Combining Forward and Reverse Osmosis for Shale Gas Wastewater Treatment to Minimize Cost and Freshwater Consumption

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Abstract

One of the challenges for the future of the shale gas production industry is the water management due to the large demand of water for wells drilling and fracturing and the high volumes of liquid effluent produced. On-site treatment is a convenient option for the reuse of the shale wastewater as drilling water for subsequent wells, which simultaneously reduces the freshwater consumption and the waste volume. While conventional desalination technologies are suitable for the treatment of flowback water, they are not appropriate for the hypersaline produced water, which is typically disposed into underground injection wells. In this work, we propose a mathematical model to address the optimal design of an on-site treatment for both flowback and produced waters, combining reverse and forward osmosis, to simultaneously minimize the freshwater consumption and the specific cost of the fracturing water. The results obtained show a clear trade-off between both objectives and highlight the potential of the proposed technology combination to give an environmentally friendly solution to the shale gas produced water.

Keywords: shale wastewater reuse, optimal on-site treatment, water resource preservation, zero liquid discharge.

1. Introduction

Shale gas production requires significant water demand for wells exploitation and a huge volume of wastewater is generated since nearly 70 % of the drilling water returns to the surface, as flowback water (FBW) and produced water (PW), with different salinities. Freshwater (FW) is generally used for hydraulic fracturing because fracturing additives degrade in saline water. Freshwater scarcity and wastewater regulations pose significant challenges to shale gas production. Therefore, the treatment of shale gas wastewater entails a double benefit: the treated water can replace the freshwater (FW) necessary for the completion of additional wells (known as internal reuse) and final waste volumes are reduced. On-site treatment is an increasingly preferred option for wastewater management. FBW can be treated by conventional desalination technologies, such as distillation or reverse osmosis (RO), but these technologies are not appropriate for the high-salinity of PW (more than 120,000 ppm TDS). Currently, in the US, 40 % of PW is disposed by injection into deep underground wells (classified as Class II by US EPA). However, this practice is not expected to be allowed in Europe (Estrada and

Bhamidimarri, 2016). Thus, an effective management of PW will be mandatory in the near future, as the shale gas industry continues its expansion.

Forward Osmosis (FO) is a promising alternative for difficult to treat waste streams. FO can be used as a standalone desalination process or it can be considered an advanced pretreatment process for other technologies. FO has many advantages among other membrane technologies. The high rejection of many contaminants and its low propensity for membrane fouling, along with the low electricity consumption, confer the process a great potential for water treatment. Some studies have been carried out in order to test the effectiveness of FO for the treatment of shale gas wastewater (Coday et al., 2014). However, all of them employ FO to extract water from FBW using different draw solutions, which must be recovered in additional separation processes. In this work, we propose the use of PW as draw solution for the concentration of effluent streams from other shale wastewater treatments, while diluting PW, thus facilitating its desalination. To this purpose, we propose a mathematical model based on a superstructure that combines RO and FO for the optimal design of an on-site shale gas wastewater treatment system, with the aim of minimizing simultaneously FW consumption and the specific cost of fracturing water (FracW) for subsequent wells. The minimization of FW consumption through the reuse of wastewater implies, additionally, the reduction of the overall liquid waste produced by the shale gas exploitation.

2. Problem statement

The proposed superstructure comprises a RO unit, used as desalination technology, which product water can replace FW; two FO units; and mixers and splitters allowing all possible connections among the different units (Figure 1). The purpose of the FO processes is twofold: they act as pretreatments for the RO and as waste concentrators. The feed solutions for FO 1 and FO 2 are the sludge from the FBW pretreatment (also carried out on-site) and the concentrated brine of the RO process, respectively.

