PRACTICAL EXPERIENCES WITH FLUIDIZED BED HEAT EXCHANGER FOR EVAPORATION OF WASTE WATER

***M. C. van Beek[1], A. S. Awalgaonkar[1]**
[1] Hanzeweg 35N, 3771 NG, Barneveld, Netherlands. vanbeek@klarenbv.com (corresponding author)

ABSTRACT

Fluidized bed heat exchangers provide an on-line and in-line cleaning mechanism for applications where the heat transfer surface is prone to fouling. Fouling is a well-known problem for forced circulation evaporators for the treatment of waste water. In a fluidized bed heat exchanger the scouring action of a fluidized bed of particles is used to keep the surface clean despite deposition by precipitation and particulate fouling. This paper discusses recent experiences as gathered in a commercial project. In the commercial project which was commissioned in 2018 an existing full-scale evaporator for the treatment of waste water from a dyestuff producing company was retrofitted with the fluidized bed arrangement. The retrofit required addition of some specific components for the operation of a fluidized bed like an inlet channel for particle distribution and a vessel for separation of particles from the circulating fluid. Initially the separator vessel was designed based on mechanical sieve separation, however during commissioning it was found too vulnerable for clogging after which it was successfully modified to a separation system by gravity. This paper discusses the design considerations as made and experiences gathered.

After the retrofit the plant performance has remained at 100% evaporation rate where before the plant lost half its evaporation capacity within a period of 2 to 3 weeks. The non-fouling performance was shown when using spherical ceramic particles.

The major payback by the fluidized bed heat exchanger lies in the increased evaporation capacity at a fraction of the cost of the investment in new MEE. In addition also the cost for cleaning is eliminated.

INTRODUCTION

Fouling is a severe problem for evaporators treating waste water streams. To tackle the problem of fouling, companies apply various solutions such as amongst others chemical cleaning, high pressure water jet cleaning and redundancy in equipment. The application of a fluidized bed in heat exchangers that are prone to fouling provides an on-line and in-line cleaning mechanism, where the particles are carried through the tubes. Here they impart mild scraping effect on the heat exchanger tubes thereby removing any deposit at an early stage of formation. The technology of application of a fluidized bed in heat exchangers has been around since the late 1970's and is extensively described in [1]. This technology has been applied for a variety of process fluids [3-4]. The use of the self-cleaning technology and the application in evaporators has been discussed in [2] where it was shown that when using the fluidized bed technology higher concentrations can be reached which has a very substantial effect on the required investment and the operational expenses of a waste water treatment system going to zero liquid discharge. This article focusses on the experience collected in the application of the fluidized bed in a vertical shell & tube heat exchanger of a forced circulation evaporator to treat waste water from a dyestuff manufacturing company in India. The client was looking for a solution for their serious fouling problem and understood the principle behind the technology but wanted to be convinced by a first application. The fluidized bed has been applied as an retrofit in an existing evaporator by addition of equipment necessary for operation of a fluidized bed.

The article provides the background on the existing evaporator and describes the severity of fouling problem for the client along with the changes made for the retrofit into a fluidized bed heat exchanger. Subsequently, the practical experiences during commissioning and operation of the retrofitted heat exchanger are shared. Finally the article compares the performance of the evaporator before and after the retrofit.

BACKGROUND

The retrofit was executed at a dyestuff manufacturing company which produces a variety of dyestuff products and each product has its particular process and hence a particular waste water stream. The multi effect evaporator (MEE) plant treats the waste water coming from all the processes thus the composition of the waste water is not constant. The MEE plant consist of 4-effects and applies a thermocompressor (TVR). On average the steam temperature into the 1st effect is 115ºC. The maximum evaporation capacity reached with this plant is around 4.8 m^3/h.

Operational Experience prior to the retrofit

The evaporator plant is normally operated for a period of 12 to 15 days and shut down for 5 to 7 days for cleaning with high pressure water jet. Post-cleaning the plant runs at 80% of the capacity on day 0 and the capacity drops to 50% before the next cleaning. From the operational experience of this multi effect evaporator plant the 1st effect is the heat exchanger which encounters the most fouling and is the limiting factor for operation of the entire plant. The subsequent effects of the MEE plant also encounter fouling but lesser as compared to the first effect of the plant.

