is a paradigm shift in produced water treatment technology occurring at SAGD facilities?

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abstract

Over the past few years, a paradigm shift has occurred in the treatment of produced water for Steam Assisted Gravity Drain (SAGD) heavy oil recovery facilities. The shift has been away from the use of warm lime softening (WLS), filtration, and weak acid cation (WAC) ion exchange to pretreat de-oiled produced water to an approach using falling film, mechanical vapor compression (MVC) evaporation to produce steam generator feedwater. Today, about 16 such evaporators are operating, under construction, or in various stages of delivery in Alberta and overseas.

Many new SAGD facilities are evaluating MVC evaporation as the "baseline" approach with the "traditional" WLS / WAC system being treated as a secondary alternative, along with other alternative approaches. This shift in methodology is due to a combination of technical and economic factors, increased reliability and availability associated with MVC evaporation, and, perhaps most significantly, due to the potential to use standard drum boilers and alternative fuels for steam generation (as opposed to the use of Once-Through Steam Generators (OTSG) required with the "traditional" approach). Requirements for increased water recovery at SAGD facilities, which are made possible by MVC evaporation, also play a significant role in the shift towards produced water evaporation.

This paper presents a technical and economic evaluation of the shift towards produced water evaporation, increased water re-use and recovery, use of standard drum boilers, and the use of alternate fuels at SAGD heavy oil recovery facilities.

introduction

Over the past few years, water treatment and steam generation methods for heavy oil recovery processes have rapidly evolved. Traditionally, especially for cyclic steam operations, once-through steam generators (OTSG), driven by natural gas, have been used to produce about 80% quality steam (80% vapour, 20% liquid) for injection into the well to fluidize the heavy oil. However, the relatively new heavy oil recovery method referred to as steam assisted gravity drainage (SAGD), requires 100% quality steam for injection. In order to allow the continued use of OTSG for SAGD applications, a series of vapour-liquid separators is required to produce the required steam quality. For both SAGD and non-SAGD applications, pretreatment of the OTSG feedwater has consisted of silica reduction in a hot or warm lime softener, filtration, and hardness removal by weak acid cation (WAC) ion exchange. In most cases, the OTSG blowdown is disposed of by deep well injection. A simplified block flow diagram of this traditional approach to produced water treatment and steam generation is provided in Figure 1.

As the use of the SAGD process became increasingly common for heavy oil recovery in Alberta and worldwide, the traditional methods of produced water treatment and steam generation were re-evaluated to determine whether other alternative methods may provide more technically and economically viable solutions. One such alternate method of produced water treatment, namely the use of vertical tube mechanical vapour compression (MVC) evaporation, has rapidly become the "baseline" approach against which other technologies are evaluated. This technology has been evaluated, by several Alberta oil producers, to provide numerous technical and economic advantages over the traditional approach. In addition, the evaporative produced water treatment technology allows the use of standard or "packaged" drum boilers in lieu of OTSG for steam generation, providing further technical and economic benefits.

This paper compares the use of MVC evaporation and drum boilers for produced water treatment and steam generation with traditional methods. Both technical and economic criteria are presented. MVC evaporation for produced water treatment has been implemented by Total Canada (formerly Deer Creek Energy), Connacher Oil & Gas, and Suncor at their Firebag Stage 2 and Cogeneration and Expansion (C&E) facilities. Total Canada and Connacher have also implemented the use of drum boilers for steam generation downstream of the MVC units. Several other oil producers plan to implement the combination of MVC evaporation and drum boilers at SAGD facilities in Alberta in the very near future.

description of produced water treatment methods

In order to provide a technical and economic comparison of MVC evaporative produced water treatment methods and the traditional approach, a brief summary of each technology is required. The following provides a process overview of both methods of produced water treatment and steam generation.

traditional produced water treatment

Figure 1 shows a traditional produced water treatment system after a variety of oil separation processes have been utilized to recover oil and remove oil from the water. This method of produced water treatment has been applied to both SAGD and non-SAGD applications. The process that reduces silica to low enough levels to be utilized in an OTSG is either a warm or hot lime softener (WLS or HLS) followed by a filtration system. Calcium and magnesium are also reduced in the lime softener, which lightens the load for the WAC ion exchange system. The major chemicals added in the softener are lime and magnesium oxide. These chemical systems require chemical silos and solids transport equipment. Other chemical additions are also required in the form of a coagulant and a polymer. The chemical additions reduce silica content to manageable levels for the OTSG.

