This article discusses the comparison of Multiple Effect and Vapor Compression for USP Purified and WFI quality water for the pharmaceutical industry.

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Water Systems Utilizing Multiple Effect and Vapor Compression Technologies Compared

by George Gsell

Introduction

The critical nature of water systems within the biotech and pharmaceutical industries brings them under scrutiny from a variety of perspectives. This scrutiny is to ensure the quality of water is available to meet the requirements of the U.S. Pharmacopoeia as it relates to the product being manufactured. A clear understanding of the processes that go into a water system, and how they compare to and interact with one another, can aid us in developing systems that produce a high quality of water in a reliable and cost effective manner. All too often, additional processes are installed within a water system with the intent of improving upon the quality of the system. Overly complex systems typically generate additional costs through validation, testing, plant space, utilities, maintenance, and operations staff. The reliability of these systems diminishes as the number of components within them increases. In addition, there is tremendous focus on general issues such as validation, welding, surface finish, software development, factory and site acceptance testing. This focus further highlights the need to develop water systems that are concise and effective.

Where Water For Injection (WFI) is required within a system, it is common practice to produce this water via distillation. The method of distillation used to produce WFI often drives a number of other issues, such as the system of pretreatment and whether or not this system can be used for any other form of water production, such as USP purified or perhaps boiler feedwater, as examples. Distillation of pretreated water for WFI production is commonly done by way of multiple effect or vapor compression evaporation.

Multiple Effect (ME) and Vapor Compression (VC) distillation plants both produce water of WFI quality. As a manufacturer of both processes, we are often asked to explain the differences. Why would one choose one system over the other? The answer lies in the fact that they are both fundamentally different thermodynamic processes well documented in various text.[1,2] Each process dictates its own requirements, some of which may not be readily apparent. The feedwater pretreatment requirements for each process may be substantially different. The utilities, footprint, maintenance and operating parameters are different. The intent of this article is to provide information so that the reader can have a broader perspective of issues in determining which process is best for a particular application. The theory of each process will be reviewed along with utility requirements, feedwater requirements, misconceptions within the industry, system design, and economics.

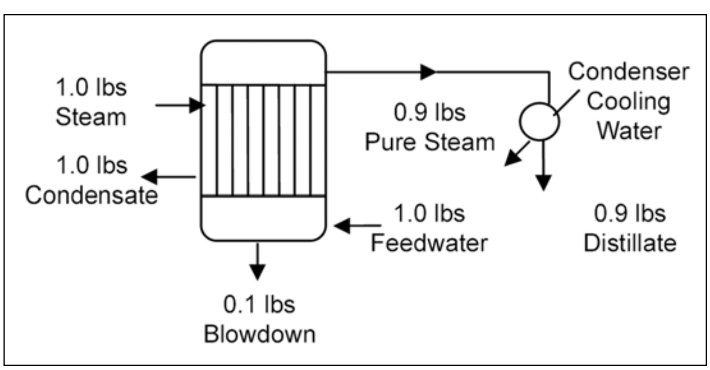

Figure 1a. 1.0 lbs of steam produces 0.9 lbs of distillate in a single effect evaporator.

Basic ME Theory

Consider the basic ME process. "If a pound (lb) of steam is sup-

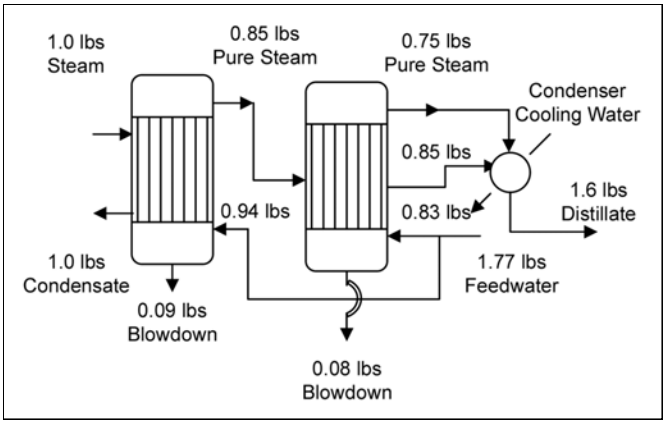

Figure 1b. 1.0 lbs of steam produces 1.6 lbs of distillate in a double effect evaporator.

