Fuel 180 (2016) 301–313

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

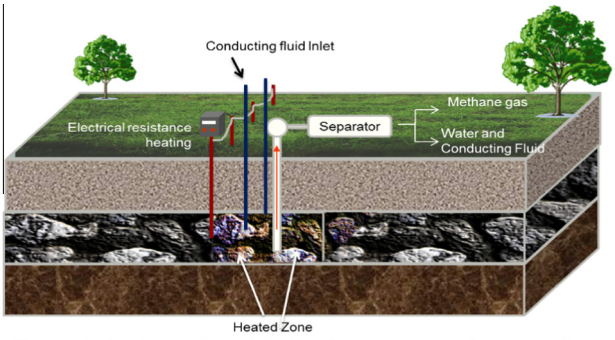
Full Length Article

Investigation of thermal stimulation of coal seam gas fields for accelerated gas recovery

Ali Shahtalebi [a], Chawarwan Khan [a], Anastasia Dmyterko [b], Pradeep Shukla [a,*], Victor Rudolph [a,*]

[a] School of Chemical Engineering, The University of Queensland, St Lucia, Brisbane, Australia
[b] School of Earth Science, The University of Queensland, St Lucia, Brisbane, Australia

GRAPHICAL ABSTRACT



Concept of enhanced coal-bed methane recovery by subsurface heating

ARTICLE INFO

Article history:
Received 31 January 2016
Received in revised form 13 March 2016
Accepted 14 March 2016
Available online 31 March 2016

Keywords:
Thermal stimulation
Coal seam gas
Diffusion
Permeability

ABSTRACT

In coal seam gas production, interventions to increase well productivity from poorly performing wells need to be matched to the nature of the coal, which may include: fracture stimulation if the permeability is low; and matrix stimulation if gas flow is restricted by the matrix diffusion. Increasing the coal bed temperature will assist in matrix stimulation by increasing the diffusion flux and in-turn enhance the well productivity.

Four different coal samples were studied against the temperature influence on methane storage as well as its transport inside the pores. It is found that a change in temperature, for e.g. $\Delta T \sim 40\,^{\circ}C$, may be expected to cause a three to four fold improvement in diffusivity. The experimental data was utilized in theoretical simulation of coal seam bed. By increasing the bed temperature, the total amount of methane recovered is higher, however, the economic benefit of extra methane produced is too small to justify the thermal stimulation of the bed. The true benefit of thermal stimulation lies in the enhanced rate of recovery which results in improving the NPV of the produced gas. Several production-well case scenarios were examined to determine the favourable conditions for implementing thermal stimulation technique and to determine if such a method could be commercially implemented on the field.

1. Introduction

Simplistically, the transport of methane out of a coal seam comprises two steps that operate in series: the diffusion of methane

* Corresponding authors.
E-mail addresses: pradeep.shukla@uq.edu.au (P. Shukla), v.rudolph@uq.edu.au (V. Rudolph).

http://dx.doi.org/10.1016/j.fuel.2016.03.057
0016-2361/

through the micro-pores and meso-pores (in combination referred here as 'matrix diffusion') into the micro-cracks and cleat system in the coal, followed by viscous (Darcy) pressure driven flow to the extraction well.

In a consecutive process, if the resistances to gas flow are very different, then the rate will be effectively determined by the greater resistance. Thus, coal seams that have a high permeability and a low diffusivity will be dominated by diffusion transport, whereas coal seams that have high diffusivities and short diffusion paths but low permeabilities, will be dominated by pressure dependent Darcy flow.

Both extremes are known to exist (e.g. in the US, Pocahontas coal is reported to be dominated by permeability, whereas the Pittsburgh seam is controlled by diffusion) [1,2]. Another example might be semi-anthracite or anthracite coals which often have very high gas contents and are quite well cleated, but are seldom gas targets because of their very slow gas desorption rates (or matrix diffusivity rates).

Interventions to increase well productivity will need to be matched to the nature of the coal: there is obviously little to be gained by fracture stimulating a seam if the permeability is already high and gas flow is restricted by the matrix diffusion. Enhancing production in this case requires that the diffusivity or the diffusion path length (or both) be improved.

Stimulation methods to increase permeability are well established. In contrast, diffusion stimulation is seldom addressed in the literature. One immediately apparent way to increase diffusivity is to increase the coal bed temperature.

