Comparing Evaporative Technologies for the Recycling of Produced Waters

Relatively recent advance refinements of evaporative technologies have enabled a cost effective solution for a variety of wastewater treatment and recycling applications—particularly in applications where there are high TDS (Total Dissolved Solids).

BY STEPHEN BROWN

Evaporation, or distillation, is the oldest form of treatment capable of removing soluble contaminates from water or other solvents. But until recently it was rarely used in wastewater treatment or water recycling. The high capital and operating costs associated with distillation had limited its use to applications where the water could not be treated with other technologies or where the recovered distilled products had sufficient value to warrant the additional cost.

With introduction of the Resource Recovery and Reclamation Act in 1974, specialized applications developed in the metal finishing, electronics and manufacturing sectors have spurred the advancement and refinement of evaporative technologies so that they are now a cost effective solution for a variety of wastewater treatment and recycling applications—particularly in applications where there are high TDS (Total Dissolved Solids).

One of the most promising of these applications is in the treatment and recycling of produced water.

CHOOSING THE RIGHT EVAPORATION SYSTEM FOR PRODUCED WATER

Evaporation takes place in three distinct forms: nucleate boiling, thin film and flash. All three forms have been used in commercially available systems for product separation, concentration and water recovery. The physical characteristics of the product being distilled dictate the form of evaporation used. In general, highly concentrated wastewater, like produced water, is best handled by flash evaporation/distillation. Thin film and nucleate boiling systems tend to foul and scale more quickly than flash-based systems, since the actual evaporation is taking place on the heat exchanger surface, thereby depositing the soluble contaminates directly on the heat exchange surface. Forced flash systems using pumps and spray nozzles have the added advantage of higher shear forces and lower film temperatures on the heat exchangers. This helps to reduce fouling and scaling tendencies. Additionally, forced-flash distillation systems have a greater effective surface area created by the spraying of the product, thereby reducing the physical size of the evaporator.

In addition to the form of evaporation, systems are often categorized by type of heat exchanger and orientation. Heat exchangers can vary from calandari, tube, to plate and spiral type. Heat exchanger orientation can vary from horizontal to inclined to vertical, depending upon design. Film-type heat exchange surfaces can be further divided into falling, rising and mixed mode.

The heat for evaporation can be supplied by direct fired fuels, hot water, steam, thermal fluids, electric heaters or stack gasses. Ultimately, the selection of a specific type of evaporation/distillation system is application specific and highly dependent on the physical characteristics of the product being distilled, the desired quality of the end products, available facilities and utilities, cost of operation, and the value of the end products. The nature of produced water limits the practical choices to forced flash distillation with multiple effects or mechanical vapor recompression technologies.

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NEW DEMAND FOR EVAPORATION IN OIL AND GAS PRODUCTION

Until recently, the oil and gas industry had very little application for evaporation as a means to recover clean water from produced water. However, the recent boom in hydraulic fracturing, coupled with regulatory changes in places like Pennsylvania, has created the demand for water recovery and reuse from produced water sources.

The physical characteristics of produced water, specifically the extreme Total Dissolved Solids content (soluble salts) make distillation the only practical choice for water recovery. Produced waters typical have Total Dissolved Solids in excess of 100,000 parts per million (ppm,) thereby eliminating the use of all other traditional technologies like reverse osmosis. Although additional technologies have been introduced during the past 10 years, none of them truly remove soluble contaminates effectively and reliably.

The extremely high chloride, sulfate and hardness concentrations in produced water and brackish water sources can interfere with the effectiveness of the hydro-fracturing chemistries and contribute to down-hole corrosion and scaling. While the exact

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water quality required to for hydro-fracturing is highly debated, the escalating cost and increasing scarcity of fresh water sources in the southwest is not. The need for recycled water will further increase as new regulations are enacted by other states following Pennsylvania's lead.

A Multistage CAST® (Controlled Atmospheric Separation Technology) distillation vessel under construction at ThermoEnergy Corporation's manufacturing plant in Worcester, MA.

SELECTION AND DESIGN OF MULTI-STAGE AND MECHANICAL VAPOR RECOMPRESSION EVAPORATORS

Both multi-stage and MVR evaporators are capable of producing distilled quality water from produced water. Distilled water quality ranges from 100 to 500 ppm TDS depending upon the initial TDS of the produced water and the level of concentration of bottoms (waste) obtained. Typical systems are capable of attaining final concentration ranging from 270,000 ppm to 350,000 ppm TDS. The limiting factor is the actual concentrations of the ionic contaminates—usually sodium chloride, calcium sulfate, calcium carbonate, barium sulfate and strontium sulfate and other similar salts—and the solubility of these salts. Without additional technologies, such as crystallizers or other methods of solids extraction, the ability of both types of evaporators to concentrate produced water/produce distillate are limited by precipitation.

The selection of one technology over the other is primarily based upon economics. The key drivers are cost and availability of the prime energy source, initial capital investment and non-energy operating costs such as labor, maintenance and spare parts inventory.