plied to an evaporator, it can be shown to produce 0.9 lbs of vapor from a pound of water with the remaining 0.1 lbs of water being withdrawn as blowdown containing impurities. The steam vapor formed is useful and pure."[1] In the biopharm industry, if this vapor is taken to a condenser, we have the basis of what is commonly called a pure steam generator with sample cooler - *Figure 1a*. Alternatively, this system could be called a *single effect* evaporator.

"If however, the original pound of steam is supplied to a process as shown in Figure 1b, and the vapor formed in the first evaporator is used as a heat source for a second evaporator operating at a lower pressure than the first, an additional utilization could be made of most of the heat. If both evaporators are fed in parallel with raw water, about 0.85 lbs of pure water would be formed in the first *effect* and about 0.75 lbs would be formed in the second effect. For each pound of steam supplied, about 1.6 lbs of distillate can be produced. When the vapor formed in the first effect is reused as the heating medium in a second effect, this is called a *double effect* evaporator. When applied to three effects, this is called a *triple effect* evaporator (Figure 1c) and the original pound of steam produces about 2.25 lbs of distillate".[1] The actual amount of distillate produced by the steam (given a fixed steam supply) is also a function of the raw water temperature. Conversely, for a fixed output of distillate, the steam consumption will vary somewhat with the raw temperature. The lower the raw water temperature, the higher will be the steam consumption. In practice, feedwater heat exchangers are used to minimize this variation.

In order to maintain temperature differences for heat transfer between the vapor from one effect and the boiling water of the next effect, the pressure of each succeeding evaporator must be lower than its predecessor. Where a number of effects are employed in a multiple effect still, the first effect operating pressure and temperature are typically more than 100 psig and 325°F. The energy input to the first effect is degraded and used in each succeeding effect. The fixed costs of additional effects ultimately dissipate the savings in energy that results from a large number of effects.

The efficiency of a distiller is often expressed in terms of *Economy (E),* which is defined as the mass of distillate produced in pounds (Md) relative to the amount of energy input and can be given by:

E= Md/1000BTU energy input

In the example above, the single effect evaporator has an economy of 0.9, the double effect evaporator has an economy of 1.6, and the triple effect evaporator has an economy of 2.3. A useful tip to remember is that the economy of a multiple effect distiller will always be some number less than the number of effects in the process.[2] It should be noted that the multiple effect process dictates that a certain amount of process cooling water be used for condensing the vapors from the last effect. The amount of cooling water required is a function of several factors including the number of effects on a given unit, the temperature of the cooling water supply, the operating temperature of the plant, and the desired distillate temperature. A portion of the heated cooling water is typically used to feed the ME process itself. However, not all of this cooling water can be used as feedwater, so a large portion

