TO: Texas Hazardous Waste Research Center

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PROJECT TITLE: Coupling of Produced Water Treatment and Flare Recovery in Unconventional Oil and Gas Production

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Project Description

Gas field produced water (GFPW) desalination is gaining special attention due to limitations of traditional deep-well reinjection methods in shale gas fields. Although conventional vapor compression processes are technologically feasible for handling GFPW, they are energy-intensive and costly. It is worth noting that natural gas flaring at the production site wastes plenty of heat that could be used to save energy consumption for GFPW desalination. In this project, a conceptual design of thermal vapor compression (TVC) powered by the flared gas is proposed and virtually simulated. Sensitivity analysis is also performed to establish the relations between the system design variables (i.e. performance ratio and specific heat transfer area) and operating conditions such as boiling temperature in the evaporator, compression ratio, and expansion ratio of the ejector. Furthermore, the unit product cost is estimated based on the system design and operating conditions. It shows that the proposed thermal vapor compression (TVC) powered by the flared gas simulated here shows considerable economic benefits, and it offers a new option for the flared gas utilization.

Data Preparation

Flow rate and composition of GFPW

Nowadays, the treatment capacity of a mobile vapor-compression system can reach 205 m^3/day. In our case, 200 m^3/day is set as the feed capacity in our simulation. Table 1 listed the feed of GFPW and flare gas according to the literature.

Table 1 Characteristics of typical shale gas and GFPW.

Flared gas composition	**Mole percentage (%)**	**GFPW composition**	**Mass concentration (mg/L)**
Methane	79.4	Na^+	36400
Ethane	16.1	Ca^{2+}	11200
Propane	4.0	Cl^-	75940
CO_2	0.1	--	--
Nitrogen	0.4	--	--

Modeling and Simulation

The thermal vapor compression (TVC) is a process in which saline water is heated and evaporated by compressed steam. It is particularly attractive to treat GFPW at small to medium capacities on site with the advantages of flexibility to load variation, simple construction and absence of moving parts. The process flowsheet is depicted in Fig. 1. The flare gas is fed into the steam boiler under low pressure (5mbar) with 7% excess air; and the flue gas temperature is set at 120°C in order to obtain high thermal efficiency in the boiler while avoiding any acid condensation. The partially condensed steam (HOUT) from the evaporator can be reused as the boiler feed to avoid external fresh water withdrawal.