The clarate is filtered prior to being treated with the WAC ion exchange system, which reduces magnesium and calcium. Sludge produced from this softening process has high water content and is separated with a centrifuge. The sludge must be disposed of in some manner. Centrate is recycled back to the process.

The WAC ion exchange system is regenerated with hydrochloric acid and caustic. Reduction of metals such as calcium, magnesium, and iron to low levels occurs in the exchange process. WAC does not reduce silica any further than the lime softening process. The strong regeneration waste is neutralized and possibly recycled to the softening system or disposed in some other manner. The resin bed rinses are recycled back to the softening system.

Conventional treatment of produced water being processed in an OTSG produces a blowdown, which is about 20% of the boiler feedwater volume and results in a brine stream, which is about fivefold the concentration of the boiler feed. This stream must be disposed of by deep well injection or, if there is limited or no deep well capacity, by further concentrating the blowdown with a zero liquid discharge Brine Concentrator and Crystallizer system, producing a dry solid for disposal. Some of the OTSG blowdown can be recycled to the softener system but as the solids are cycled up in the system, more maintenance issues are evident in the OTSG.

vertical tube, falling film, mechanical vapor compression (MVC) technical overview

Falling film vertical tube evaporators have the highest heat transfer characteristics of all evaporator types. A high heat transfer coefficient is needed to efficiently evaporate the water and save energy. The vertical tube, falling film arrangement, in conjunction a with proprietary brine distribution system, allows evaporation to occur with reduced fouling effects by keeping surfaces wetted at all times.

The vapour compression cycle is the key to energy efficiency in these systems. The amount of energy put into evaporation is about 1/20th of the energy needed to evaporate water. This is because of the nature of the thermodynamic cycle, which does not have to provide the energy to vaporize the water. The compression energy is used to elevate the existing steam temperature without having to provide the initial energy to evaporate the water. The steam temperature (and pressure) is elevated, and is then condensed transferring heat to the brine for evaporation, which produces steam for the compression cycle.

A simplified vertical tube, falling film, vapour compression evaporator system used to treat produced water is shown in Figure 2. This system is much simpler than the traditional physical-chemical produced water treatment system depicted in Figure 1. Additional details showing the vapour compression cycle are shown in Figure 3 and Figure 4. A photograph of the 3,000 gpm falling film vapour compression evaporator system at Suncor Firebag Stage 2 is presented in Figure 5.

De-oiled produced water enters a feed tank where the pH is adjusted. The wastewater is pumped to a heat exchanger that raises its temperature to the boiling point. It then goes to a deaerator, which removes non-condensable gases such as oxygen. Hot deaerated feed enters the evaporator sump, where it combines with the recirculating brine slurry. The slurry is pumped to the top of a bundle of two-inch heat transfer tubes, where it flows through proprietary liquid distributors which ensure a smooth, even flow of brine down each tube. As the brine flows down the tubes, a small portion evaporates and the rest falls into the sump to be recirculated.

The vapour travels down the tubes with the brine, and is drawn up through specially designed mist eliminators on its way to the vapour compressor. Compressed vapour flows to the outside of the heat transfer tubes, where its latent heat is given up to the cooler brine slurry falling inside. As the vapour gives up heat, it condenses as distilled water. The distillate is pumped back through the heat exchanger, where it gives up sensible heat to the incoming wastewater. A small amount of the brine slurry is continuously released from the evaporator to control density.

The OTSG or drum boiler blowdown can be recycled to the evaporator feed, eliminating the need to dispose of this waste stream, without affecting recovered water quality. The evaporator blowdown is disposed of via deep well injection or treated further by a crystallizer. Utilization of a crystallizer would eliminate all liquid wastes making the entire system a zero discharge system. (The crystallizer produces a dry cake material for disposal.) A photograph of a typical zero liquid discharge crystallizer system, similar to those recently installed in Alberta, is presented in Figure 6.

