FLUIDIZED BED HEAT EXCHANGERS FOR THE EVAPORATION OF WASTE WATERS: DESIGN ADVANTAGES AND OPERATIONAL EXPERIENCES.

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ABSTRACT

Evaporation of water containing dissolved solids for water recovery, solids recovery or liquid waste volume reduction is a common practice in several industries. These types of evaporators are often affected by severe fouling which negatively affects their operation. A solution to fouling problems in evaporators is the use of fluidized bed heat exchangers.

In this paper the working principle of a fluidized bed heat exchangers in combination with forced circulation evaporation is explained. Furthermore, two operational experiences of fluidized bed evaporators are presented. To conclude, the general advantages resulting from the use of fluidized bed evaporators for the case of produced water from gas or oil fields is presented in terms of CAPEX and OPEX.

INTRODUCTION

In several industries evaporation of water containing dissolved solids for water recovery, solids recovery or liquid waste volume reduction is a common practice. Some examples of these industries are the bio-ethanol or alcohol, pulp and paper and hydrocarbon extraction industries.

In the alcohol and bio-ethanol industry the bottom product of distillation, the vinasse or stillage, is usually evaporated in multiple stage evaporation trains. Condensate recovered in these trains is re-used in the production facility, while the concentrated product is further dried for dry biomass recovery.

A similar process is used in the pulp industry. Black liquor out of Kraft digesters is evaporated in multiple stage evaporation trains prior to feeding the concentrated liquor as fuel into burners for steam production. Chemical components used in the pulp digestion process are recovered out of the resulting ashes of the concentrated black liquor combustion.

In oil and gas extraction brine or produced water is a byproduct. Regulations for fresh water recovery from brine are becoming stricter, which makes operating costs for disposal expensive. Therefore, oil companies are paying more attention to systems to treat this water in an economically efficient way (Boschee, 2014). A commonly used configuration is the combination of forced circulation or falling film evaporation with mechanical vapor recompression (MVR) in which vapor out of one stage is compressed and used as heat input in the shell side of the evaporator. The condensate can be re-used at the plant while the discharge can be further concentrated in crystallizers, dryers or just disposed in solar ponds for further evaporation. In some cases, the remaining liquid discharge is re-injected in wells.

In all these cases, highly mineralized water is evaporated at high temperatures. The combination of high mineral concentration and high temperatures causes these water solutions to precipitate minerals which crystalize as a scaling layer on the walls of the heat exchangers of the evaporators. Fouling of heat exchangers in these applications results in:

- Production losses or reduced operation capacity
- Over sizing and / or redundancy of equipment
- Increase in maintenance costs
- Disposal of waste streams from cleaning using chemicals
- Use of expensive pre-treatment plants to limit fouling

To reduce the fouling effects, concentration levels can be limited due to the relation between concentration level and fouling tendency (Challa, 2015). This adds a limitation into the maximum waste water volume reduction. In cases where there is a requirement for Zero Liquid Discharge (ZLD) this limitation results in increased investment and operating costs of downstream systems for further concentration.

To avoid these problems associated with fouling, fluidized bed heat exchangers can be used for evaporation of waste water.
In this paper, the functioning of this technology in combination with evaporation is explained. Further operational experiences of two applications are presented. The first application shows long time operation with long periods between maintenance inspections and no fouling issues. The second application shows the possibility to reach high discharge concentration levels in a produced water evaporation application without any scaling problems. Advantages of using fluidized bed evaporators in produced

water applications are then illustrated by means of a techno-economic assessment in the next section of this paper.

FLUIDIZED BED EVAPORATOR

The operating principle of the self-cleaning fluidized bed heat exchangers is based on the circulation of cleaning particles through the tubes of a vertical shell and tube heat exchanger as illustrated in Figure 1. A fouling liquid flows upwards through the tube bundle of the heat exchanger that incorporates specially designed inlet and outlet channels. In the inlet channel the solid particles are fed to the fluid using a proprietary distribution system to ensure a uniform division of particles over all the tubes. The particles are fluidized by the upward flow of liquid where they create a mild scouring effect on the wall of the heat exchanger tubes, thereby removing any deposit at an early stage of fouling formation. When the fluid velocity is higher than the falling velocity of the particles, they are lifted to the top of the heat exchanger at a velocity equal to the difference between the fluid velocity and the falling velocity. The particles are collected in the outlet channel and brought into the separator where they disengage from the liquid and are returned to the inlet channel through a down comer pipe. Then the cycle is repeated.