Nature of Fouling

The fouling layer developed at the inside of the tube is blackish in color. The layer is hard and strongly adhered to the surface of the tubes. The thickness of the layer varies between 1 and 3 mm in thickness and in some cases even higher. The fouling layer developed is insoluble in water and in hydrochloric acid with 10% concentration. Upon inspection of the tube bundle some of the tubes were found to be completely blocked with this type of fouling layer. Considering the high fouling tendency of the fluid especially in the 1st effect, the retrofit was carried out for the 1st effect of the evaporator plant. Based on the performance after the retrofit, the retrofit of the other effects would be considered.

RETROFIT DESIGN

In order to retrofit an existing heat exchanger into a fluidized bed heat exchanger, certain changes in the configuration are required. The existing configuration, dimensions & sizing of the heat exchanger constrains the reconfiguration of the heat exchanger. The required changes and corresponding constraints are described below from a thermodynamic and mechanical aspect.

Thermodynamic Aspect

The existing heat exchanger had three tube-side passes with 1/3rd of the total number of tubes contributing in each pass and each tube operating at velocities of about 2 m/s in the tubes. For operation of a fluidized bed of particles, it is required that the flow in the tubes is upwards and the velocity in the tubes is roughly a factor three times lower than the existing velocity.

The reduction in velocity in the tubes has an effect on the required length of the tubes. Equation (1) indicates the relation between the velocity and length of the tubes required

$$\frac{L}{D_o} = \left(\frac{D_i}{D_o}\right)^2 * \left(\frac{\rho_l c_p}{4 * U_o}\right) * v * \left(\frac{\Delta T}{LMTD}\right) \quad (1)$$

For the same tube diameter, temperature difference over the tubes and overall heat transfer coefficient the required length of the tube reduces as the velocity in the tubes is reduced. As the reduction in velocity in tubes is a factor ~3 the length will reduce with the same factor.

For the same heat duty and assuming the same temperature increase over the tube, the number of tubes needs to increase with the reciprocal of the velocity reduction.

So, for this case, with the existing system being 3-pass and having a velocity of 2 m/s, the configuration could be changed to a single tube-side pass configuration with reduced velocity.

Since, after the retrofit, both the flow velocity and the length have reduced the pressure drop over the bundle also has reduced significantly. The effect is even more when one considers the effects of a reduced tube cross section due to fouling. The benefit of a reduced pressure drop by these effects is partly lost due to the pressure drop to fluidize the particles in the inlet channel and the heat exchanger tubes. The net effect is a reduction in pressure drop.

Mechanical Aspect

To retrofit the existing heat exchanger into the self-cleaning configuration, some components of the existing heat exchanger needed to be modified and some components were added. The inlet and outlet bonnets are modified such that the heat exchanger can operate with single tube pass. Below the tube bundle an inlet channel is installed. This inlet channel allows the addition of particles. At the bottom of the inlet channel there is a flow distribution plate that ensures even distribution of flow into the inlet channel. In the upper section of the inlet channel an inlet device is installed which ensures a uniform distribution of the liquid and particles into the bundle. Above the bundle a plate is installed that has holes of a diameter smaller than the tubes in the bundle which create locally high velocities to avoid particles falling back into the tubes. Above the bundle the modified outlet bonnet is installed with a modified outlet pipe on the side that connects the outlet bonnet to the flash vessel. In this outlet pipe a sieve plate is installed as shown in figure 1. The sieve allows the liquid to flow into the flash vessel, but prevents particles to go through. Upstream of the sieve plate, a fall pipe is connected in which particles can fall together with part of the liquid flow into the particle separator. In the particle separator particles fall to the bottom of the vessel and then into the downcomer while liquid flows upwards. The top of the particle separator is connected back to the outlet pipe between the heat exchanger and the flash vessel, downstream of the sieve plate. Another sieve plate is installed in the top of the vessel to prevent flow of particles to the flash vessel. The particles are returned from the particle separator to the inlet channel through a down-comer and the cycle is repeated.