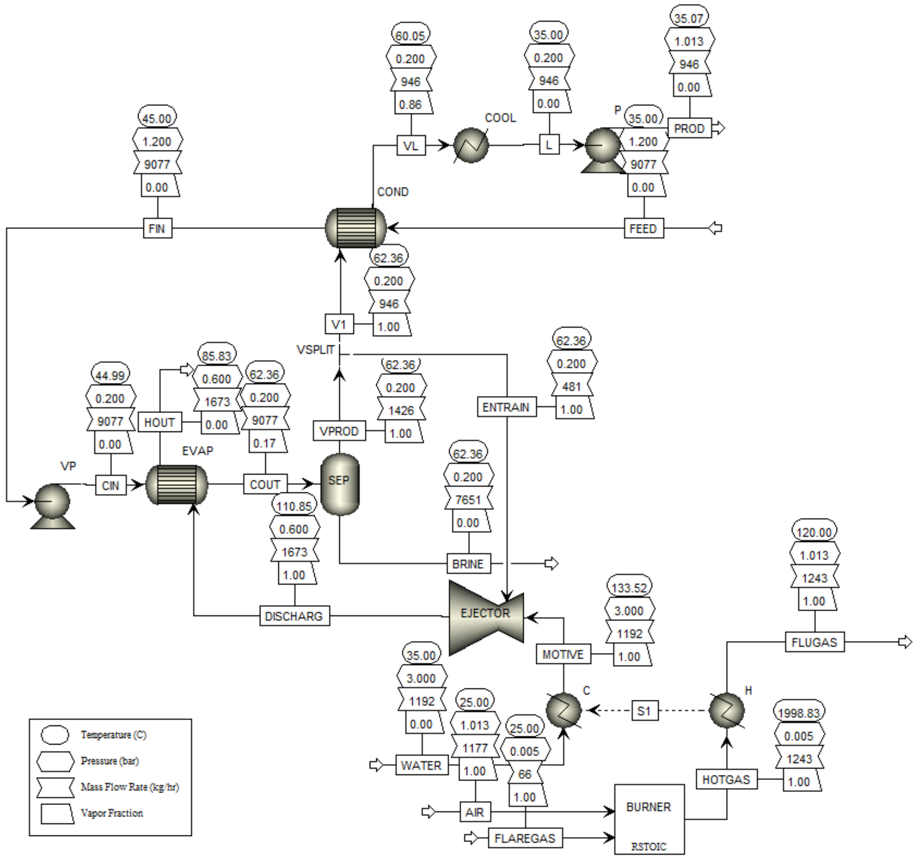

Fig. 1. Aspen Plus process flow diagram for TVC powered by the flared gas.

ENRTL-RK is one of the common property methods to describe physical properties of electrolyte systems up to very high ionic concentrations and it is used in this simulation.

Results and Discussion

Selected stream results of the base case are listed in Table 2 and their corresponding operating conditions are listed in Table 3 according to the previous literature.

Table 2. Selected stream results of TVC powered by the flared gas (base case).

	Air	**Brine**	**Feed**	**Flaregas**	**Prod**	**Vprod**	**Water**
Temperature (°C)	25.00	62.40	35.00	25.00	35.10	62.40	35.00
Pressure (bar)	1.013	0.200	1.200	0.005	1.013	0.200	3.000
Mass flow (kg/hr)	1177.11	7651.19	9077.36	66.30	945.55	1426.17	1192.20

Stream Flow (kg/hr)							
Water	0	6529.77	7955.94	0	945.55	1426.17	1192.20
NaCl	0	0	0	0	0	0	0
$CaCl_2$	0	0	0	0	0	0	0
N_2	902.84	0	0	0.38	0	0	0
O_2	274.27	0	0	0	0	0	0
CO_2	0	0	0	0.15	0	0	0
CH_4	0	0	0	43.31	0	0	0
C_2H_6	0	0	0	16.46	0	0	0
C_3H_8	0	0	0	6.00	0	0	0
Na^+	0	330.39	330.39	0	0	0	0
Ca^{2+}	0	101.66	101.66	0	0	0	0
Cl^-	0	689.37	689.37	0	0	0	0
NaCl(s)	0	0	0	0	0	0	0
$CaCl_2$(s)	0	0	0	0	0	0	0
$CaCl_2 \cdot H_2O$	0	0	0	0	0	0	0
$CaCl_2 \cdot 6H_2O$	0	0	0	0	0	0	0
$CaCl_2 \cdot 4H_2O$	0	0	0	0	0	0	0
$CaCl_2 \cdot 2H_2O$	0	0	0	0	0	0	0

From the flow rate ratio of the flared gas (FLAREGAS) and the vapor product (VPROD), we obtain that 46.5 m^3 (1.64 MMBtu) of flared gas is required in our process to produce 1 m^3 of fresh water, where the average heating value and density of the flared gas are assumed to be 35.31 MBTU/m^3 and 0.8 kg/m^3 at atmospheric pressure respectively. This energy-water ratio is much higher than those of the large scale seawater desalination processes according to the recent paper from Glazer, et.al [19] (MSF: 0.18-0.28 MMBtu/m^3, MED: 0.15-0.28 MMBtu/m^3, MVC: 0.11 MMBtu/m^3, and MD: 0.14 MMBtu/m^3). Furthermore, based on the average volumetric flow rate of flared gas (9600 m^3/well/day) and the energy-water ratio mentioned above, the average fresh water that could be produced from the TVC process is estimated to be 206

m^3/well/day, which is much lower to the seawater processes (MSF: 750-1500 m^3/day, MED: 1500-5000 m^3/day, MVC: 4500-6800 m^3/day, MD: 4700-6100 m^3/day). The energy-water ratio can be lowered by many ways, such as recycling of the brine, adding more effects to increase the thermal efficiency etc.

Table 3. Operating conditions and system design variables.

Operating conditions	**Base case**	**Low**	**High**
Boiling temperature (°C)	62.4	71.3	51.9
Compression ratio (p_d/p_e)	3.0	4.0	2.0
Expansion ratio (p_m/p_e)	15.0	10.0	25.0
Entrainment ratio (f_e/f_m)	0.41	0.16	0.87
System design variables			
Performance ratio	1.20	0.83	1.81
Specific heat transfer surface area (m^2/(kg/s))	53.16	43.66	91.99

Cost Estimation

Parametric values used in the cost estimation of TVC are summarized in Table 4.