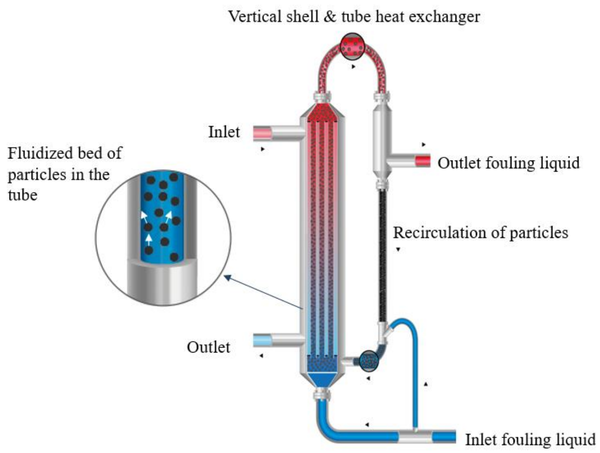

Figure 1. Principle of fluidized bed heat exchanger

To control the amount of particles fed to the inlet, a part of the inlet flow to the heat exchanger is used to push the particles from the downcomer into the inlet channel. Changing the amount of particles is one of the parameters to influence the cleaning mechanism. Other parameters are particle size, particle material and the fluid velocity. The cleaning particles can be:

- Cut metal wire
- Glass beads
- Ceramic beads

The diameters may vary from 1 to 4 mm. The material selected also needs to be corrosion resistant to the media involved. Extensive descriptions of fluidized bed heat exchangers have been previously published by Klaren (2012).

Fluidized bed heat exchangers can be used as forced circulation evaporators by combining a regular fluidized bed heat exchanger and a flash vessel downstream the liquid outlet. The principle of such a system is shown in Figure 2. In this configuration, it is important to suppress boiling in the heat exchanger by allowing enough back pressure, since the effects of vapor bubbles in the heat exchanger tubes can be detrimental to the fluidized bed's stability. The outlet liquid is flashed through an orifice into a flash vessel with a lower pressure where liquid and vapor are separated. Most of the liquid is recirculated back into the heat exchanger while a small fraction is taken out as the discharge flow. The amount of discharge allows to control the solids concentration in the recirculation flow.

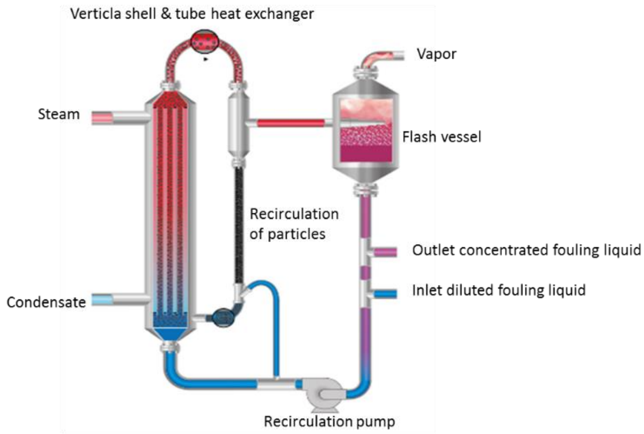

Figure 2. Principle of fluidized bed heat exchanger with flash vessel

The forced circulation evaporator with fluidized bed heat exchanger can be implemented in almost any type of evaporation configuration such as MVRs, thermo-compressor or multiple effect evaporator trains.

REFERENCE CASES

More than 80 fluidized bed heat exchangers have been installed since the 1970's. Some of these heat exchangers have been installed in evaporator applications. In this paper operational experiences from two of these applications are presented.

Evaporator of waste water from Sochu distillation

In a Sochu factory where fermented rice is distilled a fluidized bed heat exchanger was installed in a forced circulation evaporator to evaporate their vinasse. A fluidized bed heat exchanger was selected to avoid scaling of inorganic species present in vinasse such as $CaSO_4$, $MgSO_4$ and Na_2SO_4 among others. The system was installed in 1997 and it is still running to this day.