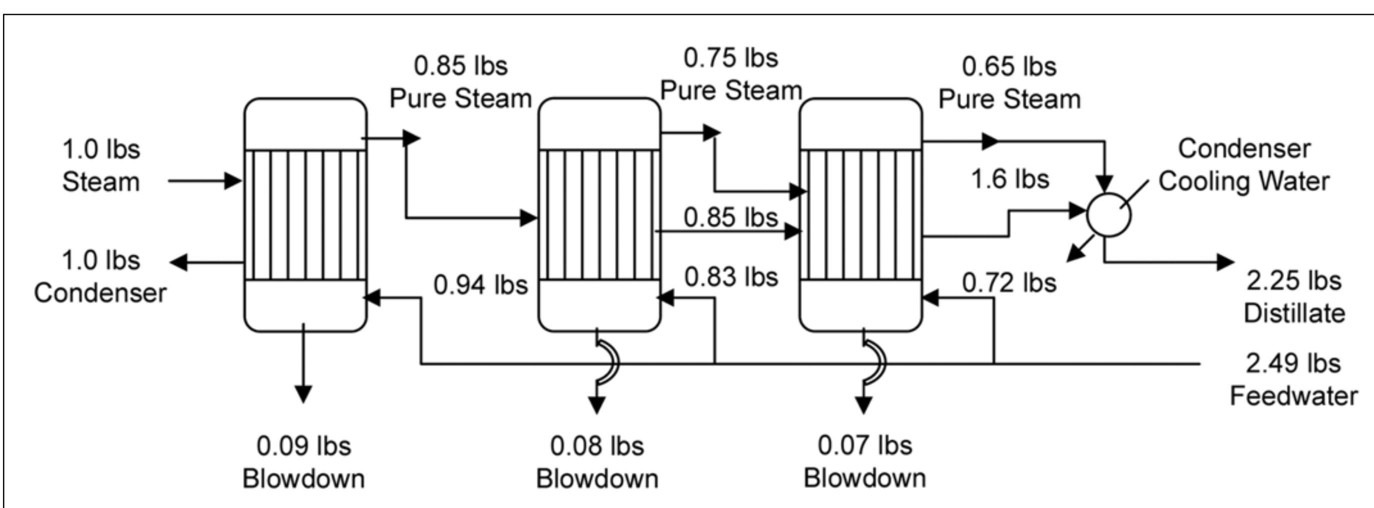

Figure 1c. 1.0 lbs of steam produces 2.25 lbs of distillate in a triple effect separator.

"In theory, it would take approximately 10 effects in a multiple effect plant to match the performance of a vapor compression distiller producing hot WFI."

is typically wasted unless this cooling water is subsequently used as a preheated feed to another process.

Basic VC Theory

The vapor formed within the single effect evaporator (Figure 1a) contains nearly as much heat as is present in the steam supplied to the evaporator. The vapor is condensed with water as a means of heat removal. As noted earlier, this is a waste of both thermal energy and cooling water.

Now consider the basic vapor compression process. If it were not for the fact that the vapor generated is at a lower pressure than the original steam supply, it would be possible to circulate the vapor back to the heating surface and evaporate continuously. A temperature difference must exist between the steam and generated vapors or no heat will be transferred. The vapor from the evaporator can be compressed and in so doing, the temperature of the vapor is raised. The practice of recompressing a vapor to increase its temperature and permit its reuse is called thermocompression or mechanical vapor compression. In the biopharm industry, the latter is used with a mechanical centrifugal compressor. The cost of supplying the necessary amount of compression is relatively small compared to the value of the latent heat in the vapor. The compressed vapor is discharged to the opposite side of the heating surface from which it is generated. In doing so, because a temperature difference now exists across the heating surface, the compressed vapor condenses as WFI giving up its latent heat energy imported through compression to the water on the opposite side of the heating surface. More vapor is generated from the water and the cycle of compression, heat rejection, and evaporation continues. In the vapor compression process, no process cooling water is required to complete the cycle. However, some cooling water is required to remove heat from the compressor although this is an insignificant amount.[3]

Vapor Compression (VC) plants, as used in the biopharm industry, have only a single evaporator. The economy of the VC cycle is primarily a function of compressor efficiency and the amount of heat recovered within the cycle through heat exchange between the outgoing distillate and blowdown streams and the incoming feedwater stream. The steam consumption of the process is reduced as more heat is recovered - *Figures 2a and 2b*. In either case, for a given output of distillate, the compressor energy remains constant.

The economy of a vapor compression distiller producing 180°F WFI is about 7.5. The economy of a vapor compression distiller producing ambient temperature WFI or USP purified water is about 20.