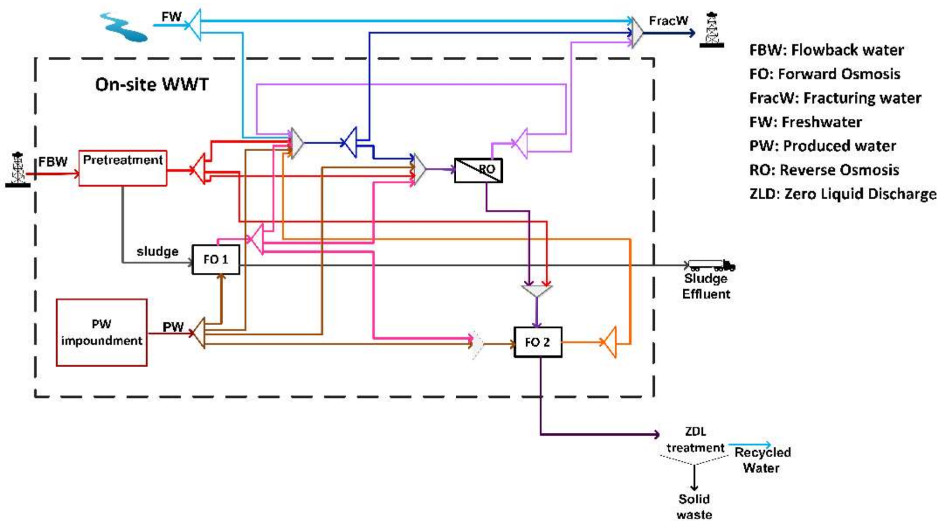


Figure 1. Scheme of the superstructure proposed for the on-site shale wastewater treatment.

PW (conveniently pretreated and stored from previous wells, as explained below) is the draw solution for both FO units, where it is diluted before entering the RO process. At FO 1, the sludge from the FBW pretreatment is concentrated since part of its water is transferred to the draw solution, thus reducing its volume and, consequently, its disposal cost. At FO 2, the rejected brine from RO is also concentrated to be transported to an off-site facility where ZLD could be achieved, thereby obtaining more clean water that could be recycled for other uses. The introduction of the PW in the treatment system provides to this water a solution different from being disposed into underground wells. The goal is to design an on-site treatment system which minimizes simultaneously freshwater consumption and fracturing water cost, aiming, at the same time, to achieve ZLD.

3. Mathematical formulation

The mathematical formulation for the model proposed consists of mass balances in mixers, splitters and RO and FO units, as well as the corresponding performance models for these processes, leading to a non-linear programming (NLP) problem of the form:

$$\begin{aligned} \min_{\mathrm{x}} \ & \{ STC(\mathrm{x}), FWC(\mathrm{x}) \} \\ s.t. \ & \mathrm{h}(\mathrm{x}) = 0 \\ & \mathrm{g}(\mathrm{x}) \le 0 \end{aligned} \tag{1}$$

where x represents the continuous variables, such as flowrates, concentrations and membrane areas, STC (x) is the specific total cost objective and FWC (x) is the freshwater consumption objective. This bi-objective optimization problem is solved using the ε-constraint method (Ehrgott, 2010), which leads to a set of Pareto optimal solutions.

3.1. RO and FO models

The performance of the membrane processes is modelled by simplified models based on the osmotic pressure law (Eq. (2) and (3)), where concentration polarization has been neglected to avoid the introduction of additional complexity to the model (Salcedo-Diaz et al., 2014),

$$F_p^{RO} = A^{RO} S_{memb}^{RO} \left(\Delta P - \Delta \pi \right) \tag{2}$$

$$F_p^{FO} = A^{FO} S_{memb}^{FO} \left(\pi_d - \pi_f \right) \tag{3}$$

where F_p is the permeate flow across the membrane, S_{memb} is the membrane area, A is the membranes' permeability to water, ΔP and Δπ are the pressure applied and the osmotic pressure difference between both sides of the RO membrane, and π_d and π_f are the osmotic pressures of the draw and feed solutions in the FO processes, which depend on their respective TDS concentrations.

