 1.25. In the same way as a centrifugal compressor, the gas enters the eye of the impeller along its axis, exiting radially by means of centrifugal forces. The fan impeller and housing is of welded plate construction with reinforcing rib stiffeners as required. Gearboxes are generally not required, as the drive system gives the required speed of the impeller.

3.4.1.7. Single-Stage, Centrifugal Compressors. The main feature of this type of compressor is the overhung impeller and the compact arrangement of compressor and gearbox. Motor, gearbox and compressor are mostly mounted on a common base-frame. Cast materials are used for the compressor casing. The impellers, which are highly stressed by the high tip speeds of 400 m/s, are made of high-quality materials such as chrome-nickel steels or titanium alloys.

3.4.1.8. Multi-Stage, Centrifugal Compressors. This type of compressor is used for large volumetric flow rates and high saturated steam temperature increases. The multi-stage centrifugal compressor is formed by the arrangement of several stages on a single shaft. After leaving one stage, the gas flows through a diffuser and interstage channel before entering the next impeller stage. The impeller shaft runs on bearings in the casing and is

driven by a separate helical gear. For increasing the efficiency and for avoiding unacceptably high temperatures in the casing, water can be injected into the interstage channels.

In order to reach pressure ratios exceeding 10, single-stage machines can also be connected in series. If the impellers were driven from a central drive with several pinions, the relevant unit would be called a two-, three-, or four-impeller compressor.

3.5. Compressor Drives

Different types of prime mover can be used for driving vapor recompressors. In each case, the drive is selected on the basis of its efficiency and the type of drive power available.

Electric motors are commonly used as drives. They offer considerable advantages due to the standardization of sizes and types of protection, their low power/weight, power/volume, price/performance ratios and minimum maintenance requirements.

3.5.1. Three-Phase Asynchronous Motors

Three-phase asynchronous motors operate, according to the number of pairs of poles, at synchronous speeds of 3000, 1500, 1000 or 750 rpm (50 Hz, idle speed) or, if frequency converters are used, at variable speeds. Two types of motor are available: low voltage, and high voltage motors. Low voltage motors generally operate at capacities of up to 630 kW or 1,250 kW for supply voltages of 400 V or 690 V, respectively. High voltage motors and converters can be used for capacities of up to approximately 6,000 kW. The efficiency of asynchronous motors is constant over a wide load range.

3.5.2. Direct Current Motors

Variable speed, direct current motors are recommended for frequent partial load operation at high efficiency. They put a much lighter load on the operating current system during start-up than three-phase asynchronous motors. Their disadvantages are their higher

prices and maintenance requirements. Compared to frequency controlled asynchronous motors, the direct current motor has lost some of its importance.

3.5.3. Gas Engines

Gas engines are used if insufficient amounts of electrical energy are available. Good efficiencies, of up to 90 percent, are reached if the waste heat from the cooling water and exhaust gas can be used, for example, for preheating purposes. The purchase price of a gas engine for waste heat recovery is considerably higher than that of a comparable electric motor. Its maintenance costs, which are several times higher than those of electric motors, are also a disadvantage.

3.5.4. Steam Turbines

The use of a variable speed steam turbine as the prime mover of a compressor is sensible if the exhaust steam can be recovered. In this case, the relatively poor efficiency of a single-stage steam turbine, which may be used for price reasons, is of secondary importance.

3.6. Compressor Controls Ways

Evaporation plants heated by Mechanical Vapor Recompressors generally operate steadily to a limited extent, i.e. parameters such as mass flow rate, pressure and temperature fluctuate over time. Variations in evaporation rate (i.e. partial load operation) over a wide range are often desired. Therefore, different heat rates must be transferred. These changes in plant capacity are achieved by changing the temperature or pressure profiles.

The compressor design must take into account these variations in plant performance against the design duty. The operating behavior of the plant is depicted in the so-called plant characteristics or performance curves. It shows the relationship between the necessary saturated steam temperature increase and the drawn-in vapor mass flow. The

operating behavior of the plant should be determined by tests to a large extent, or should at least be estimated.

The evaporator and compressor characteristic curves must correspond to each other for optimum operation of the vapor recompressor plant. Specific changes in the flow conditions on the suction or pressure side of the compressor, for instance the suction pressure, allow the control concept to be varied. A variety of control concepts based on different performance criteria are available. The following methods are preferred:

3.6.1. Speed Control

Controlling the impeller speed and, consequently, the circumferential speed can influence the volumetric flow rate and the compression ratio. For speed control, a three-phase asynchronous motor equipped with a frequency converter is most commonly used. Especially for steep characteristic curves, i.e. for large changes in pressure against small changes in volume flow, control by continuous speed adjustment is advantageous. In the study this kind of speed controller is used which was made by the ABB company.

The advantages of frequency converter operation are:

- Depending on the design, the motor can be operated at 20 to 60 percent above its nominal speed so that a step-up gear is not required in most cases.
- At start-up coupling is not required.
- By limiting the starting current, the supply mains are not overloaded during start-up.
- Favorable partial load efficiencies are achieved.

3.6.2. Vane Control

The vane control principle allows changes to the flow characteristic of the impeller. For this purpose, inlet guide vanes are installed in the suction nozzle of the compressor. The inlet guide vanes are adjusted from the outside by means of a drive. Whereas the compressor speed remains constant, the efficiency and performance of the impeller is changed. Vane control is advantageous for characteristic plant curves based on

considerable pressure changes in relation to the displaced volume. This results in a large control range and good partial load efficiencies.

3.6.3. Diffuser Control

Adjustable vanes in the diffuser ensure a large change in the mass flow rate with low efficiency decrease and flat characteristic plant curves. Diffuser control is used if the necessary temperature profile in the evaporator must remain approximately constant.

3.6.4. Inlet Pressure Control

If the process can take place at different temperatures, and the plant is not thermodynamically connected with other plants, the simple concept of controlling the pressure at the inlet by adjustments to the process parameters can be used. This control system ensures maximum variations in the mass flow rate, by changing the steam density at the evaporator separator, within the lower and upper process temperature limits. In many cases, a sufficiently large control range of the plant can be achieved in this way without special mechanical changes being necessary. Inlet pressure control can also be combined with one of the mechanical types of control, thus providing a particularly large control range. Another possibility is the control of centrifugal compressors by throttling the suction line, thereby changing the mass flow rate. This type of control results in unfavorable partial load efficiencies.

4. MATERIALS AND METHODS

4.1. Equipments used for Construction of MVR Evaporator

Different parts of the MVR (Evaporator, Vapor-liquid separator, Heat recovery tank) were either bought from second hand machine shops as such or constructed from stainless steel by welding according to the scheme in Fig.5.1.

Main components for automatic operation were stainless steel feed and circulation pumps, a compressor and an electronic drive unit for the control of the compressor speed. Details of these components are given in the Results section.

Measuring devices for temperature and pressure etc. are used at different places of the instrument. A digital T-transmitter (using thermocouples) together with a switch for 10 positions allowed readings of the temperature at different positions of the apparatus:

- Feed at input of heat recovery tank.
- Feed at the output of recovery tank.
- Distillate at the input of heat recovery tank.
- Distillate at the output of recovery tank.
- Concentrate.
- Vapor before the compressor.
- Vapor after the compressor.

Pressure was also measured using gauges at the input and output of the compressor. Distillate output was measured using a flow meter, beaker and a stopwatch. Rotation speed of the compressor as well as the energy consumption (in kW) of the compressor could be read directly from the drive unit.

4.2. Types, Sources and Characteristics of Collected Wastewaters

Besides tap water the following seven types of wastewater were taken for testing the performance of the Mechanical Vapor Recompression (MVR) evaporator system.

1. Oily Wastewater
2. Chrome–Laden Wastewater
3. Detergent Wastewater
4. Solvent Wastewater No.1
5. Solvent Wastewater No.2
6. Zinc Galvanizing Wastewater
7. Textile Wastewater

The details of collected wastewaters are given below.

4.2.1. Oily Wastewater

A representative sample of oily wastewater was obtained from an automobile metal parts manufacturing industry named Arfesan situated at Gebze, Istanbul, where manufactured metal parts, are washed prior to surface treatment processes etc. in oil-removing baths. The grease and oil from surface of the manufactured parts accumulate in water baths and generate oily wastewater. There is a need to treat this wastewater to reduce pollutant concentration to the specified limit described in Table 18.2 of SKKY (1988) standards before ultimate disposal. The sample was collected at this stage and treated in the designed Mechanical Vapor Recompression (MVR) evaporator system. The important characteristics of the oily wastewater are given in Table 4.1.

Table 4.1. Important characteristics of oily wastewater.

PARAMETERS	UNITS	VALUE
pH	–	11.36
Conductivity	$\mu\text{S/cm}$	8310
Oil contents	mg/L	5600
COD	mg/L	3040

4.2.2. Chrome–Laden Wastewater

At the Arfesan industry, as mentioned above in the case of oily wastewater, the same automobile parts after removing oil and grease are dipped in chromic acid solution for metal finishing. The industry is using chromate chemicals, which are imported from Germany and are supplied in 25 kg bags in solid form. The composition of the imported chemicals is given below.

- < 40 percent Fluorosilic acid
- > 10 percent Chromium trioxide or chromic acid CrO_3
- < 10 percent Ammonium dichromate $(\text{NH}_4)_2\text{Cr}_2\text{O}_7$

At Arfesan, above mentioned chemicals are being used at the rate of 3 kg per 200 L of water to produce 1.5 percent solution by weight. The capacity of each metal finishing bath is 200 liters. The temperature of these baths is maintained at 35°C. The above mentioned chemicals are highly soluble in water and provide Cr^{6+} in the solution. The important characteristics of said chrome-laden wastewater are given in Table 4.2.

Table 4.2. Important characteristics of chrome-laden wastewater.

PARAMETERS	UNITS	VALUES
pH	–	2.5
Conductivity	μS/cm	50250
Cr ⁶⁺	mg/L	1150
Cr ³⁺	mg/L	293
Total Cr	mg/L	1443

4.2.3. Detergent Wastewater

The sample was collected from a detergent manufacturing industry named APS, situated at Tuzla, Istanbul. The important characteristics of the detergent wastewater are given in Table 4.3.

Table 4.3. Important characteristics of detergent wastewater.

PARAMETERS	UNITS	VALUE
pH	–	12.4
Total Solids	g/L	9.478
Total Dissolved Solids	g/L	9.282
COD	mg/L	8000.5

4.2.4. Solvent Wastewater No.1

This sample was obtained from Fako İlaçları A.Ş. Hammadde Fabrikası, Ayazağa, Istanbul. The wastewater sample was taken after synthesis process as shown in Figure 4.2.

The industry is producing domestic wastewater at a rate of 15 m³/day and industrial wastewater at a rate of 15-20 m³/day. At present, the industry is treating its wastewater in two stages. At the first stage, the industrial wastewater is treated chemically by means of precipitation, coagulation, sedimentation and filtration. At the second stage, the domestic wastewater and chemically treated wastewater are mixed and are treated biologically. After filtration, the sludge is sent to İZAYDAŞ.

