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Review Article

Subsurface methane leakage in unconventional shale gas reservoirs: A review of leakage pathways and current sealing techniques

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ABSTRACT

Shale gas extraction is seen to be a bridge fuel to the future due to lower GHG emissions compared to oil. However, it is also one of the most controversial topics due to the involvement of fracking in their production. Based on the analysis performed in this review we found that despite hydraulic fracture propagation being a possible conduit of methane leakage, the major cause of gas leakage is through leaking wells within the vicinity of fracturing sites. Remedial attempts have revealed promising yet inconsistent results, with no concrete method established for the methane leakage mitigation from shale gas wells.

1. Introduction

Production from conventional fossil fuel resources is decreasing as these reserves continue to deplete, on the other hand the demand for energy is ever increasing. Natural gas has recently gained significant interest as a “bridge fuel” to the future that will develop energy security and reduce dependence on conventional oil and coal resources (Howarth, 2014). With further prospect of a cleaner burning fuel, natural gas has the potential to provide immediate climatic benefits. Shale gas reserves have been termed the energy of the future, due to the fact that the combustion of gas releases significantly less carbon dioxide (CO_2) compared to oil and coal (Zhang Dongxiao, 2015). On the other side, there are concerns associated with the release of natural gas such as methane to the atmosphere and contamination of ground water through leakage process during its production. It is important to understand how critical such environmental concerns are, and what would be the overall impact of production and utilising natural gas on our health and environment. In this study we summarised the studies conducted on the concept of methane leakage through fracking process and concluded how possible sources of methane leakage can be controlled. Therefore, despite its advantages, the extraction from shale gas reservoirs remains to be an ongoing environmental debate on risks and advantages associated with its production. Opposing arguments are mainly based on the environmental concerns and health risks, posed by the uncontrolled release of gases such as methane (CH_4) through fracking process (Zhang Dongxiao, 2015). The cause of methane leakage from oil and gas exploration have been directly attributed to unconventional extraction of shale gas via hydraulic fracturing stimulations. With uncertainties in the extraction process, pro-fracking groups emphasize on the safety of hydraulic fracturing, whereas opposing parties base their arguments on the uncontrolled nature of fracture propagation resulting from hydraulic fracturing. In theory, hydraulic fracturing has the potential to provide methane migration pathways via the intersection of naturally present geological faults in the subsurface, also leakage may happen via inadequately abandoned oil and gas wells (Dehghan et al., 2015). The latter refers to current well abandonment practices which involve setting a series of cement plugs deep inside wells to restrict flow of hydrocarbons (Jackson et al., 2013). The cement commonly used for this process (Portland cement) readily undergo chemical degradation with time in the presence of various substances such as carbon dioxide (CO_2) (Carey et al., Howarth, 2015; Hirst. and Buckle., 2013; Howarth and Ingraffea, 2011; Kutchko et al., 2008; Carey et al.; Analysis and performance, 2007; Bruckdorfer, 1986). The presence of CO_2 can be from naturally occurring geological sources or from the injected carbon dioxide during carbon capture and storage (CCS) process in depleted oil and gas reservoirs. Therefore, in cement based well abandonment procedures, CO_2, degrades cement and forms conduits for gas escape. Carey et al., in 2007 found that CO_2 leakage through casing-cement and casing-shale formation happened during CO_2 sequestration process, and they concluded cement in contact with CO2 was heavily carbonated and created a pathway for CO_2 migration (Hirst. and Buckle., 2013). In terms of shale gas extraction, instances of propagating fractures intersecting wells with reduced integrity may lead to migration of methane towards leakage pathways. Furthermore, for economic reasons, abandoned wells are regularly used to extract groundwater which is fed directly to domestic and

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Table 1
The advantages and disadvantages of shale gas production and extraction (Howarth, 2014), (Howarth, 2015).

Advantages	Disadvantages
Burns cleaner leading to low CO_2 emissions compared to oil and coal	Leakage of methane leads to environmental benefits being nullified
Vast global reserves waiting to be tapped Cheaper fuel alternative to coal	Hydraulic fracturing process generates high levels of waste water
Creates more jobs as new reservoirs being tapped	Leakage pathways allow subsurface aquifer contamination
Provides energy security and aids the advancements of developing countries	Hydraulic fracturing is claimed to increase regional tectonic activities (earthquakes)
Enables the high CO_2 emitting countries to reduce emissions	Provides hindrance in advancements of renewable energy sector

commercial water supply lines that create a direct link for methane to invade groundwater reserves and its escape into the atmosphere (Howarth, 2014).

Thus, the extraction of shale gas remains debatable. Some of the pros and cons of shale gas resources as a source of fuel are summarised in Table 1.