The disposal method of the brine must be known prior to designing a produced water evaporator system. Crystallization can process highly dispersed brines while physical chemical treatment can prove to be more problematic. Adjustments are required for neutralization and filtering when dispersants are present in concentrated brine. Evaporative systems designed to produce brines for disposal sometimes require modified scale preventive techniques.

emergence and evolution of vertical tube, falling film, mechanical vapour compression (MVC) evaporation for produced water treatment

As the heavy oil recovery industry shifted further toward the use of the SAGD process, the unit operations, which made up the produced water treatment and steam generation portions of the facility required re-evaluation. Initially, familiarity with the design and operation of the traditional processes tended toward the continued use of warm lime softeners and WAC ion exchange systems for produced water treatment and OTSG followed by deep well injection for steam genera ion and waste disposal. However, when the SAGD process was viewed from a fresh perspective, setting aside the historical approaches developed for non-SAGD facilities, several questions arose regarding the use of the traditional treatment scheme:

(1) Does it make sense to continue to use OTSG, which only produce 70%-80% quality steam, when 100% quality steam is required?

(2) Is the use of vapour-liquid separators following OTSG to achieve 100% quality steam a "force-fit" based on the historical use of OTSG in non-SAGD applications?

(3) Should a simpler method of producing 100% quality steam be used, such as the use of standard drum boilers, as is done in other industries requiring 100% quality steam?

(4) If standard drum boilers are used for steam production, can the produced water treatment scheme be simplified and made more economical while providing water of sufficient quality to use in drum boilers?

(5) If drum boilers are used for steam generation, can alternate fuels be used in lieu of costly natural gas?

(6) Can the entire produced water treatment and steam production process be simplified, made more reliable, and provide an increased on-stream availability?

(7) Can the volume of liquid waste be minimized or eliminated in cases where deep well injection is not technically viable or is unattractive from a regulatory or community acceptance standpoint?

The emergence of evaporators followed by conventional drum boilers as the preferred produced water treatment and steam generation process evolved over several years of proven performance in the heavy oil recovery industry, starting in 1999. The initial introduction of evaporation into the SAGD market was used in conjunction with the WLS/WAC systems. The blowdown from the OTSG steam separators was effectively processed by an evaporator and crystallizer combination in a zero liquid discharge (ZLD) system. All water was recycled in this plant with only solids discharged off site. The demonstrated success of this plant proved that evaporation of produced water with high reliability was possible.

Based on the proven reliability of the evaporation process, in 2002 evaporation was selected to replace the traditional WLS/WAC process to treat produced water at the Suncor Firebag Stage 2 facility. At this location, produced water is concentrated about 60 times with the evaporator distillate being used as makeup to an OTSG. Drum boilers were not selected at that time since there was insufficient data to ascertain that the evaporation process could reliably produce distillate with sufficient quality to be used with high pressure drum boilers.

Two more similar facilities were installed between 2002 and 2003, which provided additional data regarding the reliability and technical viability of the produced water evaporation process.

In 2004, Total Canada (formerly Deer Creek Energy) elected to take the next step in the evolution of the produced water evaporative process. At their Joslyn Phase II facility, Total Canada installed a produced water evaporation system followed be a standard, packaged drum boiler in lieu of an OTSG. They also decided to install a ZLD crystallizer system to reduce the evaporator waste to a dry solid, thereby eliminating all liquid waste from the facility.

Today, there are about 16 produced water evaporators operating or under construction in Alberta and overseas. Dozens more are in the planning stages and are due to be released for construction, some as early as this year. The evolution of the implementation of produced water evaporators in lieu of the traditional WLS/WAC approach marks a significant milestone in the advancement of SAGD technology and its economic viability.

technical and economic comparison of MVC evaporative produced water treatment to traditional methods

Since the first implementation of SAGD evaporative produced water treatment in 2002, many, in fact most of the Alberta oil produces have conducted studies to determine whether evaporative produced water treatment or traditional methods provide the most technically and economically viable solutions for their specific application. These studies have been conducted for facilities as small as 10,000 barrels per day of bitumen production, and as large as greater than 200,000 barrels per day.

It was first thought by many in the industry that evaporative produced water treatment may only be economically viable for relatively small facilities (i.e., less than approximately 30,000 barrels per day of bitumen production). Initial studies, conducted around 2003, seemed to validate this assumption.

However, as more actual capital, installation, and operating cost data became available from the evaporative produced water treatment systems installed in Alberta, the results of continued studies began to show that the evaporative method was technically and economically viable for large facilities as well as relatively small systems. In fact, studies recently conducted show that the economics are at least, if not more advantageous for the larger facilities as compared to the smaller applications. This conclusion is consistent across virtually every study conducted by industry experts.