In comparing the two processes, vapor compression is generally considered a more efficient means to produce distilled water. In theory, it would take approximately 10 effects in a multiple effect plant to match the performance of a vapor compression distiller producing hot WFI. Although the measure of economy takes into account all forms of energy used, in practice, the actual price of electricity, steam, and cooling water have a major influence in comparing the operating costs of the two distillers. This is because the vapor compression process derives a portion of its energy requirements from an electrically driven centrifugal compressor as well as steam while the multiple effect process is driven principally by steam.[4]

Energy Consumption and Cost

Tables A and B represent typical energy consumption and cost values for both multiple effect and vapor compression distillers producing 600 gallons per hour of WFI. Energy costs are variable in the vapor compression process depending upon if the water is produced hot or at ambient temperature. Where large amounts of water are produced, the difference in energy costs can be significant. When ambient temperature

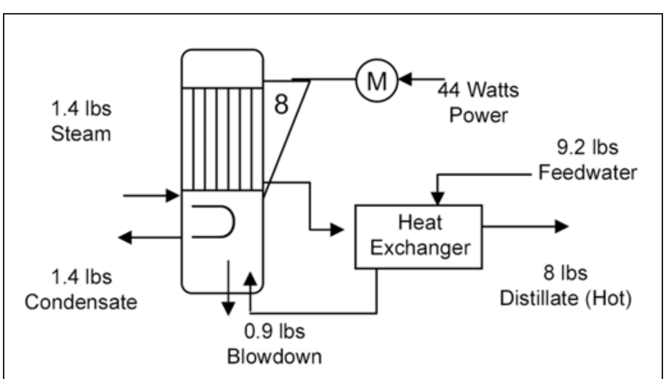

Figure 2a. Hot WFI (180°F) production via vapor compression. 1.4 lbs steam and 44 watts electricity = 8.0 lbs distillate.

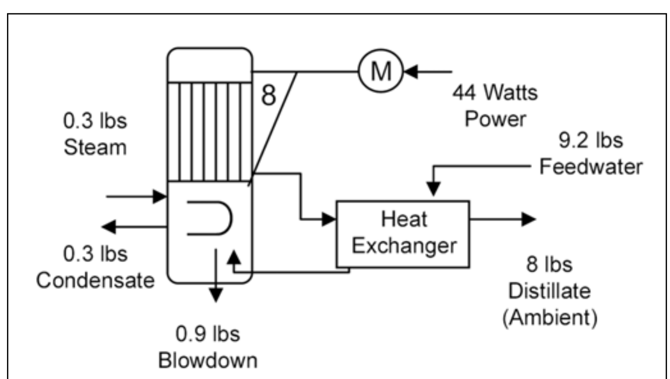

Figure 2b. Ambient production (WFI or USP) via vapor compression. 0.3 lbs steam and 44 watts electricity = 8 .0 lbs distillate.

"The water quality issue can be further explained by examining some of the fundamental principals to achieving a certain quality of product from a distiller."

water is produced, heat is recovered, and the energy cost of the VC process is cut in half.

In the example presented, electricity cost was input at 7 cents per KW hr., steam costs were input at $7.75 per 1000 lbs, and cooling water was considered at $2.00 per 1000 gallons. A shift in the costs for electricity or steam will influence the operational costs of a given distiller. Each distiller should be evaluated based upon prevailing rates for utilities. Your supplier will calculate the energy consumption of a given system when provided with your basic cost data.

Another important consideration is the initial cost of the plant. In the example given, a six effect multiple effect plant was used because the capital expenditure of this size multiple effect unit typically compares with that of a vapor compression plant. Adding effects to the multiple effect plant will reduce its energy consumption, but increase the initial cost. Properly operated and maintained distillers will have a life expectancy greater than 20 years. Some work has been published that indicates the total life cycle costs of a simple VC distiller with softening pretreatment to be comparable to that of membrane and ion exchange based systems.[8]

Feedwater Requirements

One of the major differences between the two processes is in the feedwater quality requirements. The objective of any pretreatment system is to eliminate scale forming constituents from the feedwater as well as minimize the potential for corrosion. The maximum operating temperature of a multiple effect plant is within the first effect and is typically in excess of 325°F. As such, it is most common that the feedwater supplied to this type of plant is DeIonized (DI), Reverse Osmosis (RO) permeate (Figure 3), or a combined RO/EDI product. In addition, some method of dechlorination is always required.