3.2. Objective functions

The economic objective function is the specific total cost, STC ($/m^3), which is calculated using Eq. (4)

$$STC = \frac{TAC}{FracW} \tag{4}$$

where TAC is the total annual cost ($/y) and FracW ($m^3/y$) is the flowrate of the water used for the completion of a wellpad, which can be freshwater from a natural resource, reused water from previously exploited wellpads or a mixture of both. The TAC comprises the investment and maintenance cost of the membrane units, the electricity cost, the FBW pre-treatment cost, the disposal cost of the pre-treatment sludge, the cost of the off-site treatment and the freshwater cost.
The second objective function is the freshwater consumption itself, FWC (m^3/h). Obviously, both objective functions are not completely independent since the freshwater cost is considered to compute the STC. However, the cost of FW is very low in comparison with other the contributions. Therefore, the solution representing the minimum STC will, presumably, use a great percentage of freshwater, while the solution corresponding to the minimum FWC is expected to exhibit a higher cost.

4. Case study

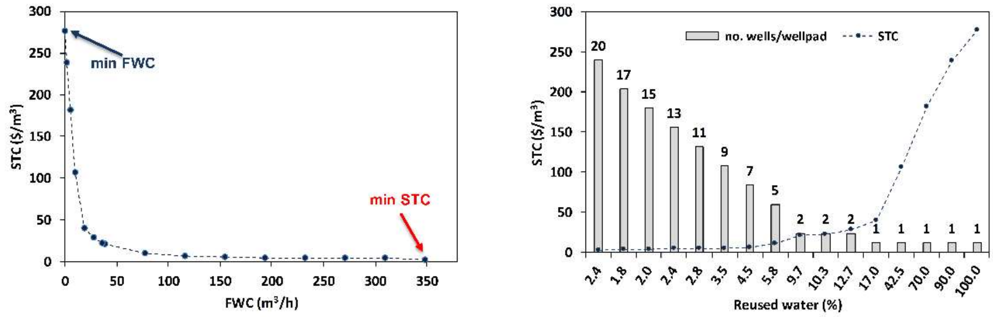
The described formulation is applied to the following example.
According to Lira-Barragán et al. (2016), the flowrate required for each well completion is 428.57 m^3/d and the average flowback water flowrate, coming out each well during the firsts weeks after the completion, is 178.57 m^3/d. In this study, we consider wellpads that can contain from 1 to 20 wells. Therefore, the above-mentioned values are taken as lower bounds for the FracW and FBW flowrates, respectively. Obviously, the PW does not come from the same wellpad as the FBW since it returns to the surface during a long period of time after the well completion. Therefore, the PW used here should be available from previously exploited wells, conveniently pretreated and stored.

The TDS concentrations of both FBW and PW streams are key for the effectiveness of the desalination system. Unfortunately, their composition varies from site to site, which difficults the generalization of a shale gas wastewater treatment model. In this work, we use data reported in the literature (Zendehboudi and Bahadori, 2017) from typical wells in the Marcellus shale. Specifically, the TDS concentration used for FBW is 66,000 ppm and for PW, 261,000 ppm. Moreover, some restrictions must be used to ensure the correct performance of the model. For example, a maximum TDS concentrations of 45,000 ppm and 2,000 ppm have been imposed to the stream entering the RO unit and the final FracW, respectively. Additionally, a minimum concentration of 200,000 ppm has been enforced to the brine stream exiting the FO 2 unit, to facilitate the off-site ZLD treatment. Apart from the concentration restrictions, a maximum value for the membrane areas has been fixed to enable the use of mobile treatment units.

The cost parameters used are taken from: Yang et al. (2014), Slutz et al. (2012), commercial prices for the membrane modules and Eurostat (2015).

