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Simulation and economic evaluation of a coupled thermal vapor compression desalination process for produced water management

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A B S T R A C T

Produced water management at oil and gas fields is gaining vast attention due to its large volume, high salinity and high disposal cost. Opportunities for disposal by such methods as remote injection are shrinking and increasingly costly. On the other hand, gas flaring at the oil and gas fields wastes large amounts of thermal energy that could potentially be used to reduce the produced water disposal cost. In this paper, a coupled thermal vapor compression (TVC) desalination process powered by flare gas is proposed and rigorously simulated in Aspen Plus. Based on that, the energy intensity and unit product cost ($/vol. of product) are estimated and compared with multistage flash (MSF), multi-effect distillation (MED), mechanical vapor compression (MVC) and reverse osmosis (RO). Sensitivity analysis is also performed to obtain the ranges of energy intensity and production cost, which are influenced by the water salinity, boiling brine temperature, compression ratio, and motive steam pressure. Results indicate that the proposed TVC process is technically viable and cost-effective at most locations; it could also save roughly one-third of the disposal cost compared to the remote injection method.

1. Introduction

After a typical hydraulic fracturing operation, the water-based fracking fluid mixed with natural formation water that gradually flows back to the wellhead is known as produced water (Ground Water Protection Council and ALL Consulting, 2009). It is the single largest waste stream at the oil and gas production site, with complex components such as oil, grease, heavy metals, radionuclides, fracking chemicals, formation solids, salts, dissolved gases, etc (Igunnu and Chen, 2012; Ahmadun et al., 2009). Deep-well injection is currently the predominant method for produced water disposal, accounting for 95.2% of the total reported amount (Clark and Veil, 2009). Lately, new wastewater management strategies such as on-site recycle and reuse have drawn vast attention due to the following two reasons. First, the rapid growth of shale oil and gas projects has depleted the availability of local injection sites in some area in the U.S: 7 in Pennsylvania, 6 in New York, 74 in West Virginia and 159 in Ohio (Boschee, 2014). Second, on-site recycle and reuse has shown considerable savings over direct disposal at many locations. For example, at Montney Shale, disposal with recycle costs only $2.75/bbl (Boschee, 2014; Paktinat et al., 2011) while disposal without recycle costs $8/bbl. At Marcellus Shale, the economic benefit is even larger when the disposal cost is $10–12/bbl (Silva, 2012; Gaudlip and Paugh, 2008) due to the long distance.

To be recycled and reused, produced water salinity has to be reduced below certain level depending on the usage. Mixing produced water with low-salinity freshwater is the easiest method, but is rarely available and enlarges wastewater volume. The real solution is desalination. Among desalination processes, mechanical vapor compression (MVC) and reverse osmosis (RO) are the most mature technologies on the market, while new emerging technologies such as membrane distillation (MD) and electrodialysis (ED) are growing rapidly. Despite the higher energy consumption than RO (Thiel et al., 2015), MVC is more technically viable for feeds with salinity higher than 47,000 mg/L (Drewes, 2009) and generates high-quality permeate (2–10 mg/L) with less stringent pretreatment requirements. However, since MVC is powered by high-grade electrical energy (Shaffer et al., 2013), it may not be able to operate without existing power grid.

On the other hand, natural gas flaring, which is basically the controlled burning of natural gas, is the common practice for handling surplus wellhead natural gas during production due to safety concerns. Tremendous effort has been made to minimize the flare (Mourad et al., 2009; Xu et al., 2009; Oguejiofor, 2006);

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nevertheless, the percentage of flare remains substantial in areas with rapid growth of new projects. In Bakken shale, 30% of raw gas is flared mainly due to the lack of pipeline construction (Salmon and Logan, 2013). In Texas, the percentage of statewide natural gas production that is flared, with a little surprise, acutally climbed from 0.1% to 0.6% between 2007 and 2013 (Railroad Commission of Texas (2015)). Since large amounts of heat are literally wasted during flaring, the strategic coupling of desalination and flaring attractively reduces two waste streams and produces freshwater with versatile usage.

Recently, Glazer (Glazer et al., 2014) reported in a brief paper that if all the energy from flaring was used by thermal desalination processes like multistage flash (MSF), multi-effect distillation (MED), MVC and MD, the treated water (up to 540 million m^3) would be sufficient for the hydraulic fracturing of up to 28,000 wells, exceeding the water demand for all new wells (15,041 wells) in Texas in 2012. Although the preliminary estimation sounds encouraging, a detailed design and simulation of the suitable process is needed to demonstrate technical and economic feasibility. Apparently, MVC is powered by electricity and may not be able to couple with flaring directly. Therefore, this paper reports the process simulation and detailed analysis of a thermal vapor compression (TVC) desalination process coupled with gas flaring in terms of its energy intensity and production cost. The process simulation is accomplished using Aspen Plus® simulation software.