Furthermore, part of the main flow is used to push particles from the downcomer to the inlet channel. This is achieved by installing a booster pump. The suction port of the booster pump is connected to the discharge of the main recirculation pump while the discharge port of the booster pump is connected to the bottom part of the downcomer. In this way, the recirculation flow fed to the heat exchanger is divided into a main flow, direct to the heat exchanger, and a control flow, to the downcomer via the booster pump. By varying the control flow, it is possible to control the amount of particles in the tubes.

The special arrangement at the outlet of the heat exchanger as employed for the separation of particles from the fluid was designed considering the space availability. Also with the arrangement selected, the required modifications for the equipment and the existing plant were minimum and thus was economically attractive. Figure 1 shows the arrangement at the outlet of the heat exchanger.

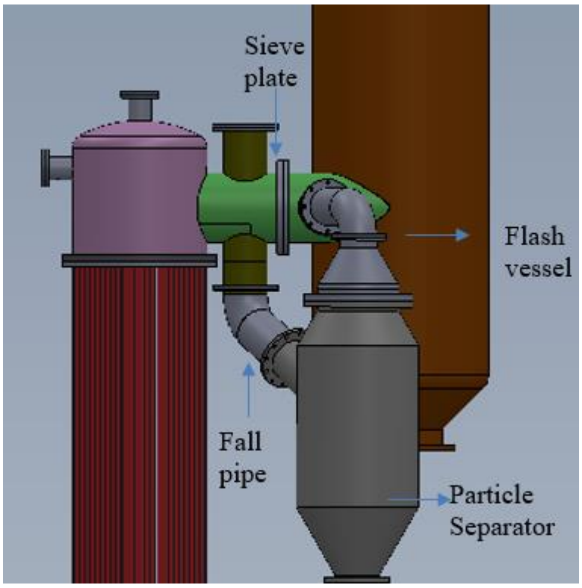

Figure 1:Outlet pipe & particle separator arrangement – Separation based on mechanical separation using sieve

PRACTICAL EXPERIENCE

Commissioning

With the additional equipment erected and installed as described in the previous section, the system was prepared for commissioning with spherical cleaning particles 3 mm in diameter and made of ceramics. In the initial commissioning trials the sieve construction as designed to separate the particles from the main stream led to problems with clogging of the sieve by dirt. This dirt was present in the system, as the flash vessel and the piping to and from the heat exchanger contained some old deposits that came loose during the longer stand-still period. It was also experienced that once the sieve in the main outlet pipe got clogged, more flow passed through the fall pipe and particle separator resulting in increasing pressures limiting stable operation.

Based on the experience of the initial commissioning and taking into account that there will always be pieces of dirt present in the system that have the tendency to block any sieve, the particle separation philosophy was, with the approval of client, changed to separation by gravity.

Separator based on gravity

To convert the unit to particle separation based on gravity, a larger vessel had to be installed between the heat exchanger bundle and the flash vessel. Therefore, the flash vessel was relocated such that the fluid from the outlet of the heat exchanger entered the particle separator with a 90º downward oriented bend where ceramic particles disengage from the fluid and fall downwards into the downcomer and the fluid reverts in direction and leaves the vessel from the top where it enters the flash vessel. Figure 2 shows the general arrangement with the modified particle separation philosophy.

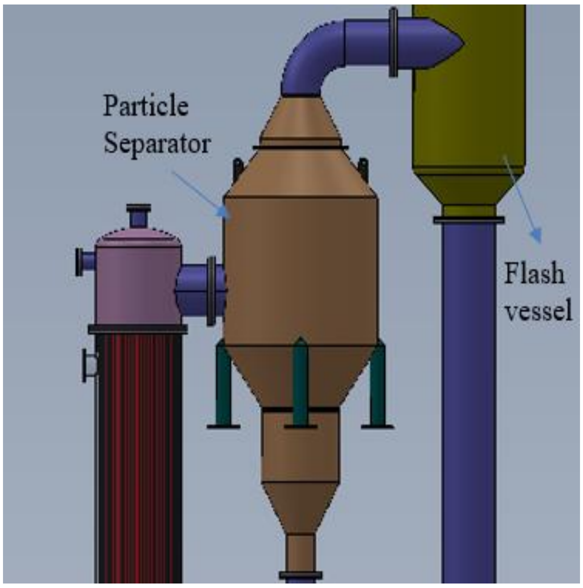

Figure 2:Modified arrangement of the particle separator - Separation based on gravity