Type/Model	Multiple Effect 6ME600	Vapor Compression VC600 GPH Hot/Cold
Product Water WFI (1)	10 gpm	10 gpm
Feedwater (2)	11 gpm	11 gpm
Cooling Water	8 gpm	0
Electricity	3.6 kw(3)	26.5 kw
Steam Supply	1240 lbs/hr @100 psig	650 lbs/hr @40 psig - Hot 180 lbs/hr @40 psig - Cold
Physical Dimensions	160"L x 62"D x 133"H	103"L x 80"D x 117"H
(1) Product Water @190°F (2) Feedwater taken @70°F (3) Power included feed and distillate pump		

Table A. Multiple effect and vapor compression utilities.

Vapor compression plants on the other hand take a relatively low grade of energy in the form of low pressure steam and raise the temperature and pressure of the raw water vapor from slightly above atmospheric pressure such that the plant operates at 215-230°F. As such, it is common practice for VC plants to operate with feedwater only processed by a softener for hardness removal and carbon filtration for dechlorination - *Figure 4*. In some cases, a membrane plant may be used or preferred to remove silica, high alkalinity, or other constituents. There is nothing to preclude the use of RO as a pretreatment step for VC if so desired.

Common Misconceptions

There are a number of misconceptions associated with each process that should be clarified.

1. A common misconception is that the water in a ME plant is repeatedly distilled from one effect to another yielding some benefit to the user. In fact, each effect within a ME plant produces its own output in parallel and the product water from one effect is not redistilled in another. Both vapor compression and multiple effect distillers evaporate a given volume of water only once, converting it to steam and condensing this steam separately.

2. Another misconception is that the combined softener and vapor compression approach is not capable of producing as high a water quality as the RO/ME approach. Both distillation processes generate a water quality meeting the requirements of the US Pharmacopoeia for WFI.[5] RO will certainly reduce the total dissolved solids and endotoxin levels within the feedwater to a still. In some cases, this "belt and suspenders" approach to ensuring water quality

	Multiple Effect 6ME600	Vapor Compression VC600 GPH Hot & Cold Operation
Electricity @ $0.07/kw hr	$1,764/yr	$12,985/yr
Cooling Water @ $2.00/1000 gal	$6,720/yr	$0/yr
Steam Supply @ $7.75/1000 lbs	$67,270/yr	$35,262/yr - Hot $ 9,765/yr - Ambient
Calculated running cost $/yr	$75,754	$48,247 - Hot $22,750 - Ambient
$1000/gal	$18.04	$11.49 - Hot $5.42 - Ambient
Assume 7000 hrs/year operation		

Table B. Operating economics of multiple effect and vapor compression stills.

may be desired or required. However, the RO pretreatment schemes commonly associated with ME installations are not installed to improve water quality, but are required to inhibit scaling and corrosion in the higher temperature effects.

Millions of gallons of WFI are produced using VC absent of a membrane pretreatment step. Typically, these stills are preceded by either softeners or ion exchange.[6] The conductivity of this water is normally 0.2-0.5 microsiemens.[7] VC plants with simple softening have been demonstrated to produce WFI with endotoxin below the detectable limit of 0.005 Eu/ml.

The water quality issue can be further explained by examining some of the fundamental principals to achieving a certain quality of product from a distiller.

Both vapor compression and multiple effect distillers evaporate a given volume of water only once, converting it to steam, and condensing this steam separately. The phase change from liquid to steam is the principal driver in generating high purity water absent of dissolved solids that can influence the water quality as measured by conductivity. Evaporators also use disengagement height and gravity to aid in the separation process. The disengagement space is the distance between the raw water level in the evaporator and the higher level at which the steam vapor crosses to the condensing surface. As the vapor rises up through the disengagement space, the force of gravity removes entrained water droplets which might otherwise affect the quality of the water produced - *Figure 5*.

Both multiple effect and vapor compression evaporators have additional aids to separation at the upper levels of the disengagement space. A variety of designs are available, including demister pads, impingement baffles, centrifugal separators, and others.

Assuming that the designer of the ME or VC still does a good job of incorporating disengagement height and a separation aid to remove dissolved solids from the water that would otherwise contribute to a high conductivity, the other constituents to eliminate that can contribute to a high conductivity are dissolved gasses with an ionic charge such as carbon dioxide and ammonia. Both of these are liberated from the raw water upon heating, when present, and vented through a deaerator or condenser.