The boiling point elevation was zero. The important characteristics of the solvent wastewater are given in Table 4.4.

Table 4.4. Important characteristics of solvent wastewater No.1.

PARAMETERS	UNITS	VALUE
pH	–	2.5
Conductivity	µS/cm	64480
COD	mg/L	70000

PROCESS FLOW DIAGRAM OF SULTAMICILLIN PRODUCTION

Raw Material + Energy (Electricity + Gas)

- ACETONE – PURE
- AMPICILLIN ANHYDROUS
- PENCILLANIC ACID OXYMETHYL C
- N.N. DIMETHYLFORMAMIDE – PURE
- ETHYL ACETATE – PURE
- ISOPROPYL ALCOHOL – PURE
- METHYL ACETOACETATE
- METHYLENE CHLORIDE – PURE
- SODIUM BICARBONATE
- SODIUM METABISULFITE
- SODIUM CHLORIDE
- SODIUM HYDROXIDE (LIQUID) 40-50 Percent
- SODIUM IODIDE
- P. TOLUENESULFONIC ACID
- ETHYLAMINE

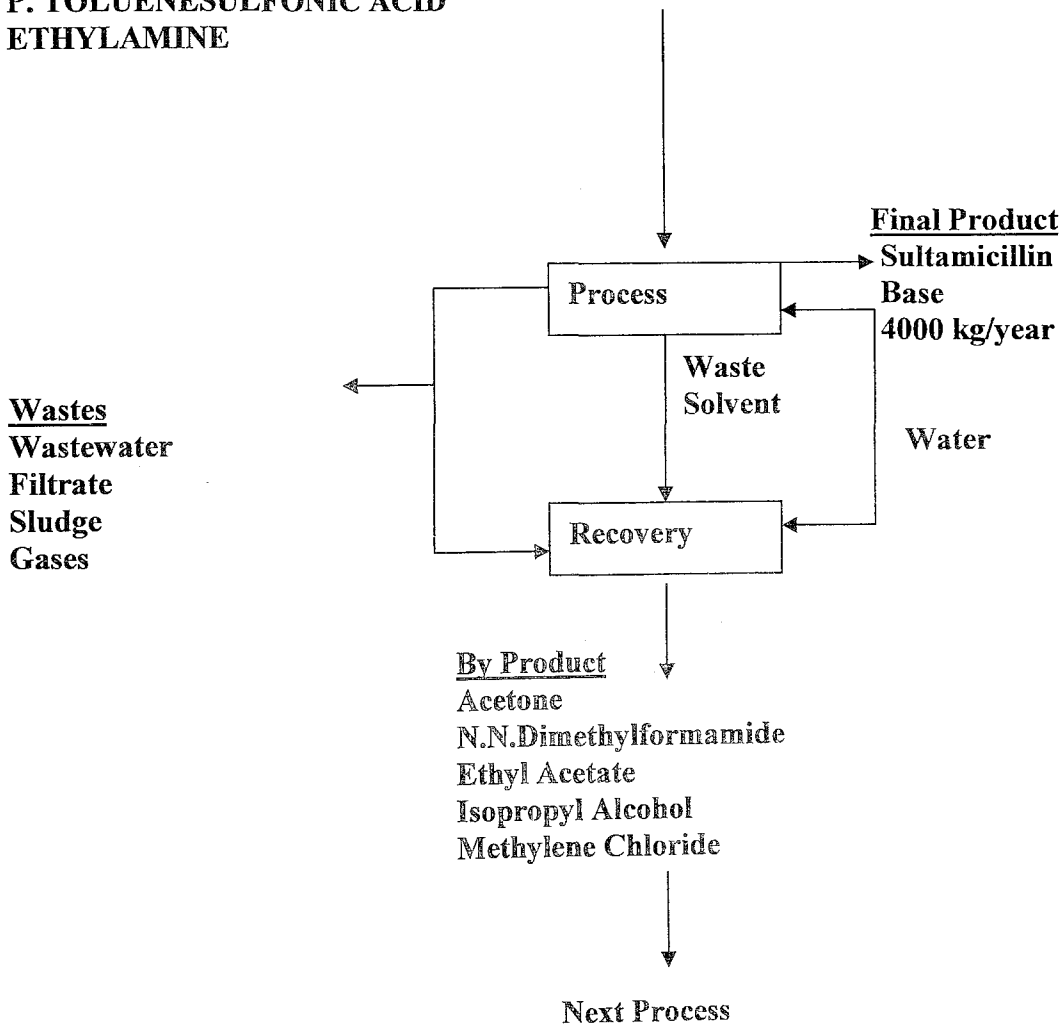


Figure 4.1. Process flow diagram for solvent wastewater No.1

4.2.5. Solvent Wastewater No.2.

The second type of wastewater sample was collected for treatment from the same industry. The sample of wastewater was after another synthesis process as shown in Figure 4.3. The smell of the sample was also bad. The important characteristics of this wastewater are given in Table 4.5.

Table 4.5. Important characteristics of solvent wastewater No.2.

PARAMETERS	UNITS	VALUE
pH	—	6.3
Conductivity	$\mu\text{S}/\text{cm}$	1825
COD	mg/L	30000

PROCESS FLOW DIAGRAM OF RANITIDINE HCL PRODUCTION

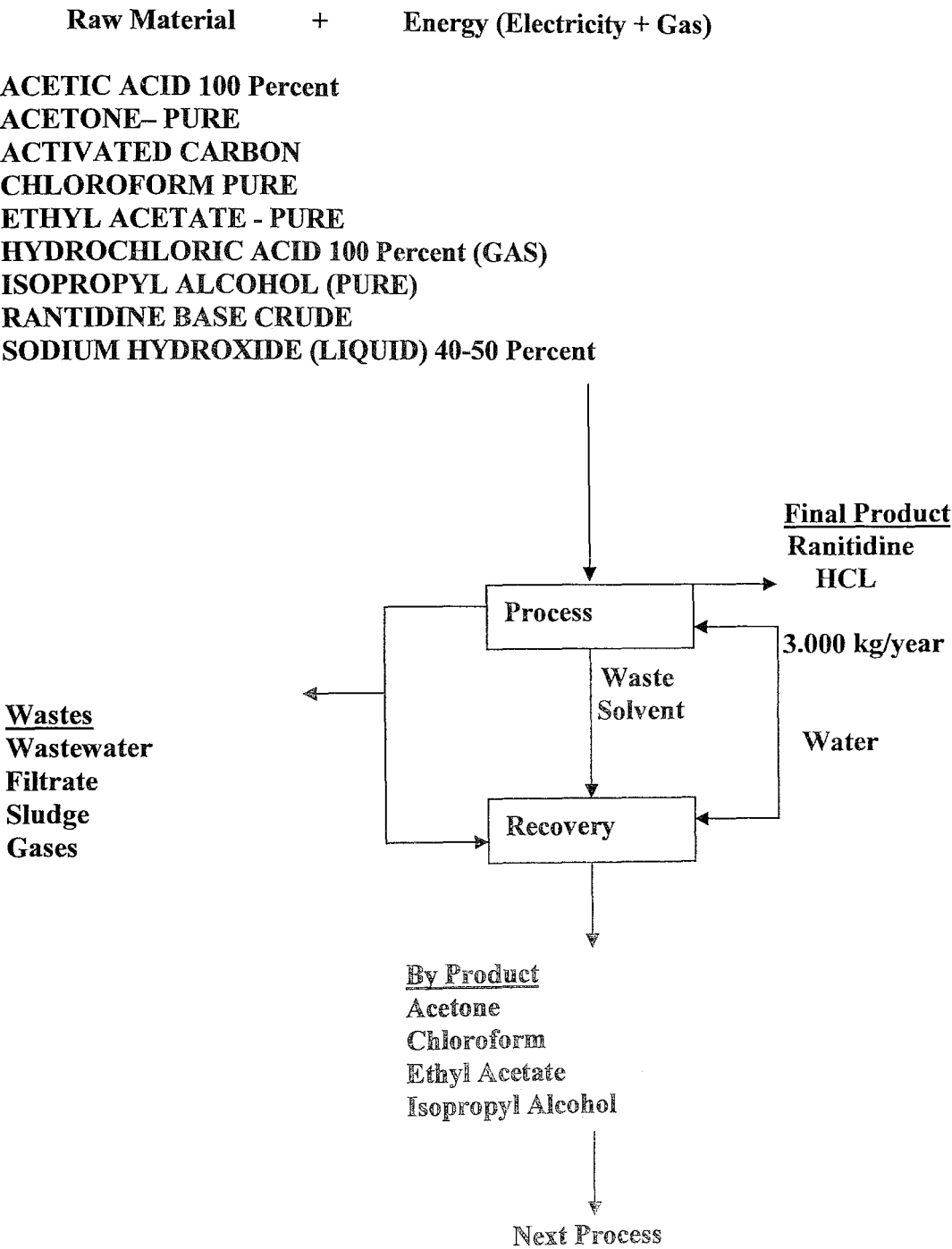


Figure 4.2. Process flow diagram for solvent wastewater No.2.

4.2.6. Zinc Galvanizing Wastewater

This sample of zinc galvanizing wastewater was collected from Alka limited, a galvanizing industry at Gebze, Istanbul, where zinc is galvanized on different shapes of iron and steel elements by hot-dip galvanizing technique. The term “hot-dip galvanizing” refers to the process of dipping clean steel or iron into molten zinc and letting it there until it reaches the temperature of the molten zinc. It is then withdrawn slowly, allowing complete retention of the accepted zinc coating.

Sometimes, this coating is not achieved to the desired level, requiring decoating of iron and steel coated elements. Therefore, the coated parts are dipped in dilute sulfuric acid, where coated zinc is washed along with dissolving of some iron particles as well.

Following this process, the industry is producing one ton per day of zinc and iron-laden wastewater. The important characteristics of said wastewater are given in the Table 4.6.

Table 4.6. Important characteristics of zinc galvanizing wastewater.

PARAMETERS	UNITS	VALUE
pH	–	1.5
Conductivity	µS/cm	268160
Zinc	mg/L	35320
Iron	mg/L	3810

4.2.7. Textile Wastewater

The effluent of textile industry was collected for treatment from Diktaş Dikiş İplik Sanayii ve Ticaret A.Ş. Cevizli, Istanbul. The industry is producing 400 tons wastewater

per day. It was observed that wastewater had no boiling point elevation. The important characteristics of the textile wastewater are given in Table 4.7.

Table 4.7. Important characteristics of textile wastewater.

PARAMETERS	UNITS	VALUE
pH	–	11
Conductivity	$\mu\text{S/cm}$	7700
COD	mg/L	2000

4.3. Experimental Procedures

In order to obtain good results it is always recommended to standardize and optimize every machine and equipment. The same was done for the designed Mechanical Vapor Recompression (MVR) evaporator system. First of all normal tap water was supplied to the MVR evaporator system and standardized for distillate against energy consumption (both electricity and steam). Then, wastewater samples were treated using MVR evaporator.