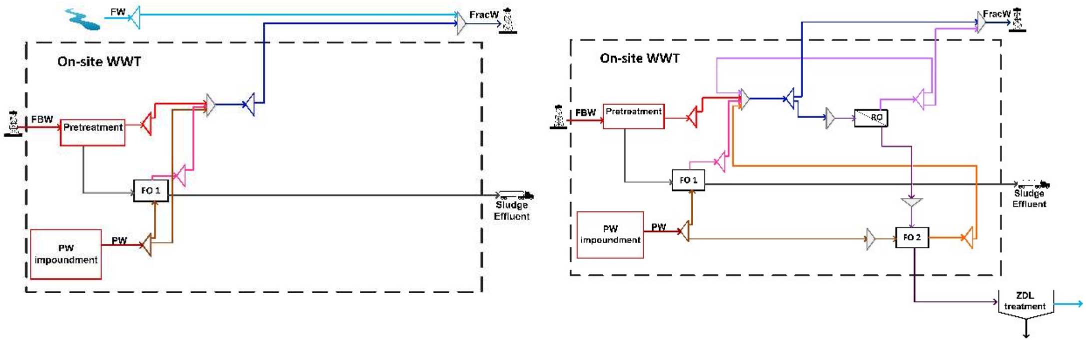
5. Results and discussion

The model has been implemented in GAMS 28.4.2 (GAMS, 2017) and solved, using BARON version 16.12.7 (Sahinidis, 2017), to global optimality. The results obtained show a clear trade-off between FWC and the STC of the fracturing water required for the completion of a new wellpad (Figure 2a). Through the reuse of wastewater, the FW consumption can be even avoided but only at the expense of a huge increase in the drilling water cost. The Pareto frontier, shown in Figure 2a, represents a set of optimal solutions, each of which can have different structure, stream flowrates and concentrations, sizes of the RO and FO units and ratios of reused water. Figure 2b shows the percentage of reused water with respect to the total fracturing water, the number of wells that could be stimulated with this amount of water and the STC for each Pareto solution. In Figure 3, the flowsheets of the extreme Pareto solutions are depicted. The system with the minimum STC (2.69 \$/m^3) uses mainly FW (only 2.4 % of FracW is reused water). In this case, only the minimum enforced FBW flowrate and a small PW flowrate are employed. These streams are blended with FW to meet the FracW concentration restriction, resulting in a FracW flowrate high enough for the completion of 20 wells. On the other hand, the solution with the minimum FWC does not use fresh water at all. All the resulting fracturing water is treated wastewater from other wellpads. This structure combines the RO process with both FO 1 and FO 2 units, which are used to dilute the PW before entering the RO membranes, as well as for the concentration of the FBW pretreatment sludge and the RO brine. However, due to the size constraint, the resulting water is just enough for the completion of a single well. The highly expensive cost of this solution (276.65 \$/m^3) arises from the contribution of all treatments, including that carried out at the off-site facility. In fact, when the proportion of reused water exceeds 10 %, the STC increases dramatically, despite the low FracW flowrate obtained (Figure 2b).



a) b)

Figure 2. Pareto set of optimal solutions: a) Pareto frontier; b) Reused water proportion, number of wells and STC corresponding to each solution.



a) b)

Figure 3. Flowsheets of the resulting structures for the extreme solutions of the Pareto frontier: a) minimum STC; b) minimum FWC.

6. Conclusions

In this work, we propose a mathematical model to address the design of an optimum on-site FBW desalination system combining reverse and forward osmosis, which, in turn, can manage the hypersaline PW from previously exploited wells, seeking for the simultaneous minimization of the specific total cost of the fracturing water and the freshwater consumption. This model is applied to a case study where the water required for the completion of a wellpad, can be provided as freshwater from natural resources, reused water from previous wellpads, or as a mixture of both. The solution shows the trade-off between the fracturing water cost and the freshwater consumption and highlights the potential of FO to offer a solution for the problem of PW disposal. In sight of the results, it is technically possible to use only reused water for the exploitation of new wells. However, the cost of a cubic meter of treated water would be approximately 100 times higher than the same quantity of freshwater. Therefore, an intermediate solution would be a more reasonable option for the design of the proposed system for the attainment of shale gas drilling water.

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