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Effect of subsurface soil moisture variability and atmospheric conditions on methane gas migration in shallow subsurface

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ABSTRACT

A major concern resulting from the increased use and production of natural gas has been how to mitigate fugitive greenhouse gas emissions (predominantly methane) from natural gas infrastructure (e.g., leaky shallow pipelines). Subsurface migration and atmospheric loading of methane from pipeline leakage is controlled by source configurations and subsurface soil conditions (e.g., soil heterogeneity and soil moisture) and are further affected by atmospheric conditions (e.g., wind and temperature). However, the transport and attenuation of methane under varying subsurface and atmospheric conditions are poorly understood, making it difficult to estimate leakage fluxes from methane concentration measurements at and above the soil surface. Based on a series of controlled bench-scale experiments using a large porous media tank interfaced with an open-return wind tunnel, this study investigated multiphase processes controlling migration of methane from a point source representing a buried pipeline leaking at fixed flow rate (kg/s) under various saturation and soil-texture conditions. In addition, potential effects of atmospheric boundary controls, wind (0.5 and 2.0 $\mathrm{m\,s^{-1}}$) and temperature (22 and 35 °C), were also examined. Results showed the distinct effects of soil heterogeneity and, to a varying degree, of soil moisture on surface methane concentrations. In addition, results also showed the pronounced effects of wind and, to a lesser degree, of temperature on surface methane concentrations in the presence of varying soil and moisture conditions. The observed subsurface methane profiles were simulated using the multiphase transport simulator TOUGH2-EOS7CA. Observed agreement between measured and simulated data demonstrates that for the conditions studied, multiphase migration of a multicomponent gas mixture (including methane) under density-dependent flow can be adequately represented with a Fickian advection-diffusion (or dispersion) model (ADM) framework. The dominant effect of saturation over the soil texture, could also be inferred from numerical characterization.

1. Introduction

Despite continuing efforts to reduce greenhouse gas loading to the atmosphere to mitigate climate change, anthropogenic emission of greenhouse gases has accelerated during the last decade (2000–2010) compared to the preceding decade (Intergovernmental Panel for Climate Change; IPCC, 2014). The energy supply sector (inclusive of all energy extraction, conversion, storage, and transmission to final-users), the largest contributor to global greenhouse gas emissions, was responsible for 35% of the total anthropogenic emissions in 2010 (IPCC, 2014). Consequently, the energy sector has recently received renewed attention with the perspective of reducing future emissions by adopting low-carbon technologies in energy production. Fossil fuel-switching, in particular, is considered a promising strategy to reduce greenhouse gas emissions from the electricity-generation sector. Natural gas, in this regard, plays a role as a "transition fuel" when shifting from the high-carbon fossil fuels (coal and oil) to more environmentally-friendly renewable energy substitutes in the future (Levi, 2013). Notably, natural gas has a considerably smaller greenhouse gas footprint compared to that of coal in terms of greenhouse gas emissions per unit of energy produced in fossil fuel chains; natural gas is less intensive (290–930 $\mathrm{gCO_2eq/kWh}$) than oil (510–1170 $\mathrm{gCO_2eq/kWh}$) and coal

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Nomenclature

D_{β}^{κ}	Molecular diffusivity of component κ in phase β ($m^2\,s^{-1}$)
$\boldsymbol{g}$	Gravitational acceleration vector ($m\,s^{-2}$)
$\boldsymbol{F}$	Darcy flux vector ($kg\,m^2\,s^{-1}$)
$\boldsymbol{k}$	Intrinsic permeability (m^2)
k_r	Relative permeability (−)
M	Mass accumulation term ($kg\,m^{-3}$)
$\boldsymbol{n}$	Outward unit normal vector
P	Total pressure (Pa)
P_c	Capillary pressure (Pa)
$\boldsymbol{q}$	Mass flux ($kg\,m^{-2}\,s^{-1}$)
S	Saturation (−) Saturation (−)
t	Time (s)
T	Temperature (°C)
u	Wind velocity ($m\,s^{-1}$)
V	Volume (m^3)
X_{β}^{κ}	Mass fraction with phase subscript and component superscript (−)
X	X-coordinate (m)
Y	Y-coordinate (m)
Z	Z-coordinate (positive upward) (m)
T_D	Exponent for temperature dependence of diffusivity (−)

Greek symbols

α	1/Po in van Genuchten's capillary pressure function (Pa^{-1})
β	Phase index (subscript)Phase index (subscript)
Γ	Surface area (m^2)
κ	Mass components (superscript)
λ	van Genuchten's *m* (−)
μ	Dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	Density ($kg\,m^{-3}$)Density ($kg\,m^{-3}$)
τ	Tortuosity (−)
ϕ	Porosity ($m^3\,m^{-3}$)

Subscripts and superscripts

g	Gas
l	Liquid
w	Water
S	Saturation
max	Maximum
r	Residual
0	Reference value

(675–1689 gCO_2eq/kWh) (IPCC, 2011) and therefore is a promising energy surrogate for the coming decades (Cathles et al., 2012).