The next step was to treat seven different types of industrial wastewater samples collected from several different industries by using Mechanical Vapor Recompression evaporator. The amount of each wastewater sample treated was 2000-2500 liters. After treatment of one type of wastewater the system was washed out before supplying the other type of wastewater. The evaporator tubes were also cleaned thoroughly first chemically and then mechanically in order to remove scaling by opening the evaporator. After cleaning and washing the MVR system, the system was again standardized as mentioned above by using normal tap water.

4.4. Analytical Techniques for Different Types of Wastewater

4.4.1. Boiling Point

Boiling point is an important parameter for treatment of industrial wastewater by evaporation. Because energy consumption is directly proportional to boiling point of a solution, any elevation in boiling point means increase in energy consumption that ultimately leads to substantial rise in the cost of treatment.

Boiling point of each type of wastewater was measured in the laboratory by boiling the wastewater in a beaker and recording its boiling point on a thermometer. In this way boiling point elevation of wastewater, if any, was observed.

4.4.2. Analytical Procedure

All measurements were conducted during study, in accordance with Standard Methods (1992) of Water and Wastewater Analysis APHA, otherwise mentioned.

4.4.2.1. Turbidity Measurements. Turbidity measurements of samples were performed by using Hach 2100 P model turbidimeter.

4.4.2.2. pH Measurements. pH Measurements of samples were performed by using WTW model pH meter.

4.4.2.3. Metal Analysis. All metals were determined in samples by using Perkin Elmer Analyst 300. Concentrated sulfuric acid (98 percent) was used to digest the samples.

5. RESULTS AND DISCUSSIONS

Results can primarily be divided into two parts:

- Design, construction and start-up of the Mechanical Vapor Recompression (MVR) evaporator system.
- Testing the performance of the apparatus using some industrial wastewaters.

5.1. Design and Construction of the Mechanical Vapor Recompression (MVR) Evaporator

The flow diagram of the designed Mechanical Vapor Recompression (MVR) evaporator system is shown in Figure 5.1.

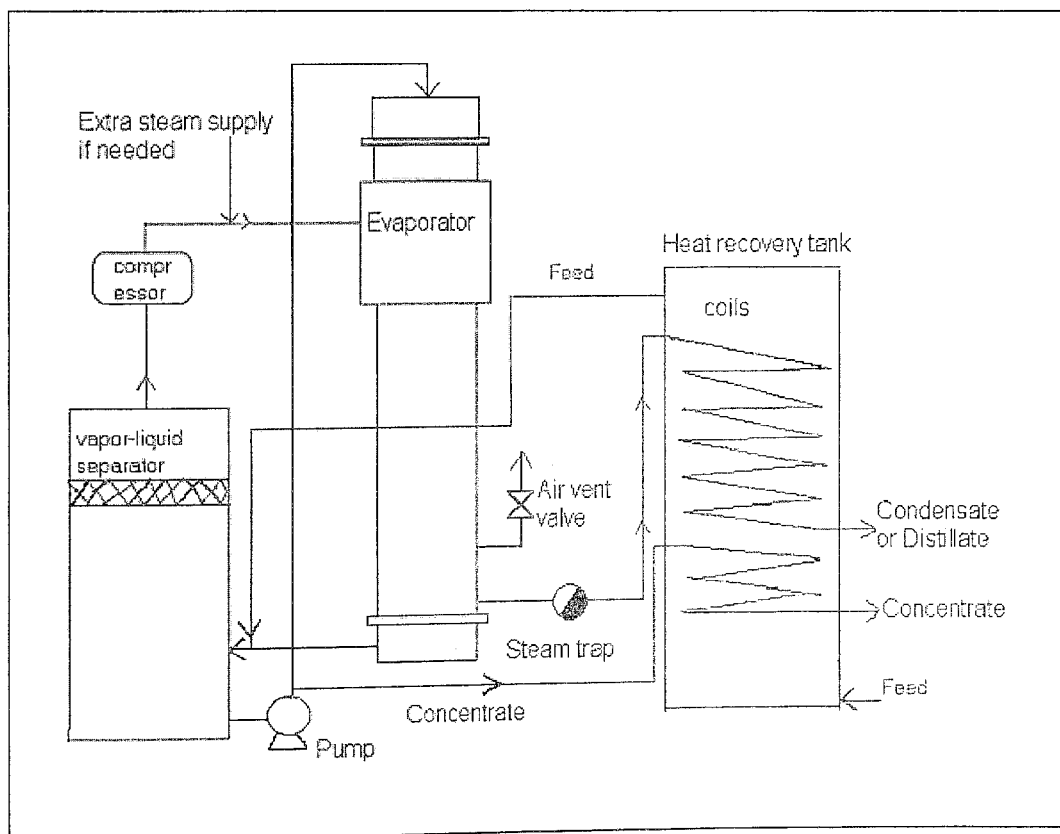


Figure 5.1. Flow diagram of the MVR evaporator system.

It consists of the following main parts all mounted on a skid as shown in Figure 5.2.

- (i) Evaporator
- (ii) Vapor separator body
- (iii) Compressor and controller
- (iv) Heat recovery tank

These units were coupled with each other by welding 2-4 centimeter stainless steel pipes.

5.1.1. Evaporator

This stainless steel unit, a vertical shell and tube type heat exchanger, was bought as such from a second hand equipment store. Top cover together with the liquid distributor, as well as the bottom cover was constructed by our workers

Length of the evaporator	= 1.98 m
Diameter of the shell	= 30 cm
Total number of tubes	= 33
Inner diameter of each tube	= 2.9 cm
Outer diameter of each tube	= 3.1 cm
Total surface area of the tubes	= 6.36 m ²

The wastewater to be treated is distributed to all the tubes on the top of the evaporator by annulus technique, in such a way that the wastewater travels down along the walls of the tubes without filling them. The vapors that are gradually formed and increased also travelled downward (which it must do, for the only outlet is near the bottom of the evaporator body). As a result, the velocity of both wastewater and vapors reaches its maximum at the bottom of the tubes. The wastewater and vapor mixture leave at the bottom end of the tubes and are conducted in the vapor separator.

A stainless steel pump (Lowara) ensures the forced recirculation of wastewater from the bottom of vapor separator to evaporator in order to obtain high heat transfer.

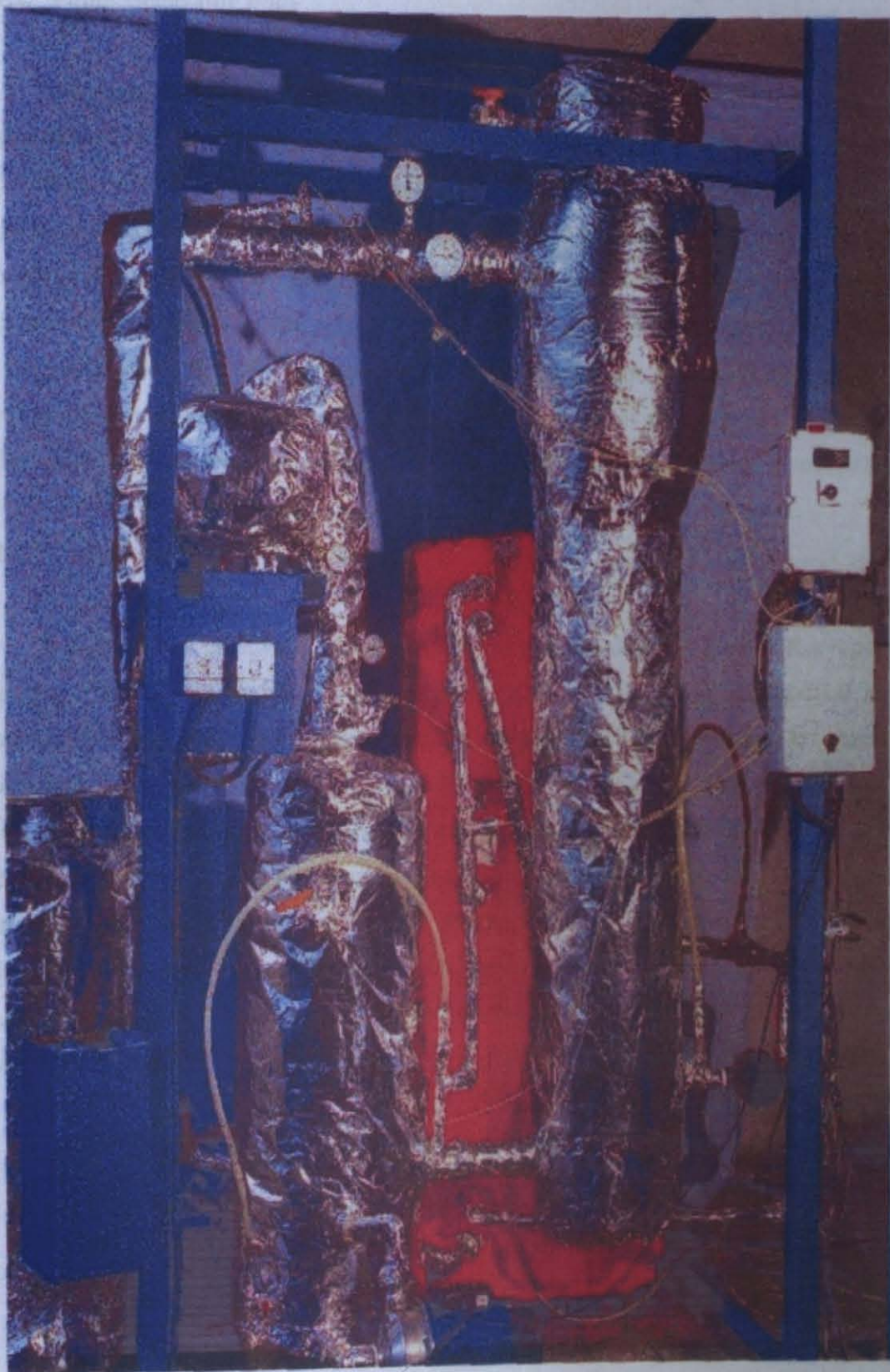


Figure 5.2. Photograph of Mechanical Vapor Recompression (MVR) evaporator system.

5.1.2. Vapor Separator Body

The vapor separator body is fabricated in such a way that it permits introducing the vapor tangentially to periphery of the separator, causing a circular motion, which separates the vapors from the concentrated wastewater by centrifugal force. Another advantage of separate construction of the vapor body separator is that the tubes in the evaporator body are easily accessible for cleaning. In the vapor body separator the arrangement of mist eliminator is also made for the high performance of the compressor (blower). From the top of the vapor separator body, the vapors enter to the compressor, and from the bottom one portion of concentrated wastewater is circulated into the evaporator and the other is collected as final concentrated wastewater after passing through coil of heat recovery tank.