Multi-stage evaporators typically rely on natural gas as the prime energy source. MVR evaporators require either an electric motor or internal combustion engine to supply power to the compressor. The selection of one method over the other once again depends on economics dictated by the previously mentioned drivers. In most instances the electric motor will prevail as the best choice when actual life cycle costs are analyzed.

Both types of evaporators will require similar types of heat exchangers and pumps, however MVRs are generally required to operate at higher temperatures than MSEs. This is a function of compressing the vapor. Centrifugal and rotary lobe type compressors typical to most MVRs are practically limited to compression ratios of 1.7 to 2.0. The compression ratio is defined as the outlet pressure of the compressed vapor divided by the compressor inlet vapor pressure. The corresponding increase in temperature of the vapor ranges from 28°F to 38°F. At 212°F and 240°F the specific volume of a saturated vapor is 26.8 ft3/lb and 16.3 ft3/lb respectively. Lowering the operating temperatures to 162°F and 190°F yield specific volumes of 73.9 ft3/lb and 40.9 ft3/lb respectively. This increase in specific volume practically limits the efficient operation of MVRs to temperatures in excess of most engineering plastics tolerances, thereby requiring the use of Duplex Stainless Steel, Ni-Alloys or Titanium. The use of these materials in construction significantly impacts the initial capital investment and the ability to make field repairs.

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Mobile TurboFrac® 65 BPD produced water recycling systems can be deployed at the well site for smaller capacity applications.

Likewise, the overall thermal efficiency and initial capital cost of an MSE is determined by the number of stages. Limiting the operating temperature so that engineering plastics like FRP and CPVC can be used, and applying practical approach temperatures between stages, limits the design to four stages.

In either case, careful consideration to heat exchanger design must be given due to the corrosive and scale producing nature of concentrated produced water. Clean-in-place and redundant heat exchanger designs must be considered to maintain optimum heat transfer and operational up time.

MSEs can be designed with concentrate from the last stage, lowest temperature and concentration, feeding the previous stage. Cascading the feed backwards from stage to stage reduces scaling and fouling potential of the heat exchangers since only the first stage heat exchanger is exposed to the highest concentrations of salts. In a four stage system, each heat exchanger is roughly one quarter the size of the primary heat exchanger/condenser in an MVR with comparable throughput. This allows for the use of a smaller, lower cost redundant heat exchanger to be incorporated with a CIP system.

The concentration of produced water can create boiling point elevations in excess of 7°F. It is very important to note that 7°F rise in boiling point results in a 31.4 percent loss in heat transfer for an MVR operating with a 1.7 compression ratio and a 10°F temperature differential across the primary heat exchanger for the product being evaporated, similarly a 21.4 percent loss in heat transfer is obtained with a 2.0 compression ratio.

PRINCIPLE OF OPERATION FOR MULTI-STAGE EVAPORATORS

MSEs are relatively simple in operation. Heat is provided typically by a high efficiency natural gas fired, low-pressure hot water boiler. The product to be evaporated is pumped through a heat exchange and is heated by the hot water. The heated and pressurized product is sprayed into the first stage process vessel. This vessel is maintained under a slight vacuum causing a portion of the sprayed product to evaporate. The vapor formed is drawn into a condenser where the heat of vaporization of the condensing vapor is used to heat the product to be evaporated in the next stage. Each subsequent stage operates at lower pressures and temperatures allowing the vapor from the preceding stage to be used as the heat source. Ultimately, the heat of vaporization is discharged to atmosphere in the last stage through a condenser and a cooling source. The cooling source can be an air cooled heat exchanger, cooling tower or wastewater if the latter is available. The feed for each stage is preheated using secondary heat exchangers to capture the sensible heat from the condensate/distillate to increase the overall thermal efficiency of the system. A four-stage MSE with heat recovery can approach a Coefficient of Performance (COP) of 3.8.

PRINCIPLE OF OPERATION FOR MECHANICAL VAPOR RECOMPRESSION EVAPORATORS

MVR evaporators usually operate as a single-stage system. Not unlike an MSE, the product to be evaporated is circulated through a heat exchanger using a centrifugal pump discharged into the process vessel for evaporation. The heat needed for evaporation can initially be supplied by a boiler or electric heater. The vapor formed is mechanically compressed, thereby increasing the pressure and temperature. The pressurized and heated vapor is sent to the primary heat exchanger/condenser. The higher temperature of the compressed vapor allows it to heat the produced water to be evaporated while condensing to form the distillate. Additional heat is usually recovered from the distillate by a secondary heat exchanger

A ThermoEnergy TurboFrac 65 BPD pilot system is recycling produced water in the Permian Basin.

and is used to preheat the incoming feed to increase the overall thermal efficiency. MVRs operating on seawater (35,000 ppm TDS) have reported Coefficients of Performance (COP) in excess of 10. However, the much higher TDS encountered in produced water (typically ≥100,000 ppm TDS) and the associated elevation in boiling point adversely affect the overall thermal performance, reducing the COP to ≤ 7.0.