However, fugitive atmospheric emissions from leaky natural gas infrastructure may largely offset intended environmental benefits of natural gas usage since methane (CH_4), the predominant component of natural gas, has a global warming potential 86 times greater than CO_2 on a 20-year basis and 25 times greater over a 100-year time horizon (Jackson et al., 2013). (Note that the greenhouse gas potency is sensitive to the time frame of interest because CH_4 is converted to CO_2 in decadal scales.) Recent studies revealed that coal-to-gas switching would bring meaningful climate forcing benefits (in both short-term and long-term scenarios) provided fugitive CH_4 emissions are maintained below about 3% of gas production (Lelieveld et al., 2005). Nevertheless, the latest statistics on atmospheric methane leaks in gas supply chains are not conclusive and vary between 5%–1% (e.g. Howarth et al., 2011; Cathles et al., 2012). The present inventory-based leakage estimates are particularly incomplete and involve a wide range of uncertainties including invalidated emission factors (Karion et al., 2013; Lamb et al., 2015), undercounted "super-emitters" (Brandt et al., 2014), underrepresented high-emission production technologies (e.g., liquid unloading; API/ANGA, 2012), and unsolved issues in emission estimation methods (e.g., Pétron et al., 2012; Levi, 2012), etc. Several pipeline emission surveys conducted along major U.S. urban city roads also revealed surprisingly high CH_4 leaks (Jackson et al., 2013; Phillips et al., 2013) which were generally attributed to the aging underground gas infrastructure (USEPA, 2014) where more recently, Lamb et al. (2015) reported decreasing methane emissions. Importantly, all estimates, predictions, and recommendations in the USEPA (2014) study were made based on above-ground concentration measurements, with very limited attention paid to the controlling mechanisms of fate and transport of natural gas/methane in the shallow subsurface around the leaking pipelines under differing near-surface atmospheric controls.

Natural gas gathering, transmission and distribution pipelines range in material composition from high strength steel or copper to flexible plastic and can range in size from 40 to 6 in. in diameter, depending on the location and use (Folga, 2007; Transportation of Natural Gas, 2016). Although new steel and plastic pipelines are less prone to leaks than their older counterparts, aged pipelines, made of cast iron or unprotected steel, often leak due to earth movement, breakdown of joints and corrosion of unprotected steel, and graphitization (i.e., natural degrading to softer elements over time) of iron pipelines. Pipelines are usually placed in a trench 1.5–4 feet below ground. In the U.S., the depth is specified according to federal regulations (Transportation of Natural Gas, 2016) and depends on the pipe diameter, soil or rock type, terrain characteristics, etc. Upon laying the pipe, the trench is backfilled with excavated material. As backfilling often involves mechanical compaction (causing a low-permeability zone), additional materials, sometimes of different soil types, are used to achieve a level surface. If the excavation was done in rocky formations, a layer of broken rocks may be placed above the pipeline thus forming a high-permeability layer. In brief, differently- characterized layers are often found within the backfill zone above a leaky pipeline, which may markedly affect the subsurface methane migration.

Transmission mains typically carry natural gas at high-pressure conditions (~3500–9600 kPa) whereas low pressure conditions (1.5–2000 kPa) prevail in distribution systems. Consequently, in the event of a leak, the mechanism of gas emission into the surrounding porous medium, as well as the domain of influence of the leak, will vary depending upon the pressure conditions of the pipelines. In practice, high-pressure (advection-controlled) leaks are relatively easy to detect and fix up, while detecting small and diffusion-controlled leaks, as is the case presented in this study, is challenging.

The methane migration length scales from a leaky distribution pipeline may vary broadly in the range of 2–10 m (Okamoto and Gomi, 2011, Yan et al., 2015, and Xie et al., 2015) depending upon the burial depth, soil properties and moisture status (discussed below) as well as on the gas composition. With regard to gas composition, natural gas is composed almost entirely of methane (>94%) in transmission and distribution systems, however less methane contents may present in production (79%) and processing (87%) stages. (USEPA, 2003).

Fate and transport of methane in soil are primarily controlled by subsurface conditions such as heterogeneity, soil moisture, temperature, and pressure gradients (Poulsen et al., 2003). For example, gas migration in a texturally heterogeneous soil system (e.g., in the presence of a low-permeability clay lens embedded in a sandy formation) will be markedly different from that of a homogenous soil system due to the different texture- (or porosity-) induced tortuosity effects (Ho and Webb, 2006). Similarly, soil moisture