Figure 3 shows the CFD analysis result for the flow distribution and velocities in the particle separator. It is clear from figure 3 that above the inlet, the flow velocities are lower or equal to the falling velocity of ceramic cleaning particles. Thus avoiding any particle carryover to the flash vessel.

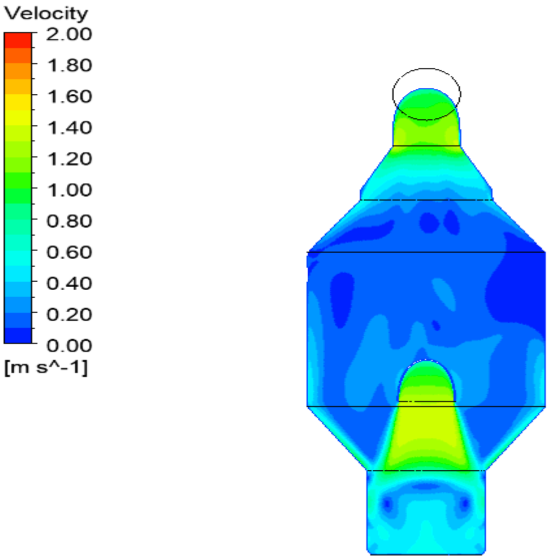

Figure 3: CFD result for flow distribution and velocities in particle separator

Apart from the change in particle separator, during commissioning, a coarse strainer mesh was added in the bottom bonnet to prevent bigger dirt pieces clogging the distribution system. By addition of an inspection opening in the bottom bonnet the dirt pieces can be removed from the strainer during short productions stops. For a similar purpose strainers were installed in the suction line of booster pump preventing dirt pieces from entering the pump and clogging the control flow line. With these modifications the plant was successfully commissioned and handed over to operations.

Operation & Monitoring

The operation of the fluidized bed of particles in the heat exchanger is monitored primarily by the pressure drop across the tubes. The pressure drop over the tubes is composed of a component as a result of the flow through the tubes and another due to fluidization of particles. This pressure drop due to fluidization of particles is given by equation (2).

$$\Delta p_{FB} = (1 - \epsilon) * (\rho_p - \rho_l) * g * L \qquad (2)$$

In equation (2) ϵ is the porosity of the fluidized bed. Porosity is defined as the volume fraction of fluid per volume of the tube. A higher porosity means that per unit of volume there are fewer particles. The porosity in the heat exchanger tube is an indication of the cleaning intensity. For the retrofit as executed, the design porosity for operation was 94%. This means a 6% volume fraction of particles in the tubes. Therefore as per equation (2), the pressure drop across the tubes was maintained to a value such that the porosity in the tubes is around the design porosity. During operation, the porosity in the tube can be controlled by adjustment of the control flow which for this project was done by changing the RPM of the booster pump.

The second parameter which is closely monitored is the pressure at the discharge of the recirculation pump. If the pressure at the discharge of the pump deviates and is higher as compared to the setpoint which is known after commissioning trails, this would indicate clogging of the distribution system or the heat exchanger tubes. A higher discharge pressure would shift the operating point of the recirculation pump. The pump will then operate at lower flow and higher head which is an undesirable situation. To compensate for an additional pressure drop and to avoid a reduction in flow, a throttle valve between the discharge of the pump and the inlet into the heat exchanger can be opened to such an extent that the pressure at the discharge of the pump remains unchanged.

RESULTS & INSPECTION

The plant performance is monitored by a daily balance of the feed entered, the condensate as collected and the product taken from the MEE. From the balance the daily average evaporation rate in m^3/h is calculated. Figure 4 shows the evaporation capacity as function of the hours of operation of the plant with the original configuration and after the retrofit of the 1st effect to the self-cleaning fluidized bed heat exchanger. The data shown below is as received from the operations team of the plant.