5.1.3. Compressor

A single stage positive displacement blower was installed for the MVR evaporator systems. The said blower consists of two lobes or rotors. These two symmetrical rotary pistons revolve in opposite directions timed to one another. The medium to be conveyed flows into the blower housing that surrounds the two rotors. From there, it is moved via positive displacement in the chambers formed between the rotors and the housing toward the discharge side. There is no internal compression in the rotating blades. The vapors are compressed in the compartment on the pressure side by the positive displacement principle. A small gap remains between the lobes during rotation, and they do not actually touch. At the instant when one rotor tip passes the edge of the discharge port as can be visualized from Figure 5.3.

The other important specifications of the blower are as follow:

Volumetric flow rate capacity	= 13 m ³ /min
Power consumption	= 16-23.4 kW
Maximum operating speed of the lobes/rotors	= 4200 rpm
Discharge pressure - inlet pressure	= 1000 mbar
Maximum pressure ratio	= 2
(Discharge pressure to inlet pressure)	
Maximum discharge temperature	= 160 °C

The blower was coupled to run with a three-phase asynchronous motor. The capacity of the motor was 20 kWh. The motor speed was controlled by an efficient variable speed controller, according to the load of the blower. The power consumed by the system (motor) could be read directly by this speed controller during operation.

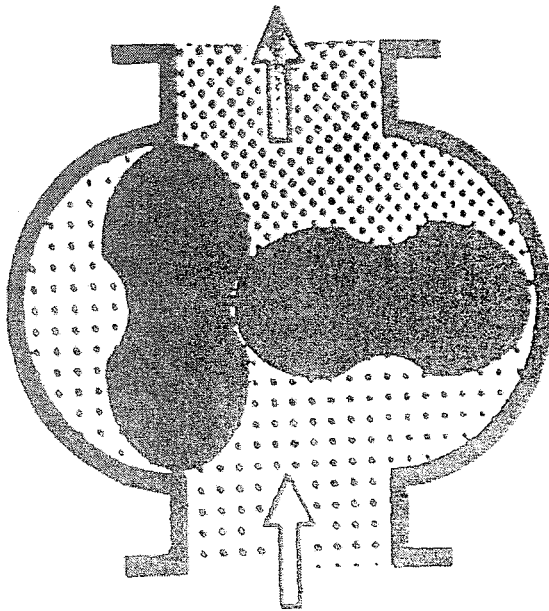


Figure 5.3. Operating principle for rotary piston blower (Heinz, 1989)

5.1.3.1. Speed Control. Controlling the impeller speed and, consequently, the circumferential speed can influence the volumetric flow rate and the compression ratio. For speed control, a three-phase asynchronous motor equipped with a frequency converter was used. Especially for steep characteristic curves, i.e. for large changes in pressure against

small changes in volume flow, control by continuous speed adjustment is advantageous. In the study this kind of speed controller was used, which was supplied by the ABB Company.

The advantages of frequency converter operation are as follow:

- Depending on the design, the motor can be operated at 20 to 60 percent above its nominal speed so that a step-up gear is not required in most cases.
- At start-up coupling is not required.
- By limiting the starting current, the supply main is not overloaded during start-up.
- Favorable partial load efficiencies are achieved.

5.1.4. Heat Recovery Tank

This tank was bought as such from a second hand equipment store. The heat of the condensate/distillate and the concentrate was utilized to heat up the feed/wastewater in the 500 L capacity tank. The construction material of tank was also stainless steel and was well insulated to avoid the heat losses. These arrangements were made to recover the heat instead of using heat exchanger due to financial constraints. The tank had two coils in which heated condensate/distillate and concentrate were passed and on shell side of the hollow tank, feed/wastewater was passed as shown in Figure 4.1. The lengthy coil in the tank was used for condensate/distillate due to higher quantity and temperature than concentrate. The other shorter coil in the tank was used for the concentrate. As a result of heat exchange, feed/wastewater was heated up and consequently the condensate/distillate and the concentrate were cooled down.

5.1.5. Flow Control

During evaporation the water level inside the evaporator was measured by a magnetic level controller which allowed automatically keeping the concentrate level constant by turning the feed pump on and off. The amount of liquid inside the evaporator was constant at a value of about 50 liters. The pressure before the compressor was at about

ambient pressure while after the compressor it was maximally 0.5 bars higher. A steam trap at the outlet of the heat exchanger allowed only liquid water to leave the evaporator.

5.2. Startup of the Apparatus

After construction and the first start-up attempts many difficulties were observed at different parts of the system. These difficulties did not allow running the evaporator for more than 10 minutes. The problems were partly due to wrong construction (improper position of the compressor, leaks), wrong operation (omitting the discharge of the uncondensable gases), wrong materials (HDPE covered thermocouples melted) as well as not initially functioning drive unit (stopped after a few minutes of operation). Solving all these problems were time consuming but allowed at the end a continuous evaporation over many days, which was the prerequisite for further performance testing of the apparatus.

After obtaining stable conditions of evaporation the performance of the MVR was studied first with tap water and then later with different wastewaters concerning:

- Energy Consumption and Cost per ton of distillate:
 - (a) Electricity
 - (b) Steam
- Quality of the Condensate/Distillate.

Table 5.1 portrays all the important parameters, which are taken into account while assessing the performance and efficiency of the system with tap water.

Table 5.1. Relevant parameters during evaporation with tap water

Sr. No.			Condensate or Distillate	Concentrate	T ₁	T ₂	ΔT	P ₁	P ₂	ΔP
	RPM	kW	(L/h)	(L/h)	(°C)	(°C)	(°C)	(bar)	(bar)	(bar)
1	596	0.5	61.16	1	101	104	3	0.08	0.26	0.18
2	710	0.6	67.1	1	100	104	4	0	0.2	0.2
3	770	0.75	78.5	1	102	106	4	0.1	0.35	0.25
4	830	0.9	87.50	1	103	109	6	0.13	0.40	0.27
5	889	1.0	96	1	103	108	5	0.15	0.4	0.25
6	1063	1.45	120	1	103	109	6	0.21	0.5	0.29
7	1183	1.95	138	1	103	110	7	0.22	0.53	0.31
8	1304	2.2	149	1.5	102	110	8	0.21	0.53	0.32
9	1424	2.55	162	1.5	101	110	9	0.1	0.5	0.4
10	1541	2.9	174.6	2	101	112	11	0.12	0.5	0.38
11	1660	3.2	187	2	101	111	10	0.1	0.5	0.5

The second column gives the rotation speed of the compressor in rpm as adjusted by the electronic drive unit. The third column gives the consumed electrical power of the compressor at a certain rpm, which can be displayed together with the rpm directly on the monitor of the electronic drive unit. Column 4 gives the measured distillation rate at different rpm. The distillation rate was measured after attaining quasi-steady state conditions (approx. after 10 min) by measuring the distillate volume per time. As expected increasing the compressor speed also increases the distillation rate. The concentrate output rate as seen in column 5 can be chosen by adjusting the concentrate adjusting valve. This valve was closed at the start up period until the concentration of the components inside the evaporator reached a desired value.

The important criteria here are:

1. The higher the concentration of the solutes inside the evaporator the smaller the volume of the wastewater for further processing. Volume reductions by a factor of 100 or 1000 are possible.
2. Boiling point elevation more than a few degrees decreases the distillation rate.
3. Any precipitate formation inside the evaporator due to too high concentration of the solutes should be avoided. It is aimed to take out the concentrated hot solution, cool it down for allowing crystallisation of pure solutes. If desired the mother liquor can be returned back to the evaporator.

Columns 6 (T_1) and 7 (T_2) show the temperature while columns 9 (P_1) and 10 (P_2) show the pressure before and after the compressor respectively. Their difference is the driving force of the heat transfer in the heat exchanger (evaporator) at different compressor speeds.

At steady state condition, the tap water was heated up to 72 °C by heat transfer from the concentrate and distillate carrying coils in the heat recovery tank. Up to 99 percent of clean water was recovered as condensate/distillate at different flow rate.

It is clear that by increasing the compressor speed higher temperatures and pressures can be achieved at the output of the compressor, which results in a higher distillation rate due to higher temperature difference at both sides of the evaporator/heat exchanger. On the other hand Table 5.1 and 5.2 show that the energy consumed per ton of distillate also increases with increasing compressor speed. This means that high distillation rate (low investment cost for a certain distillation duty) is coupled with a high running cost. For the constructed MVR evaporator the optimum working range seems to be 3-4 tons of distillate/day with a cost of 2.5-3 US\$ of energy/ton of distillate.

As the cost of electricity in Turkey is 0.1 US\$ for one kilowatt-hour (kWh) and steam cost is nearly 20 US\$ per 1000 kg, during conducting the experiment it was deduced that for treating one ton of each sample 60 kg of steam is required. So the cost of steam is 1.2 US\$ per ton of treated sample.

Table 5.2. The operating cost at different conditions when sample was simple tap water.

Experiment No.	Power Consumption	Output rate of Condensate or Distillate	Electricity Consumption	Electricity Cost/Ton of Condensate or Distillate	Total Cost
	kW	L/h	kWh/ton	US\$	US\$
1	0.5	61.16	8.17	0.82	2.02
2	0.6	67.1	8.94	0.89	2.09
3	0.75	78.5	9.55	0.95	2.15
4	0.9	87.5	10.28	1.02	2.22
5	1.0	96	10.41	1.04	2.24
6	1.45	120	12.08	1.20	2.40
7	1.95	138	14.10	1.41	2.62
8	2.2	149	14.76	1.47	2.67
9	2.55	162	15.74	1.57	2.77
10	2.9	174.6	16.66	1.66	2.82
11	3.2	187	17.77	1.78	2.98

The conductivity of distillate was 13 $\mu\text{S}/\text{cm}$ as compared to 135 $\mu\text{S}/\text{cm}$ of the feed water, which is a reduction of 90.37 percent. Since the conductivity of the water is one of the important parameter for assessing its quality, so the quality of tap water was analyzed on this basis. Table 5.3 gives the performance of MVR evaporator.

Table 5.3. Input and output parameters for normal tap water.

PARAMETERS	INPUT	OUTPUT	
	Feed water	Concentrate	Distillate
pH	6	6	6
Conductivity, $\mu\text{S}/\text{cm}$	135	258	13

Figure 5.4. depicts the variation of steam, electricity and total cost in terms of US dollars per ton per day. The graph summarizes the total average operational cost after running many experiments at steady state conditions. To get optimum results, amendments were also carried out during experimentations.