Despite the reduced CO_2 emissions and numerous economic advantages of shale gas extraction, the possibility of methane leakage with already growing concerns of global warming remains to be a hindrance in widespread shale gas development. Methane is a highly potent greenhouse gas (GHG) with a global warming potential (GWP) 72 times more than CO_2 (Hirst. and Buckle., 2013). In April 2011, Howarth et al. stated in their report that the footprint of GHG from shale gas resources was approximately 20% greater than that of coal, and the sheer amount of emissions to date in 2011 suggests that the climatic benefits of using natural gas have already been eliminated (Howarth and Ingraffea, 2011). Similarly, in 2015 Howarth (2014) further argued that due to the potency of methane as an environmentally detrimental substance, the benefits of shale gas resources, both commercial and economic, are quashed by the amounts of methane leakage from unconventional wells (Howarth, 2014). In addition to contamination concerns, the complications of shale gas extraction and the associated problems, stem back to a lack of understanding of the leakage mechanisms and complex geological systems. Limited number of published documentation is available (Howarth, 2014; Jackson et al., 2013; Howarth, 2015; Howarth and Ingraffea, 2011; Schwartz, 2015; Zoback. and Copithorne., 2010; Grasby. et al., 2016; Warner and Darrah, 2012; Brownlow et al., 2016; EPA, 2012) and some of them provide contradictory information. High costs and difficult data collection methods have further limited the reliability of collected data and as a result, all national estimates of methane leakage quantities come from the extrapolation of regional data. Furthermore, any advancements in shale gas extraction have predominantly been in the US (Howarth and Ingraffea, 2011; Yeh et al., 2017; Gvakhariaet al, 2017; Brandtet al, 2016), thus further reducing the area of study to a single region.

The aim of this review is to provide an understanding of the concerns of methane leakage from shale gas extraction. The review outlines the sources and quantities of methane leakage as a contaminant gas from the exploitation of shale gas reserves and further explores the current methods to record and mitigate the leakage of subsurface gases. However, with limited information available for the remediation of subsurface methane leakage, some references will be made to the leakage of CO_2 from CCS (Carbon Capture and Storage) studies.

1.1. Sources of methane leakage

The major sources of methane leakage can be split into two categories. The first category is the propagation of hydraulic fractures and how they interact with naturally occurring geological features, and with man-made subsurface features, such as conventional wells. The other sources of methane emissions are related to venting and flaring activities of gas well operators (Hirst. and Buckle., 2013; Gvakhariaet al, 2017).

A study conducted by Zoback et al. (Zoback. and Copithorne., 2010) in 2010 stated that the major concern surrounding shale gas production was the possibility that the subsurface fracturing operations may extend beyond the target formation and form a link to shallow aquifers. Despite being considered theoretically possible, the presence of geological layering in the overburden strata suggests that the unaided propagation of fractures thousands of feet upwards is highly unlikely. This statement was analysed by Zhang et al. (Zhang Dongxiao, 2015) in 2015, who came to similar conclusions, stating that a more realistic means of leakage may occur from induced fractures extending to natural faults in the subsurface. The viability of natural features providing a means of contaminants migration can be seen from the occurrence of thermal springs. With the consideration of a long geological timescale, deeply seated circulation of steam shows that the communications between the subsurface and surface are realistically possible. One such documented case is the Canadian Rocky Mountains. A study in the mountain area was undertaken by Grasby et al. (Grasby. et al., 2016) in 2016 to assess the occurrence of methane within spring waters. The study stated that the temperature of each spring was directly correlated to the circulation depths, with temperatures ranging from 30 °C to 118 °C in the region, and methane quantities fluctuating between 0.00480 and 0.361% of total gases. However, one case, the Toad river spring, showed up to 23.3% methane is present in samples, with max temperatures of 118 °C and circulation depths of 3.8km. An isotopic analysis of the water from the Toad spring showed high levels of carbon isotope 13 based methane, $\delta^{13}C_{CH4}$, suggesting the presence of the gas was mainly from thermogenic sources, resulting from the decay of organic matter (Grasby. et al., 2016).

The high level of methane and deep circulation depths of the spring channels suggests that the circulation path may have intersected a dense network of naturally occurring fractures in the subsurface. Springs showing trace amounts of methane also demonstrate shallower circulation depths, while deeper circulation channels display higher methane percentages. This suggests that the geological features intersecting subsurface spring channels are mainly located at increased depths, such as the 3.8km deep channel circulation in the Toad spring. Furthermore, the scattered occurrence of naturally deformed basins in the region may have amplified the subsurface intersection of spring circulation paths with methane sources. It is important to note that the spring water samples that were collected, showed the presence of microorganisms in them, which are called methanotrophs. Methanotrophs are microorganisms which thrive in anaerobic, methane rich environments and oxidise methane to CO_2 by 10–90% (Grasby. et al., 2016). Thus, the true amount of methane present in the water samples cannot be conclusively stated.

The study conducted in the Canadian mountains displays the theoretical possibility of induced and naturally occurring fractures interacting to form leakage channels. Thus, the presence of a fracture network within the vicinity of an induced fracturing site poses the risk of leakage pathway creation. Furthermore, many formations contain dormant natural fractures, filled with calcite or quartz composition cement that may act as planes of weakness and points of fracture propagation (Dehghan et al., 2015). With concerns of regional stress redistributions caused by induced fracturing operations, the reopening of inactive fractures poses the concerns of pathways extending beyond intent. However, a study on the behaviour and response of fracture propagation in cement blocks by Deghan et al. (Dehghan et al., 2015), stated that the feasibility of fracture propagation via the interaction of induced fractures with natural fractures is only possible if the strike and