The following sections summarize the technical and economic comparison of the two methods of produced water treatment. This information is a compilation of data and conclusions drawn from several studies conducted by oil producers, engineers, and consultants over the past few years. While specific economic parameters and assumptions vary by site, the conclusions drawn are consistent between the studies conducted. Following the general conclusions presented below, specifics on economic comparisons are also presented.

technical comparison of evaporative produced water treatment to the traditional approach

Recent studies concluded that the traditional de-oiling, softening, filtration, and ion exchange produced water treatment scheme depicted in Figure 1 is complex, costly, produces several waste streams requiring disposal, is labor intensive, requires the use of OTSG, and requires vapor/liquid separation systems (to produce the required 100% steam quality for SAGD process). Evaporation as an alternate approach to produced water treatment was found to be simpler, more cost effective, more reliable, reduces the size and complexity of the steam generation system, and allows for the use of alternate fuels. This simplified method of produced water treatment is shown in Figure 2. The lime softener (WLS or HLS), filtration, WAC exchange systems, and possibly certain de-oiling steps are eliminated.

Using evaporation as the treatment process instead of lime softening and WAC has several technical advantages. These technical advantages include:

- Evaporators effectively "decouple" the produced water system from the boiler feed system, such that upsets in de-oiling do not reach the steam generators.
- Evaporation is evaluated as a more robust and higher reliability technology, and can be used on more difficult to treat produced and make-up waters.
- Boiler feed quality is dramatically improved (by almost four orders of magnitude), resulting in improved boiler reliability.
- Evaporation is the only proven method of treating produced water to meet feedwater requirements for the use of drum boilers.
- Evaporative produced water treatment coupled with drum boilers allows for the use of alternate fuels.
- The need for vapour/liquid separators are eliminated since drum boilers produce 100% quality steam.
- Physical separation processes using solid chemical additions are eliminated, simplifying the process and reducing the total number of unit operations and chemical handling.
- High water content sludges are eliminated.
- Overall operational and maintenance requirements are reduced.
- Evaporation maximizes water recovery and reuse, reduces make-up water requirements by 50-70%, and minimizes or eliminates liquid blowdown. This provides both economic and environmental benefits.
- Evaporation allows for the use of brackish water for make-up rather than surface water. This is particularly important given the large number of SAGD projects expected to proceed in Alberta.
- If ZLD is required due to a lack of disposal well capability, the evaporative approach to produced water treatment results in a ZLD system that is much smaller than that required if the physical-chemical produced water treatment approach is used.
- Boiler blowdown is recycled to the evaporator feed, eliminating boiler blowdown disposal requirements.
- Boiler blowdown and heat recovery equipment is reduced in size and complexity.
- Improved turndown capabilities for both the water treatment system (evaporators) and the boiler system. This is particularly useful during start-up and ramp-up periods. Also allows for more rapid start-up than the traditional approach.
- Oil removal equipment may be reduced.

The traditional approach, using WLS, WAC, and OTSG does have some technical advantages over the evaporative method. These advantages include:

- Although fouling severity and frequency have proven to be minimal in the operating produced water evaporators, there is a finite risk that severe fouling could limit steam production.
- Although the expected time between cleanings of drum boilers is expected to be much longer than the time between OTSG cleanings with the traditional approach, drum boilers cannot be

"pigged" like OTSG. Chemical cleaning is required.

- Higher water quality is required for the use of drum boilers as compared to OTSG.

When comparing the evaporative produced water treatment approach, including the use of drum boilers for steam generation, to the traditional method, oil producers and engineering firms have concluded that the technical advantages of the evaporative approach far outweigh the advantages of the traditional method. These advantages, coupled with the economic advantages discussed below, have resulted in the shift to evaporative produced water treatment in the past few years.

economic comparison of evaporative produced water treatment to the traditional approach

Several economic studies comparing the evaporative produced water treatment approach, including the use of drum boilers, with the traditional approach, including the use of OTSG, have been conducted over the past 3 years. The results of the economic evaluations are dependent upon the assumptions used to conduct the comparison. For example, if a fully modularized design approach is assumed, the installation costs for the facility will be dramatically lower. The use of modularization may benefit one produced water treatment approach over the other, depending on the relative installation costs for the two approaches. Modularization is always recommended for evaporative produced water treatment systems.