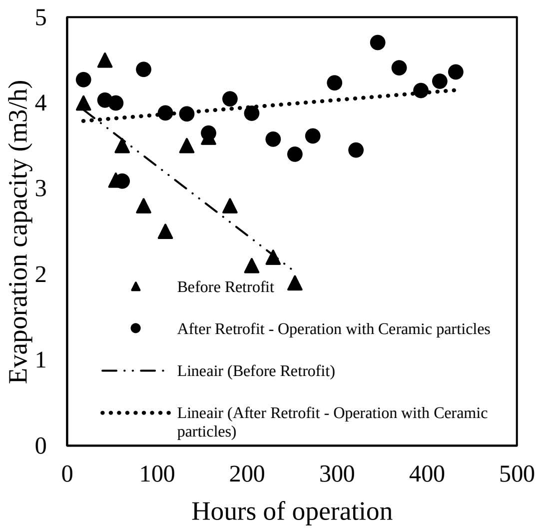

Figure 4: Variation of evaporation capacity before and after the retrofit over 400 hours of operation

During the first 400 hours of operation with the fluidized bed the evaporation capacity has an increasing slope as compared to the operation with the conventional heat exchanger. Although the heat exchanger tubes were cleaned before the retrofit using high pressure water jet cleaning, not all tubes were 100% clean. Therefore, over the duration of 400 hours, likely some part of the existing fouling layer was removed due to the scouring action of fluidized bed. This hypothesis, that the tubes were not 100% clean was later confirmed during an inspection where tubes with some fouling layer were discovered. This existing fouling layer also had a negative effect because, parts of the scale layer that came loose resulted in clogging of some tubes that subsequently were filled with particles. Figure 5 shows a picture of the top side of the tube bundle that was taken during an inspection as was done after 400 hours of operation.

Figure 5: Inspection of the heat exchanger tubes of the first effect after 400 hours of operation

During the inspection also the other effects were inspected. It was stated by plant personnel that the tubes of effect 2, 3 and 4 were cleaner than before the retrofit of the first effect. Figure 6 shows the tubes of third effect

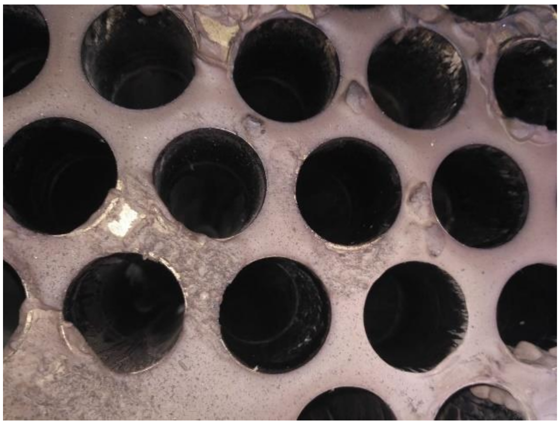

Figure 6: Inspection of the heat exchanger tubes of the third effect after 400 hours of operation

A possible explanation for the observation that the fouling in the other effects that were not retrofitted had reduced as well could be that the application of fluidized bed has reduced the size of solids in the system because of the grinding effect by the particle motion. The reduction of the solids size has helped in reducing the particulate fouling in the other effects of the MEE plant.

Considering the observations during the inspection, the heat exchanger tubes were again cleaned to remove old layers and the tubes clogged with particles were cleared. Subsequent to the inspection and the cleaning of the tubes the heat exchanger was restarted. Figure 7 shows the variation of evaporation capacity with further operation of the plant.