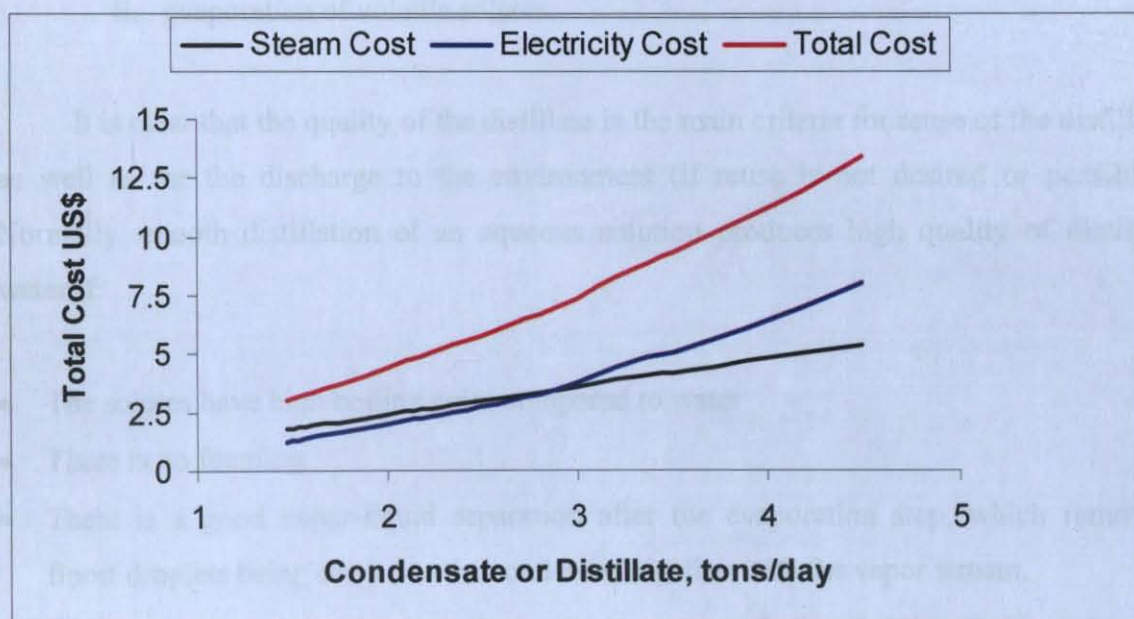


Figure 5.4. Steam, electricity and total cost for the recovery of condensate or distillate tons per day.

5.3.1. Only Wastewater

A typical sample for city wastewater was obtained from Ararua Automobile parts manufacturing industry located at Gurgaon, Haryana. After investigating all aspects of the wastewater, the waste is washed before a surface treatment in an oil removing tank.

5.3. Tests with Wastewaters

After the detailed study of the evaporator distillation efficiency and cost with tap water we tested the MVR evaporator using typical industrial wastewaters. The aims of these tests were:

1. To see the quality of the distillate.
2. To see the concentrating of solutes and coupled effects like;
 - i. boiling point elevation,
 - ii. fractionated crystallization of valuable solutes.
3. To observe the response of the MVR evaporator under conditions of;
 - i. foaming,
 - ii. evaporation of volatile solutes.

It is clear that the quality of the distillate is the main criteria for reuse of the distillate as well as for the discharge to the environment (if reuse is not desired or possible). Normally smooth distillation of an aqueous solution produces high quality of distilled water if:

- The solutes have high boiling point compared to water
- There is no foaming
- There is a good vapor-liquid separation after the evaporation step, which removes finest droplets being carried to the condenser together with the vapor stream.

The main goal in these experiments with different wastewaters was to find out if the distillate quality is in accordance with discharge limits without the need for any further treatment.

5.3.1. Oily Wastewater

A typical sample for oily wastewater was obtained from Arfesan automobile metal parts manufacturing industry located at Gebze, Istanbul. After manufacturing of metal parts, the parts are washed before a surface treatment in an oil removing bath by dipping.

At this stage the sample is collected and treated in the designed Mechanical Vapor Recompression (MVR) evaporator.

The oily wastewater was evaporated up to 86 percent. No boiling point elevation was observed up to evaporation of 86 percent. So, the consumption of energy and cost was the same as in the case of tap water.

The results in Table 5.4 show that the COD removal efficiency of 92 percent was achieved. With respect to COD, the result by MVR evaporator system was within the limit of SKKY (1988), as shown in Table 5.5. Oil content was less than the limit of SKKY (1988) on 24-hour composite base but it was higher on 2-hour base.

The results seem to show that evaporation of oily wastewater cannot be extended much above 3.9 percent oil content. The distillate will very probably need further treatment for not exceeding discharge limits. In this respect membrane treatment of oily wastewaters seem to be superior to evaporation since membranes are known to be able to concentrate oily wastewaters to oil contents above 50 percent, so that their reuse as fuel is possible.

Table 5.4. Parameters observed before and after treatment of oily wastewater.

PARAMETERS	INPUT	OUTPUT	
	Feed	Concentrate	Distillate
pH	11.36	11.85	6.25
Conductivity, μS/cm	8310	50670	318
Oil contents, mg/L	5600	39005	16
COD, mg/L	3040	19320	250

Table 5.5. Comparison of the output of MVR evaporator system with the standards of SKKY (1988).

PARAMETERS	SKKY (1988) STANDARDS FOR AUTOMOBILE SECTOR (TABLE 18.2)		RESULTS ACHIEVED BY MVR SYSTEM
	Composite sample on 2 h base	Composite sample on 24 h base	
Oil content, mg/L	20	10	16
COD, mg/L	400	30	250
pH	6-9	6-9	6.25

The photograph of input wastewater, output concentrate and distillate are shown in Figure 5.5. Although a marked difference in the visual quality can be observed between these three samples a small turbidity in the distillate is recognizable. This turbidity increased if the evaporation was extended above 86 percent.

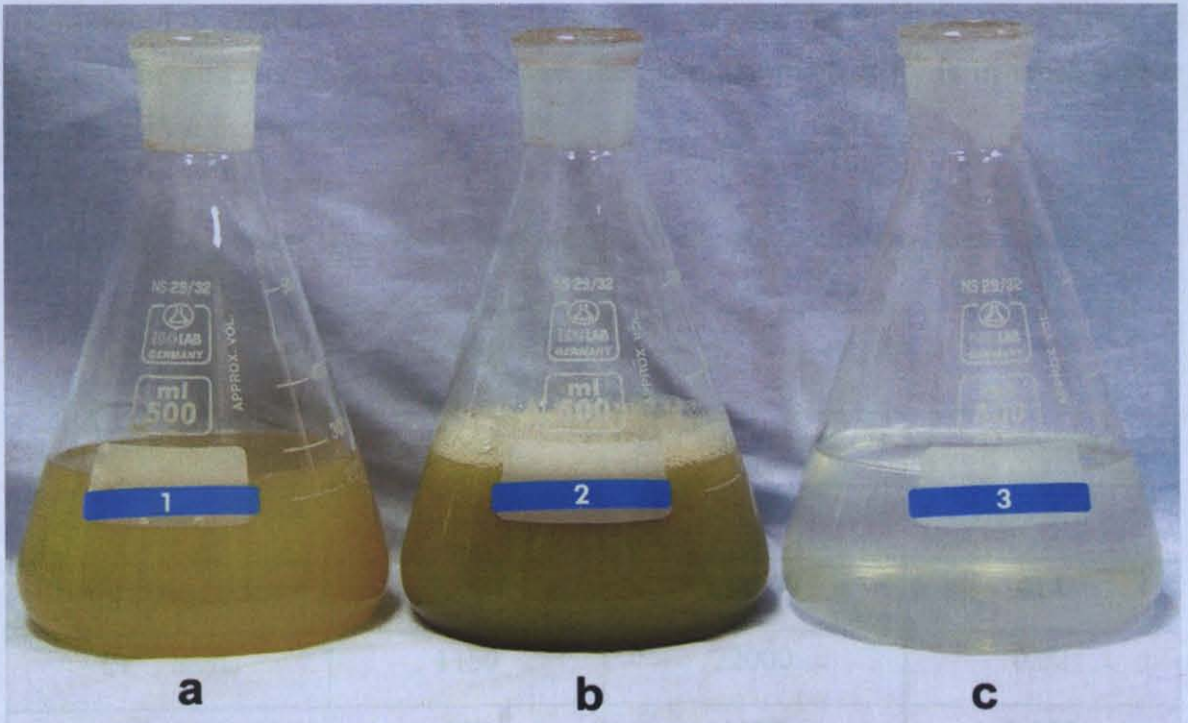


Figure 5.5. Visual comparison for oily (a) wastewater, its (b) concentrate, and (c) distillate from MVR evaporator system.

5.3.2. Chrome–Laden Wastewater

Hexavalent chromium is a highly toxic metal as well as a suspected carcinogen. It poses both a danger to human health and to the environment as well. Upon weakening, the chrome solution in the bath is replaced by a new one. Chromium is a “hazardous constituent” so spent chromium plating baths are handled as hazardous wastes and are therefore treated carefully before ultimate disposal.

The Arfesan industry is producing one ton of spent chrome wastewater per day. The wastewater sample was collected and put under trial in MVR evaporator system. The output results are presented in the Table 5.6.

The recovery efficiency of clean water (distillate) was 95 percent and concentration factor was 20. The concentration factor was calculated by dividing the feed volume by concentrate volume. This result was obtained at 3.57 ton/day workload of evaporator. At this running condition, the separation efficiency was more then 99.9 percent for Cr^{6+} , and Cr^{3+} , as shown in Table 5.6. It was observed that the quality of distillate deteriorated when the workload of evaporator was increased than this rate resulting in higher conductivity. It may also be observed from Table 5.6 that the more hazardous, Cr^{6+} is in much higher proportion than the corresponding Cr^{3+} .

Table 5.6. Parameters observed before and after treatment of chrome-laden wastewater.

PARAMETERS	INPUT	OUTPUT	
	Feed	Concentrate	Distillate
pH	2.5	1.5	3.5
Conductivity, $\mu\text{S}/\text{cm}$	50250	138000	414
Cr^{6+} , mg/L	1150	22000	0.02
Cr^{3+} , mg/L	293	1109	0.125
Total Cr, mg/L	1443	23109	0.145

The above optimum conditions were achieved with temperature and pressure ranges of ΔT 7 °C and ΔP 0.3 bar, respectively. At these conditions the electricity consumption was 14.57 kWh/ton with steam requirement of 60 kg/ton. The boiling point elevation up to evaporation of 90 percent was only 0.5 °C. The total cost calculated was not more than 2.66 US\$/ton for the treatment of above wastewater. The comparison of the results from MVR system with SKKY (1988) standards is given in Table 5.7.

Table 5.7. Comparison of output of the MVR evaporator system with SKKY (1988) standards for automobile industry (Table 18.2).

PARAMETERS	UNIT	SKKY (1988) STANDARDS	MVR OUTPUT
Cr ⁶⁺	mg/L	0.05	0.02
Total Cr	mg/L	0.5	0.145

Table 18.2 of SKKY (1988) is for automotive production plants including car, tractor, minibus, motor cycle and bicycle manufacturing units. The results obtained from MVR evaporator system are well below the standards of SKKY (1988).