Many of these studies have been conducted in the past 12 months and virtually all studies have come to the same general conclusion; the evaporative method of produced water treatment is more economical, on both an installed capital and a life-cycle cost basis, than the traditional approach. Some studies have included the use of ZLD and other have assumed post-treatment of the evaporator blowdown followed by deep well injection.

The following is a compilation of the economic conclusions drawn from these studies. Facility sizes range from 10,000 barrels per day of bitumen production to in excess of 200,000 barrels per day with steam to oil ratios ranging from about 2.5 to 3.5.

- The evaporative method of produced water treatment combined with drum boilers resulted in 8-10% lower total installed costs for the combined oil treating, water treating, steam generation, and heat recovery facility as a whole. This assumes a modularized approach is taken for the evaporator system. Capital costs for the entire facility, prior to installation, were typically about equal between the evaporative and traditional approaches. The majority of the savings was in installation. For cases where a ZLD system was included, total installed cost savings were approximately 4-7% for the facility as a whole.
- The evaporative approach resulted in 1-6% lower operating costs over the life of the plant. This value does not only take into account the operating cost comparison between the two water treatment methods, but also the operating costs associated with steam generation (i.e., a comparison of drum boiler and OTSG operating costs, including boiler blowdown heat recovery and handling systems and fuel consumption). A summary of the major economic parameters compiled from these studies are as follows:
  - Fuel consumption for the drum boiler was 1-5% lower than the OTSG, depending on such factors as boiler feed temperature. Fuel consumption can account for 80-95% of the total operating cost for the system, depending on the source of the fuel. Therefore, even a 1% fuel savings provides a significant advantage for the evaporative approach.
  - Use of drum boilers provides the ability to consider the use of alternate fuels, which can result in significant energy savings compared to natural gas. Although the studies assumed that alternate fuels can only used with the evaporative/ drum boiler approach, the comparisons do not reflect the use of alternate fuels. That is, credit has not been given in the economic evaluation for the use of alternate fuels.
  - Electrical costs for the evaporative approach were typically 30-40% higher than the traditional approach. Electricity accounted for about 4-15% of the total system operating cost. This relatively wide range is due to differing sources and costs of boiler fuel. If natural gas is used (high cost), the fraction of the operating costs due to electricity is lower,

where if an alternative fuel is used, the electrical cost becomes more significant.

- Total chemical costs for the evaporative approach were about 10-20% lower than the traditional approach. This is despite the fact that the evaporation system uses considerably more caustic than the traditional approach. Chemicals accounted for about 3-5% of the total operating costs.
- Source water and disposal costs were approximately 40-60% lower for the evaporative approach. These items contribute about 1% to the overall operating cost.
- Other miscellaneous costs, which amount to about 1% of the total operating costs, were roughly equivalent between the two produced water treatment methods.

- The evaporative approach resulted in significant net present value (NPV) savings. The majority of the savings is attributed to total installed cost savings of the facility and savings attributed to reduced consumption of boiler fuel (either natural gas or alternate fuels). If alternate fuels are used, the savings are dramatic since fuel consumption amounts to about 80-95% of the total operating costs. NPV savings ranged from $10MM to $25MM per 10,000 barrel per day of bitumen production, excluding the use of alternate fuels.
- Significant reductions in operating and maintenance costs (materials and labor) for the produced water treatment and steam generation systems were realized with the evaporative approach. Savings are in the range of 10-20%.
- Reduced sludge disposal and waste handling costs were realized for the evaporative approach. The evaluations included costs for post treatment of the evaporator blowdown prior to deep well injection or, in some cases, included costs associated with ZLD. Savings were in the range of about 30-60%.
- A 4-8 month reduction in overall project schedule was realized with the evaporative approach. This includes schedule savings associated with the use of drum boilers in lieu of OTSG.
- Due to the simplicity and reliability of the evaporative produced water treatment system, a 2-3% increase in the entire facility's on-stream availability is anticipated with the use of the evaporative method. This credit was not applied to the economic analysis results provided above. That is, this availability increase would serve to further improve the NPV savings realized for the evaporative approach and serves to increase oil production.
- If a cogeneration facility were available, the operating cost savings and NPV savings provided above would be further increased for the evaporative approach. Cogeneration was not assumed in the capital and operating cost comparisons provided above.
- The evaporator and drum boiler combination provides improved turndown capability as compared to the traditional approach, which significantly improves both economics and operability during the ramp-up phase of the SAGD facility.