CAPITAL COST CONSIDERATIONS BETWEEN MSE AND MVR

The capital cost of an MSE is highly dependent upon the nature of the produced water to be processed, the available facilities and energy sources, and the materials of construction.

Engineering plastics can be utilized for the fabrication of process vessels, piping and pumps, providing the operating temperature can be maintained below 190°F. This allows for much less expensive overall construction costs. Typical fabrication costs for a 2,500 barrel/day four-stage, low temperature MSE can range from 2.8 to 4 million dollars.

As with the MSE, the actual capital cost of an MVR is dependent upon the same drivers. However, due to the higher operating temperatures of most MVRs, the use of engineering plastics is limited. Typically, process vessels, piping and pumps need to be fabricated with expensive alloys. This increases the overall cost of fabrication. Additionally, the compressors and related controls are more expensive than hot water boilers and air cooled chillers. This increases the typical cost of fabrication from 4 to 6 million dollars for a comparable 2,500 barrel per day system.

PERFORMANCE CONSIDERATIONS

Distillate Quality—Both MVRs and MSEs are capable of producing high quality distillate from produced water. Small variations in performance may be observed based upon overall design and incoming water parameters. In general distillate quality can be expected to be less 500 ppm TDS for either technology.

Recovery—Recovery is defined as the percent of distillate produced versus the quantity of feed processed. The actual recovery is usually limited by the solubility and concentration of the various salts contained in the produced water. Typical recoveries range from 60 to 80 percent. However, the recovery of an MVR may be limited due to the increase in boiling point as the concentration of the salts increase. Careful consideration of this effect must be given when sizing compressors, motors and heat exchangers.

OPERATING EXPENSES

The following tables summarize the energy consumption, operating cost and capital amortization of a typical four-stage MSE versus an MVR.

TABLE 1

	Four-Stage MSE	MVR
Power (Kw)	277	641
Heat (Million BTU/hour)	7.5	
Energy Consumption (Kwh/bbl intake)	23.7	26.7
Capital Cost ($/Barrel)*	$0.68	$1.00

*Five-year amortization of capital, 2,500 BBLS/day influent

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The following table presents the assumptions that were used to compare a four-stage MSE operating costs to an MVR.

TABLE 2

Parameter	Value
Influent Total Dissolved Salts (mg/l)	100,000 mg/l
Water Recovery (%)	60
Natural Gas Costs ($/MMBTU)	$4.50
Electricity Costs ($/Kwh)	$0.12
Intake volume (Barrels per day)	2,500

The following table compares a four-stage MSE operating costs to an MVR.

TABLE 3

	Four-Stage MSE	MVR
Operating Costs / barrel	$0.70	$0.74
Capital Cost ($/bbl)**	$0.68	$1.00
All-in Per Barrel Cost	$1.38	$1.74

*Data compiled from ThermoEnergy, Colorado School of Mines, Company Reports, Department of Energy and other Technical Documents.
**Five year amortization of capital, 2,500 BBLS/day influent

MAINTENANCE AND COMPLEXITY OF EQUIPMENT

Both the MSE and MVR systems share many similar components, such as heat exchangers, pumps, valves, process instruments, PLC and HMI and will require essentially the same type and quantity of maintenance. However, the significant difference between the two technologies is the compressor required by the MVR. The compressor requires an oil sump, pump and cooler to protect shaft bearings. Shaft seals will require cooling and flushing water. The compressor must be dynamically balanced to prevent damage due to excess vibration.

All of these items require automated monitoring and control to protect the compressor. Compressors are subject to sudden and catastrophic failures caused by erosion, corrosion and imbalance from contact with fouling and scaling-concentrated produced waters.

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The stocking of mission-critical spare parts for the compressor adds a significant cost to the initial capital investment. The differential of maintenance cost between an MSE and an MVR has been estimated to be as much as 2 percent per year of the initial capital investment.

CONCLUSION

Both multi-stage and mechanical vapor recompression technologies are well proven and time tested in seawater type applications. Additional field experience will ultimately determine which of the two technologies is more useful for the oil and gas industry. The five-year life cycle cost, less maintenance of $1.38/barrel versus $1.74/barrel would clearly point to the MSE as the economic choice. Factoring in the incremental estimated maintenance cost of $0.11 per barrel for the MVR, as well as the additional level of mechanical complexity and the associated risks, the choice of MSE over MVR becomes even more compelling. □

About the Author:

Stephen Brown is Chief Technology Officer at ThermoEnergy Corporation. He is a degreed Mechanical Engineer with advanced studies in fluid and thermo dynamics. Steve has more than 30 years of experience in designing, fabricating, and installing process equipment in diverse industries. He was a major contributor to the development of ThermoEnergy's Controlled Atmosphere Separation Technology and Ammonia Recovery Process, and is co-holder of two ThermoEnergy Corporation patents. Steve has received several awards for environmental stewardship, including two Massachusetts Governor's awards and the EPA Environmental Innovators Award.