The hypothesis underlying this study is that well productivity can be sufficiently improved under some reservoir conditions to commercially justify thermal stimulation. This would rely predominantly on the increased rate of production providing more gas in the early production years such that the present value (PV) of incremental revenue would exceed the PV of any incremental heating costs. An increase in the coal temperature also affects the residual methane content at the end of drainage, for e.g. study reported by Salmachi and Haghighi [3], which permits slightly more total gas to be recovered (a higher ultimate gas recovery), however this is likely to be of much smaller economic consequence than the improved production rate. The reason is that this value is only realized at the end of the reservoir life, so the discounted present value is diminished.

This paper provides quantitative, experimental measures for several coal samples obtained from 2 different sites in Queensland, Australia. The test includes

- adsorption equilibrium and it's temperature relationship;
- diffusivity and the temperature–diffusivity relationship;
- unstressed permeability and the permeability–temperature relationship.

And based on these experiments provide a number of simple reservoir simulation case studies to illustrate the feasibility of thermal stimulation and its sensitivity to various reservoir characteristic parameters (permeability, diffusivity, porosity, cleat spacing).

2. Materials and methods

The vital temperature dependent properties which dictate the quantity and kinetics of gas release from coal seam were experimentally measured and their temperature relationship were determined. The coal samples used in the study was obtained from different sites in Queensland, Australia and labelled as CS1 and CS2 for samples which were obtained from well 1 and CS5 and CS6 for samples obtained from well 2 [CS – Coal Sample]. The samples from each well were obtained from slightly different depth, for example CS1 was obtained from approx. 1004 mRT from top while CS2 obtained from 1082 mRT from the surface. The samples obtained from different depth helps to understand the diversity in the gas transport properties in a particular seam.

2.1. Methane gas storage measurement

The methane gas sorption on coal bed is an exothermic process, hence desorption equilibrium shifts favorably upon temperature increase. In-order to determine the theoretical maximum amount of recoverable gas at high temperature, we experimentally measured the methane storage capacity of coal samples at different temperatures. The total gas adsorption analysis in the selected coal samples were carried out at low pressure (1 bar) as well as high pressure (to a maximum of 12 bar). The adsorption measurements were carried out at 3 different temperatures. The low pressure adsorption tests were carried out in a volumetric experimental setup, while the high pressure tests were performed using a gravimetric instrument. Prior to the adsorption analysis, the samples were crushed and sieved to obtained particles in the range of 30 μm. Further the samples were carefully degassed to remove any moisture and pre-adsorbed gases.

2.2. Kinetic experiments and diffusion measurement

The temperature dependency of diffusion kinetics is governed by Arrhenius law and increases considerably as the temperature is raised, hence experiments were conducted to determine the diffusion behavior by changing the temperature. The diffusion information was obtained using time resolved adsorption kinetic experiment conducted using the volumetric adsorption system. In a typical test, the pre-treated and degassed sample was dosed with fixed amount of methane and the change in the pressure was recorded by the pressure transducer. In a fixed volume closed system, the total moles of gas in the cell is conserved. Within the closed system the amount of gas lost from the gas phase is equal to the amount of gas adsorbed in the solid.

The instantaneous adsorption in solid phase was thus calculated based on the change in the pressure of the gas phase as per Eq. (1) below

$$P_t = P_{init} + \frac{M \cdot Z \cdot Rg \cdot T}{Ve}(N_{init} - N_t) \quad (1)$$

where P_t is the pressure in the cell measured by the transducer at time t; P_{init} is the initial cell pressure at time $t = 0$ (i.e. just after dosing the gas in the cell); M is the mass of the sample in the cell; Rg is the gas constant; T is temperature in the cell; Z is the gas compressibility factor; Ve is the dead volume of the cell; N_{init} is the initial moles of gas adsorbed before dosing the gas in the cell and N_t is the specific moles adsorbed at any instant time 't'. The kinetic measurements were carried out at three different temperatures, i.e. 30, 50 and 70 °C.

2.2.1. Zero time correction in kinetic measurement

The kinetic measurement using volumetric technique has an inherent issue with the zero time pressure measurement which leads to incorrect data. At time $t = 0^-$ the inlet valves opens to dose the fixed amount of gas in the sample cell and the pressure is recorded and at time $t = 0^+$ the valves closes which results in slight increase in the cell pressure. This effect which is caused due to valve dynamics is often merged together in the adsorption value at zero time resulting in incorrect results. While, such an effect can be ignored if the diffusion inside the sample in extremely slow, however for samples with sufficient amount of mesopores where