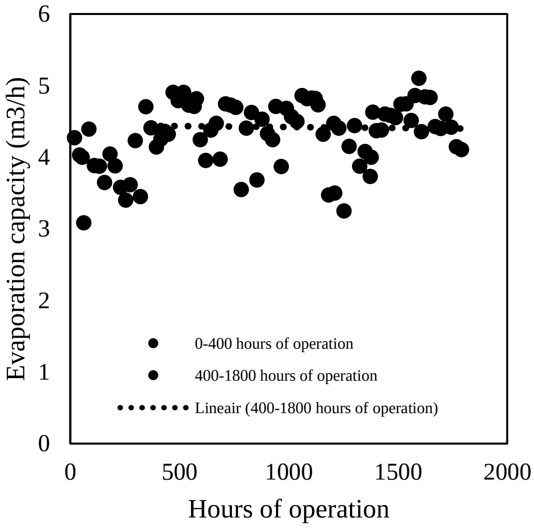

Figure 7: Variation of evaporation capacity with operational hours, plant operating with ceramic particles

Figure 7 confirms that with longer term operation, the evaporation capacity has remained stable for the plant. The curve fit shown is only for operation after 400 hours when the tubes were cleaned, and the curve proves constant evaporation.

CONCLUSION

The plant performance after the retrofit of the 1st effect has proven the performance of a fluidized bed as an on-line and in-line cleaning mechanism. While before the retrofit the evaporation capacity reduced with 50% within 200 hrs, after the retrofit the evaporation capacity remained constant. The increased evaporation capacity reduces the necessity of investments in new MEE plants making the business case for the retrofit positive.

The retrofit of the 1st effect not only effected the fouling behavior of this effect but also reduced the fouling in subsequent effects. Although there is no hard proof for this, it is expected that a reduction in size of the solids in the system is the cause for this.

The clogging of tubes as was observed was considered to be caused by old fouling layers breaking loose and getting stuck in the tubes being the onset of a total blockage of the tube. To verify if this is correct, future research will be done to understand the tube clogging. In this research also the experience with new tube bundles and bundles of various tube diameters will be included.

For the application of the fluidized bed technology in heavy fouling evaporator cases, a mechanical sieve construction will limit continuous operation where a separation by gravity gives a more robust solution. A separation by gravity will on the other hand require additional space.

The first period of operation has shown that the system can be effectively monitored by the pressure drop over the tubes and that changing the RPM of the booster pump gives an easy control of this pressure drop.

NOMENCLATURE

List all symbols used within the manuscript, their definitions, and their SI units.

c_p	Specific heat of the fluid kJ/kgK
D	Diameter of heat exchanger tubes m
g	Acceleration due to gravity m/s^2
L	Length of heat exchanger tubes m
$LMTD$	Log mean temperature difference °C
Δp	Pressure drop Pa
ΔT	Temperature rise over the tubes °C
T	Temperature, °C
Uo	Overall Heat transfer coefficient
v	Velocity of fluid in the tubes m/s
ρ	Density kg/m^3
ϵ	Porosity

Subscript

Subscripts and superscripts should be identified under a separate second-level heading.

i	inner
l	liquid
o	outer
p	Particle

REFERENCES

[1] Klaren, D.G. and de Boer, E.F., *Self-Cleaning Fluidized Bed Heat Exchangers for Severely Fouling Liquids and their Impact on Process Design*, Heat Exchangers- Basic Design Applications, ed. Mitrovic, J., 2012 free online edition available at http://www.intechopen.com/books/heat-exchangers-basics-design-applications.

[2] M. Cancela Vallespin, P. Kedia and M.C. van Beek, *Fluidized bed heat exchangers for the evaporation of waste waters: design advantages and operational experiences*, Conference proceedings 2017 Heat Exchanger Fouling & Cleaning Conference, Aranjuez, Spain.

[3] R. M. Behbahani, H. Müller-Steinhagen and M. Jamialahmadiz, *Heat Exchanger Fouling in Phosphoric Acid Evaporators - Evaluation of Field Data*, Proceedings Heat Exchanger Fouling and Cleaning: Fundamentals and Applications, Engineering Conferences International, 2003.

[4] Ming-yan Liu Yang Yang Xiu-lun Li Wan-da Nie Ning-sheng Ling Li-jia Pan, *Concentration of Gengnian'an extract with a vapor–liquid–solid evaporator*, AIChE Journal, Volume 51, Issue3, Pages 759-765, 2005.