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Review

An overview on exploration and environmental impact of unconventional gas sources and treatment options for produced water

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ABSTRACT

Rising global energy demands associated to unbalanced allocation of water resources highlight the importance of water management solutions for the gas industry. Advanced drilling, completion and stimulation techniques for gas extraction, allow more economical access to unconventional gas reserves. This stimulated a shale gas revolution, besides tight gas and coalbed methane, also causing escalating water handling challenges in order to avoid a major impact on the environment. Hydraulic fracturing allied to horizontal drilling is gaining higher relevance in the exploration of unconventional gas reserves, but a large amount of wastewater (known as "produced water") is generated. Its variable chemical composition and flow rates, together with more severe regulations and public concern, have promoted the development of solutions for the treatment and reuse of such produced water. This work intends to provide an overview on the exploration and subsequent environmental implications of unconventional gas sources, as well as the technologies for treatment of produced water, describing the main results and drawbacks, together with some cost estimates. In particular, the growing volumes of produced water from shale gas plays are creating an interesting market opportunity for water technology and service providers. Membrane-based technologies (membrane distillation, forward osmosis, membrane bioreactors and pervaporation) and advanced oxidation processes (ozonation, Fenton, photocatalysis) are claimed to be adequate treatment solutions.

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1. Introduction

Increasing global gas consumption promotes the search for new gas reserves. Over the past decade, the exploration of low permeable rock formations has grown significantly. In particular, recent advances in drilling technologies, as well as in completion and stimulation techniques (i.e., steps required to transform a drilled well into a producing well, such as casing, perforation, installation of production tree, among others), have allowed more economical access to a significant number of unconventional gas reservoirs (Jackson et al., 2014).

The difference between conventional and unconventional gas is related to the geological characteristics of the corresponding reservoir rocks, and not to its chemical composition (i.e., it is all natural gas). Tight gas (TG), shale gas (SG) and coalbed methane (CBM) are the three main types of gas included in the so-called "unconventional" gas category (Wang et al., 2014). Natural gas trapped into limestone or sandstone rocks is named as TG, while that found in the fine grain sedimentary rocks known as shales is called SG. CBM refers to the gas generated and stored within coal seams (McGlade et al., 2013), typically found in non-profitable coal reservoirs with large depth or poor quality coal. Its extraction is achieved by depressurization of the coal seam by withdrawal of the water present inside it.

Recent estimates suggest that unconventional gas represents 40% (Fig. 1a) of the world's technically recoverable remaining natural gas, with 5%, 8% and 27% for CBM, TG and SG, respectively (39 trillion m^3 of CBM, 54 trillion m^3 of TG, and 193 trillion m^3 of SG) (McGlade et al., 2013; Shaffer et al., 2013). Unconventional gas extraction in the U.S. increased the total dry natural gas production (i.e., conventional and unconventional) by 35% from 2005 to 2013 (Coday et al., 2014; EIA, 2015). Fig. 1b shows that SG production is growing faster than the other unconventional natural gas sources, with very optimistic projections until 2040. However, the future exploration of this type of resources depends on many uncertainties, such as the size and physical characteristics of the respective reservoirs.

The increase in the exploration of these resources is in part due to the higher gas flow rates that are now possible by implementing advanced drilling techniques, such as horizontal and directional drilling, combined with stimulation techniques, such as hydraulic fracturing (HF). Such drilling allows fracturing long horizontal sections of the well, thus accessing extensive gas-bearing formations. However, regardless of the gas source, many environmental concerns are associated to HF, such as induced earthquakes, air pollution, large surface and/or groundwater withdrawal, generation of large volumes of complex wastewater (often referred as "produced water") and risk of fresh water contamination. Such environmental concerns are increasing with the exploration of these unconventional gas sources, and appropriate solutions to treat produced water are nowadays required.

A few review/overview articles dealing with the treatment and desalination of produced water have already been published. The conventional technologies used to treat offshore and onshore conventional gas derived produced water were summarized in literature (Fakhru'l-Razi et al., 2009). Other authors (Igunnu and Chen, 2012) reviewed the oil field produced water treatment technologies, suggesting that those based on electrochemistry were promising to produce clean water and to recover valuable metals. Desalination techniques applicable to high-salinity SG produced water were also reviewed (Shaffer et al., 2013), giving particular attention to three desalination technologies: mechanical vapour compression (MVC), membrane distillation (MD) and forward osmosis (FO). State of the art membrane processes, such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO), were also reviewed (Alzahrani and Mohammad, 2014). Other authors (Abousnina et al., 2015) summarized the similarities and differences between the water produced from exploration of conventional hydrocarbon and unconventional CBM resources, concluding that RO is used in most cases in the U.S. and Australia and that FO is a notable candidate for sustainable management of produced water in CBM exploration. A combination of technologies was suggested to treat chemicals used in HF, because the most common currently-applied treatment technologies (e.g., sedimentation, gas flotation, and filtration) are unlikely to remove significant amounts of these compounds present in produced water. Biological treatments appear as viable options to reduce the chemical oxygen demand, while RO or evaporation-based technologies are more appropriate for desalination. Advanced oxidation and electrocoagulation processes are promising, although more demonstration activities are needed (Camarillo et al., 2016). Membrane technologies showing the management perspectives for Saudi Arabia as case study were overviewed (Drioli et al., 2015), whereas treatment options, including clarification, membrane filtration (UF and RO), ion exchange softening and capacitive deionization, as well as additional options for brine management (e.g., disposal methods, membrane technologies and thermal technologies), were discussed in another article (Millar et al., 2016).

Our present contribution aims to overview (i) the exploration of unconventional gas sources (in particular the HF advances in implementation and operation), highlighting the importance of SG exploration; (ii) the physical, chemical and microbial composition of the three unconventional gas derived produced waters; (iii) the environmental impact and legal framework of this activity; and (iv) the recent advances in the technologies to treat produced waters from unconventional gas sources, introducing the chemical oxidation technologies (COTs) and the advanced oxidation processes (AOPs), such as photocatalysis, ozonation and Fenton processes, together with a brief reference to the membrane technologies that were already reviewed in literature.

2. Hydraulic fracturing (HF) for extraction of unconventional gas

To start the full-production of unconventional gas from a reservoir, many previous steps are required, including drilling, well completion and stimulation. Road accesses and/or trucks are also needed to manage the large volumes of surface water and/or groundwater used during construction of the well pad (that may take about 3 weeks) and respective stimulation. The well is drilled using a mixture of water, mud and drilling additives, enlarging the diameter and going deeply in consecutive steps until reaching the target zone (Torres et al., 2016). Several cycles of drilling, casing