3. A distiller's operating temperature is sometimes associated with having an influence over the quality of water it produces. Assuming the distiller is operating within its design parameters, this is not the case. The ME evaporator operates over a temperature range, and while the top temperature in the first effect may reach more than 325°F, the bottom temperature in the last effect typically operates at around 220°F, and each effect produces only a portion of the product. In the vapor compression process, all of the vapor (product) reaches a top temperature of 250°F. As a practical matter, both processes operate well above the generally accepted sanitization standard. The evaporators operate at different temperatures because thermodynamics dictates they do so. The temperature differences between the two processes have no influence on the water quality.

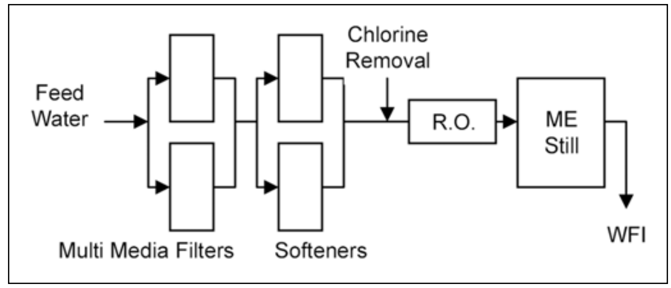

Figure 3. Typical ME pretreatment.

4. Broad statements are sometimes made regarding the maintenance or reliability of one distiller (ME vs VC) versus another. The reliability of a distilling unit can be evaluated numerically as a function of the number and type of components, their operating environment as well as their availability for replacement or repair. Both distillers have a multitude of instruments, valves, controls, gaskets, seals, and like items that contribute to time in the routine preventive maintenance program. The mathematical reliability of either distiller diminishes with the increasing number of these items. Different manufacturers use these items in different quantities depending upon the operating control philosophy. There are some major differences between the ME and VC distillers that should be taken into account when evaluating reliability.

The mechanical compressor is a source of maintenance on the VC process not present on the ME system and the compressor can be a reliability concern if not properly maintained. Evidence is available that indicates with proper preventive maintenance, VC plants do operate very reliably with no unscheduled downtime. Another aspect of a VC distiller that is unique relative to the ME distiller is the evaporator. VC distillers in the biopharm industry employ a single evaporator operating at slightly above atmospheric pressure.

The ME distiller uses multiple evaporators and a separate condenser that are each code stamped vessels operating at a higher temperature and pressure than the VC process. As such, the reliability exposure relative to the number of evaporators and their operating environment is greater on the MEF distiller.

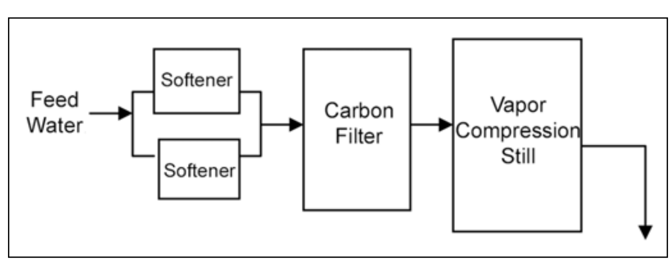

Figure 4. Typical VC pretreatment.