2. Methodology framework

The proposed research includes four progressive stages as shown in Fig. 1. **Stage I:** *Data preparation*. Necessary design parameters such as the stream information, equipment type, operating conditions, vessel geometry, chemical reactions, *etc*., are gathered from literature and simplified when appropriate for simulation purposes. **Stage II:** *Base case simulation*. With the design parameters and property method selected, the proposed process will be constructed as the base case. This is the most time-consuming stage involving the modification of calculation sequence and verification of results with previous literature. **Stage III:** *Sensitivity Analysis*. Based on the base case results, critical design variables affecting the thermal efficiency and system performance will be adjusted systematically to determine their correlations. **Stage IV:** *Economic evaluation*. Unit product cost of the base case considering fixed and operating cost is obtained first. From sensitivity results in stage III, cost range due to the variation of four critical design variables and the market fuel price will be identified. Finally, cost of the new process is compared with current management solutions.

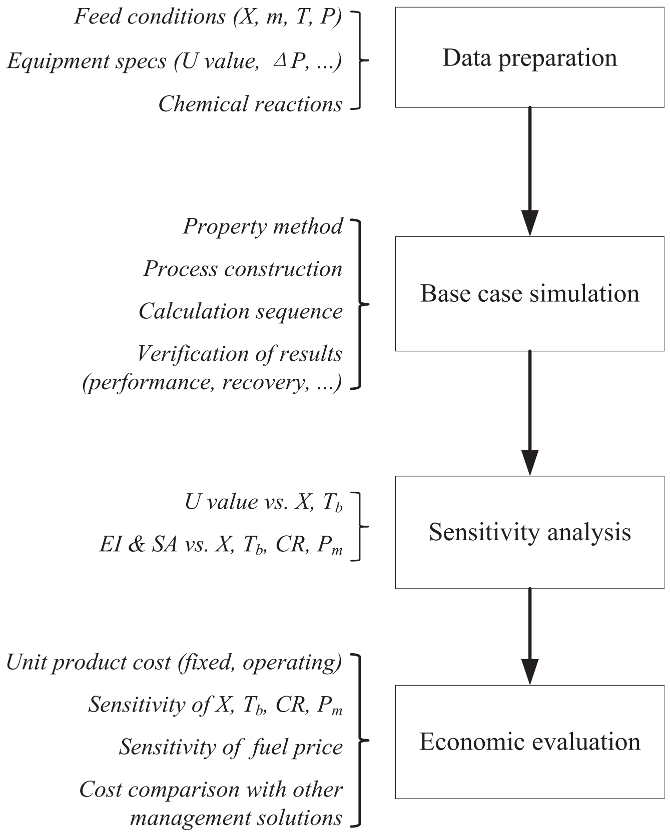

Fig. 1. Methodology framework.

3. Data preparation

3.1. Characteristics of produced water and flare gas

Salinity of produced water varies widely from 1000 mg/L to 400,000 mg/L (Clark and Veil, 2009) depending on numerous factors, making it unrealistic to standardize the composition. However, 95–98% (Thiel et al., 2015) of the dissolved ions (on a molal scale) are sodium (Na^+), calcium (Ca^{2+}) and chloride (Cl^-); while other minor components such as magnesium (Mg^{2+}), potassium (K^+), carbonate (CO_3^{2-}), *etc*., contribute less than 1%. Although minor components also contribute to thermodynamic properties of the solution, their impact on separation energy is limited (Thiel et al., 2015). What's more, excluding minor components improves the convergence speed of the model in a sensible way due to the substantially fewer equations. Therefore, a Ca–Na–Cl ternary mixture with design composition from field samples (Thiel and Lienhard, 2014) (Table 1) is used in our simulation. Due to the simplification of components, Cl^- molal concentration is adjusted to maintain electroneutrality.

Volumetric flow of produced water typically diminishes with the production days. For example, the initial flow at Marcellus shale is around 1400 m^3/day (Glazer et al., 2014); it drops to only 150 m^3/day after 10 days. For steady-state simulation, the feed volumetric flow is specified as 670 m^3/day (30,000 kg/hr), by taking the average of the initial 10 days of production (Glazer et al., 2014). On the other hand, flare gas composition is represented by that of the wellhead natural gas containing mostly methane and ethane (>95%) (Laurenzi and Jersey, 2013) (Table 1), and its volumetric flow will be determined by mass and energy balances of the model.

3.2. Property method

Binary interaction parameters reported by Tanveer (Tanveer and Chen, 2016) is applied in ELECNRTL property method for this simulation since it demonstrates better agreement with experimental data than using the default parameters. In particular, the missing binary interaction parameters between ($Ca^{2+}Cl^-$) and (Na^+Cl^-) H_2O in the default database are supplemented and those between H_2O and ($Ca^{2+}Cl^-$), H_2O and (Na^+Cl^-) are updated for the prediction of salt precipitation (NaCl(s), $CaCl_2$–$2H_2O$(s), $CaCl_2$–$4H_2O$(s), $CaCl_2$–$6H_2O$(s)). Such a method is valid for electrolyte solution with temperatures up to 200 °C and concentrations up to salt saturation (Tanveer and Chen, 2016), which covers our simulation needs.