conclusions

1. The combination of vertical tube falling film evaporation and standard drum boilers has several technical advantages over the traditional approach including increased reliability, reduced maintenance and operations requirements, less chemical handling, and increased simplicity.
2. Economic advantages of the produced water evaporator and drum boiler combination include reduced capital, operating, and lifecycle costs, and the potential for an accelerated project schedule.
3. The potential use of alternate fuels in the drum boiler further enhances the economic advantages of the evaporative produced water treatment approach.
4. Environmental benefits to the evaporative produced water treatment approach include minimizing or eliminating the use of surface source water, use of brackish water in lieu of surface water, and minimizing or eliminating liquid discharge.
5. Based on the technical and economic advantages of the evaporative produced water treatment approach, there has been a "paradigm shift" in SAGD produced water treatment technology away from traditional methods and instead

focusing on evaporative produced water treatment.

6. Economic comparisons of produced water treatment approaches are site specific and detailed conclusions will vary. However, there is a consensus in the industry that the majority of new SAGD facilities will use evaporative produced water treatment methods, with a minority continuing to utilize traditional methods.

nomenclature

HLS = Hot Lime Softening

MVC = Mechanical Vapor Compression

OTSG = Once-Through Steam Generator(s)

SAGD = Steam Assisted Gravity Drainage

WAC = Weak Acid Cation

WLS = Warm Lime Softening

ZLD = Zero Liquid Discharge

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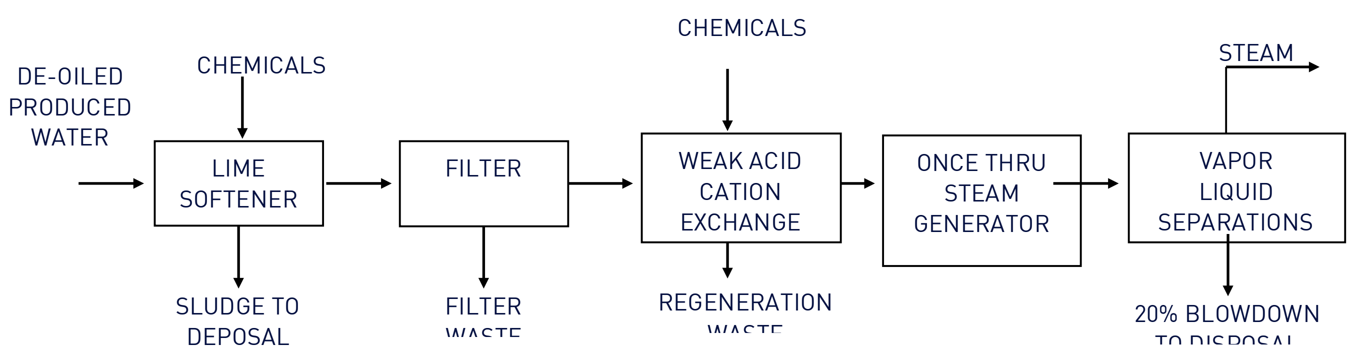