Figure 3. Picture of the Evaporator of waste water from Sochu distillation made in December 2016.

In Figure 3 the heat exchanger is the long column located in the center of the image inside the support structures. At the top of the image the flash vessel can be observed together with the steam line.

A process flow diagram of this application is shown in Figure 4.

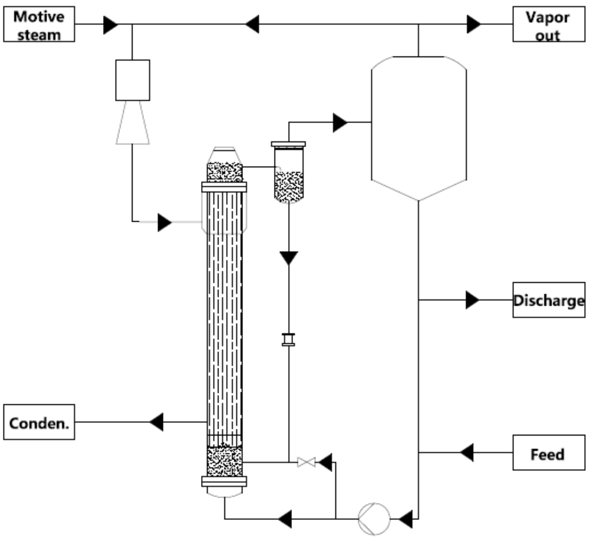

Figure 4. Process diagram of the Evaporator of waste water from Sochu distillation.

The vinasse feed is added to the recirculation line by which concentrated vinasse is pumped into the fluidized bed heat exchanger. In the exchanger the vinasse is heated up prior to be flashed in a flash vessel. Part of the vapor leaving the flash vessel is mixed with motive steam at higher pressure at a thermo-compressor and used as heat input in the shell side of the heat exchanger. Most of the vinasse is further recirculated while a portion of it is discharged. The discharged vinasse is hauled and used for agricultural purposes. The system works under vacuum conditions. The main process conditions of the system are summarized in Table 1.

Table 1. Average process conditions of evaporator of waste water from Sochu distillation

Feed flow (m3/h)	2
Recirculation flow (m3/h)	180±10
Flash steam pressure (kPa)	22.5±1
Motive steam pressure (kPa)	500～590
Motive steam flow (kg/h)	620±30
Concentration ratio	<2

The key parameters of the fluidized bed heat exchanger are highlighted in Table 2.

Table 2. Key parameters of self-cleaning fluidized bed evaporator of waste water from Sochu distillation

Heat exchanger tube length (m)	6
Number of tubes	97
Tubes diameter (mm)	Ø34 x 1.2
Heat transfer area (m^2)	85
Tubes flow velocity (m/s)	0.65
Type of cleaning particles	Metal wire 2mm
Heat transfer coefficient (W/m^2K)	930

During the first 3 years of operation with this system the maintenance inspection was done once every year. Inspections were done on basis of a planned schedule since the system in place was new to the operator. After three years, given the good functioning of the system, the maintenance inspection was changed to once every 5 years. From the maintenance inspection, it can be concluded that:

- Due to particles erosion refill of particles needs to be done after 7 years of operation.
- Erosion of critical parts such as tube bundle or proprietary design parts for correct flow distribution does not occur. Parts in the tube side were SS 304 as were the particles. Only several parts designed to the purpose of protecting flow distribution parts do erode and need to be replaced every 5 years. Erosion in tubes is monitored through regular inspection. It is nor observed nor expected since particles superficial velocities are low, below 2 cm/s, and have its main direction component parallel to the tube surface.
- Fouling of tubes does not occur and full capacity is kept over time.

The most important conclusion that can be drawn from this installation is that the tubes of the fluidized bed evaporator remain clean during operation for the specified operation period. Therefore, the design duty of the system can be maintained at all times. In Figure 5 the evolution of the heat transfer coefficient together with the motive steam flow is shown for the period between March 2016 and December 2016. From this Figure, it can be observed that the trend line of the heat transfer coefficient is constant. The relative broad scatter of data for the heat transfer coefficient is a result of a calculation in which daily averages for discharge flows have been compared to instant measurement points for feed flow.