The photograph of input wastewater, output, concentrate and distillate are shown in Figure 5.6. A marked difference in the visual quality can be observed between these three streams.

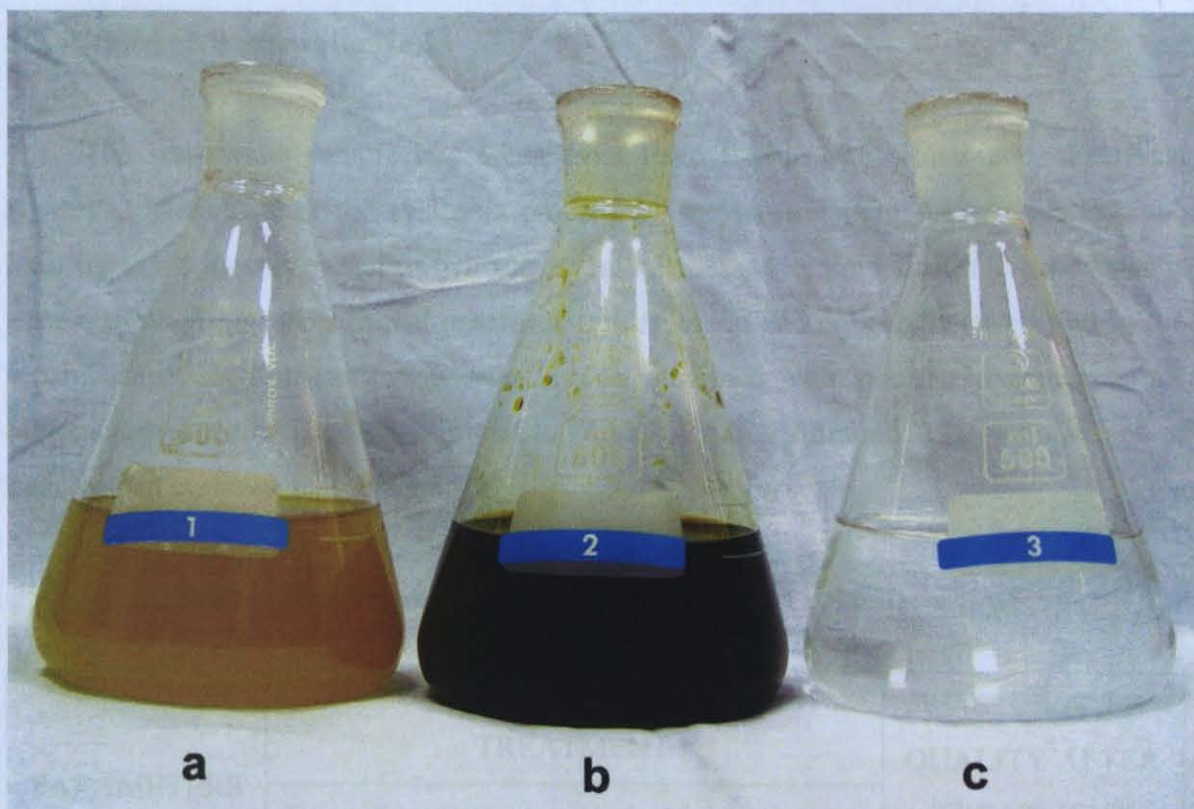


Figure 5.6. Visual comparison for chrome-laden (a) wastewater, its (b) concentrate, and (c) distillate from MVR evaporator system.

The results with chrome-laden wastewaters show that the distillate can be discharged to the environment without any further treatment. Concerning the possibility of reuse of the valuable solutes, the concentrate contains besides chromate also other metal ions like $\text{Fe}^{2+}/\text{Fe}^{3+}$ or Al^{3+} depending on which metal part is dipped into the chromate solution. The valuable solute is here chromate and possibly its reuse requires a precipitation and separation of these metals by neutralization and filtration. A preliminary laboratory experiment showed that a clean chromate solution can be obtained by this way easily.

5.3.3. Detergent Wastewater

This sample was taken for trial from the APS, detergent manufacturing industry at Tuzla, Istanbul. While treating the sample with MVR evaporator system an almost creamy foam was the only output from both distillate and condensate outlets. It seemed that this kind of wastewater definitely cannot be treated with our constructed evaporator.

5.3.4. Solvent Wastewater No.1

The wastewater sample was taken from Fako İlaçları A.Ş. Hammadde Fabrikası Ayazağa, Istanbul after the synthesis process as shown in Figure 4.1. At present, the industry treats its wastewater in two stages. In the first stage, the industrial wastewater is treated through physicochemical processes (precipitation and coagulation etc.) and in the second stage; the domestic wastewater is also combined with industrial wastewater for biological treatment. The sludge is sent to İZAYDAŞ after filtration. The performance of their system is shown in Table 5.8.

Table 5.8. Current treatment plant performance of Fako İlaçları A.Ş.

PARAMETERS	WASTEWATER QUALITY BEFORE TREATMENT		WASTEWATER QUALITY AFTER TREATMENT
	Domestic wastewater	Industrial wastewater	
COD, mg/L	500-1250	7500-25000	500-1000
Total-N, mg/L (TKN+NO ₃ -N+NO ₂ -N)	50	300-1500	200-300

The pH value of the collected sample was 2.5 with pungent smell. After trial, on distillate side the odor remained same as before, it was concluded that some other chemicals having boiling points lower than that of water also evaporated from sample along with water vapors during evaporation. The sample was run at different rates but the results remained unchanged. The boiling point elevation was zero, so the operation cost was equivalent to that of tap water. Although the results in Table 5.9 show a good reduction of conductivity, the distillate has a higher COD than the original feed i.e. a solvent with a lower boiling point than water is condensing preferably in the distillate while still being present in the concentrate. Neither distillate nor concentrate can be discharged due to the high COD. Therefore the experiments with this wastewater showed no separation effect, which can be of value.

Table 5.9. Parameters observed before and after treatment for solvent wastewater No.1.

PARAMETERS	INPUT	OUTPUT	
	Feed	Concentrate	Distillate
pH	2.5	3.5	2.5
Conductivity, $\mu\text{S}/\text{cm}$	64480	372120	1956
COD, mg/L	70000	60000	77000

The photograph of input wastewater, output, concentrate and distillate are shown in Figure. 5.7. A marked difference in the visual quality can be observed between these three streams.

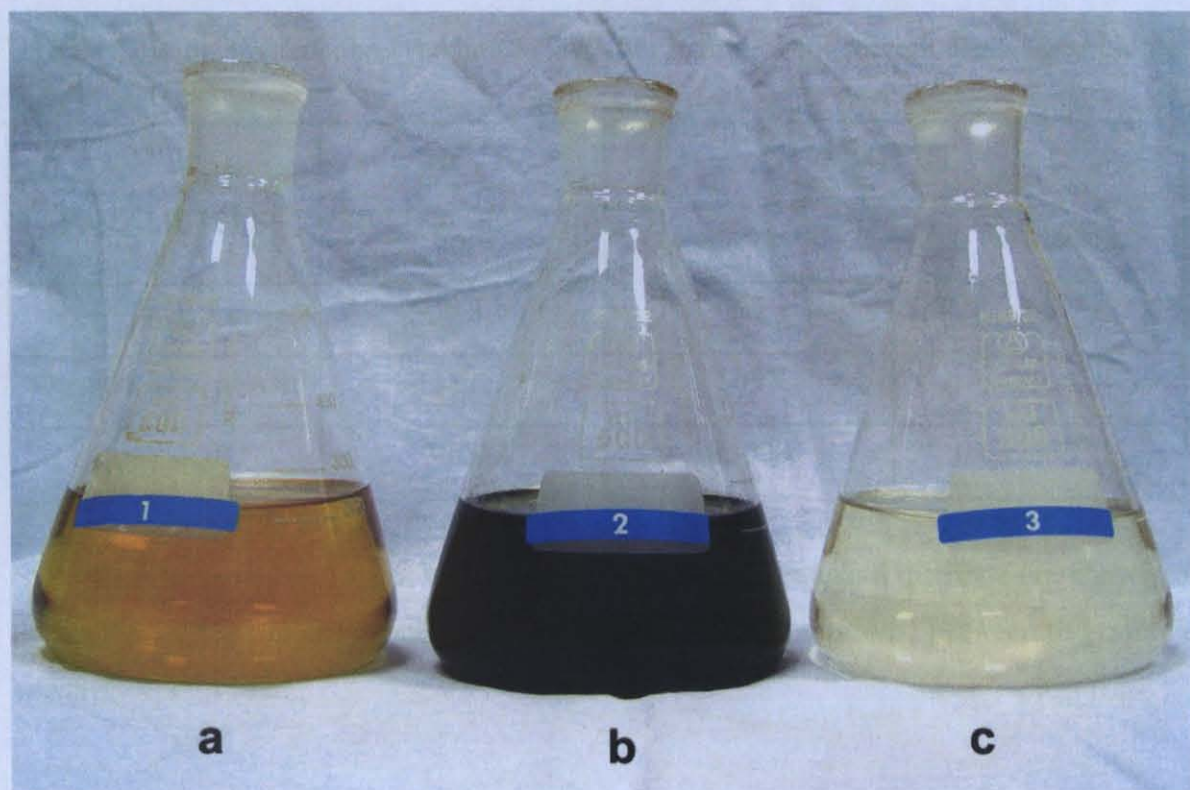


Figure 5.7. Visual comparison for solvent (a) wastewater No.1., its (b) concentrate, and (c) distillate from MVR evaporator system.

5.3.5. Solvent Wastewater No.2.

This solvent wastewater sample was collected for the trial from the above mentioned industry described in Section 5.1.4, but from another synthesis process. The evaporation was conducted up to 90 percent. The boiling point elevation was zero, so the operation cost was also equivalent to that of tap water.

After treatment in MVR evaporator system the distillate had a distinct odor and it was observed that the results were somewhat better (Table 5.10.) in terms of COD removal (59 percent) compared to those obtained from the treatment of solvent effluent No.1. However, neither distillate nor concentrate can be discharged due to the high COD. Therefore the experiments with this wastewater too showed no separation effect, which can be of value.

Table 5.10. Parameters observed before and after treatment for solvent wastewater No.2.

PARAMETERS	INPUT	OUTPUT	
	Feed	Concentrate	Distillate
pH	6.3	5.2	5.5
Conductivity, $\mu\text{S}/\text{cm}$	1825	5093	391
COD, mg/L	30000	36000	12175

The photographs of input wastewater, output, concentrate and distillate are shown in Figure 5.8. A marked difference in the visual quality can be observed between these three streams.