Table 4. Parametric values used for the cost estimation of TVC processes.

Parameter description	**Symbol**	**Value**
Natural gas price ($/$m^3$)	p_n	0.18 (0.07-0.28)
Plant availability	f	0.9
Electricity cost ($/kWh)	c	0.1
Electricity consumption (kWh/m^3)	w	0.65
Chemicals cost ($/$m^3$)	k	0.025
Labor cost ($/$m^3$)	l	0.5
Amortization factor	a	0.065

Annual interest rate	i	0.05
Plant life (years)	n	30
Aggregation factor for heat exchangers	f_a	1.1
Specific cost of heat exchangers ($/m^2)	C_{sh}	195

The calculation results of the direct capital cost are listed in Table 5.

Table 5. Direct capital cost of TVC powered by the flared gas.

Equipment Name	**Cost ($/yr)**
Boiler	200,000
Ejector	80,000
Evaporator and Condenser	$2.48\, f_v SA$
Pumps	$1600\left(\frac{q_{pt}}{7.5}\right)^{0.3}$
Rest	$18181\, f_v^{0.1773}$

The unit product cost of the conventional TVC processe vs. the flare gas powered process is compared in Fig. 2.

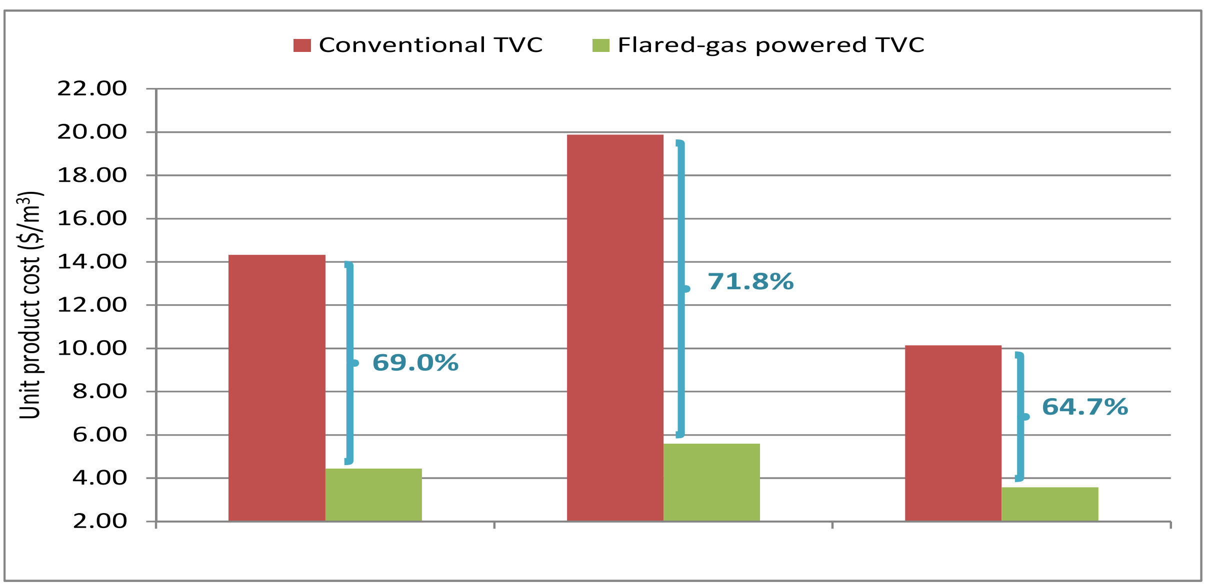

Fig. 2. Comparisons of the unit product cost of the two processes in different cases.

List of Publications and Presentations

1. Chen, L. W., Z. X. Tian, H. H. Lou, “Sustainable Manufacturing and Water Sustainability,” Sustainable Water Management and Technologies, D. H. Chen (eds.), CRC Press/Taylor & Francis Group, Boca Raton, FL, in press, 2015.
2. Chen, L. W., Q. Xu, H. H. Lou, Simulation and Analysis of Thermal Vapor Compression for Gas Field Produced Water Desalination Powered by On-site Flared Gas,” submitted, Journal of Cleaner Production.