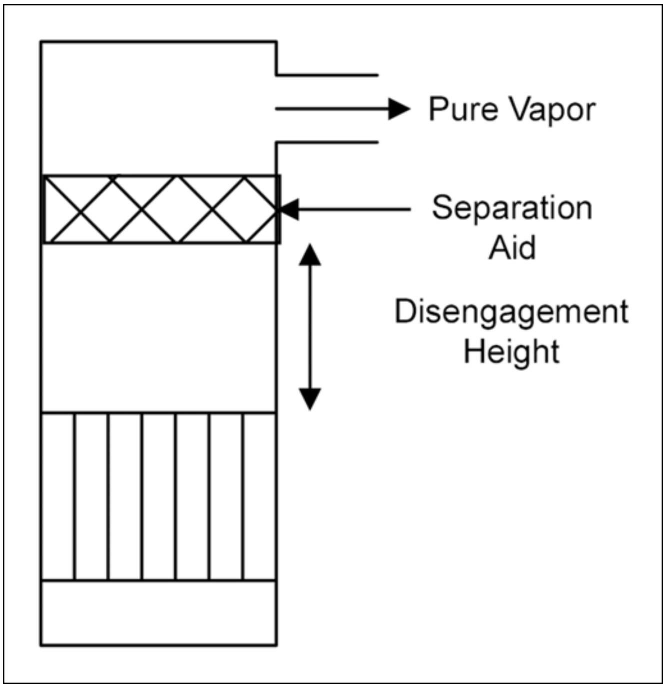

Figure 5. Evaporator fundamentals for achieving water quality.

Both ME and VC distillers are widely used and each has proven to be very reliable. The reliability is directly related to the preventive maintenance and the preventive maintenance effort on both distillers is similar. The maintenance and associated reliability of one distiller versus another is substantially overshadowed by the larger system of pretreatment and distribution upstream and downstream of the distiller. Literature has been previously published that indicates a significantly higher reliability for a still system with simplified pretreatment.[8]

One should evaluate the entire water treatment system and the requirements dictated by a particular system to get a comprehensive view of maintenance and reliability. The water system designs can vary substantially given the type of product water required, the feedwater quality one has to treat, and the type of distiller selected. Often the design options vary so substantially that it is easy to see which offers more reliability and less maintenance.

System Design

System design should start with a determination of the quantity and quality of each type of water to be produced. Where one grade of water quality is to be produced, the design considerations are fairly straight forward for those conversant with the options available. Quite often however, two grades of water quality such as USP purified and WFI are produced. The relative quantities of each may initially guide the designer toward a particular system design concept. Before finalizing a particular design, it is advisable to assess the quality of the raw water feed and determine what feedwater pretreatment processes will be dictated for the design under consideration.

Where large amounts of USP purified water are required and small amounts of WFI are required, it is common to install a RO/EDI system for the production of the USP purified water and a small distiller for the production of the WFI since the quality requirements for each of these grades of water differ - *Figure 6*. The distiller could be either an ME or VC since both will produce equivalent WFI quality water. If the raw water source has high levels of silica or some other constituent such that RO would be required as pretreatment