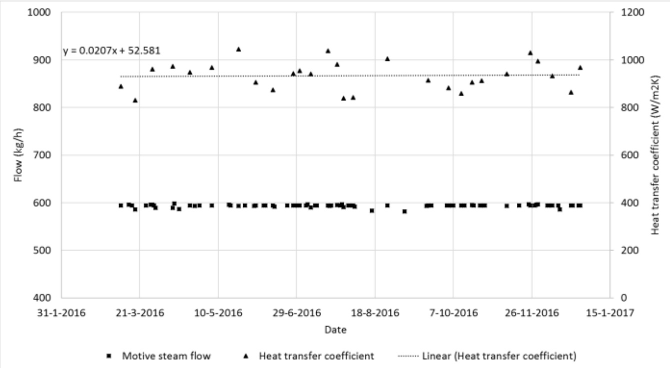

Figure 5. Evolution of the heat transfer coefficient March 2016 and December 2016

Evaporator of produced water

In 2008 a test unit for the evaporation of produced water out of oil fields was built in Texas, USA. Even though the unit did not have a long operation, it brought interesting results that show the advantages of the fluidized bed technology in produced water applications.

Figure 6. Picture of the Evaporator of produced water made in November 2015 (not in operation).

In Figure 6 the two high columns at the right side of the image are the fluidized bed heat exchangers (pre-heater and evaporator). The vessel in the center with a sight glass is the flash vessel.

A process flow diagram of this application is shown in Figure 7.

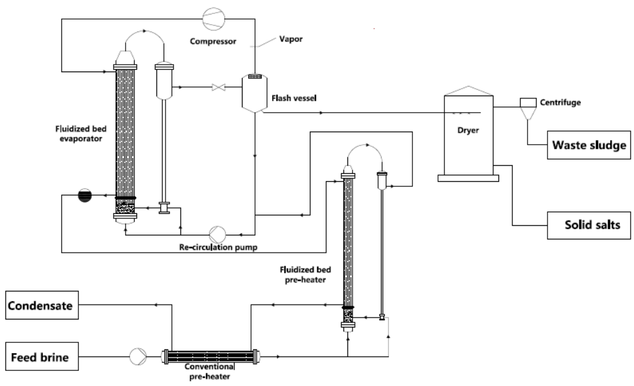

Figure 7. Process diagram of the evaporator of produced water

The produced water feed is added to the recirculation line after having been preheated by hot condensate in a regular shell and tube preheater and a fluidized bed preheater. In the recirculation line concentrated produced water is pumped into the feed flow of the fluidized bed heat exchanger. In the main fluidized bed heat exchanger the flow is heated up prior to being flashed in a flash vessel. The vapor leaving the flash vessel is compressed in a blower and used as heat input in the shell side of the heat exchanger. The condensed water is further used as heat input in the preheating train. A portion of the recirculation flow is discharged. The discharge is fed into a dryer for ZLD. The remaining sludge is sent to a cyclone. This system did not make use of any softening treatment. The main process conditions of the evaporation stage of the system are summarized in Table 3.

Table 3. Average process conditions of evaporator of produced water

Feed flow (m3/h)	0.4
Recirculation flow (m3/h)	22
Flash steam pressure (kPa)	120
Compressed steam pressure (kPa)	270
Compressor power duty (kW)	27
Concentration ratio	Variable

The key parameters of the fluidized bed heat exchanger are highlighted in Table 4. In this table, the parameters are given only for the recirculation flow of the heat exchanger.

Table 4. Key parameters of self-cleaning fluidized bed evaporator for produced water

Heat exchanger tube length (m)	2
Number of tubes	7
Tubes diameter (mm)	Ø42 x 1.65
Heat transfer area (m^2)	3.4
Superficial flow velocity (m/s)	0.79
Type of cleaning particles	Metal wire 2.5 mm
Heat transfer coefficient (W/m^2K)	1500~2100

The system was operated with two different types of feed brine. A first test was made with brine synthetically produced dissolving NaCl up to 35,000 ppm (seawater like). Furthermore, the unit was tested with real brine from West Texas. This brine had a concentration of 170,000 mg/l of dissolved solids. The exact composition of this brine was not analyzed.

