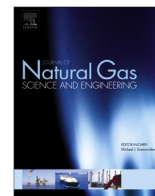




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Utilization of aquifer storage in flare gas reduction

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ABSTRACT

Flaring associated gas from oil wells has resulted in concerns about CO₂ emissions and wasted energy. In this paper, an integrated flare gas reduction system that combines natural gas liquids separation and underground storage of lean gas in aquifers is studied. This flare gas reduction system takes advantage of peak natural gas demand and prices in winter. Therefore, revenues from both lean gas natural gas liquids sales would compensate for the year-long natural gas liquids separation costs. Aquifer permeability and depth are the major factors in determining the storage cost, which should be lower than the marginal revenue derived from the seasonal difference in natural gas prices. The site selection method and governing equations are presented, and a case study applying the proposed system to the Bakken oil field was performed. The results indicated that when aquifer permeability was low (<200 mD), permeability had a larger impact on the storage cost than aquifer depth, and the cost decreased with increasing permeability and depth. When aquifer permeability was relatively high (>200 mD), depth was the dominating factor and the cost increased with depth. Ranges of permeability and depth for which the storage cost is lower than the seasonal price difference of natural gas were determined. The economic estimation approach presented in this paper can be used to select appropriate storage sites and rich gas processing technologies.

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1. Introduction

Associated gas refers to natural gas, which exists as free gas or dissolved gas in reservoirs, produced from oil wells. At the wellhead, this gas is usually a mixture of methane (CH₄), ethane (C₂H₆), propane (C₃H₈), butane (C₄H₁₀), pentane (C₅H₁₂), and higher-order alkanes. Since many oil fields are remotely located and the cost of recovery is high, each year a significant amount of associated gas is simply combusted as flare gas. It is estimated that about 5.3×10^9 Mscf of associated gas are flared annually worldwide (World Bank, 2011a). This flaring results in the emission of more than 300 million tons of carbon dioxide (CO₂) into the atmosphere, equivalent to the emissions from approximately 77 million cars. If the associated gas were instead used for power generation, it could provide more electricity than the entire continent of Africa consumes (750×10^9 kW h) (World Bank, 2011b). Gas flaring has led to increasing environmental concerns relating to greenhouse gas emissions and wasted energy sources (Rahimpour et al., 2011; Saidi

et al., 2014). Therefore, flaring the gas may no longer be an option. For the industry and research communities, this is an opportunity to develop new, economical approaches to efficiently recover the associated gas.

A conventional flare gas reduction system separates natural gas liquids (NGL) from the rich associated gas at the wellhead. The NGL, which is comprised of C₃H₈, C₄H₁₀, C₅H₁₂, and heavier components, has a high market value and can be used as petrochemical feedstock and fuels. Consequently, the sale of NGL is used to subsidize the flare gas reduction system. The remaining lean gas, which has a lower emission profile than the rich gas and is comprised mainly of CH₄ and smaller amounts of C₂H₆, is flared (Wocken et al., 2013). However, the lean gas can be easily utilized for power generation, transportation fuel, or gas-to-liquids production (Wood et al., 2012), or be transported as a compressed gas (Wocken et al., 2013), or used in gas-to-liquids production (Wood et al., 2012). Currently, due to the higher value of NGL, lean gas recovery is not attractive to oil producers. Monetizing the lean gas would generate additional revenue and compensate for the cost associated with NGL separation, promoting reduction of gas flaring. When considering monetizing the lean gas, one should keep in mind that, like many other commodities, natural gas follows a general supply and