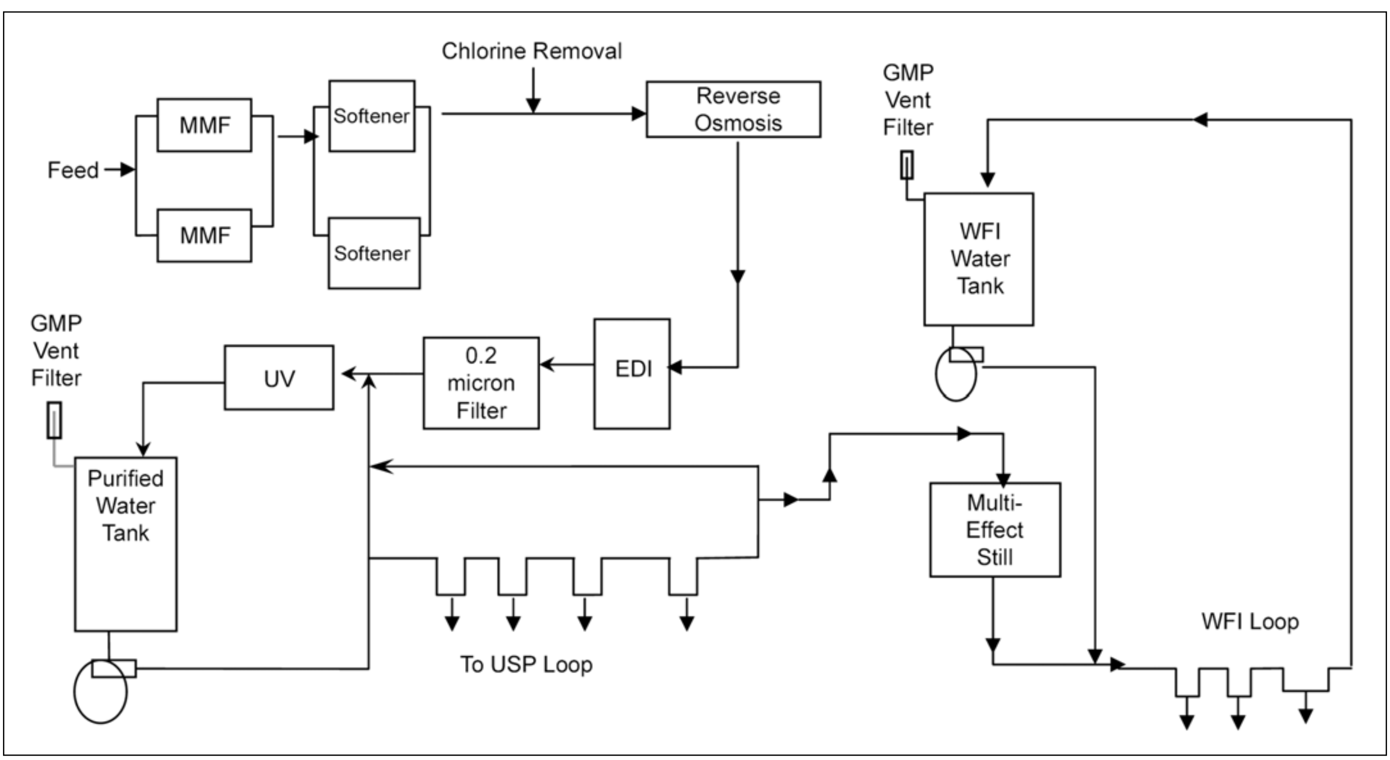

Figure 6. USP purified water system with RO/EDI and ME for the WFI.

to the distiller, it is common to feed the distiller from the USP purified system in place. In this case, and considering a small amount of WFI is required, an ME distiller is often used although the use of VC is not excluded.

As systems grow larger, (more than 200 GPH), the advantages of operating VC may weigh more heavily. Overall utilities are typically reduced unless an ME plant employs a large number of effects. Feedwater for the VC can often be taken from the dechlorinated and softened water supply allowing the size of the RO/EDI system to be reduced.

As the percentage of WFI production increases, it is becoming more common to produce all of the water to the higher grade via the vapor compression. This is especially the case if a simplified dechlorination and softening pretreatment scheme can be used - *Figure 4*. This eliminates the need to produce, store, distribute, maintain, and validate two separate grades of water - *Figure 6*. Note that quite often the RO/EDI systems employed for the production of USP purified water are hot water sanitizable. These systems are more complex, but have the intended benefit of controlled bio-growth within the system. In some cases, the water produced from the RO/EDI systems is reheated for hot storage.

Summary

The most appropriate design of a given water system is not always readily apparent and is sometimes found through an iterative process. It is best to have a complete understanding of all of the processes employed in producing a given quality of water. These processes often “stack up” and feed off of one another as a necessity, but sometimes the necessity is not actually there.

The obvious benefit of distilling all of the water is the higher quality of product. The less obvious, but equally beneficial, feature is that the water can be produced via distillation and distributed either hot or at ambient temperature on demand with the associated benefits to operating efficiency of the VC cycle.

The raw water quality that one has to start with can have a major influence on the type of system employed. If RO is not required as a feedwater pretreatment step, the system may be greatly simplified. An early determination of the different water qualities and quantities to be produced in the future can have a large impact on the final design output. When a significant percentage of the water required is WFI quality, it may be justified to produce all of the water to the WFI standard. This is especially the case where hot water USP systems would otherwise be employed. The choice of process should be evaluated on a case-by-case basis. Relevant factors for consideration typically include the methods of pretreatment given the feedwater quality, the ratios of various water qualities to be produced, capital and operational expenditures, system validation, facility layout, as well as control and maintenance of the system.

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