The unit operated with a constant heat transfer coefficient throughout the test. A concentration of 400,000 mg/l of the discharged flow was reached during testing and the discharge contained suspended solids. The stated concentration accounts for the combination of suspended and dissolved solids and was obtained through mass balance calculations by flow measurements of feed and discharge flows.

TECHNO ECONOMIC ASSESMENT

In this assessment, the investment and operational costs of the installation and use of a produced water treatment system making use of a fluidized bed heat exchanger are compared to a conventional system making use of a regular forced circulated evaporator. Furthermore, both options are compared to the baseline scenario in which produced water is reinjected into a well.

In Figure 8 the typical configuration of a conventional evaporation system for produced water is presented together with the configuration of a fluidized bed evaporation system. In both systems, a pre-treatment stage is required (left). The main difference between these systems is the need of a softening system in the case of the conventional system. The softening system is required to decrease the scaling tendency at the evaporator's heat exchanger. Since scaling does not occur in the fluidized bed heat exchanger due to the scouring action of the bed, the softening step is not required. The difference between systems in the evaporation stage (center) is the use of the fluidized bed technology in the heat exchanger. In both cases, it is assumed that the discharged flow is reinjected into a well (right).

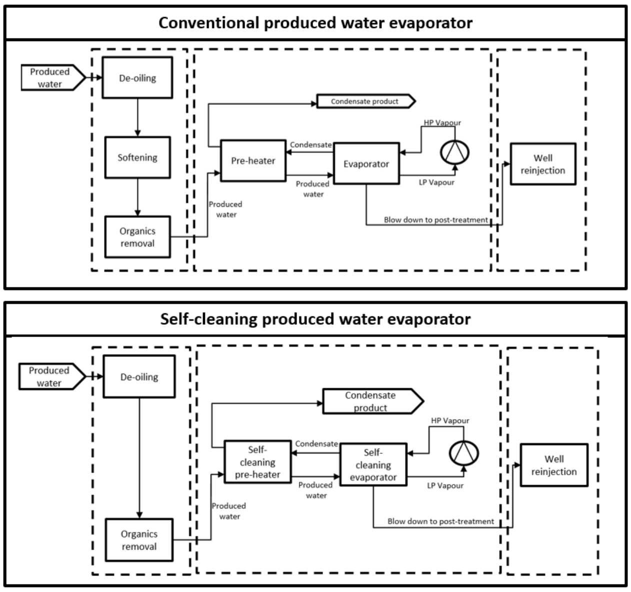

Figure 8. Configuration of conventional and fluidized bed produced water evaporators.

In Table 5 the assumed process parameters for both options are presented.

Table 5. Process parameters of conventional evaporator and fluidized bed evaporator

Process parameter	Conventional evaporator	Fluidized bed evaporator
Feed flow (bbl/day)	2,500	2,500
Feed concentration (mg/l)	110,000	110,000
Discharge flow (bbl/day)	1,125	705
Discharge concentration (mg/l)	250,000	400,000
Vapor flow (kg/h)	9.5	12.3
Compressor duty (kW)	385	480

The systems compared here treat the same amount of water. However, the concentration levels reached at the fluidized bed evaporator are higher than for the conventional evaporators. Despite the use of softeners, conventional evaporators limit their concentration levels to values close to 250,000 mg/l to avoid severe fouling. The fluidized bed heat exchanger has proven non-fouling performance at concentrations as high as 400,000 mg/l. This results in a higher volume reduction of almost a factor 2 due to a higher water evaporation rate.

A comparison of the estimated investment cost for these system is shown in Figure 9.

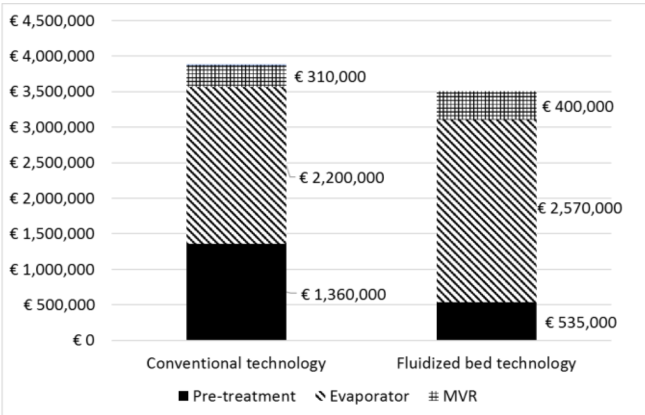

Figure 9. Investment costs of conventional and fluidized bed produced water evaporators.