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Nomenclature*Symbols*

CH ₄	methane
C ₂ H ₆	ethane
C ₃ H ₈	propane
C ₄ H ₁₀	butane
C ₅ H ₁₂	pentane
CO ₂	carbon dioxide
<i>D</i>	depth (m or ft)
<i>h</i>	aquifer thickness (m or ft)
<i>i</i>	annual interest rate
<i>k</i>	permeability (mD)
<i>n</i>	specific heat ratio
<i>n.s.</i>	number of compression stages
<i>P</i>	pressure (MPa or psi)
<i>q</i>	volumetric flow rate (m ³ /s or Mscf/d)
<i>r</i>	radius (m or ft)
<i>r.c.</i>	compression ratio
<i>R_g</i>	relative gas constant (kJ/(kg K))
<i>T</i>	temperature (K, °C, or °R)
<i>t</i>	duration (d)
<i>y</i>	project life (year)
<i>w_C</i>	specific energy requirement (kJ/kg)
<i>Z</i>	compressibility factor
<i>ρ</i>	density (kg/m ³)
<i>η</i>	efficiency
<i>μ</i>	viscosity (cp)

Subscripts

AQ	aquifer
C	compressor
comp _{in}	compressor inlet

comp _{out}	compressor outlet
dis	discharge
<i>e</i>	constant pressure at the outer boundary of the aquifer
inj	injection
ptr	petroleum unit
<i>R</i>	°Rankine
SI	International System of Units
wellD&C	well drilling and completion
<i>w</i>	well
0	environment temperature condition

Acronyms

FH-HC	Fox Hill – Hell Creek aquifer
NGL	natural gas liquids
O&M	operating and maintenance

Units

°C	degree Celsius
cp	centipoise
d	day
ft	feet
K	degree Kelvin
kg	kilogram
kJ	kilojoule
kPa	kiloPascal
kWh	kilowatt-hour
m	meter
mD	millidarcy
Mscf	thousand standard cubic feet
m ³	cubic meter
MPa	mega Pascal
psi	pounds per square inch
°R	degree Rankine
s	second

demand curve. As an example, in the United States, natural gas is a seasonal fuel whose consumption during the winter peak can be higher than in the off-peak season by 70% (U.S. Energy Information Administration, 2011). The market price of natural gas reflects a similar seasonal fluctuation. Production peak of natural gas usually occurs in the summer months, when gas prices are low due to low consumption. During the winter, the price steadily increases as the market demand for fuel and heating increases. Data from the U.S. Energy Information Administration shows the natural gas industrial price in the market fluctuates through the production peak in the summer to the consumption peak in the winter (U.S. Energy Information Administration, 2015). Fig. 1 displays the natural gas industrial price in USD/Mscf from 2012 to 2014. In the chart, the period from May to November is the off-peak season, and the period from December to April is the peak season. The average market price of industrial natural gas is \$5.34/Mscf in winter (peak season) and \$4.47 in summer (off-peak season). The peak season natural gas market features high demand and consequent high prices.

The purpose of this study is to examine the possibility of using aquifer storage to recover the value of lean gas at locations upstream of natural gas processing plants. An integrated flare gas reduction system that couples NGL separation and aquifer storage of lean gas is proposed (Fig. 2). This process assumes that an NGL removal system, which extracts and sells NGL from the rich associated gas, is already in place. However, instead of being flared, the lean gas is then stored in the aquifer and sold during the

consumption peak, when both demand and price are higher. Storing and selling the lean gas will increase revenues to cover the separation cost, providing motivation for installing the integrated system. It is clear that the cost of lean gas storage is a key factor in determining the profitability of the proposed integrated system. The sum of the storage cost and NGL separation cost should be lower than the sale revenues from the lean gas and NGL. In the following sections, the calculation method and governing equations of aquifer natural gas storage for this model are first introduced. Then the model is employed in a case study of the Bakken oil fields in North Dakota, United States. Costs associated with storing lean gas in two major regional saline aquifers are calculated and compared. Characteristics of the cost variation as a function of permeability and depth are summarized. Finally, the range of permeability and depth required to guarantee favorable economics of the storage system is determined. The proposed system is expected to increase revenue for oil producers for which lean transport infrastructure is available. The methodology presented in this study can be applied to other basins to analyze the feasibility of similar systems.

2. Methodology and governing equations

Underground storage of natural gas is vital to effectively balancing a variable demand market with a nearly constant supply provided by the pipeline (Katz and Tek, 1981). The natural gas is injected into storage reservoirs when market demand falls below

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