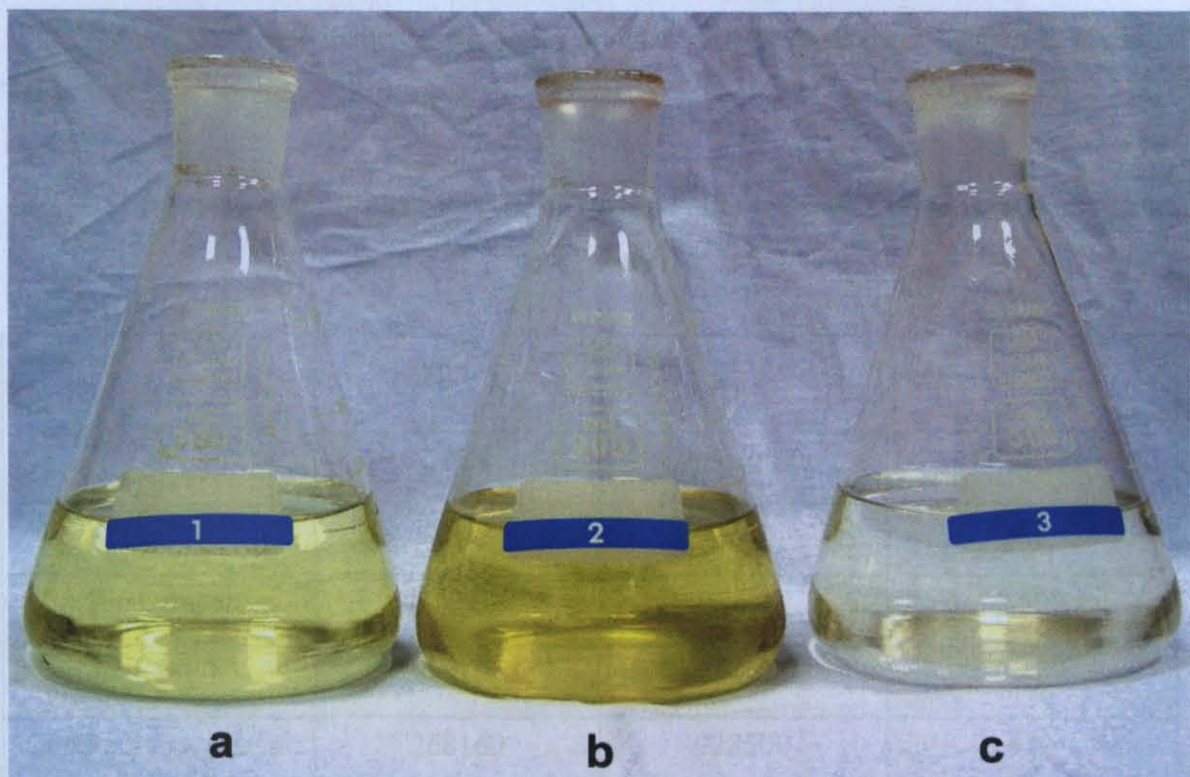
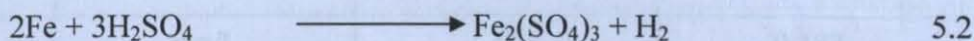
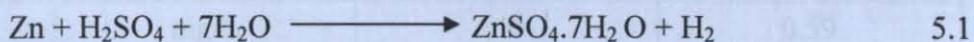


Figure 5.8. Visual comparison for solvent (a) wastewater No.2., its (b) concentrate, and (c) distillate from MVR evaporator system.

5.3.6. Zinc Galvanizing Wastewater

This sample was collected from Alka limited, galvanizing industry at Gebze, Istanbul. During the process of decoating, zinc is washed along with iron when substandard zinc coated elements are dipped in sulfuric acid. The reactions involved are as under:



The pH value of the said wastewater was 0.5. The observed boiling point elevation was 2 °C for the wastewater. The evaporation was done up to only 75 percent to avoid choking of the system. The collected hot concentrated solution was allowed to cool down. White crystals of hepta zinc sulfate settled down in the container. Mother liquor was again sent back to the MVR evaporator.

The comparison between input and output of MVR evaporator system is given in Table 5.11.

Table 5.11. Parameters observed before and after treatment for zinc galvanizing wastewater.

PARAMETERS	INPUT	OUTPUT	
	Feed	Concentrate	Distillate
pH	1.5	0.5	4.0
Zinc, mg/L	35320	—	0.590
Iron, mg/L	3810	—	0.187
Conductivity, $\mu\text{S}/\text{cm}$	268160	928500	432

Table 5.11 shows a good conductivity decrease in the distillate and that the heavy metals concentrations are below the limits of SKKY (1988). The comparison of the results from MVR evaporator system with SKKY (1988) standards is given in Table 5.12.

Table 5.12. Comparison of output of the MVR evaporator system with SKKY (1988) standards for hot zinc galvanizing industry (Table 15.7).

PARAMETERS	UNIT	SKKY (1998) STANDARD	MVR OUTPUT
Zinc (Zn)	mg/L	5	0.59
Iron (Fe)	mg/L	50	0.187
pH	—	6-9	4

Since we are evaporating an acid solution only hence pH is lower than the limits (but close to the border). The results here show that the distillate can be discharged to the environment after a minor treatment like sending the distillate over a Dolomite filter $\text{CaCO}_3/\text{MgCO}_3$ or by pH adjustment.

The concentrate on the other hand has a valuable solute, ZnSO_4 which can be crystallized easily. Therefore this case was studied closer for judging about the feasibility of evaporation.

Table 5.13 shows an evaporation cost of 2-3 US\$/ton of wastewater. The wastewater contains zinc besides iron and may be minor amounts of other heavy metals. Cooling a hot concentrated acid solution allows separation of almost pure $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ crystals with iron staying in solution. A possible processing-scheme of this wastewater is shown in Figure 5.9.

Table 5.13. The operating cost at different conditions with zinc-laden wastewater.

Experiment No.	Power Consumption kW	Output rate of Condensate or Distillate L/h	Electricity Consumption kWh/ton	Electricity Cost/Ton of Condensate or Distillate US\$	Total Cost US\$
1	0.52	61.0	8.52	0.85	2.05
2	0.63	66.7	9.45	0.94	2.14
3	0.77	78.0	9.87	0.99	2.19
4	0.93	86.3	10.78	1.08	2.28
5	1.3	96.0	13.54	1.35	2,55
6	1.47	118.6	12.39	1.24	2.44
7	1.98	136.2	14.54	1.45	2,65
8	2.41	147.8	16.31	1.63	2.83
9	2.86	159.9	17.89	1.79	2,99
10	2.95	175.3	16.83	1.68	2.88
11	3.7	185.	19.98	2.00	3.20

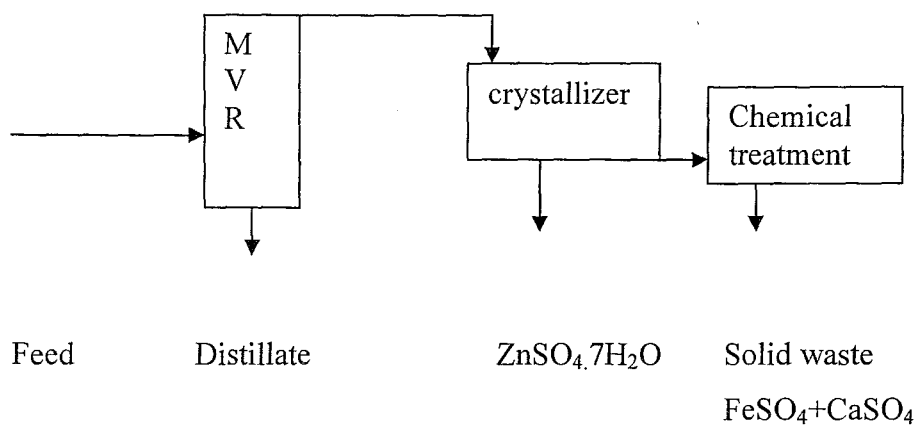


Figure 5.9. Possible processing-scheme of zinc-laden wastewater by MVR evaporator system.

After crystallization of zinc the rest of solution (possibly 20 percent) can be neutralized with lime for precipitation of iron together with CaSO_4 .

The analysis results of recovered hepta zinc sulfate are as under:

Zn Content	: 20.14 percent
Fe Content	: 0.65 percent
Pb Content	: 23.92 ppm
Total Nitrogen Content (TKN+NO ₃ -N+NO ₂ -N)	: Nil
pH of 10 percent solution	: 3.71
SO ₄ ²⁻ Content	: 26.54 percent
Mg Content	: Nil
Insoluble Content	: 0.3 percent

The comparison of hepta zinc sulfate recovered from the system and marketed hepta zinc sulfate fertilizer is given in Table 5.14.

Table 5.14. Comparison of hepta zinc sulfate recovered from the system and marketed hepta zinc sulfate fertilizer (Pakistan Standard, 1998).

CONTENTS	RECOVERED HEPTA ZINC SULFATE	MARKETED HEPTA ZINC SULFATE
Zn	20.14 percent	21.0 percent (Min.)
Mg	Nil	0.5 percent (Max.)
Pb	23.92 ppm	30 ppm (Max.)
Insoluble	0.3 percent	1.0 percent (Max.)

The molecular weight of hepta zinc sulfate ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$) is 287.57. So 65.38 kg of zinc produces 287.5 kg of hepta zinc sulfate. Since one ton of zinc galvanizing wastewater carry 35.32 kg of zinc, 155.33 kg of hepta zinc sulfate can be obtained from it. The price of hepta zinc sulfate in Turkey is about 0.4 US\$ per kilogram, therefore the price of 155.33 kg of hepta zinc sulfate will be 62.13 US\$.

The value of the distillate is about 1 US\$ if reuse is possible (which will possibly be the case). The costs of evaporation of one ton of this wastewater is about 3 US\$ and the cost of chemical treatment is estimated to be below 1 US\$.

As a summary even if the cost, which is normally paid by the wastewater providing industry, is deducted the theoretical MVR plant will end up in earning, about 59 US\$ per ton of wastewater.

The photographs of input wastewater, output, concentrate and distillate are shown in Figure. 5.10. A marked difference in the visual quality can be observed between these three streams.