The overall investment cost of a conventional evaporation system is higher than for a fluidized bed system. The main difference between both systems is the cost of the pre-treatment. This is two times more expensive in conventional evaporation systems because a softening system is required. For this application the cost of the softening system amounts to approximately €825,000. De-oiling and organic removal are required in both cases with the same level of investment cost. For there is no need for softening, the investment for the fluidized bed system is lower despite a higher cost for the self-cleaning evaporator compared to a conventional evaporator and despite a higher cost for the compressor due to its higher capacity.

A comparison of yearly operational costs of these arrangements is shown in Figure 10. In the operational expenses the cost of well reinjection is incorporated using a Figure of 3.0 €/bbl (U.S. Department of Energy, 2004). An industrial power price of 0.1 €/kWh has been assumed.

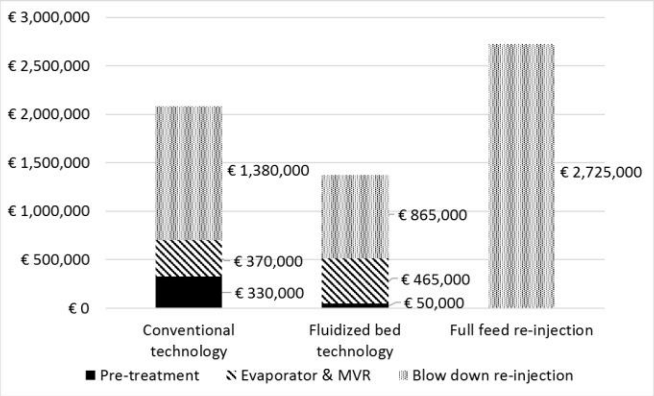

Figure 10. Yearly operational costs of conventional, fluidized bed produced water evaporators and baseline case.

The operational costs of the fluidized bed system are lower than the cost of conventional system. The reason is the higher cost for pre-treatment due to the use of softening for a conventional system which amounts to € 280,000 per year. Furthermore, the higher discharge flow also causes extra disposal costs in the conventional system. This cost-wise positive difference is only partly lost due to additional cost (in absolute terms) for the fluidized bed evaporator caused by the higher energy consumption resulting from the higher amount of evaporation capacity.

Although both systems show benefits with respect to well reinjection, the fluidized bed system has lower investment and operating costs. In Table 6 financial indicators are presented that show the financial performance of the investment in a produced water evaporation system. In this evaluation the yearly cost of well reinjection is taken as a baseline reference.

Table 6. Financial indicators

Project comparison over 10 years	Convent. evaporator	Fluidized bed evaporator
Investment	3.870 M€	3.505 M€
Internal Rate of Return (IRR)	11.18 %	46.18 %
Weighted Average Cost of Capital (WACC)	9.00%	9.00%
Net present value (NPV)	300 k€	4,800 k€
Return on investment (ROI)	58 %	266 %
Payback period	6.5 year	3.1 year

Both investments result in interesting financial returns. However, the investment in a fluidized bed system gives a faster payback time with a substantial higher IRR and ROI.

CONCLUSIONS

The conclusions of this work are the following:

1. Evaporation of waste waters is often hindered by severe heat exchanger fouling
2. Fluidized bed heat exchangers offer a solution in several industries to prevent fouling of heat exchangers in evaporators
3. Fluidized bed heat exchangers have proven to improve operational performance in evaporator applications
4. The use of fluidized bed heat exchangers allows concentrating produced water to 400,000 mg/l without suffering from fouling, even when no softening is used
5. Use of fluidized bed heat exchangers in produced water applications allows to decrease both investment and operational costs as compared to conventional forced circulation evaporators
6. Installation of a fluidized bed evaporation system offers an IRR of over 40% when compared to full feed well-reinjection.

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