Figure 1: Traditional Produced Water Treatment and Steam Generation System

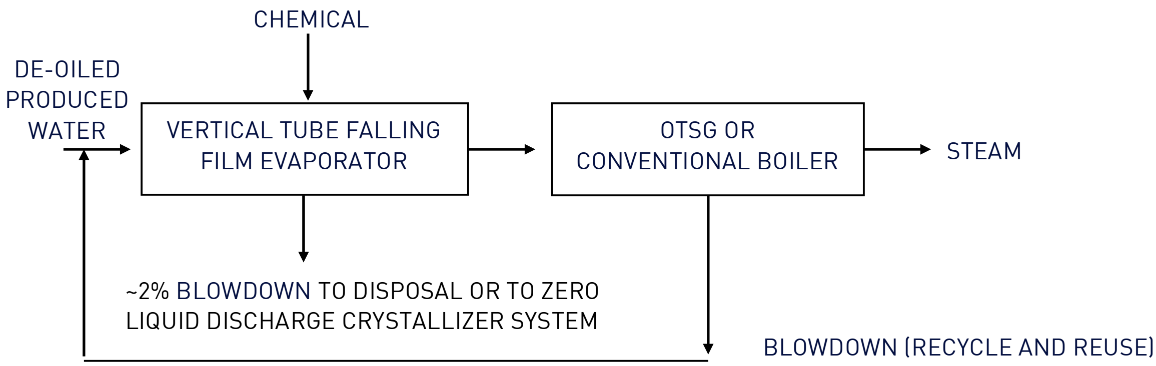

Figure 2: Evaporative SAGD Produced Water Treatment and Steam Generation System

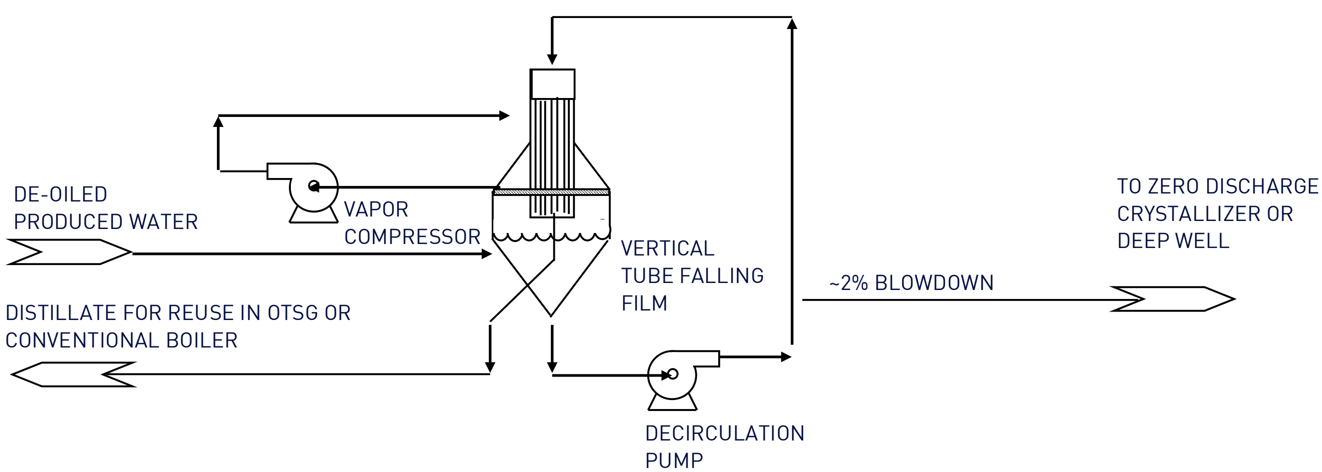

Figure 3: Simplified Vapour Compression Falling Film Evaporator System

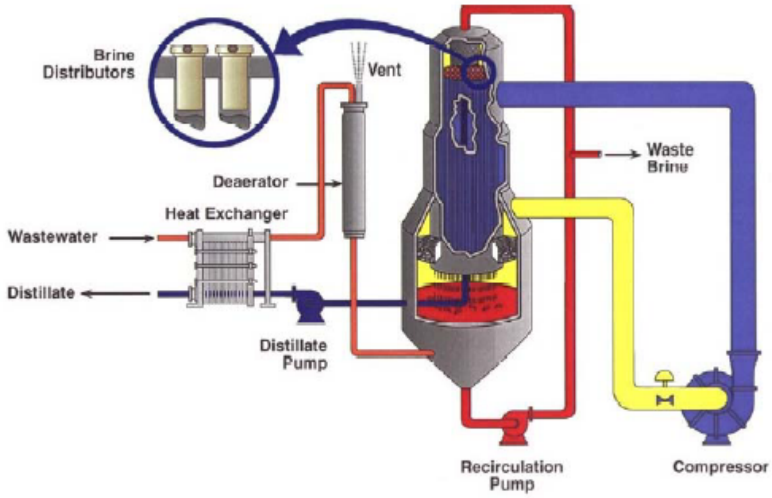

Figure 4: Vertical Tube Falling Film Vapour Compression Evaporator Schematic

Figure 5: 3,000 gpm Produced Water Evaporator System at Suncor Firebag Stage 2

Figure 6: Typical SAGD Zero Liquid Discharge Evaporator and Crystallizer System