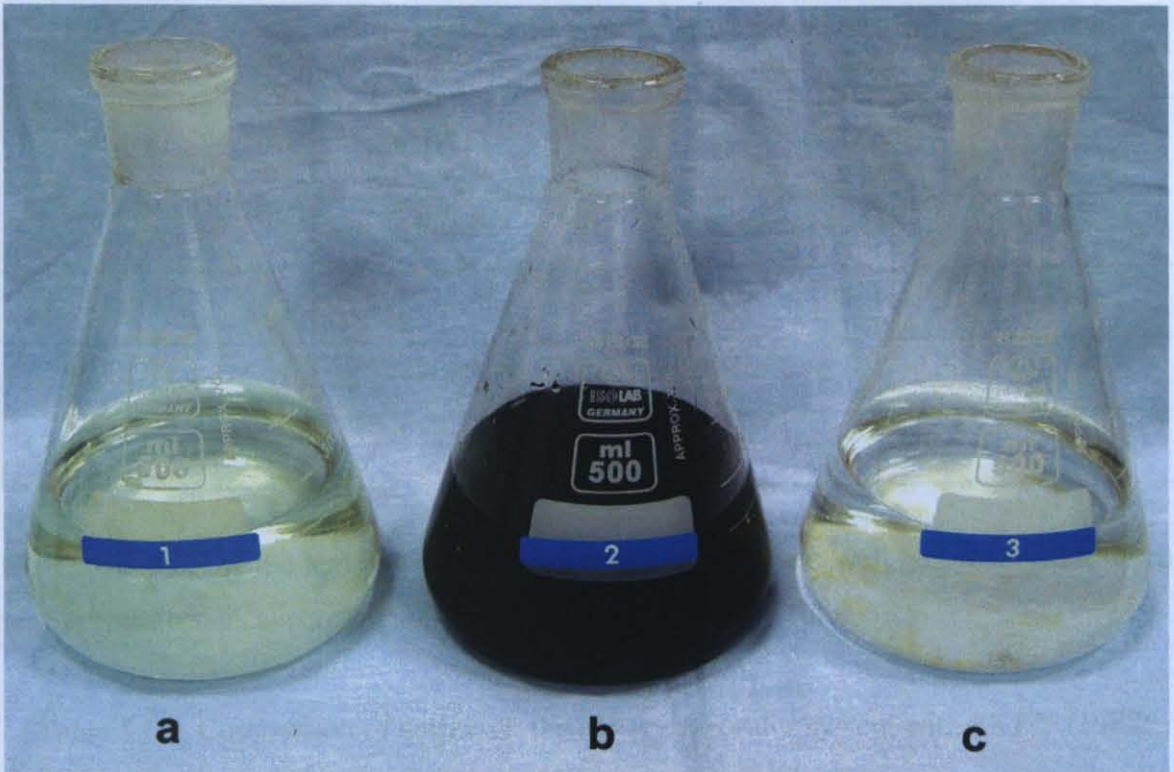


Figure 5.10. Visual comparison for zinc laden (a) wastewater, its (b) concentrate, and (c) distillate from MVR evaporator system.

5.3.7. Textile Wastewater

The effluent of textile industry was collected for treatment from Diktaş Dikiş İplik Sanayi ve Ticaret A.Ş. Cevizli, Istanbul. It was observed that wastewater had no boiling point elevation. Ninety five percent of the total wastewater was achieved as distillate of very fine quality and was devoid of any color. Chemical Oxygen Demand (COD) removal efficiency was obtained as 93.2 percent. The operating cost was similar as for treatment of normal tap water. The input and output results are given in Table 5.15.

Table 5.15. Parameters observed before and after treatment of textile wastewater.

PARAMETERS	INPUT	OUTPUT	
	Feed	Concentrate	Distillate
pH	11	11.5	6.0
COD, mg/L	2000	7840	136
Conductivity, $\mu\text{S}/\text{cm}$	7700	48090	23

The result of the textile wastewater in terms of COD was well below for all kinds of textile wastewaters according to SKKY (1988), as shown in Table 5.15.

Table.5.16. Comparison of output of the MVR evaporator system with SKKY (1988) standards for textile wastewater (Table 10).

PARAMETER COD, mg/L	SKKY (1988) STANDARDS		MVR OUTPUT
	Composite sample on 2 h base	Composite sample on 24 h base	136
Table 10.1 for threading wastewater	350	240	—
Table 10.2 for woven fabric wastewater	400	300	—
Table 10.3 for cotton wastewater	250	200	—
Table 10.4 for woven wastewater	400	300	—

The photograph of input wastewater, output, concentrate and distillate are shown in Figure. 5.11. A marked difference in the visual quality can be observed between these three streams.

Although the distillate with a conductivity of $23 \mu\text{S}/\text{cm}$ is of a quality of almost pure water; the reuse of this high quality water, does not justify the high evaporation costs of 2.5-3.0 US\$/ton, since raw water used in this industry is normally 1 to 1.5 US\$/ton in Turkey.

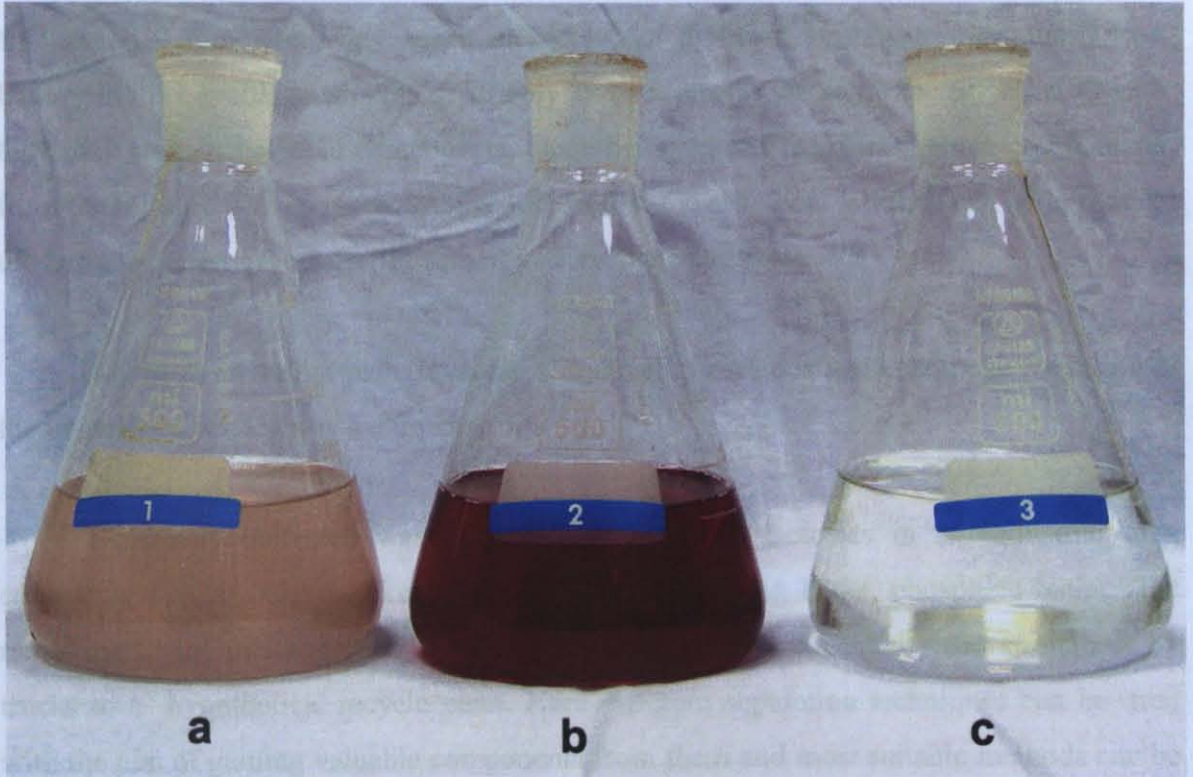


Figure 5.11. Visual comparison for textile (a) wastewater, its (b) concentrate, and (c) distillate from MVR evaporator system.

6. CONCLUSIONS AND RECOMMENDATIONS

Although as a principle of waste management: "recycling is always preferred compared to treatment", this is seldom realized in practice. The reason is that the small amounts (1-2 tons every day, week or month) of different wastewaters produced in a factory are not worth to process separately and recycle in the same factory even though they may contain valuable components. Once being mixed recovering some components from the mixture is even more problematic, so that the only goal left then can be to reduce the harm to the environment (the aim of wastewater treatment).

This study at a pilot plant level aims to develop methods and encourage recycling at the expense of wastewater treatment:

"Separately collected wastewaters from different factories in an industrial area containing similar solutes (like chromate baths, degreasing baths, phosphate baths, zinc removing baths, pickling acid baths etc) can be carried in different sized containers by trucks to a hypothetical recycle plant. Here different separation techniques can be used with the aim of gaining valuable components from them and most suitable methods can be developed for each type of wastewater. Such a separate collection and truck-transport is a prerequisite of increasing the amounts to be processed so that recycling gets worth".

It is recommended that evaporation (MVR technology) in such a recycle plant would play a central role due to different reasons:

- This study has shown that (excluding some problematic cases like solvent and detergent containing wastewaters) the distillate, which can be up to 99 percent of the initial wastewater volume, can be discharged directly to the environment without any fear of exceeding legal limits. This is not true for classically treated wastewaters which is much more polluted and exceed legal limits very often in practice. For example chemical precipitation of heavy metals may not be complete since complexing agents are usually present (as in galvanic industry), or in biological treatment due to temporal

overloading or due to the presence of non biodegradable organics, limits are often exceeded.

- It is the easiest method to obtain the solutes in a concentrated small volume, which can be marketed either as solution or as solid (after crystallization or evaporation in an open evaporator to dryness). Membrane technology can not concentrate solutes to similar extent (ionic species or small organic molecules cannot exceed concentrations of 5-10 percent due to increase of osmotic pressure).
- Even separation of the constituents of a mixture is possible by fractionated crystallization. Chemical precipitations usually end up in a mixture of hydroxides (e.g. heavy metal filter press cakes).

Concerning the costs, experiments with MVR here showed that 2.5 to 3.0 US\$ are necessary for distillation of one ton of wastewater. This is a huge improvement comparing to simple evaporation (80 liters of oil/ton) but it is still too high compared to classical water treatment. On the other hand experiments with different wastewaters have shown that the distillates, with the conductivity values of 200-500 $\mu\text{S}/\text{cm}$, is of higher quality than most of the raw water sources (well water carried with trucks in Turkey which have a market value of 1 to 1.5 US\$/ton. İSKİ (İstanbul Su ve Kanalizasyon İdaresi) tap water has 300 microSiemens/cm and costs 3.0 US\$/ton).

If the distillate can be used or marketed as raw water the evaporation costs will be reduced by the value of recycled water. This means that the end cost of about 1.0-1.5 US\$/ton makes evaporation with MVR only feasible if valuable components are recovered from the concentrate. Therefore evaporation should not be considered as an alternative to classical wastewater treatment for cases like mixed textile wastewaters where recovery of chemicals is not possible. However, if the classical treatment is insufficient (or cost more than 3.0 US\$/ton) as in cases like high organic load (wool washing, slaughterhouse wastewaters), high organic load with high inorganic or toxic load (olive mill, antibiotics manufacturing wastewaters, landfill leachate) this method can again be considered.

On the other hand the results with the zinc galvanizing wastewater in this work show that the market value of a solute can be in order of magnitude greater than the evaporation costs, hence making recycling favorable against water treatment. It is suggested that this

feasibility picture is not an exception but rather a rule since zinc sulfate is not an exceptionally expensive chemical.

It is believed that this work demonstrates on a pilot plant scale that using MVR-technology recovery and recycling of some common industrial wastewaters (after separately collecting and transporting to a recycle-center) can be a profitable business.

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